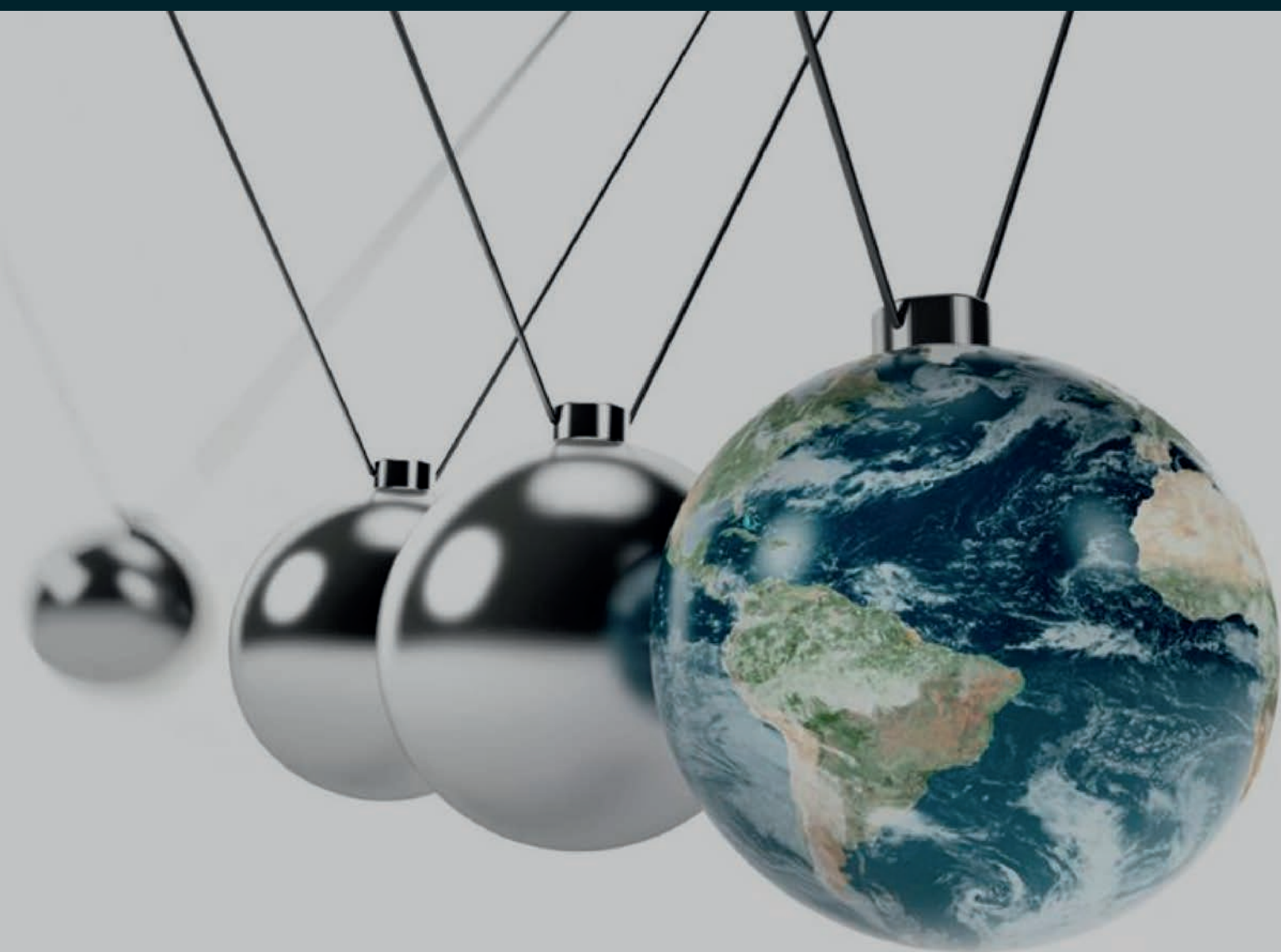


Environmental Outlook on the Triple Planetary Crisis

Stakes, Evolution and Policy Linkages



Environmental Outlook on the Triple Planetary Crisis

STAKES, EVOLUTION AND POLICY LINKAGES

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Please cite this publication as:

OECD (2025), *Environmental Outlook on the Triple Planetary Crisis: Stakes, Evolution and Policy Linkages*, OECD Publishing, Paris, <https://doi.org/10.1787/257ffbb6-en>.

ISBN 978-92-64-71679-7 (print)
ISBN 978-92-64-46691-3 (PDF)
ISBN 978-92-64-55595-2 (HTML)

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Foreword

This OECD Environmental Outlook focusses on the triple planetary crisis of climate change, biodiversity loss and pollution. It develops an integrated modelling framework that links socio-economic drivers and environmental outcomes as well as an analytical framework for exploring the complex interlinkages between the challenges at multiple levels, including their drivers, pressures, states and policy responses.

The report contains a total of seven chapters. **Chapter 1** introduces the stakes of the triple planetary crisis and their notable biophysical and policy linkages and establishes key contributions of the Outlook.

The following two chapters present model-based projections on how environmental change may unfold through to 2050 based on the policies that are currently in place. **Chapter 2** unpacks the common and underlying drivers of the triple planetary crisis. **Chapter 3** examines the current and projected state of each dimension of the triple planetary crisis, providing quantitative insights into the evolution of mutually reinforcing challenges.

The subsequent three chapters turn to policy interlinkages. **Chapter 4** develops a clustered approach to analysing the interactions between policies that aim to tackle climate change, biodiversity loss and pollution and provides a conceptual overview of potential synergies and trade-offs. **Chapter 5** presents a policy stocktake based on the Biennial Transparency Reports (submitted under the Paris Agreement) and the National Biodiversity Strategies and Action Plans (submitted under the Convention on Biological Diversity) of ten countries examine the extent to which synergies and trade-offs are currently considered. **Chapter 6** explores the synergies and trade-offs between responses to climate change, biodiversity loss and pollution at the implementation stage through four deep dives on: (i) renewable energy expansion, (ii) management and expansion of protected areas, (iii) air pollution control and (iv) nutrient management. **Chapter 7** summarises the key findings and presents a roadmap for policy action to tackle the triple planetary crisis.

Acknowledgements

This report was conceptualised and directed by Shardul Agrawala, Head of Division of the Environment and Economy Integration Division (EEI) in the Environment Directorate of the OECD. The OECD Environment Policy Committee (EPOC) was responsible for the oversight of the report. The model-based analysis underpinning the Outlook was a collaboration between OECD and the IMAGE-GLOBIO team at the Netherlands Environmental Assessment Agency (PBL). This report was edited by Shardul Agrawala, Yuko Ishibashi and Rob Dellink (all OECD Environment Directorate).

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The analysis benefitted from valuable feedback from Enrico Botta, Bob Diderich, Rocío García, Johannes Goeschl, Kumi Kitamori, Yuval Laster, Mathilde Mesnard, Walid Oueslati, Eeva Leinala, Jane Richardson, Emily Seftel, Jo Tyndall (all OECD Environment Directorate), Hubertus Gay, Koen Deconinck, Hugo Valin (OECD Trade and Agriculture Directorate) and Scott Vaughan (the International Institute for Sustainable Development).

Modelling contributions from PBL Netherlands Environmental Assessment Agency were provided by the IMAGE-GLOBIO team led by Detlef van Vuuren: Astrid Bos, Vassilis Daioglou, Jonathan Doelman, Alexandra Marques, Rob Alkemade, Arthur Beusen, Ioannis Dafnomilis, Elena Hooijschuur, Martijn van der Marel and Elke Stehfest. External partners Willem-Jan van Zeist (Wageningen Social & Economic Research) and Jelle Hilbers (Radboud University) are gratefully acknowledged for their contribution to the model-based analysis. Claudio Belis (European Commission Joint Research Centre) and Andreas Gavros (Fincons SpA) also provided the results of TM5-FASST.

The following external experts also contributed to the draft report and analysis: Ethan Addicott, Ian Bateman, Amy Binner (Land, Environment, Economics and Policy Institute, University of Exeter Business School), James Rising (University of Delaware) and Tamma Carleton (University of California, Santa Barbara).

Ijeoma Inyama-Dalles and Illias Mousse Iye (OECD Environment Directorate) provided administrative support. Elizabeth Del Bourgo, Emma De Roy, Max Doughty, William Foster, Rozalia Harsanyi (OECD Environment Directorate) as well as Johanna Gleeson, Elisabeth Schoeffmann and Yumiko Sugaya (OECD Communications Directorate) contributed to communication and outreach aspects of the report. Meral Gedik (independent consultant) prepared the report for publication.

Financial contributions from Canada, the European Union, Germany, Italy, Japan, Korea, Luxembourg, the Netherlands and Sweden are gratefully acknowledged.

Editorial

As governments navigate elevated policy uncertainty and pressures on global growth prospects, they also face the need to make progress on their environmental objectives. The triple challenge posed by climate change, biodiversity loss and pollution – from plastics to harmful chemicals – continues to intensify and requires effective solutions.

These environmental challenges have wide-ranging implications for ecosystems, human health, economic growth and well-being. This Environmental Outlook provides a comprehensive evidence base to help policymakers better understand interlinkages among these challenges. For example, climate change and pollution are key drivers of biodiversity loss. Indeed, the OECD projects that climate change will surpass land-use change as the main driver of biodiversity loss by 2050. In turn, biodiversity loss compromises ecosystem resilience to extreme weather events and pollution, with direct consequences for our air, water and soil.

The Outlook also identifies practical levers to support more co-ordinated, integrated and effective policy responses. The green energy transition is one key priority for addressing the triple challenge. Expanding renewable energy can reduce carbon emissions, improve air quality and ease climate-induced pressures on ecosystems. However, without careful planning, clean energy infrastructure can also create new challenges, including pressures on natural habitats and waste management concerns at the end of technology lifecycles.

The policy implications are clear: climate change, biodiversity loss and pollution cannot be addressed separately in isolation. By drawing on the insights in the Outlook's policy roadmap, governments can develop a more co-ordinated approach to better harness synergies and manage the risk of trade-offs among policy tools.

The OECD remains committed to supporting countries in developing and implementing more integrated, evidence-based approaches to address the triple challenge, and lay the foundations for more resilient, sustainable growth in the years to come.



Mathias Cormann,

OECD Secretary-General

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Abbreviations and acronyms

AFOLU	Agriculture, Forestry and Other Land Uses
BC	Black carbon
BECCS	Bioenergy with carbon capture and storage
BTR	Biennial Transparency Report
CBD	Convention on Biological Diversity
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CFC	Chlorofluorocarbon
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
CRM	Critical raw material
EIA	Environmental impact assessment
EJ	Exajoule
EPR	Extended producer responsibility
EV	Electric vehicle
F gases	Fluorinated gases
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne
INMS	International Nitrogen Management System
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resource Panel
IUCN	International Union for Conservation of Nature
KMGBF	Kunming-Montreal Global Biodiversity Framework
LCA	Lifecycle assessment
LPI	Living planet index
Mha	Million hectares
MSA	Mean species abundance
Mt	Million tonnes

Mt CO ₂ e	Million tonnes of carbon dioxide equivalent
N	Nitrogen
N ₂ O	Nitrous oxide
NbS	Nature-based solutions
NBSAP	National biodiversity strategy and action plan
NC	National communication
NDC	Nationally determined contribution
NH ₃	Ammonia
NH ₄ ⁺	Ammonium
NM VOC	Non-methane volatile organic compound
NO ₂	Nitrogen dioxide
NO ₃ ⁻	Nitrate
NO _x	Nitrogen oxides (including nitric oxide and nitrogen dioxide)
O ₃	Ground-level ozone
ODS	Ozone-depleting substance
P	Phosphorus
PES	Payments for Ecosystem Services
PFAS	Per- and Polyfluoroalkyl Substances
PM	Particulate matter
POP	Persistent organic pollutant
PPP	Purchasing power parity
PV	Photovoltaic
S	Sulphur
SDGs	Sustainable Development Goals
SEA	Strategic environmental assessment
SEEA EA	System of environmental-economic accounts ecosystem accounting
SLCP	Short-lived climate pollutant
SO ₂	Sulphur dioxide
SO ₄ ²⁻	Sulphate
SO _x	Sulphur oxides
UNEA	United Nations Environment Assembly
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compound
WHO	World Health Organization

Executive Summary

The triple planetary crisis of climate change, biodiversity loss and pollution poses a growing threat to the environment and the economy. While each of these challenges is pressing, interlinkages can magnify their cumulative impact while creating opportunities for synergistic action. This *Environmental Outlook* aims to inform an integrated policy approach that accounts for common drivers, pressures and mutually reinforcing impacts of climate change, biodiversity loss and pollution.

Key Findings

The three challenges have interlinked common drivers

Projections based on integrated biophysical and economy-wide modelling in this *Outlook* suggest that, under current policies, between 2020 and 2050:

- Global GDP is projected to more than double (from USD 126 trillion to USD 283 trillion), equivalent to 2.7% annual average growth. Large parts of Asia and Africa are projected to experience faster growth.
- Environmental pressures are primarily driven by growth in specific economic sectors, spurred by socio-economic trends of population and economic growth.
 - Agriculture will remain the main driver of land use change, responsible for 87% of land conversion. Intensification in agricultural production will mitigate but not prevent an increase in agricultural land.
 - Fossil fuel use is projected to increase by 16% (from 466 to 541 exajoules), with a shift towards natural gas. Amid ongoing electrification of the energy system, renewables power generation is projected to more than double (from 80 to 209 exajoules).
 - Primary materials use is projected to increase by roughly half (from 96 to 145 Gigatonnes) while global water withdrawal is expected to increase by 17%.
- Technological and behavioural changes will enable some decoupling between environmental pressures and economic growth. However, these factors are projected to slow – but not halt – global demand growth of energy, food, materials and water.

Environmental pressures underpinning the triple planetary crisis are set to intensify along several dimensions

As environmental pressures rise, climate change, biodiversity loss and pollution are set to worsen over time and reinforce each other. Modelling projections suggest that, under current policies, between 2020 and 2050:

- Global mean temperatures will continue to increase (from 1.2°C in 2020 to 2.1°C in 2050 above pre-industrial levels). Climate change is also projected to become the main driver of biodiversity loss before mid-century.

- The terrestrial mean species abundance index is projected to further decline (from 59.7 to 56.5). This is equivalent to the conversion of pristine habitat of more than 4 million km² into an area where all the original species have been lost.
- As regards pollution, the situation is mixed.
 - Concentrations of particulate matter and ozone are projected to decline in most regions, driven by reduction in emissions of precursor gases. Sulphur dioxide emissions, for instance, are projected to significantly decline in all regions (with a 64% decrease globally). This decline, however, will accelerate warming due to the cooling effect of sulphur dioxide.
 - Pollutant emissions to water and soil are projected to continue to increase, not least ammonia (with a 43% increase globally).
 - Mismanaged plastic waste is projected to increase from 83 to 138 million tonnes, leading to an increase in global plastic leakage to the environment from 22 to 37 million tonnes.

There is ample potential for more integrated policies, but much more needs to be done

- The linkages among climate change, biodiversity loss and pollution may suggest that addressing one challenge automatically helps tackle the other two. However, interactions between policies underscore the potential for synergies and trade-offs. Failing to consider these interactions can result in policy gaps and missed opportunities from more integrated action.
- A first-of-its-kind stocktake of 20 national documents across 10 countries (Argentina, Australia, Canada, the People's Republic of China, France, India, Indonesia, Japan, Peru, and Uganda) finds that:
 - Biennial Transparency Reports and National Biodiversity Strategies and Action Plans include relatively extensive discussions on the linkages between climate change and biodiversity in terms of their biophysical impacts.
 - Considerations of how climate change and biodiversity loss might affect the severity and extent of pollution are largely lacking.
 - Policies targeted at managing trade-offs – particularly for pollution – are sparse.
- Deep dives demonstrate opportunities for a more integrated approach for renewable energy expansion, management and expansion of protected areas, air pollution control and nutrient management.

Six policy levers can support the development of more synergistic responses

Three foundational levers can lay the groundwork for integrated policy approaches to fundamentally address the triple planetary crisis and its underlying drivers:

- Addressing key gaps in research and assessment through better targeting of research funding and by leveraging (inter)national scientific assessment processes on climate change, biodiversity loss and pollution.
- Strengthening the consideration of interlinkages between these three challenges in national reporting frameworks for multilateral environmental agreements. In addition, developing national approaches to tackle pollution comparable to those for climate change and biodiversity can help prevent blind spots.
- Aligning finance and resource allocation towards jointly addressing the challenges posed by the triple planetary crisis. Synergies can be promoted by embedding interlinkages in multilateral environmental and development finance, using national budgeting processes to incentivise collaboration across ministries and ensuring support measures are well-targeted.

Complementarily, specific considerations for clean energy, material resources and food systems can help enhance synergies and minimise the risks for trade-offs, while also addressing social and distributional concerns such as job and income losses, affordability, and access to food and energy:

- Better assessing and managing unintended impacts of the clean energy transition so that the adverse biodiversity and pollution impacts do not become an impediment to accelerated renewable energy expansion. Spatial planning and regulatory tools such as licensing and permitting, as well as better management of end-of-life fates, can help limit potential adverse impacts of renewables expansion on biodiversity and pollution control objectives.
- Transitioning to a more resource-efficient and circular economy to address the significant environmental impacts of resource use on the triple planetary crisis. Action is needed across the materials lifecycle, including mainstreaming the circular economy within other policy domains, exploiting synergies with resource-intensive sectors, strengthening and realigning incentives, and leveraging demand-side interventions.
- Policies are needed to reduce the environmental footprint of food production and consumption. This is critical to reducing greenhouse gas emissions, mitigating ecosystem degradation from agricultural land use expansion and intensification, and alleviating nutrient pollution. Governments can consider revising regulations and safeguards with an aim to reduce emissions, shift diets and decrease food loss and waste.

1

Motivation, analytical framework and overview of the Environmental Outlook

Climate change, biodiversity loss and pollution are increasingly referred to under the framing of the triple planetary crisis, recognising the complex interlinkages at the levels of the underpinning planetary processes and the policies developed in response. This introductory chapter first provides the context and the stakes of the interlocking challenges and establishes the key contributions and the outline of the new OECD Environmental Outlook. It then summarises the notable biophysical linkages and introduces the emerging policy landscape that calls for a more integrated and synergistic policy approach. Finally, it provides a review of the past work and outlines the methodological approach taken in the Outlook.

1.1. Introduction

Climate change, biodiversity loss and pollution – the three elements of what is now called “the triple planetary crisis” – are a growing significant risk to human health, well-being, the environment and the economy. Although each challenge is individually pressing, their complex interlinkages can amplify their impacts while also opening up opportunities for more integrated policy action.

Anthropogenic emissions of greenhouse gases (GHG) are responsible for the observed increase in global surface temperature since the industrial revolution (IPCC, 2023^[1]). 2024 was the warmest year since 1850, 1.6 °C warmer than the pre-industrial level (Copernicus Climate Change Service, 2025^[2]). This exceeded, for the first time in history, the lower bound threshold set forth by the Paris Agreement to limit “the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C [...]” (Paris Agreement, 2015^[3]). The Sixth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) concludes that climate change is already affecting every inhabited region across the globe, with human activity contributing to many observed changes in weather and climate extremes. This includes heat waves, wildfires, heavy precipitation and the associated flooding, sea level rise and drought. Changes in climatic variables including temperature and precipitation patterns may affect crop yields and food security, as well as having negative consequences on human health. Under current climate mitigation policies, median global warming could reach 2.4 to 3.5°C by 2100 (IPCC, 2022^[4]). The latest scientific evidence also suggests that tipping points in the climate system could be crossed even under low levels of warming (IPCC, 2021^[5]).

Biodiversity is broadly defined as “the variability among living organisms from all sources, including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems” (United Nations, 1992^[6]). While there is no universal indicator that can adequately capture all the dimensions, functions and complex interactions of biodiversity (Magurran, 2021^[7]), available metrics suggest that global biodiversity is in overall decline (OECD, 2021^[8]). The last Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) global assessment report found that around 25% of the species in plant and animal assessed groups were threatened with extinction – a larger proportion than ever before. Jointly, the extent and physical condition of natural ecosystems deteriorated by 47% on average, relative to their earliest estimated states (IPBES, 2019^[9]). The accelerating trends of biodiversity decline are a concern, as it compromises valuable and often irreplaceable ecosystem services. For example, agricultural production can be compromised by biodiversity loss, as approximately 75% of global food crop types (equivalent to 35% of global crop production in volume), including fruits and vegetables, rely to some extent on pollination from bees, butterflies and other insects (IPBES, 2017^[10]). If insufficient action is taken, there will be further acceleration in the rate at which species become extinct around the world, which is already at least tens to hundreds of times above the average over the past 10 million years.

Pollution (defined broadly as the introduction of substances and forms of energy into the environment with adverse impacts on human health and the environment) is widespread, multifaceted and affects all media: air, water and soil. Pollution has significant adverse health consequences, with estimates suggesting it was responsible for 9 million premature deaths in 2019, equivalent to one out of six deaths around the world (Fuller et al., 2022^[11]); see also Annex Table 1.A.1 on a select examples of health impacts. Air pollution was responsible for the majority of pollution mortality (6.7 million premature deaths), in which 62% of deaths were attributed to ambient particulate matter (PM_{2.5}), while water pollution, including unsafe drinking water and sanitation, was estimated to be responsible for 1.4 million premature deaths (Fuller et al., 2022^[11]). Soil pollution is also pervasive. Estimations suggest that there are over 5 million contaminated brownfield sites around the world (Hou et al., 2023^[12]).¹ Meanwhile, 38% of global municipal solid waste was uncontrolled (e.g. not collected, or collected but later dumped or burned in open sites i.e. mismanaged) in 2020 (UNEP, 2024^[13]). Further, disease attributable to mismanaged waste is estimated to cause 0.4 to 1 million deaths annually in developing countries (UNEP, 2024^[13]).

The sheer variety, number and ubiquity of chemicals in modern life is illustrative of the complexity of tackling pollution. While manufactured chemicals have contributed to economic productivity, health, food security and well-being, many chemicals are also hazardous (UNEP, 2019^[14]). A range of chemicals are considered to have adverse environmental and health impacts, including developmental neurotoxicity, reproductive toxicity and immunotoxicity (Fuller et al., 2022^[11]). Lead poisoning remains a persistent challenge – responsible for 0.9 million deaths mostly due to its link to cardiovascular diseases; a number that could be six times higher according to an alternative estimate considering impacts of lead beyond increased blood pressure (Larsen and Sánchez-Triana, 2023^[15]). Agrochemicals, such as pesticides and excess nutrients applied as fertilisers, also threaten human health and negatively affect ecosystems (Devi, Manjula and Bhavani, 2022^[16]).

However, the impact of pollution could be even larger since much still remains unknown about the effects of pollutants and their impacts on human and planetary health. Each year, around 6.1 million tonnes (Mt) of plastic waste leaks into aquatic environments, of which 1.7 Mt flows into oceans (OECD, 2022^[17]). While the negative and visible effects of macroplastics on species such as entanglement are relatively well documented, the impacts of microplastics and those mediated by plastic chemicals on human health and the environment are still uncertain and possibly underappreciated (Landrigan et al., 2025^[18]). Meanwhile, Per- and Polyfluoroalkyl Substances (PFAS), known as “forever chemicals” due to their persistence in the environment, have been found in many places including drinking water, soils, food and household products in a range of countries (Wee and Aris, 2023^[19]). While research is still limited to a handful of PFAS, available epidemiological studies suggest that exposure to certain PFAS, even at low levels, can lead to negative health outcomes (Fenton et al., 2021^[20]). For instance, PFAS in-vitro and in-vivo exposure is associated with suppressed immune function (Sunderland et al., 2019^[21]). Furthermore, the International Agency for Research on Cancer has recently classified PFOA and PFOS (perfluorooctanoic and perfluorooctanesulfonic acids, which constitute two groups of PFAS) “carcinogenic to humans” and “possibly carcinogenic to humans”, respectively (Zahm et al., 2024^[22]).

1.2. Motivation and overview of the OECD Environmental Outlook

This *OECD Environmental Outlook* examines the interlinkages among climate change, biodiversity loss and pollution at multiple levels, including their interlocking drivers, environmental pressures, states and biophysical impacts, as well as in terms of policy responses. Underpinning the Outlook is an integrated modelling toolbox (Section 1.6.1) to consistently capture these sets of interlinkages. The model-based quantitative analysis charts how environmental change may unfold through to 2050 based on the policies that are currently in place, providing insights into the key channels and their magnitude as well as their potential future developments (Chapters 2 and 3). A better understanding of the regionally specific factors exacerbating the challenge can help identify policy priorities for different regions and sectors.

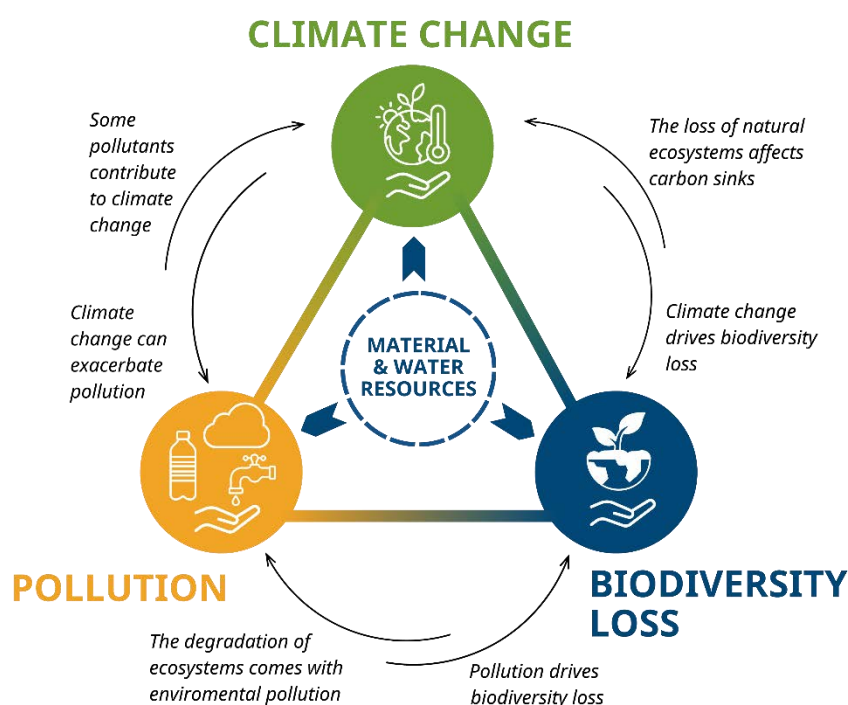
The subsequent three chapters turn to the policy interactions. Chapter 4 develops a clustered approach to identify the potential synergies and trade-offs between policy objectives by thematically categorising representative sets of policies to tackle climate change, biodiversity loss and pollution into broad clusters based on the overall objective to which they contribute. Following this conceptual analysis, Chapter 5 presents a first-ever stocktake of policy integration by reviewing Biennial Transparency Reports (BTRs) to the United Nations Framework Convention on Climate Change (UNFCCC) and the National Biodiversity Strategies and Action Plans (NBSAPs) submitted under the Convention on Biological Diversity (CBD) of 10 countries to examine the extent to which synergies and trade-offs are considered in policymaking at the national level. Chapter 6 delves into key considerations for policy integration at the implementation stage of core policy responses within four key areas: (i) renewable energy expansion, (ii) management and expansion of protected areas, (iii) air pollution control and (iv) nutrient management. Finally, insights from the modelling and the policy analysis in the Outlook are then summarised to develop recommendations on how governments can develop more integrated responses in Chapter 7.

The remainder of this overview chapter is organised as follows. First, Section 1.3 reviews the biophysical and biogeochemical interlinkages among climate change, biodiversity loss and pollution.² Next, Section 1.4 provides an overview of the interlinkages that are being recognised within multilateral frameworks. An assessment of past relevant work on the interlinkages is provided in Section 1.5 and key gaps are identified. The integrated modelling toolbox and analytical framework developed for this Outlook to address some of these research gaps are detailed next in Section 1.6.

1.3. Biophysical interlinkages between environmental challenges

Climate change, biodiversity loss and pollution interact in complex ways (Figure 1.1). For example, climate change and pollution each contribute to around 14% of the measured biodiversity loss (IPBES, 2019^[9]), along with land and sea-use changes (30%), direct exploitation of natural resources (23%), invasive alien species (11%) and other human disturbance (9%). The combination of increased temperature, low humidity and precipitation will lengthen the warmer and drier seasons with heightened risk of wildfires, which can lead to habitat degradation and loss in some regions, although it is also important to note that some ecosystems rely on fire to maintain habitat quality and stimulate regeneration (Bowman et al., 2009^[23]). A warmer climate will also increase the risk of extreme weather events such as floods that can lead to spills, leaks and release of pollutants including waste such as plastic waste into the environment. Pollution, in turn, can degrade natural habitats and adversely affect biodiversity; furthermore, some pollutants affect the climate (either as coolant or warming forcer). Loss and degradation of natural habitats, meanwhile, can compromise important regulating ecosystem services such as carbon sequestration and erosion control that are key to climate change mitigation and adaptation.

Figure 1.1. Illustration of select interlinkages



Source: Authors' own elaboration.

The sheer number of possible interactions among environmental stressors defies an exhaustive analysis (Côté, Darling and Brown, 2016^[24]). Some interlinkages are more prominent and more direct than others. Available evidence also suggests that the overall impacts of these interlinkages are highly context- and ecosystem-dependent, with variations in their magnitude and direction (Catford et al., 2022^[25]). Nonetheless, the findings from the available studies suggest that a myopic focus on one aspect may lead to mismanaged trade-offs and missed opportunities for synergies. Notable linkages are summarised in Table 1.1 through illustrative examples. These pairwise linkages are further detailed in the following section.

Table 1.1. Examples of interlinkages

Category	Examples
Climate change drives biodiversity loss	Risk of habitat disturbance, alteration and destruction from increasing carbon dioxide (CO ₂) concentrations in the atmosphere, temperature, precipitation and extreme weather events.
	Changes in climatic variables such as temperature induces genetic adaptation among species which may alter compositional biodiversity and threaten the ecological integrity of biomes.
	Increasing temperatures induce species to move to climatic conditions within their thermal range which alters interactions among species and threatens those which cannot relocate or have smaller thermal ranges. The range shifts can also affect the spread of vector-borne diseases (e.g. West Nile virus and lyme disease).
	Extreme weather events can directly harm species, reduce species richness and biomass and hinder ecosystem resilience.
Climate change amplifies the impacts of other drivers of biodiversity loss	Rising temperatures can increase the toxicity and volatilisation of some pollutants while reducing ecosystem recovery capacity and community resistance.
	Impacts of climate change (e.g. melting glaciers and polar ice) increases accessibility of remote areas which increases direct exploitation pressure (e.g. new shipping routes in the Arctic).
	Increasing temperatures may favour the spread of invasive alien species promoting biotic homogenisation.
	Ocean acidification can negatively impact marine species (in particular shell-forming and calcifying species).
Biodiversity loss accelerates climate change	Loss of marine and terrestrial ecosystems releases stored carbon and reduces future carbon storage capacity.
	The process of forest degradation and deforestation (and the resultant biodiversity loss) coupled with increasing wildfire occurrence due to prolonged dry seasons results in certain forestlands becoming net carbon emitters, further contributing to climate change.
Biodiversity loss reduces nature's climate adaption potential	Deforestation and soil biodiversity loss limit ecosystem capacity to regulate surface temperatures through photosynthesis and evapotranspiration at a local and global scale.
	Compositional and spatial changes in terrestrial biodiversity impact surface temperature through albedo, emissivity and surface roughness.
	Biodiversity loss reduces resilience to extreme weather events and rising sea levels such as the protective role of wetlands and mangroves from flooding.
Pollution drives biodiversity loss	Air pollutants – like ground-level ozone (O ₃), nitrogen oxides (NO _x), sulphur dioxide (SO ₂) and particulate matter (PM) – can reduce the effectiveness of pollinators and natural pest regulators as well as slow vegetation growth.
	Nutrient pollution can impact biodiversity by contributing to the spread of certain invasive alien species, eutrophication of water bodies, harmful algal blooms, and harmful airborne compounds.
	Pesticide pollution can increase the risk of mortality for non-target species and alter compositional biodiversity by favouring pesticide-tolerant species.
	Macroplastic pollution increases the risk of entanglement or ingestion for marine species directly harming them and increasing mortality risk in addition to plastic debris being a raft for non-native species altering their interactions by eschewing natural geographical ranges. While their environmental and health impact remains uncertain, the presence of microplastics is documented across terrestrial and aquatic ecosystems, and even in human organs and specimens.
	Heavy metals such as mercury bioaccumulate and biomagnify through food chains in freshwater ecosystems to cause significant harm to human and wildlife health.
	Endocrine disrupting chemicals compromise reproductive capacity across taxa (e.g. fish, mammals and insects).
	Deforestation reduces the capacity of forests to absorb and degrade pollutants through infiltration and percolation, and of their canopies to purify pollutants and prevent them from reaching ground-level.
Biodiversity loss compromises nature's capacity to recover from pollution	Decline in wetland dependent species threatens ecosystem services provided by wetlands such as water purification through matter decomposition and nutrient cycling. A balanced nutrient cycle – involving the movement of nutrients through soils, plants, animals, and the environment – helps remove, transform, or retain nutrients and limit pollution of water bodies.
	Pollution may reduce resilience of species if, for example, adaptation to a pollutant reduces genetic diversity and thus capacity to adapt to further stressors.

Category	Examples
Climate change alters the mobilisation patterns and properties of pollution	Rising temperatures impact pollution transfer in various ways such as pesticides accumulating in the atmosphere through vaporisation, release of pollutants from glacial melt and permafrost thaw, quicker degradation of plastics, and increasing toxicity.
	More frequent extreme weather events can increase the transfer of pollution from environmental reservoirs such as increased runoff from flooding.
	Climate change can have mixed effects upon pollutants: higher temperatures can increase volatile organic compounds (VOCs) released from various sources, but increased precipitation can reduce PM concentration.
Pollution affects temperature and other climatic variables	Air pollutants can compound climate change through warming effects, impacts upon cloud properties, precipitation, radiation and induced snowmelt amongst other things.

Source: Authors' own elaboration based on the literature reviewed in this Outlook.

1.3.1. Interlinkages between climate change and biodiversity loss

Climate change drives biodiversity loss

Climate change is one of the main drivers of biodiversity loss (IPBES, 2019^[9]), the importance of which is projected to further increase in the near future (Ortiz et al., 2021^[26]) (see also Chapter 3). While the magnitude varies both by individual taxonomic groups and biomes, climate change is estimated to result in an accelerated loss of species richness as well as areas with suitable climates (Nunez et al., 2019^[27]). An estimate suggests that the geographical range size of mammals, birds and amphibians has already declined by 18% on average over the centuries, and climate change can further trigger accelerated habitat loss (Beyer and Manica, 2020^[28]). Increased CO₂ concentrations in the atmosphere, temperature rise and changes in precipitation patterns can also directly alter the environment of natural habitats. In marine ecosystems, rising global temperatures lead to melting glaciers and subsequent rising sea levels which can cause the loss of important habitats such as mangroves, salt marshes and coral reefs – critical ecosystems supporting diverse marine life (Kibria et al., 2021^[29]) (see also Box 1.1).

Climate change affects various interrelated dimensions of biodiversity. Climate change induces various genetic and plastic (changes in physiology and morphology as well as development) responses of species,³ which alter the interactions between species and their ecological functions, cascading across scales and even threatening the ecological integrity of biomes (Bellard et al., 2012^[30]; Jaureguiberry et al., 2022^[31]).

Interactions among species are also altered by the climate-induced shifts in their geographical ranges. Since species have limited thermal (and hence geographical) performance ranges, climate change triggers species to shift to higher latitudes, altitudes and deeper water in search of more suitable climatic conditions (Pörtner et al., 2023^[32]). From fish communities in the Arctic to plant species in North America, these shifts have already been observed across continents and taxonomic groups. A recent study estimates that species have shifted along elevations at 11 m per decade and higher latitude at 16.9 km per decade on average (Muluneh, 2021^[33]). Such adaptive shifts are not viable for thermally specialised species with a narrow range of temperature variation or species already living near their tolerance thresholds, such as polar bears in the Arctic. Species that are native to insular environments, such as mountain peaks and isolated freshwater lakes, are also unable to seek new climates (Pinsky, Comte and Sax, 2022^[34]). The fragmentation of landscape further hinders the adaptive shift of species, posing obstacles to their movement (Urban, 2015^[35]).

Those unable to migrate or adapt rapidly face the risk of local extinction (Pinsky, Comte and Sax, 2022^[34]). Furthermore, the responses of species to the changing environment through evolutionary adaptation and migration are expected to become increasingly less viable due to the magnitude and accelerating pace of climate change (Sage, 2020^[36]). While there are a range of estimates and a high level of regional variability, climate change is projected to lead to the extinction of 7.9% of species on average (Urban, 2015^[35]). In

particular, climate change poses risks for extinction in regions with rich assemblages of endemic species with limited ranges (Urban, 2015^[35]). Through interactions, initial extinctions of species can lead to secondary extinctions, amplifying the impact of disturbances (Kehoe, Frago and Sanders, 2021^[37]).

Importantly, these cascading impacts can impair various provisioning and regulating ecosystem services. Genetic responses to climate change may alter interactions among species, threatening the integrity of the food web and disrupting the seasonal synchrony of various populations, for instance, between plants and their pollinators (Bellard et al., 2012^[30]). Notably, occurrences of these “phenological mismatches” have been found across regions and species (Scheffers et al., 2016^[38]), with emerging evidence highlighting the spatial decoupling of suitability for crops and their pollinators due to changes in temperature, rainfall or extreme weather events (Imbach et al., 2017^[39]). Moreover, some species in terrestrial and aquatic environments are shrinking in body size due to the desirability of large surface-to-volume ratio under warmer climate (Scheffers et al., 2016^[38]). These altered interactions and morphologies can negatively affect agricultural and fisheries productivity and threaten food security.⁴

While evidence is relatively limited, more frequent and severe extreme weather events are also linked to direct (i.e. mortality) and indirect losses (e.g. through destruction and disturbance of habitat) of biodiversity. Although attributing reduced species richness to extreme weather is challenging due to natural variability in climatic conditions (Harris et al., 2020^[40]), existing evidence suggests that acute temperature spikes can cause mass mortality (Scheffers et al., 2016^[38]), as observed in a wide range of regions and species including the bleaching and mortality of corals in the tropics (Albert et al., 2017^[41]). A literature review of over 500 observational studies quantifying responses to extreme weather events identify over 100 cases in which these events led to population decline by over 25% and 31 cases of complete species local extinction (Maxwell et al., 2019^[42]).

Importantly, these adverse impacts on biodiversity are expected to worsen over time, because recurring extreme events compromise ecosystems’ natural capacity to recover from a disturbance (Mahecha et al., 2024^[43]). For instance, cyclones can leave temporary structural damages (e.g. uprooting) to plants, with lasting impacts on mortality and reduced species diversity (Maxwell et al., 2019^[42]). Increasingly frequent marine heatwaves also have adverse impacts on most species, particularly sessile species (species lacking self-locomotion), with increased coral bleaching, reduced seagrass density and kelp biomass (Smale et al., 2019^[44]). Extreme weather events that affect hydrological dynamics (e.g. floods) also reduce riverine biodiversity measured in terms of species richness and biomass (Sabater et al., 2023^[45]).

Box 1.1. Climate change affects marine biodiversity

There are key differences in how climate change affects terrestrial, marine and freshwater environments. For marine environments, a recent meta-analysis suggests that climate change is already the second most significant direct driver of biodiversity loss, following direct exploitation (Jaureguiberry et al., 2022^[31]). Marine species are generally found to be more sensitive to the effects of climate change than species on land, although some impacts are attenuated by their greater ability to colonise new territory under water (Pinsky, Selden and Kitchel, 2020^[46]). High CO₂ concentrations trigger photosynthesis and competition from algae and seagrasses, while ocean acidification (pH reduction) caused by CO₂ dissolution can cause stress to fish and calcifying species (Sage, 2020^[36]). The impacts on species that are considered most vulnerable to both ocean warming and acidification, such as marine species at lower trophic levels (e.g. herbivore fish) and calcifying species, can result in bottom-up disruptions in the ecological dynamics through the food web (Hu et al., 2022^[47]).

Given the relative stability of the temperatures of oceans (i.e. seasonal and daily variation of temperature is significantly higher for land than for oceans), the current extent of rapid warming may exceed species’ adaptive range (Pinsky, Selden and Kitchel, 2020^[46]). Since the metabolism of marine

species is affected by temperature, which in turn affects oxygen levels (due to the inverse relation between water temperature and oxygen solubility), rising temperatures can make certain areas uninhabitable, while increasing the risk of colliding habitats for prey and predators as well as for fisheries (Stewart et al., 2014^[48]; Prince et al., 2010^[49]). This raises further concerns over food security, given the current reliance of the world population on aquatic animal food as the source of animal protein (constituting 15% of the total), particularly in low-income countries (FAO, 2024^[50]).

Climate change amplifies the impacts of other drivers of biodiversity loss

Climate change also amplifies the impacts of other drivers of biodiversity loss across marine, terrestrial and freshwater ecosystems (IPBES, 2019^[9]). Human responses to climate change can further magnify these impacts on biodiversity (Brodie and Watson, 2023^[51]). For instance, climate change is enhancing the accessibility of previously remote areas, increasing the pressures from direct exploitation such as logging and hunting activities (Brodie, Post and Laurance, 2012^[52]). Adverse impacts of climate change on economic activities, including declines in yields for agriculture, fishery and forestry, can incentivise increased activities to compensate for the loss, exacerbating the impacts on biodiversity (Wang et al., 2018^[53]). These pressures can be further amplified through the impacts of extreme weather events, health consequences, crop losses and food price shocks on poverty, which can intensify the use of natural resources as sources of livelihoods (Hallegatte et al., 2015^[54]).

While different drivers of biodiversity loss tend to be examined in isolation, the impacts of co-occurring environmental stressors can be more than additive. For instance, climate change is amplifying the impacts of habitat loss and fragmentation on biodiversity, particularly in areas characterised by high maximum temperature (Mantyka-pringle, Martin and Rhodes, 2012^[55]). Climate change also affects the toxicity of environmental pollutants and concentrations, amplifying their impact on biodiversity (Hansen et al., 2010^[56]). The combined effects of toxic pollutants and climate change on species may affect the time needed for affected populations to recover from exposure, lower community resistance to other stressors, or have lasting effects on community composition (Moe et al., 2012^[57]).

By altering the distribution of species, climate change can also indirectly amplify the risks of biodiversity loss (Noyes and Lema, 2015^[58]; Scheffers et al., 2016^[38]). For example, climate change can facilitate the spread and establishment of invasive alien species which cause biotic homogenisation whereby biological communities become more similar, resulting in alterations of soil and water characteristics (IPBES, 2023^[59]).⁵ Invasive alien species play a role in 60% of global animal and plant species extinctions, and they are considered the sole attributable driver of 16% of the extinctions (IPBES, 2023^[59]). Climate change affects their range size, although there is no consensus over the scale of the issue and the magnitude varies by taxa and by scale (Bellard et al., 2018^[60]). While the evidence is inconclusive, some studies also suggest that invasive alien species may benefit relatively more from climate change than native species. For instance, higher temperature and CO₂ enrichment increases the performance of invasive alien plants compared to native plant species (Liu et al., 2017^[61]). While the evidence substantiating the linkage between invasive alien species and climate change is more well-established for terrestrial environments, marine and freshwater environments can also be susceptible. For instance, warming ocean can also facilitate introduction and alter the environmental conditions, allowing survival and reproduction of invasive alien species in regions where they were previously unable to survive (Walther et al., 2009^[62]).

Biodiversity loss accelerates climate change

Biodiversity loss undermines its essential role in regulating the climate, accelerating climate change in a mutually reinforcing manner (Pörtner et al., 2021^[63]). Among the most well-recognised linkages is between the temperature and the capacity of natural carbon sinks. The balance between carbon stored in ecosystems and in the atmosphere is a critical determinant of the global climate (De Graaff et al., 2015^[64]).

For instance, between 2010-2019, over half of anthropogenic emissions are estimated to be captured (e.g. through photosynthesis), stored and sequestered (e.g. by the so-called “solubility pump” in the ocean, moving carbon from the surface to the interior) in terrestrial and marine ecosystems (Canadell et al., 2021^[65]). However, accelerated biodiversity loss is projected to result in the release of stored carbon, contributing to warming while simultaneously lowering the ability of ecosystems to absorb other pollutants (Weiskopf et al., 2024^[66]).

Within terrestrial ecosystems, forests act not only as carbon sinks, but also play a temperature regulating role at local and global scales as they photosynthesise and evapotranspire water from the leaves and soil and lower the surface temperature (Lawrence et al., 2022^[67]; Harris et al., 2021^[68]). Importantly, the strength of terrestrial carbon sinks hinges on the balance between photosynthesis and respiration that are both affected by temperature (Duffy et al., 2021^[69]). For example, increased respiration without a concomitant increase in photosynthesis (due to e.g. droughts inhibiting plant growth) results in degraded carbon sinks (Duffy et al., 2021^[69]). Furthermore, it has been suggested that some parts of the largest forests, such as southeastern Amazon tropical rainforests, now emit more carbon than they capture, turning natural carbon sinks into a carbon source as a result of deforestation and forest degradation (Gatti et al., 2021^[70]). Conversion of forest land in Amazonia (containing around 123 petagrams of carbon of above- and belowground biomass) resulted in a forest loss of around 17%, 14% of which is used for agriculture (Gatti et al., 2021^[70]).

Relatedly, soil plays a critical role in supporting biodiversity and carbon cycling. A meta-analysis suggests that biodiversity loss in soil reduces soil carbon respiration by 28% and plant tissue decomposition by 18% (De Graaff et al., 2015^[64]). Soil moisture and temperature feedback loops, through which the combination of heat and drought causes moisture availability disruption, leads to increases in air temperature and higher evaporative demand, further exacerbating the temperature increase (Mahecha et al., 2024^[43]).

Aquatic ecosystems are also important sinks for “blue carbon”, carbon stored in organisms in wetlands such as peatlands, mangroves and tidal salt marshes. Wetlands cover only 6% of land surfaces, yet they are estimated to contain between 20-30% of global soil carbon (Lal, 2004^[71]) and support a wide range of animal and plant species (Beers, Crooks and Fennessy, 2020^[72]). However, wetlands are reported to be being degraded and disappearing at a rate three times faster than forests. For instance, an estimate suggests that 35% of global wetlands have been lost since 1970 (Davidson, 2014^[73]).

The ocean is estimated to absorb 20-30% of carbon emissions, which can, once stored, remain in sediments for centuries (Pörtner et al., 2022^[74]). A variety of marine species ranging from planktons to mesopelagic fish sustain this vital function (Elsler et al., 2022^[75]). However, while the absorption of carbon emissions by oceans is critical for mitigating further climate change, it simultaneously causes ocean acidification. Ocean acidification in turn hinders ecological functions of marine organisms, including gaseous sulphur production of phytoplankton, accelerating warming due to reduced reflection of solar radiation (IPBES, 2019^[9]) (see also Box 1.1).

Biodiversity loss reduces nature’s climate adaptation potential

Importantly, biodiversity loss can heighten human and nature’s vulnerability to climate change. For instance, biodiversity helps buffer climate change impacts by helping regulate the hydrological cycle. Forests, at regional and global scales, can act as “biotic pumps” of water through evapotranspiration. Forests (together with rest of the land) are thus estimated to return around 60% of precipitation on land back into the atmosphere (Trenberth, Fasullo and Mackaro, 2011^[76]). In turn, forests intensify the water cycle and increase local precipitation as well as cross-continental transport of moisture vapour, facilitating precipitation in distant locations (Ellison, Futter and Bishop, 2012^[77]). Compositional and spatial changes in terrestrial biodiversity can also modify surface temperature via changes in albedo, emissivity and surface roughness (Duveiller, Hooker and Cescatti, 2018^[78]). For instance, an estimate suggests that surface energy balance changes caused by vegetation change between 2000 and 2015 are associated with an

average increase of around 0.23°C in the areas where the changes occurred (Duveiller, Hooker and Cescatti, 2018^[78]).

Biodiversity also plays a key role in protecting communities from the impact of natural disasters, over 70% of which are water-related in nature (Lee et al., 2020^[79]). Coral reefs in islands and coastal areas drastically reduce wave strength, attenuating coastal erosion and the impact of flooding events (Temmerman et al., 2013^[80]). Similarly, wetlands such as mangroves provide vital protection against storms. Biodiversity loss therefore results in weakened capacity to buffer against the impacts of natural hazards. Although more diverse ecosystems are not systematically more stable (De Boeck et al., 2018^[81]), more diverse assemblages can be more resilient against risks through the “insurance effect”, for instance, as they are more likely to contain key species that prevent degradation of the ecosystem (Mahecha et al., 2024^[43]).

1.3.2. Interlinkages between biodiversity loss and pollution

Pollution drives biodiversity loss

While quantitative assessments of pollution are available only for a handful of systematically monitored pollutants, the adverse impact of pollution on biodiversity is well-established (Jaureguiberry et al., 2022^[31]). The need to address pollution is highlighted in the Kunming-Montreal Global Biodiversity Framework (KMGBF) adopted in the late 2022 by the Parties to the CBD. Many chemicals are toxic for organisms, as indicated by the classifications under the Globally Harmonised System for the Classification and Labelling of Chemicals.⁶

Air pollution has extensive impacts on terrestrial and aquatic biodiversity. Within terrestrial environments, air pollution can threaten biodiversity by directly harming certain species and altering interactions between them, both of which raise serious food security concerns. For instance, a recent analysis demonstrates that even moderate air pollution reduces the performance of pollinators and natural pest regulators by almost a third, while leaving pest invertebrates and other herbivores relatively unaffected (Ryalls et al., 2024^[82]). Furthermore, ground-level ozone slows vegetation growth and heightens their vulnerability to pests by damaging leaves and impairing photosynthesis (EEA, 2022^[83]). Many staple food crops (e.g. wheat and soybean) are highly sensitive to ground-level ozone (Mills, Wagg and Harmens, 2013^[84]), with available estimates suggesting that ground-level ozone negatively affects crop yields, although there is a wide range of estimated losses between 2 to 27% depending on the crop types and regions (Ainsworth, 2017^[85]). While some air pollutants such as SO₂ that cause acidification of surface water and soil have declined over the years in many regions (OECD, 2017^[86]), even a low concentration of these pollutants can be lethal to fish species and impair plant growth.

Target 7 of the 2030 targets under the KMGBF also draws attention to (i) the goal to reduce nutrient pollution by at least half, (ii) the goal to reduce the overall risks posed by use of pesticides and highly hazardous chemicals by at least half, as well as (iii) the need to tackle plastic pollution (CBD, 2023^[87]). Nitrogen pollution, of which fertilisers remain the dominant source, has a number of significant linkages with biodiversity loss across ecosystems due to its uniquely cascading nature in air, water and soil (Kanter, 2018^[88]). While 60% of nitrogen lost in the environment is waterborne, the remainder is emitted as ammonia (NH₃) (25%), nitrous oxide (N₂O) (10%) and NO_x (5%) (Kanter and Brownlie, 2019^[89]; Sutton MA et al., 2013^[90]). Across ecosystems, nitrogen favours a subset of faster-growing, potentially invasive species over native species, altering the competitive interactions and therefore affecting the relative abundance of species.

While phosphorus cycle has no significant gaseous component, phosphorus constitutes a significant source of nutrient load⁷ into water, which has doubled in quantity over the last century (Beusen et al., 2016^[91]; Kanter and Brownlie, 2019^[89]). The nature of the challenges is regionally varied. While the limited use of inorganic fertilisers and the diversion of organic inputs such as manure for household cooking (Jones and Deuss, 2024^[92]) lead to negative nutrient balances (nutrient deficits) – and thus limited crop yields –

in developing regions, notably in Sub-Saharan Africa, other regions have significant phosphorus surpluses.⁸ These surpluses can be a threat for water quality, with for example critical thresholds for nitrogen concentration in surface water exceeded in 48% of Europe's total area in 2020, followed by East Asia (41%) and South Asia (21%) (see Chapter 3). Anthropogenic releases to waterbodies have resulted in an imbalance in the nitrogen to phosphorus (N:P) ratio,⁹ which can affect natural ecosystems and their food provision and carbon storage capacity (Penuelas et al., 2020^[93]).

A common challenge of nutrient pollution is eutrophication and harmful algal blooms that cause hypoxia (low oxygen) and anoxia (no oxygen), leading to increased turbidity of water in lakes and rivers (Altieri and Gedan, 2015^[94]; Amorim and Moura, 2021^[95]). Lower oxygen concentrations threaten fish and invertebrates (Whitehead et al., 2009^[96]) as well as plankton biodiversity, with cascading consequences to ecosystem functioning. In freshwater ecosystems, an estimate from a meta-analysis suggests that exposure to nitrate leads to 79% decrease in activity, 29% decrease in growth and 62% decrease in survival of species (Gomez Isaza, Cramp and Franklin, 2020^[97]). Due to the rapid development of aquaculture and waste from fish farms, green tides and blooms are now also increasingly observed in the ocean (Sage, 2020^[36]). Globally, there are over 700 coastal areas impacted by “dead zones” (Convention on Wetlands, 2021^[98]), including in continental seas from the Baltics to the Gulf of Mexico, all of which affect fisheries (Robertson and Vitousek, 2009^[99]).

Pesticides also pose a threat to non-target species (i.e. species not intended for control by pesticides) including birds, insects and pollinators and may reduce their genetic diversity (UNEP, 2021^[100]). A recent review of studies examining the impact of pesticides on non-target plants, animals and microorganisms across aquatic and terrestrial environments finds that pesticides consistently suppressed growth and reproduction across all taxonomic groups (Wan et al., 2025^[101]).¹⁰ Through the food chain, these individual impacts on non-target species can result in wider ecosystem-scale impacts (e.g. compositional biodiversity) by favouring pesticide-tolerant species (Ito et al., 2020^[102]). Pesticides disperse across the environment through water runoff, soil leaching and atmospheric transport with extensive impacts beyond areas directly used for agricultural activities (Sud, 2020^[103]). For instance, pesticide residue has contaminated aquatic environments and has adverse implications for fisheries and aquaculture (Carvalho, 2017^[104]). Despite their critical role in improving crop yields (Tudi et al., 2021^[105]), indiscriminate and excessive use of pesticides can also compromise yields of some crops in the long term, as the contaminated soil from pesticides can reduce biodiversity and hinder soil productivity (Burian et al., 2024^[106]; Naidu et al., 2021^[107]).

Furthermore, plastic pollution has garnered attention in recent years due to its cross-cutting impact on biodiversity. Plastic debris can persist in the environment for hundreds of years, breaking down into smaller particles known as microplastics. Additionally, the impacts of macroplastics including marine debris (e.g. fishing gear) on wildlife have been relatively widely documented. For instance, marine species frequently ingest or are entangled in plastics, which can harm or ultimately kill species (Gall and Thompson, 2015^[108]). A recent review also suggests that at least 206 freshwater species have likewise ingested macro and microplastics (Azevedo-Santos et al., 2021^[109]). While the impacts of microplastics are less certain, there is emerging research exploring how they might mobilise other pollutants (see Box 1.2).

While ingestion and entanglement pose immediate threats to aquatic species, plastics can also serve as rafts for non-indigenous species to eschew historical home ranges (Barnes, 2002^[110]; Hahladakis, 2024^[111]). Discarded plastics at the land-sea interface can be swept into oceans with increasingly frequent extreme weather events due to climate change, further amplifying the risk of the introduction of invasive alien species (Pyšek et al., 2020^[112]). These species, once established, can exert significant impacts on native biodiversity. Although research on the impact of plastics on terrestrial species is less established, available evidence suggests that they adversely impact plants (e.g. delaying germination) and soil fauna (e.g. lower reproduction) (Huo et al., 2022^[113]).

Box 1.2. Plastic pollution, climate change and biodiversity loss

Plastics affect biodiversity loss and climate change throughout their lifecycle (Carney Almroth and Villarrubia-Gómez, 2024^[114]). While research on the impacts of plastic pollution on biodiversity is still nascent, existing studies suggest that plastics can affect wildlife through (i) their physical characteristics, (ii) disturbances to habitats and (iii) toxicity of associated chemicals (Carney Almroth and Villarrubia-Gómez, 2024^[114]). Both micro- and macroplastics can affect species, through ingestion, entanglement and inhalation (Savoca, McInturf and Hazen, 2021^[115]; OECD, 2021^[116]). Microplastic uptake can impact foundational species such as phytoplankton that underpin biodiversity and facilitate nutrient cycling (Shi et al., 2024^[117]). Studies have cumulatively identified over 4 000 aquatic species that have been affected by micro- and macroplastics (Tekman et al., 2025^[118]). While less developed compared to the research on oceans and freshwater ecosystems, there are also some emerging studies identifying accumulation of microplastics in soils (Li et al., 2024^[119]) as well as impacts of microplastic pollution on photosynthesis of terrestrial plants along with marine and freshwater algae (Zhu et al., 2025^[120]).

Plastic pollution can further pose a risk to biodiversity due to its complex chemical composition. Many chemicals used to make plastics are ecotoxic and can be released into different environmental media across the plastic lifecycle, including at end-of-life (Carney Almroth et al., 2022^[121]). According to a recent UNEP report, more than 13 000 chemicals have been found to be associated with plastics, out of which 3 200 have been identified as having hazardous properties of concern to human health or the environment (United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2023^[122]). The report also called for increased transparency of chemicals used in plastics and their properties. Since the publication, the International Council of Chemical Associations has undertaken an effort to identify plastic additives and their properties, hazard classifications and related regulatory activities, which have been compiled in their Plastic Additives Database (ICCA, n.d.^[123]).

Importantly, due to their characteristics of random irregular shapes and pores, microplastics are suggested to absorb other contaminants and result in combined pollution (Li et al., 2024^[119]). From the potential impacts microplastics on plant and soil phosphorus (Zhou et al., 2024^[124]) to the co-occurrence of PFAS and microplastics in aquatic environment (Lukić Bilela et al., 2023^[125]), research exploring the relation between plastics and other contaminants is rapidly expanding but remains a key knowledge gap.

From production and conversion to waste management, the lifecycle of plastics is also associated with climate change, although there are also a number of positive contributions including the light weight which contributes to fuel efficiency of vehicles (OECD, 2023^[126]). Production and conversion of plastics relies on transforming fossil fuels through energy-intensive processes. End of life GHG emissions resulting from waste management practices, such as incineration, account for about 10% of total plastics-related GHG emissions (OECD, 2023^[126]). Production of plastics resulted in 3.6% of total GHG emission in 2020 (OECD, 2024^[127]). Plastics-related GHG emissions are projected to account for 5% of global emissions by 2040. While elevated, this figure is likely to be an underestimate given that informal burning of plastic waste has not been captured.

Plastic pollution may further contribute to climate change through positive feedback loops. For instance, by decreasing sea ice albedo, plastic pollution can reduce the earth's ability to reflect solar radiation (Geilfus et al., 2019^[128]). As climate change alters ocean salinity and volume, it can lead to consolidated microplastic hotspots, in turn further decreasing earth's albedo and contributing to additional warming (Welden and Lusher, 2017^[129]).

Heavy metals can bioaccumulate through food chains, posing threats to human and wildlife health. For instance, elemental mercury settles in the sediment of freshwater ecosystems (e.g. rivers) and transforms into methylmercury, which accumulates in fish species (WHO, 2021^[130]). Additionally, it is estimated that 62 Mt of electrical and electronic waste (e-waste) was generated globally in 2022 (Baldé et al., 2024^[131]). Despite the valuable raw materials in e-waste (e.g. copper, gold, silver), only 22% of the e-waste is formally collected and recycled and the fate of remaining waste is uncertain. Mismanaged e-waste can threaten ecosystems as e-waste also contains hazardous materials and persistent organic pollutants (POPs) such as flame retardants (UNEP/BRS/MC, 2021^[132]).

Endocrine disrupting chemicals (also known as endocrine active chemicals) interfere with endocrine system and affect a variety of functions, including developmental, reproductive, neurological and immunity impacts (OECD, 2018^[133]). They are found to compromise the reproductive capacity of a variety of species including fish, mammals and insects, which can cause concomitant decline in biodiversity across taxa (Noyes and Lema, 2015^[58]). Subgroups of PFAS that are listed as industrial POPs¹¹ under the Stockholm Convention persist in the environment for over a long period of time. Although there is considerable uncertainty in how PFAS affect biodiversity (Evich et al., 2022^[134]) and human health, bioaccumulated PFAS have been detected in host of aquatic species, ranging from polar bears to mussels (Kurwadkar et al., 2022^[135]).

Importantly, pollution from various sources can be interlinked in a complex manner and often occurs simultaneously. Wildlife rarely faces a single stressor or pollutant (Gomez Isaza, Cramp and Franklin, 2020^[97]). Different types of pollutants can interact to result in more than additive impacts. Although the cumulative impact of multiple stressors remains a key knowledge gap in biodiversity conservation (Gomez Isaza, Cramp and Franklin, 2020^[97]), early evidence suggests that these impacts can be substantial (Sigmund et al., 2023^[136]). For instance, the combined impacts of multiple pollutants has been found to be significant in soil biodiversity (Wang et al., 2022^[137]) and synergistic as a cause of pollinator mortality (Siviter et al., 2021^[138]).

Biodiversity loss compromises nature's capacity to recover from pollution

As highlighted in Target 11 of the 2030 targets under the KMGBF, before air, water and soil become “polluted”, biodiversity plays a myriad of roles in stabilising and restoring the environment through their self-purification capacity. A range of complex interactions underpin nature's restorative capacity, the mechanisms of which vary substantially by pollutant as well as realms.¹²

There are certain ecosystems that play an outsized role in remediating pollution. Forests absorb and degrade pollutants before they enter the water body through the process of infiltration (entry of water in the soil through topsoil pores) and reduce runoff through percolation (water diffusion from surface to the deep layer) (Cheng et al., 2021^[139]). Tree canopies purify pollutants and prevent pollutants in the upper atmosphere from reaching the ground level. For instance, canopies are suggested to reduce the ground-level ozone concentrations by up to 20%, although their capacity is reduced under drought conditions (Mills, Wagg and Harmens, 2013^[84]). Droughts induce water-stressed plants to close their leaf stomata to limit water loss, thereby impairing the uptake of ozone, which may partially explain why ground-level ozone episodes have not declined despite the marked decline in precursor emissions¹³ as a result of increasingly stricter air quality policy in Europe over the last decade (Lin et al., 2020^[140]).

Wetlands, often referred to as “the kidney of the world” (Mitsch and Gosselink, 2007^[141]), help purify water through nutrient cycling and organic matter decomposition. As transitional zones between terrestrial and aquatic environments (Zhang et al., 2020^[142]), wetlands support 37% of mammals, 20% of freshwater fish (Millenium Ecosystem Assessment, 2005^[143]). However, wetland-dependent species have declined more sharply than those dependent on other biomes (Convention on Wetlands, 2021^[98]), with a quarter threatened with extinction (Convention on Wetlands, 2018^[144]).

Pollution exceeding a certain threshold can impair the ability of species to adapt and respond to the changing environment (Noyes and Lema, 2015^[58]). For instance, adapting to one type of pollutant may reduce genetic diversity, thereby lowering the capacity for adaptation to other co-occurring and future stressors (Groh et al., 2022^[145]). The reduced capacity for restoring the environment in turn can have adverse impacts on human and planetary health. For instance, the over- and misuse of antibiotics in agriculture, and resultant soil and water pollution, is leading to antimicrobial resistance, compromising the cure for otherwise treatable infectious diseases (Zhu et al., 2019^[146]).

1.3.3. Interlinkages between pollution and climate change

Climate change increases the exposure to and toxicity of certain pollutants

Climate change can impact the ways in which pollutants mobilise through the environment, altering the patterns of exposure and impacts on human and planetary health (Biswas et al., 2018^[147]). The patterns of transfer of pollutants between environmental reservoirs, whether air to surface or ice to water, can be affected by the altered biogeochemical processes (Teng et al., 2012^[148]). For instance, pesticides accumulate in the atmosphere through increased vaporisation at higher temperatures (see Box 1.3) (Tudi et al., 2021^[105]). When the spray method of pesticide application is used, 30% or more of the pesticide can be released into the air depending on the application technique¹⁴ and other environmental conditions (Van Den Berg et al., 1999^[149]).

Box 1.3. Environmental fate and behaviours of chemicals under climate change: example of pesticides

Climate change may affect agricultural activities in ways that may end up increasing agrochemical applications (Yang et al., 2024^[150]). Once applied, pesticides transfer and deposit across different environmental media through mobilisation, photolysis, volatilisation, hydrolysis and microbiological degradation, most of which are affected by at least one climatic variable such as temperature and level of precipitation.

Compromised efficacy of pesticides due to climate change, particularly through increased transfer and accelerated degradation, imply that pesticides may need to be applied in larger quantities and more frequently to maintain crop yields (Delcour, Spanoghe and Uyttendaele, 2015^[151]). Meanwhile, the transfer can result in pesticides accumulating in surrounding environmental realms and harming non-target species. Between 10 to 50% of pesticides are estimated to be lost to the environment, making their ways into surface and groundwater (Zhu et al., 2020^[152]).

Importantly, increased temperature is likely to result in heightened prevalence of insect pests and livestock and plant diseases in temperate regions as it extends the geographical range of pest and disease vectors (Seidl et al., 2017^[153]). Extreme weather conditions such as droughts can also increase susceptibility of plants to pests (Skendžić et al., 2021^[154]). Furthermore, temperature variation is expected to contribute to the evolution of crop resistance to pesticides as the higher temperature accelerates metabolic detoxification (Matzrafi et al., 2016^[155]). These climate-induced and climate-mediated impacts on pests, as well as the accelerated degradation of pesticides under climate change, may further increase the need for pesticides (Kibria et al., 2021^[29]; Delcour, Spanoghe and Uyttendaele, 2015^[151]).

The chronic onset of climate change and extreme weather events can also lead to increased releases of pollutants from natural environmental reservoirs (Kibria et al., 2021^[29]). Similarly, climate change may increase the risk of the release of pollutants from artificial reservoirs. For instance, hazardous by-products of extractive operations stored in tailings¹⁵ ponds may be released into river catchments due to the

increased frequency of extreme weather events (Kossoff et al., 2014^[156]). More precipitation caused by rising temperatures might result in elevated runoff into water systems, allowing pollutants to leach into groundwater and release to surface waters (OECD, 2023^[157]). Conversely, lack of precipitation and reduced snowfall, and subsequently less snowmelt, may result in less groundwater recharge, compromising the capacity to restore the water quality (Gander, 2022^[158]; OECD, 2023^[157]). As climate change accelerates, it may play an even larger role in the time-delayed release of stored pollutants. For instance, snow has a large capacity to bind pollutants, resulting in glaciers storing accumulated POPs. Melting glaciers and thawing permafrost can therefore be a significant secondary source of legacy pollutants (Hung et al., 2022^[159]). Similarly, Schuster et al. (2018^[160]) suggest that the Northern Hemisphere permafrost stores twice as much mercury as the rest of the soils, atmosphere and the oceans combined, drawing attention to the severity of the risk associated with the melting permafrost.

In addition to influencing mobilisation patterns, rising temperatures can also alter the properties of pollutants. For instance, properties of plastics can deteriorate under heat, with polymer degradation resulting in the faster generation of microplastics (Wei, Yang and Hedenqvist, 2024^[161]). This may also affect the accumulated stocks of plastics in the aquatic environment due to marine heatwaves and warmer water temperature (Wei, Yang and Hedenqvist, 2024^[161]). Furthermore, highly degraded plastic waste would be less suitable to reuse and recycle.

Climate change also affects air pollution physically by modifying transport and mixture, and chemically by altering reactions of pollutants (Im et al., 2022^[162]). Changes in climatic variables such as temperature and precipitation alter the patterns of air pollutants emissions and can lead to either lower or higher pollution. For example, higher temperatures leads to higher NH₃ emissions from agriculture and anthropogenic VOC emissions from petroleum products, while also increasing biogenic VOCs from terrestrial and oceanic vegetations (Im et al., 2022^[162]). As highlighted by the “climate penalty” of air pollution, higher temperatures and increased moisture in the atmosphere can also lead to higher ground-level ozone concentrations (Donzelli and Suarez-Varela, 2024^[163]). Meanwhile, increased precipitation can reduce PM concentrations, as wet deposition serves as a key removal mechanism (Im et al., 2022^[162]).

Relatedly, rising temperatures can influence pollutant behaviour, intensifying their toxicity and bioaccumulation across systems. For most pollutants, their toxicity and lethality for wildlife are found to increase at higher temperatures (Kibria et al., 2021^[29]). In addition, increasing temperatures are often coupled with higher solar intensities, affecting emissions into the air and photodegradation of pollutants that can result in more toxic intermediate by-products (Bolan et al., 2024^[164]). Several studies also suggest that higher temperatures result in higher bioaccumulation of pollutants due to the increased metabolic rate across terrestrial and aquatic ecosystems (Kibria et al., 2021^[29]; Bolan et al., 2024^[164]). While the effect of ocean acidification on pollutants is less clear-cut, the toxicity of certain heavy metals such as cadmium, lead and mercury also increases at higher acidity. The combined impact of increased mobility and toxicity of pollutants may in turn be exacerbated by the reduced capacity of the environment to restore its quality.

More frequent extreme weather events are also exacerbating the adverse health impact of pollution. In particular, transmission potential is increasing for many of the vector-, food- and waterborne infectious diseases under climate change (Romanello et al., 2023^[165]). For instance, the coastal area that is environmentally suitable for *Vibrio* pathogen transmission (e.g. *Vibrio* spp which causes cholera and non-cholera infections (Baker-Austin et al., 2018^[166])) is expanding by 329 km a year since 1982, totalling almost 10% of global coastline in 2022 (Romanello et al., 2023^[165]).

Increasing temperatures are generally conducive for the fitness, survival, and production of pathogens (Semenza and Ko, 2023^[167]). Floodwaters from extreme precipitations can also become a means for dispersion of pathogens and cause outbreaks in dense urban areas. Importantly, while mortality from infectious diseases has declined overall over time, accelerating climate change runs the risk of undoing the progress made to date (Semenza, Rocklöv and Ebi, 2022^[168]). There are already some early warning

signs; for instance, recent evidence suggests that the geographical expansion of pathogens, such as West Nile virus in Europe, is attributable partly to the changing climate (Erazo et al., 2024^[169]).

The increased health risks of the nexus of climate change and pollution extend well beyond the spread of infectious diseases, including zoonoses. Importantly, climate change may amplify the risks of Natural Hazard Triggered Technological (Natech) accidents due to changes in intensity, frequency and location of extreme weather events, which can in turn result in pollution (OECD/European Union, 2024^[170]). Extreme weather events are also expected to have implications for air pollution, as more frequent droughts lead to more wildfires and increased PM_{2.5} (Fiore, Naik and Leibensperger, 2015^[171]). For instance, increasingly frequent wildfires bring significant health consequences beyond lives lost (OECD, 2023^[172]). Smoke from wildfires threatens respiratory and cardiovascular health through elevating the level of PM, especially when accompanied by low precipitation, while contributing to climate change through the release of GHGs into the atmosphere (Knorr et al., 2017^[173]; Im et al., 2022^[162]). Wildfires can also mobilise and release mercury contained in vegetation and soil, releasing gaseous form of mercury into air and mobilising them into water bodies (Webster et al., 2016^[174]) (see Box 1.4).

Box 1.4. The complex interlinkages among climate change, wildfires and air pollution and varying impacts of wildfires on biodiversity

Evidence suggests that, in many regions, higher atmospheric temperatures, increasing aridity of landscapes and changing lightning patterns from climate change have increased the prevalence of wildfires (Sullivan et al., 2022^[175]). For example, changes in extreme heat and drought suggest that climate change increases the risk of fires that are at least as severe as the 2019/20 Australian “Black Summer” wildfires (destroying around 6 000 buildings and resulting in at least 34 human fatalities) by at least 30% (Van Oldenborgh et al., 2021^[176]).

Wildfire smoke releases hazardous air pollutants, including PM_{2.5} consisting of organic carbon (OC) and black carbon (BC). The morbidity risk of wildfire smoke exposure, including (exacerbation of) respiratory illnesses, is well-recognised. Several studies have examined the mortality impacts attributable to wildfire-prone regions to find significant impacts on premature deaths (e.g. (Connolly et al., 2024^[177]; Matz et al., 2020^[178]; Alari et al., 2025^[179])). Recent meta-analyses also find consistent evidence of an increased risk of same-day mortality (Gould et al., 2024^[180]) as well as wildfire-induced all-cause mortality (Wang et al., 2025^[181]). A global estimate combining the impacts of short-term and chronic exposure to wildfire smoke suggests that it is responsible for 339 000 premature deaths per year (Johnston et al., 2012^[182]). A more recent estimate finds that wildfire smoke is responsible for a larger number of premature deaths (678 000 per year), with the greatest impacts in Central and West Africa and South and Southeast Asia (Roberts and Wooster, 2021^[183]). There are also concerns that mercury mobilised during wildfires can also affect surface water downstream (Sever, 2021^[184]).

Aerosol emissions from wildfires can also contribute to further warming by absorbing solar radiation when suspended and deposited (e.g. on snow) (Jiang et al., 2020^[185]). While the impacts of both suspended and deposited aerosol emissions from wildfires on climate warming vary regionally, cascading impacts can be substantial. For instance, peatland fires can release vast amounts of sequestered carbon in the soil through layers of partially undecomposed organic matter, contributing further to climate change as well as the likelihood of additional peatland fires (Kuklina et al., 2022^[186]). The 2015 outbreak of fires in Indonesia, more than half of which occurred on peatland, for instance, are estimated to have resulted in the daily emissions exceeding 16 Mt of CO₂ on most days (Harris et al., 2015^[187]).

Wildfires also have significant impacts on biodiversity, although these impacts vary widely across ecosystems. Wildfires are a natural component for certain ecosystems (e.g. boreal forests), and species

rely on them to maintain reproduction and growth levels (Hincks et al., 2011^[188]). Studies suggest that fire suppression may lead to decreases in biodiversity in certain fire-prone regions, such as the Brazilian Cerrado, where forest growth, normally curtailed by periodic fires, has encroached on the habitats of plants and ants (Abreu et al., 2017^[189]). In some instances, small-scale fires are prescribed to create heterogeneous successional habitats for the purpose of biodiversity conservation (Pastro, Dickman and Letnic, 2011^[190]). For instance, research suggests that Indigenous fire regimes that replicate historic fire temporal and spatial diversity can increase plant richness for certain plant groups (Greenwood et al., 2024^[191]). Nevertheless, wildfires are now also impacting ecosystems that are not fire-adapted, threatening many species (Kelly et al., 2020^[192]). Although the evidence is relatively limited, existing research suggests that severe wildfires can result in direct wildlife mortalities (Jolly et al., 2022^[193]). Wildfires can also diminish biodiversity indirectly, for instance by burning habitats and displacing species as well as by affecting soil quality (OECD, 2023^[172]).

Pollution affects atmospheric temperature and other climatic variables

There are notable feedback loops between climate change and pollution, of which air pollution is among the most well-documented. Air pollutants can affect climate through their impact on cloud properties, precipitation and radiation. In addition, certain air pollutants – climate forcers (Stocker et al., 2014^[194]) – have a warming effect. For instance, BC is both an air pollutant (and a primary component of PM_{2.5}) and a short-lived climate pollutant (SLCP), which also induces snowmelt when deposited. Wildfires, the spread of which is partially determined by climatic conditions, also constitute a large source of BC emissions (Bowman et al., 2009^[23]).

There are also important impacts of manufactured chemicals on climate change. Chemicals production relies heavily on fossil fuels as feedstocks (Bălan et al., 2025^[195]). Alternatives introduced as less polluting chemicals can also have unintended consequences on climate change (Bălan et al., 2025^[195]). For instance, hydrofluorocarbons (HFCs), chemicals introduced as a substitute for ozone-depleting substances banned under the Montreal Protocol, are a powerful SLCP.¹⁶ As with other feedback loops, not all are mutually amplifying. For example, air pollutants including NO_x and SO₂ are precursors to inorganic aerosols (mainly highly reflective and soluble nitrates and sulphates), which exert cooling effects on the climate by directly reflecting and scattering sunlight and indirectly altering cloud formation and precipitation patterns (Im et al., 2022^[162]).

The overall impact of aerosols on the reduction of surface temperature can be significant (IPCC, 2018^[196]), suggesting that future climate and pollution mitigation efforts could be more effective if they account for feedback loops in policy appraisals (see also Chapters 3 and 6). Although scattering aerosols altogether are estimated to offset about a third of warming impact of GHG emissions, the balance between absorbing (warming) and scattering (cooling) aerosols can vary regionally (Li et al., 2022^[197]).¹⁷ Evidence is emerging that recent reductions in, for instance, SO₂ emissions increase radiative forcing¹⁸ and thus accelerate warming (Copernicus, 2023^[198]); see also Chapter 3), although uncertainties on the effects remain, especially at the regional level.

1.4. High-level recognition of interlinkages in multilateral commitments and policy responses

Policy responses to each component of the triple planetary challenge are also closely interconnected. Policies targeting one dimension can have positive and negative spillovers on the other two. For instance, climate mitigation policies targeting GHG emissions from fossil fuel combustion can also reduce co-emitted air pollutants like PM_{2.5}, PM₁₀, NO_x, NH₃ and SO₂. On the other hand, expansion of renewables like solar and wind power, while contributing to climate mitigation objectives, could potentially lead to adverse

impacts on biodiversity through fragmentation of natural habitats and loss of certain bird and bat species, if these factors are not adequately considered in project permitting.

Similarly, many technologies that can be used to reduce environmental pressures, ranging from wind turbines to electric vehicles, rely on a set of minerals and materials (“critical raw materials, CRMs”), the mining and processing of which raise environmental and socio-economic concerns (UNEP, 2024^[199]). While CRMs and chemicals play an important role in addressing climate change, a key driver of biodiversity loss, they can at the same time pose a threat to biodiversity. Similarly, alternative materials for chemicals and plastics can in some cases also lead to the shifting of environmental burdens. These complex interlinkages underscore the need to tackle different environmental challenges in a holistic manner and to carefully consider the full environmental impacts of alternative choices – solutions to solve one environmental problem may not always be best from the integrated perspective of the triple challenge.

At the global level, the international community is making progress, although not always in a co-ordinated manner. Countries are working towards their Nationally Determined Contributions (NDCs) as a country-driven global collective response to climate change. In recent years, a growing number of countries have announced their commitments to achieve net zero emissions by mid-century. In parallel, the Parties to the CBD have successfully adopted the KMGBF in 2022, in acknowledgement of the need for policy action to halt and reverse biodiversity loss. In September 2025, the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) reached 60 ratifications required to trigger its entry into force (United Nations, 2025^[200]).

Different types of pollution have also increasingly garnered policy attention. Several WHO guidelines have provided a frame of reference for policymaking, reflecting the inextricable interlinkages between pollution and health. The WHO has recently revised its global air quality guidelines to reflect the latest scientific evidence identifying adverse health impacts associated with even low levels of pollution (WHO, 2021^[201]). In addition, the WHO recently published updated guidelines for drinking-water quality to support implementation of hazard identification and risk management through health-based targets, catchment-to-consumer water safety plans and independent surveillance (WHO, 2022^[202]). Furthermore, a new Global Framework on Chemicals (GFC) has been adopted to promote the sound management of chemicals and waste at the Fifth International Conference on Chemicals Management (ICCM5) in September 2023. Finally, at the resumed session of the Fifth United Nations Environment Assembly (UNEA – 5.2) in February-March 2022, the countries collectively committed to develop an international legally binding instrument on plastic pollution.

There is already some explicit recognition of the interlinkages in these existing intergovernmental frameworks, which provide an impetus for more integrated approach towards tackling the triple planetary crisis. The joint investigation into the interlinkages between biodiversity conservation and climate change mitigation and adaptation by the two intergovernmental bodies, IPCC and IPBES, has also suggested that biodiversity and climate change need to be considered together routinely, rather than exceptionally (Pörtner et al., 2021^[63]). The New Biodiversity Targets (for 2030) and Goals (for 2050) in KMGBF firmly establish the interlinkages among biodiversity, pollution and climate change. For instance, Target 7 and 8 respectively call for reducing pollution and minimising climate change impact on biodiversity (CBD, 2023^[87]).

Another related development is the growing emphasis on nature-based solutions (NbS) within multilateral policy landscape.¹⁹ They are gaining ground with the UNEA-5.5 resolution adopting a multilaterally agreed definition in 2022 (UNEP, 2022^[203]).²⁰ NbS with appropriate safeguards can help meet the climate objectives, while delivering biodiversity benefits (IPBES, 2019^[9]). Reflecting the broad-based support for NbS, Target 11 under the KMGBF recognises NbS and/or ecosystem-based approaches for restoring, maintaining and enhancing ecosystem services.

There is also widespread acknowledgement of the need to enhance resource efficiency, including through the transition to more circular economies. While there is no universal definition, “circular economy” commonly describes the process of decoupling natural resource extraction from economic production (McCarthy, Dellink and Bibas, 2018^[204]). Enhancing circularity can help address one of the main drivers of the triple planetary challenge – unsustainable patterns of resource use (UNEP, 2024^[205]) by closing, extending and narrowing the “material loops of the traditional linear system” in which natural resources are extracted, made into goods and eventually discarded through landfilling or incineration.

Furthermore, the interlinkages among hazardous chemicals and wastes and climate change (2021^[206]) and biodiversity loss (2021^[207]) are garnering attention within the context of the Basel, Rotterdam and Stockholm Conventions and the Minamata Convention on Mercury. Similarly, the GFC Target E6 on enhanced implementation calls on stakeholders to identify and strengthen synergies and interlinkages among chemicals and waste management and other key environmental, health and labour policies, including those relating to tackling climate change, biodiversity conservation, human rights protection and health care (Global Framework on Chemicals, 2024^[208]). The close linkages between air pollution and climate change, meanwhile, are highlighted in international initiatives like the Climate and Clean Air Coalition.

Countries around the world have started to recognise the importance of addressing the triple planetary crisis in a more co-ordinated manner to pursue synergies, as illustrated by the ministerial declarations of the fifth and sixth sessions of the United Nations Environment Assembly (UNEA), as well as the adoption of the UNEA resolution for “promoting synergies, cooperation or collaboration for national implementation of multilateral environmental agreements and other relevant environmental instruments (UNEP/EA/6/Res.4)” (UNEP, 2024^[209]).

These interlinkages at the international level are clearly important. However, despite the growing recognition of the synergies and trade-offs between environmental policies addressing the different aspects of the triple planetary crisis, policies to tackle them are often conceived and implemented in a siloed manner. Furthermore, some of the key trade-offs and synergies between the different policy objectives are fundamentally sub-national and local. Regardless of the levels, where these interlinkages are considered, they tend to focus on pairwise interactions rather than three-way interlinkages.

1.5. Past research examining the biophysical and policy interlinkages

While the triple planetary crisis has featured prominently in the international policy agenda in recent years, there is a dearth of literature that comprehensively assesses the interlinkages. Few studies look at the three challenges at the same time. One synthesis report from the UNEP shows that the achievement of the Sustainable Development Goals (SDGs) is threatened by an array of escalating and mutually reinforcing environmental risks and emphasises the need for tackling climate change, biodiversity loss, land degradation, and air and water pollution together and for policy response to become more synergistic and effective (UNEP, 2021^[210]). Another recent key contribution is the latest IPBES thematic assessment report, which highlights the importance of the interlinkages among five nexus elements of biodiversity, water, food, health and climate change (McElwee et al., 2024^[211]). The report provides a scientific assessment of the evidence on complex biophysical and policy interactions, as well as a review of projections of interactions in the future.

The existing model-based quantitative projections, meanwhile, primarily focus on pairwise challenges. This literature covers, for instance, the interactions between climate change (mitigation) and plastics (Stegmann et al., 2022^[212]), air pollution (Vandyck et al., 2018^[213]; Fouré et al., Forthcoming^[214]), and biodiversity and ecosystems (Bastien-Olvera et al., 2023^[215]), as well as the relations between nitrogen pollution and biodiversity (Schulte-Uebbing et al., 2022^[216]). A series of other studies quantify the influence of underlying drivers on multiple environmental outcomes, such as food consumption (Springmann et al., 2018^[217]; Leclère et al., 2020^[218]; Springmann et al., 2023^[219]) and energy use from coal (Rauner et al., 2020^[220]).

However, studies with a broader lens still remain relatively scarce, and have been emerging only recently in the context of the Sustainable Development Goals (SDGs) (e.g. multi-model comparison in (Soergel et al., 2024^[221])) and planetary boundaries (Richardson et al., 2023^[222]). For instance, the latest study estimated that six out of the nine planetary boundaries²¹ have already been transgressed, reinforcing the need for accelerated action to limit human pressures on the environment (Richardson et al., 2023^[222]). A recent study providing projections on the evolution of planetary boundaries suggests that policy action needs to address all dimensions of the environmental challenges. While ambitious climate action may bring synergies for air and nitrogen pollution, it is insufficient on its own to stay within safe planetary boundaries in the future (van Vuuren et al., 2025^[223]). Even integrated approaches still result in the transgression of three out of eight boundaries by 2050, highlighting the need to better account for synergies and trade-offs.

Similarly, previous global assessment modelling work rarely focused on the three-way interlinkages although there are a few studies that build on the nexus-approach of the SDGs (Willaarts et al., 2024^[224]). A substantial share focused on climate change and biodiversity loss, while sometimes covering a few dimensions of pollution (Doelman et al., 2022^[225]; van der Esch et al., 2022^[226]; Fuglie et al., 2022^[227]; Zabel et al., 2019^[228]; Moreno et al., 2023^[229]; Ohashi et al., 2019^[230]). The IPCC and IPBES global assessment reports include chapters on biophysical and policy linkages, mainly focusing on the synergies between climate change mitigation and adaptation and NbS. Another strand of the global modelling literature looked primarily at the health synergies of climate change mitigation policies highlighting large positive spillovers, but they mostly focused on health benefits from reduced ambient air pollution (Markandya et al., 2018^[231]; Hamilton et al., 2021^[232]; Reis, Drouet and Tavoni, 2022^[233]; Sampedro et al., 2023^[234]; Vandyck et al., 2018^[235]). Fewer studies looked at other types of pollution reduction synergies from climate change mitigation policies. For example, it was estimated that the adoption of ambitious policies across the lifecycle of plastics at the global level to minimise plastic leakage to the environment could reduce plastic lifecycle GHG emissions by 41% (1.7 Gt CO₂-eq) compared to a *Baseline* scenario in 2040 (OECD, 2024^[127]).

Other relevant modelling work has focused on nexus systems that do not cover the triple planetary crisis in its entirety. One relevant study analysed how land, water and energy interact in the biophysical and economic systems and assessed the global consequences of policy inaction regarding the limited availability of land, water and energy (OECD, 2017^[235]). However, the study mainly looked at biophysical bottlenecks in terms of land, water and energy resources and did not quantify impacts of the triple planetary crisis.

Three-way analysis is challenging for a number of reasons, including the availability of data and the difficulty in capturing and modelling the interactions between different dimensions of the triple planetary crisis. For instance, globally comparable data that capture various dimensions of biodiversity is scarce and dispersed. Existing modelling tools typically omit ecological processes (e.g. species interactions and adaptation to climate change) (Urban et al., 2022^[236]). The complexity of pollutant interactions and the combined impact of exposure is also difficult to capture consistently. A further layer of difficulty lies in the need to couple economic and biophysical models to meaningfully represent the drivers of the triple planetary crisis, the resulting changes in environmental conditions and how changes in the state of the environment feed back into human societies, productivity and their development pathways. Finally, bridging the scale gap between global drivers and local impacts—while accounting for how local changes in turn influence global trends—remains a major challenge, with ongoing technical developments in this area (Hertel, 2025^[237]).

One important exception to the general lack of three-way analysis is the forthcoming Global Environment Outlook (GEO). The seventh edition of UNEP's Global Environment Outlook (GEO-7) assesses two main themes: the impacts of the interlinked global environmental crises of climate change, biodiversity loss and land degradation and pollution and waste; and how these crises can be addressed through systems transformations (UNEP, 2022^[238]). The current OECD Environmental Outlook complements the analysis through environment-economy modelling projections and the in-depth analysis of policy synergies and trade-offs.

1.6. Integrated modelling toolbox and analytical framework for the *Environmental Outlook*

1.6.1. Integrated modelling toolbox

A core contribution of the *Environmental Outlook* is environment-economy projections of climate change, biodiversity loss and pollution, which remains a major gap in the literature. Given the complexity of the interactions among the different components as already outlined in this chapter, a dynamic systems approach is needed to understand the future evolution of the pressures associated with the triple planetary crisis and their impacts. The challenge lies in moving beyond the conceptual framing of the triple planetary crisis and quantitatively assessing the biophysical and economic consequences of the interconnected issues of climate change, pollution and biodiversity loss. This requires a consistent modelling framework that links socio-economic and specific drivers and environmental pressures of each aspect of the triple planetary crisis. Unlike earlier studies that tend to focus on pairwise projections, the integrated modelling toolbox developed for this Outlook allows for consistent projections of climate, biodiversity and pollution metrics.

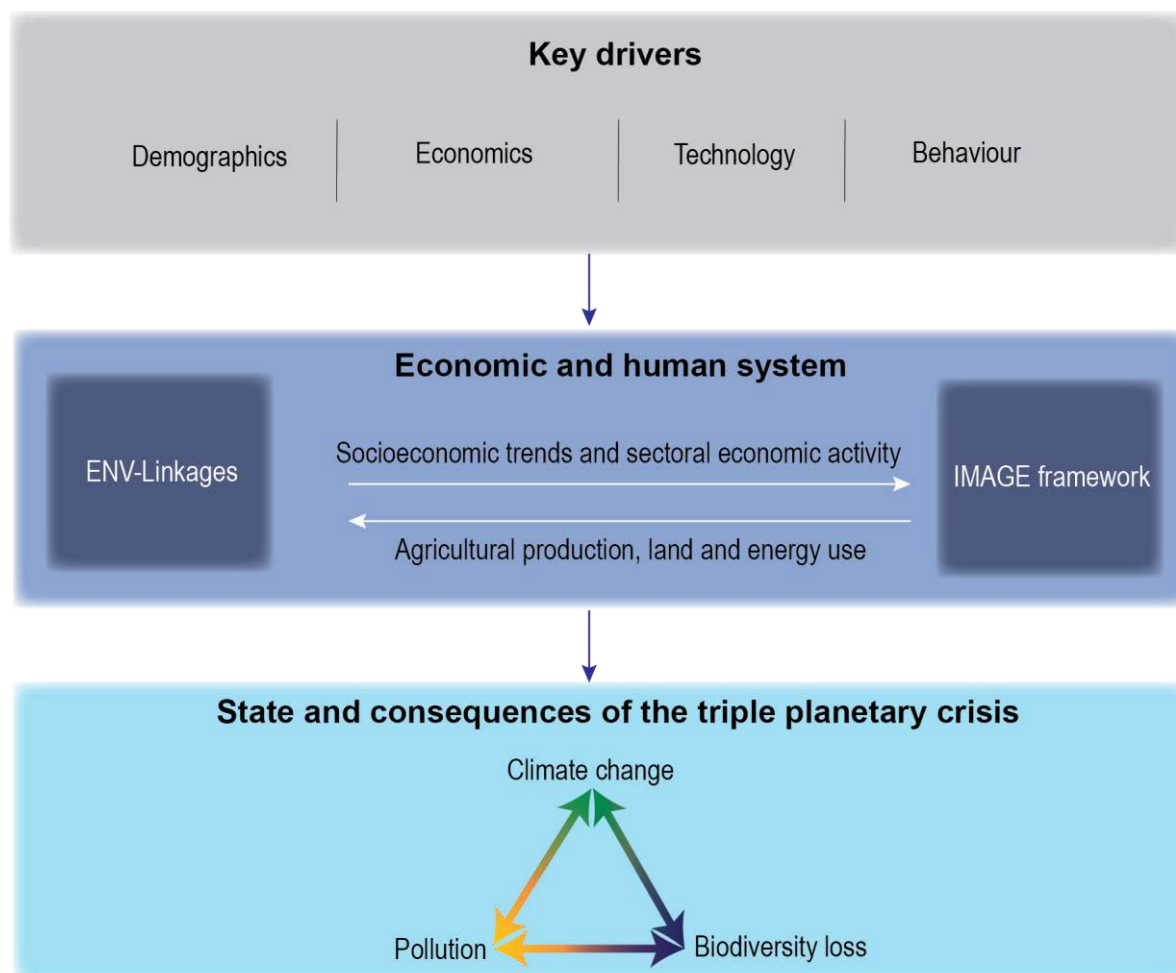
The projections are based on an integrated modelling toolbox comprising two main components: the OECD's in-house ENV-Linkages model (Annex 1.C) and the IMAGE modelling framework of PBL Netherlands Environmental Assessment Agency (Annex 1.D). The combination of the economic and biophysical models allows for quantitative analysis that recognises the close interlinkages among the economy and the environment, as well as among the different dimensions of the triple planetary crisis. The two models are further complemented with other tools such as the MAGICC model for climate and the TM5-FASST model for air pollution. Providing a broad lens on the future evolution of the triple planetary crisis, and the associated drivers, consequences and interactions calls for an assessment framework that is:

- *Integrated*, as economic activities are linked to each other via supply chains, and are linked to biophysical process through inputs (use of energy, materials, water) and their impact on the environment; an integrated framework enables a consistent quantitative assessment;
- *Multidisciplinary*, to be able to quantify both the economic and biophysical drivers, consequences, and interactions of the triple crisis, reflecting that the economy is embedded in nature and that both interact in multiple and often complex ways;
- *Economy-wide and sector-specific*, as a comprehensive picture is required for a complete assessment, covering environmental pressures for all sectors and acknowledging sectoral heterogeneity in terms of resource use, technologies and associated projections;
- *Global and spatially disaggregated* (as detailed in Annex 1.C), because there are significant differences between regions and their projected trends for the coming decades; furthermore, global changes (such as climate change) generate impacts that manifest at the local level, and local developments can drive environmental change in other regions, e.g. via international trade or transboundary pollution;
- *Dynamic*, to reflect the evolution of the challenge over time based on projections of socio-economic drivers and technological progress.

Both models are linked to ensure consistent but complementary insights (Figure 1.2). First, both models are driven by a common set of exogenous socio-economic trends that influence the activities modelled in detail. These trends include population and income growth, as well as changes in technology and behaviour. Second, key economic trends projected with ENV-Linkages, such as the impact of differences in productivity growth between economic sectors on structural change, are fed into the IMAGE modelling framework. These soft links on drivers between both models ensure that the resulting projections on production, consumption (both private and governmental) and international trade are harmonised across both models. Third, projections of land use and agricultural production in ENV-Linkages are harmonised

with the projections by the IMAGE modelling framework to ensure that the underlying biophysical trends, such as water availability and agricultural yield improvements, are adequately considered.

Figure 1.2. Overview of the linkages in the integrated modelling toolbox



Source: Authors' own elaboration.

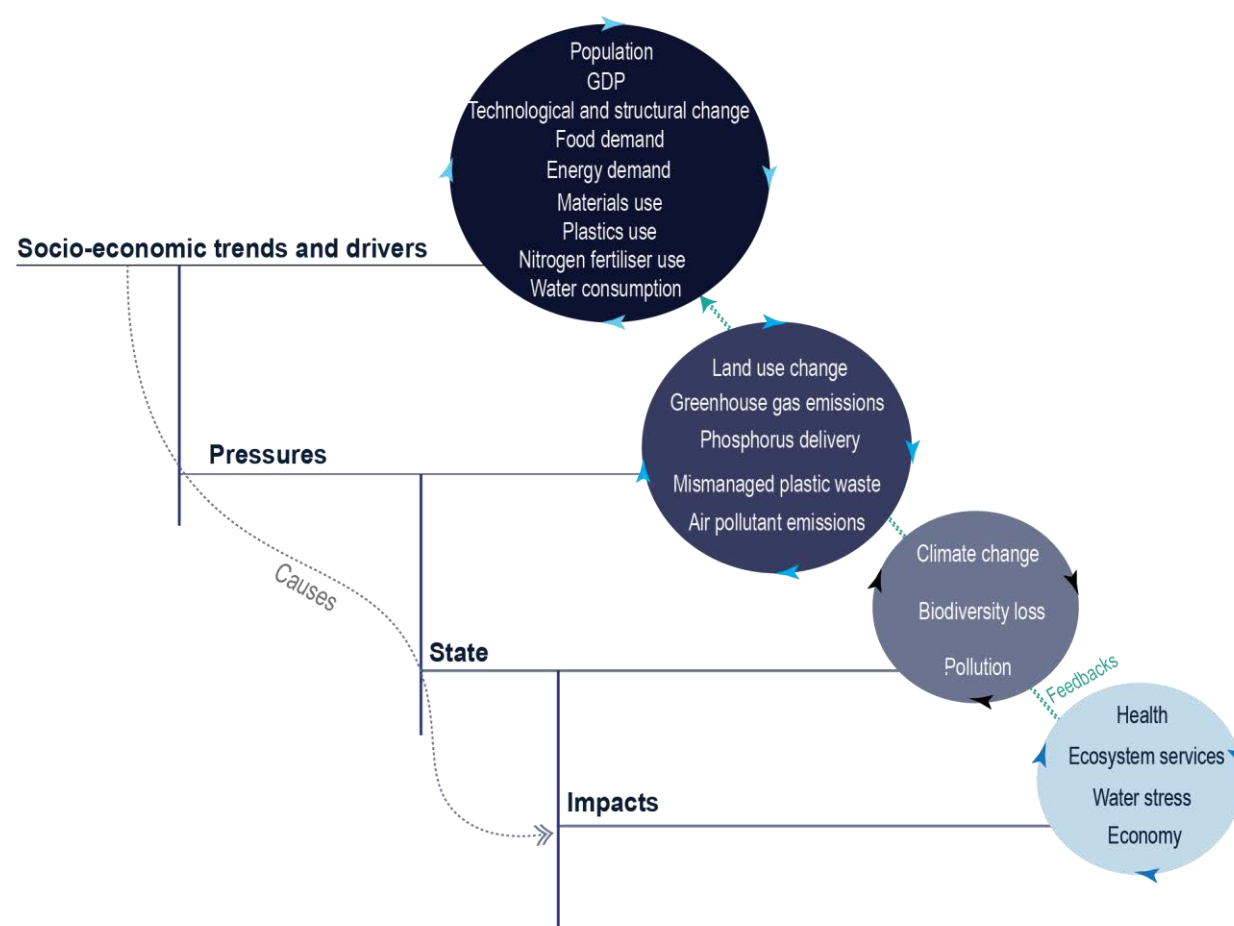
1.6.2. Analytical framework

The analytical framework helps unpack the triple planetary crisis through the consideration of the chain of interlinkages among drivers, pressures, states and impacts, which broadly reflects the driver-pressure-state-impact-response (DPSIR) framework (Hellweg et al., 2023^[239]). *Drivers*²² include direct drivers of the triple planetary crisis, such as food and energy demand, plastics and materials use or water consumption, which are in turn shaped by *socio-economic trends*: population, GDP per capita, technological and structural change. These drivers in turn lead to *environmental pressures* in the form of emissions of GHG, emissions and releases of pollutants, and land use and land use change. These pressures change the *state* of the environment over time and translate into wide-ranging *impacts* on human and planetary health and the economy.

These different components are linked together in three key ways, as indicated by the arrows in Figure 1.3. The first connection is a logical sequence related to *causality* (arrow from top to bottom): the broader underlying drivers lead to environmental pressures, which cause the triple planetary crisis and the resulting impacts. The second connection represents *feedback* effects (arrow from bottom to top): climate change,

for instance, affects plant growth and the uptake of CO₂ from the atmosphere (environmental pressure), which in turn has adverse macroeconomic consequences (socio-economic trends). Finally, a third connection shown in the figure represents *interactions within one component* (circular arrow at each level): one driver or a socio-economic trend (e.g. population growth) affects other drivers (e.g. food and energy use); one environmental pressure (e.g. land use change) affects other pressures (CO₂ emissions from agriculture, forestry and other land use); one crisis affects other aspects of the triple planetary crisis (e.g. biodiversity loss due to climate change); and one impact affects other impacts (e.g. crop yields affect health). Bringing different interlinkages (including causality and the interactions within each component) together, the analytical framework quantitatively illustrates that the triple planetary crisis is characterised by a multitude of interactions. It also demonstrates that the observed consequences result from a complex system of evolving drivers and pressures that all need to be addressed.

Figure 1.3. Drivers, pressures, state and impacts



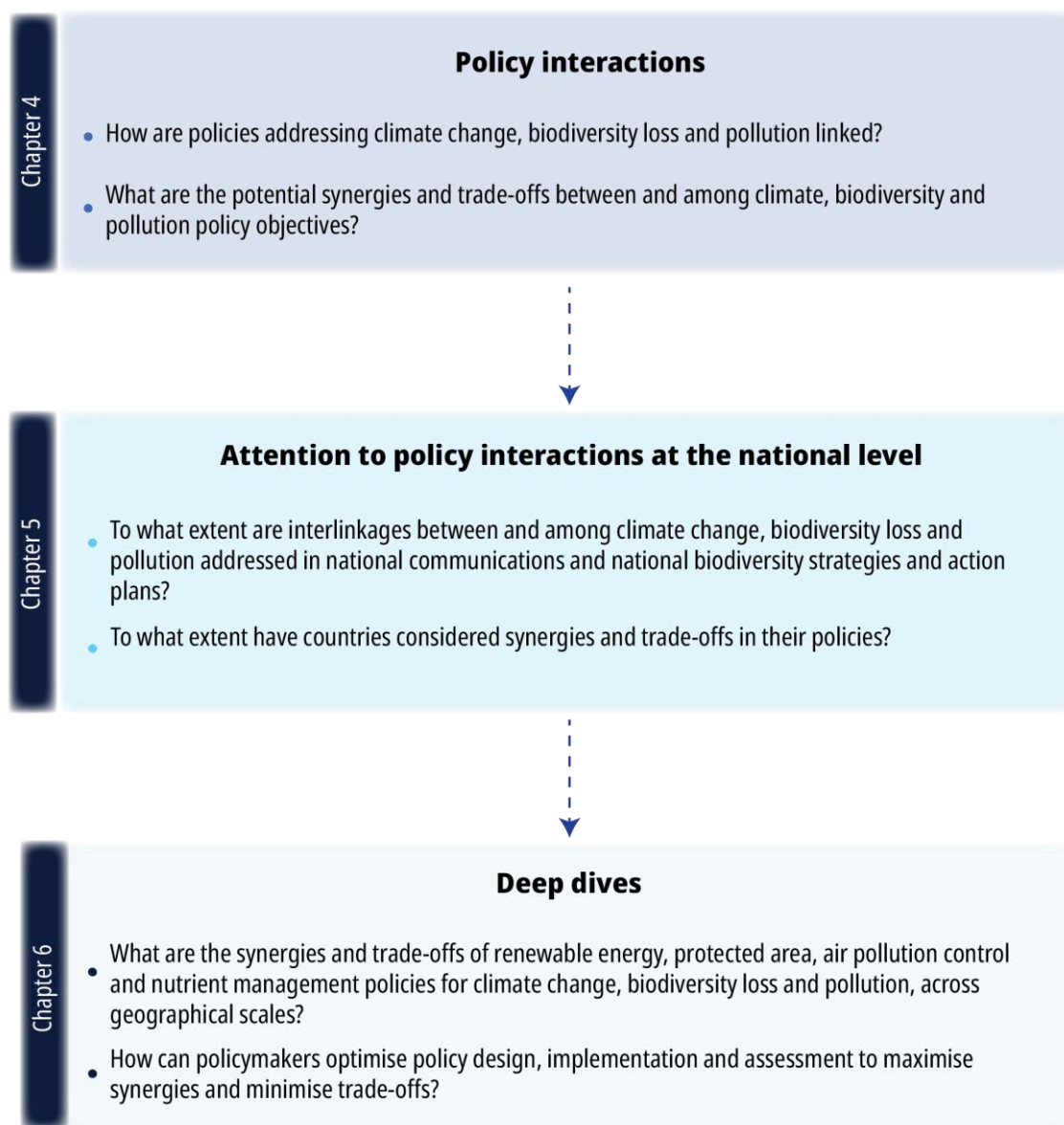
Source: Authors' own elaboration.

An important limitation of this framework is that it does not fully “close the loop”. Feedback effects of environmental degradation on the socio-economic drivers are not included in the modelling analysis (but qualitatively acknowledged in various parts). The main reason for this omission is that the magnitude of these feedback loops is highly uncertain and contested, and robust data remains elusive. For instance, recent estimates on the economic damages of climate change vary by more than an order of magnitude (IPCC, 2022^[4]), with considerable differences depending on e.g. the methodology used and the (mostly

assumed) persistence of the economic effects of climate impacts. Economic effects of loss of biodiversity and ecosystem services are even more uncertain, and the associated literature is less developed. For example, the seminal Dasgupta Review (Dasgupta, 2021^[240]) suggests that an assessment of the costs of biodiversity loss is not readily available and that assessing the value of the associated ecosystems may be more insightful. Finally, many impacts of climate change and pollution relate to human health, either through mortality or morbidity effects. Such effects are not captured in standard economic indicators: GDP impacts and healthcare costs are not useful indicators of welfare losses of lives lost. Thus, many environmental impacts are not monetary, and framing them in monetary terms (through methods like Value of a Statistical Life) is fraught with complications.

There are also interlinkages at the level of policies to tackle the triple planetary challenge. This calls for a better understanding of synergies and trade-offs and the extent to which these interlinkages are considered in policymaking and in policy implementation. These analyses of policy interlinkages at various levels can elucidate the strengths and gaps in current policy approaches and inform how policy design and implementation can be optimised to reap synergies while minimising trade-offs (Figure 1.4).

Figure 1.4. Overview of policy analysis conducted in the report



Source: Authors' own elaboration.

The following two chapters present the baseline modelling projections of the evolution of climate change, biodiversity loss and pollution through to 2050 under current policies. Building on the analytical framework, Chapter 2 unpacks the common underlying and multifaceted drivers and explores how the environmental pressures can be explained by the changes in drivers. Chapter 3 examines the current and projected state of each dimension of the triple planetary challenge and explores what the projected state in 2050 means for the economy and human health. Chapters 4, 5 and 6 examine policy interactions at the three levels outlined in Figure 1.4 (conceptualising policy interactions, attention to policy interactions at the national level, and deep dives on managing synergies and trade-offs at the implementation stage). Chapter 7 concludes with an action plan for more integrated and effective policy responses to tackle the triple planetary challenge in a holistic manner.

Annex 1.A. Observed and projected health impacts of climate change, biodiversity loss and pollution: Select examples

Annex Table 1.A.1. Examples of health impacts

	Climate change	Biodiversity loss	Pollution
Non-communicable diseases (e.g. cardiovascular and respiratory diseases)	- Heat stress represent an acute health hazard associated with reduced cardiovascular functions (Gostimirovic et al., 2020^[241]), especially for the elderly, young children and those living with underlying chronic health conditions (Ebi et al., 2021^[242]; Romanello et al., 2024^[243]). - Wildfire smoke exposure can lead to respiratory issues including worsened asthma (Reid et al., 2016^[244]).	- Biodiversity loss (e.g. loss in bacterial diversity) can contribute to the occurrence of asthma, wheezing and allergic sensitisation (Paciência et al., 2024^[245]). - Exposure to plant diversity can reduce the incidence of asthma as microbial exposure is linked to better human immune function (Donovan, Landry and Gatzolis, 2021^[246]).	- PM_{2.5} travels into deep parts of the lung and can reach the bloodstream (Thangavel, Park and Lee, 2022^[247]); air pollution is associated with cardiovascular and respiratory diseases as well as chronic obstructive pulmonary diseases and lung cancer (WHO, 2013^[248]; OECD, 2016^[249]). - Children are particularly susceptible as their immune systems are still developing, they breathe more rapidly, and they are exposed to more pollutants relative to their body size (WHO, 2018^[250]).
Infectious diseases	58% (218 out of 375) of pathogenic diseases studied were aggravated by climate change, while 16% were at times diminished (Mora et al., 2022^[251]). - Disease-carrying mosquitoes are spreading to regions where they had never been present before due to increasing temperatures (Kraemer et al., 2019^[252]; Van Wyk, Eisenberg and Brouwer, 2023^[253]). - Over four billion people, amounting to nearly half the world's population, are currently at risk from arboviruses (viruses transmitted through the bite of e.g. mosquitoes). Due to several factors including changes in climatic variables, this number is projected to increase to approximately five billion by 2050 (WHO, 2024^[254]).	- Biodiversity is among the most prominent drivers of the emergence of infectious diseases and zoonosis outbreaks (Mahon et al., 2024^[255]). Species loss can open niches that are often filled by species that tend to be hosts for zoonotic pathogens, in particular mammals such as rodents and bats (Gibb et al., 2020^[256]). - Soil biodiversity loss impairs benefits of control of pests and pathogens (Wall, Nielsen and Six, 2015^[257]). For example, soils with higher microbial diversity are more effective at suppressing enteric pathogens such as Salmonella (Samaddar et al., 2021^[258]).	- Exposure to PM can also increase hospital admissions for less studied infectious diseases such as sepsis, kidney failure, urinary tract infections and skin infections (Wei et al., 2019^[259]). - Exposure to air pollutants generally decreases the immune system's ability to fight off infections, increasing the occurrence and severity of infections of infectious diseases (Healths Effects Institute, 2024^[260]). - Plastic waste can be a conduit for vector-borne diseases, with recent data suggesting <i>Aedes</i> mosquitoes are adapted to favour laying eggs in e.g. discarded containers (Landrigan et al., 2025^[18]).
Mental health	- Heat exposure affects physical activity and sleep quality, influencing both physical and mental health (Romanello et al., 2024^[243]). - Rising temperatures along with more frequent and severe temperature extremes can cause distress (Lawrance et al., 2022^[261]). - Experience of severe or repetitive natural hazards can increase the risk of suicide (WHO, 2022^[262]); increased temperatures are associated with increased suicide rates (Burke et al., 2018^[263]).	- Access to biodiverse environments can facilitate recovery from stress, depression and other mental health-related conditions (IPBES, 2024^[264]). - Urban spaces with a larger range of natural features, such as trees, plants and birdlife are associated with better mental well-being (Hammoud et al., 2024^[265]; Buxton et al., 2024^[266]). - Interactions with nature (including wild animals) can be effective treatments for depression and anxiety (WHO/CBD, 2015^[267]).	- Exposure to solvents and vascular dementia are strongly associated, while there is suggestive evidence for additional associations between air pollutants and negative mental health effects (Radua et al., 2024^[268]). - Exposure to air pollutants leads to oxidative stress, resulting in cellular damage within the central nervous system and increasing susceptibility to psychiatric disorders (Radua et al., 2024^[268]).

			Living in areas with high air pollution is often associated with other stressors, such as noise pollution and socioeconomic disadvantages, which can act as effect modifiers on pre-existing mental health issues (Thomson, 2019^[269]).
Malnutrition and food-related health outcomes	- Extreme heat, droughts and floods affect crop yields and crop stocks while creating volatility in the quantity, diversity, and quality of food (Springmann et al., 2016^[270]), contributing to malnutrition especially for vulnerable children (nearly half of deaths in children under five are linked to undernutrition (UNICEF, 2023^[271])) and low-income households. - Increased atmospheric CO₂ lowers the projected growth in global nutrient availability per capita between 2010 and 2050 by 19.5% for protein (Beach et al., 2019^[272]). By 2050, the risk of hunger and malnutrition could rise by 20% due to climate change (UN World Food Programme, 2021^[273]).	- The decline of pollinators can threaten food security, as more than three-quarters of the world's food crops rely at least partially on pollination (Ritchie, 2021^[274]). - Lack of "agrobiodiversity" can also affect food security and nutritional diversity; nine species currently account for 66% of total crop production (FAO, 2019^[275]). Similarly, eight species provide more than 95% of total livestock and ten species account for a half of the total aquaculture production (FAO, 2024^[276]).	- Ground-level ozone can reduce crop yields. For instance, it is estimated that 16.8 million metric tons of wheat will be lost in Europe in 2050 due to ground-level ozone (Health Effects Institute, 2024^[260]). - Chemicals present in plastics may pose a challenge for human health (OECD, 2024^[127]; Wagner et al., 2024^[277]) and may disproportionately impact children and women (United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2023^[122]).
Drinking water and sanitation	- Climate change causes variability in the water cycle, contributing to increased floods, water scarcity, droughts, and water pollution (UN-Water, 2019^[278]). - Floodwaters can also disperse pathogens and cause outbreaks (Semenza, Rocklöv and Ebi, 2022^[168]).	Biodiversity loss compromises the availability and quality of water (Secretariat of the Convention on Biological Diversity, 2015^[279]); for instance, biodiverse water bodies can filter pollutants more efficiently (Cardinale et al., 2006^[280]).	Nitrogen and phosphorus pollution in the water can contribute to algal blooms, which lower water quality. Nitrates in groundwater can also reach public drinking water systems and cause harms even at low levels, especially for infants (Akinawo, 2023^[281]).
Other health impacts	Extreme weather events like storms, river floods, wildfires and droughts can have a range of mortality and morbidity impacts (Weilhammer et al., 2021^[282]).	Biodiversity loss constitutes a loss of a vital source of genetic resources underpinning modern and traditional medicine such as treatments and vaccines against chronic and infectious diseases including antibiotics and painkillers (WHO/CBD, 2015^[267]).	- Exposure to PM can lead to an increased risk of neurodegenerative diseases such as Alzheimer's, Parkinson's and dementia (Cristaldi et al., 2022^[283]; Wang et al., 2021^[284]) as well as impaired cognitive development (IPBES, 2024^[264]). - Occupational or residential exposure to certain pesticides are associated with adverse health effects including cancer (UNEP, 2022^[285]).

Annex 1.B. Framing of the various drivers of climate change, biodiversity loss and pollution in the modelling toolbox

The modelling toolbox developed for the Outlook builds on the general concept of driver-pressure-state-impact-response (DPSIR) causal links. As the first step, it examines a set of drivers of environmental change. Chapter 2 goes into details on the first step in the framework and discusses the broader socio-economic trends and specific drivers that together shape environmental pressures. The former includes e.g. demographic changes, income growth and structural change, while the latter contain a wide range of indicators, including e.g. food demand, nitrogen fertiliser use, energy demand, plastics use, materials use²³ and water consumption. The latter depend on the former and thus the specific drivers are usually expressed in the form of intensities. For example, economic activity provides the scale of production of energy-using economic activities, and energy intensity of production reflects the specific driver. Together, these represent the driver of energy demand.

There are alternatives and shortcuts to the DPSIR framework, for example by condensing the driver and pressure parts into one category. Thus, there are different ways in which “drivers” can be categorised. For example, the Global Assessment Report on Biodiversity and Ecosystem Services by the IPBES refers to the *direct* and *indirect* drivers of biodiversity loss. *Direct* drivers are both non-human and anthropogenic changes to terrestrial, freshwater and marine biomes that physically affect biodiversity (land- and sea-use change; direct exploitation of organisms; climate change; pollution; and invasive alien species), which have underlying causes that are classified as *indirect* drivers (demographic and sociocultural; economic and technological; institutions and governance; conflicts and epidemics). Roughly speaking, the direct drivers reflect the pressure-to-state stage in the DPSIR framework, while the indirect drivers reflect the driver-to-pressure stage, although these links are not fully corresponding. Meanwhile, the IPCC Sixth Assessment Report attributes observed warming (increase in surface temperature) mainly to anthropogenic drivers (changes in GHG concentrations, partly masked by cooling aerosols emissions) (see Annex Table 1.B.1), i.e. focusing more on pressures than on the underlying socioeconomic trends and specific drivers in the DPSIR framework.

Annex Table 1.B.1. Example of differences in framing of drivers

The OECD Environmental Outlook	IPBES Global Assessment Report on Biodiversity and Ecosystem Services	IPCC Sixth Assessment Report
Socioeconomic trends: - Population - GDP per capita - Structural change - Technological change and efficiency improvements Specific drivers, incl.: - Food demand - Nitrogen fertiliser use - Energy demand - Plastics use - Materials use - Water Consumption	Direct drivers of biodiversity loss: - Land-/ sea-use change - Direct exploitation - Climate change - Pollution - Invasive alien species Indirect drivers of biodiversity loss: - Demographic and sociocultural - Economic and technological - Institutions and governance - Conflicts and epidemics	Anthropogenic drivers of climate change: - Changes in GHG concentrations - CO₂ from fossil fuel combustion - CO₂ from land use, land-use change and forestry - Methane (CH₄), N₂O and fluorinated gases - Other human drivers - Cooling and warming aerosols - land-use reflectance - Ozone Natural Drivers: - Solar and volcanic drivers - Internal variability

Source: IPBES (2019^[9]) and IPCC (2023^[1])

Annex 1.C. The ENV-Linkages model

The economic system

The ENV-Linkages model is a standard computable general equilibrium (CGE) model, which is used to study the linkages between the economy and the environment. Production in ENV Linkages is assumed to operate under cost minimisation with perfect markets and constant returns-to-scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. In the short run this ensures inertia in the economic system, with limited possibilities to substitute away from more expensive inputs, but in the longer run this implies a relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo classical growth model, where economic growth is assumed to stem from the combination of labour, capital accumulation and technological progress.

Household consumption demand is the result of static maximisation behaviour, which is formally implemented as an “Extended Linear Expenditure System”. A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

Market goods equilibria imply that, on the one side, the total production of any goods or services is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) by domestic producers and the import demand.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the numéraire.

As ENV-Linkages is recursive-dynamic and does not incorporate forward-looking behaviour, price-induced changes in innovation patterns are not represented in the model. The model does, however, entail technological progress through an annual adjustment of the various productivity parameters, including e.g. autonomous energy efficiency and labour productivity improvements. Furthermore, as production with new capital has a relatively large degree of flexibility in choice of inputs, existing technologies can diffuse to other firms. Thus, within the CGE framework, firms choose the least-cost combination of inputs, given the existing state of technology. The capital vintage structure also ensures that such flexibilities are larger in the long run than in the short run.

The environmental system

The ENV-Linkages model includes a range of environmental pressures, including (GHG) emissions, emissions of air pollutants, materials use and plastics use, waste and end-of-life fates. In all cases, the environmental pressure is linked to the relevant economic activity, using factors to translate from monetary to physical units. These factors (or intensities, as they reflect the environmental pressure per unit of related economic input) are sector-, region- and time-specific (see Annex Box 1.C.1 for an explanation of the time-specific component). This allows that production of the same commodities in different regions leads to different environmental pressures.

Annex Box 1.C.1. Modelling environment-saving technological progress in ENV-Linkages

Over time, efficiency improvements (from technological improvements, learning-by-doing, etc.) allow for a partial, relative decoupling of economic activity and environmental pressure. Most technological progress that allows less use of environmental inputs (or outputs in case of emissions) per unit of output is captured by reduced use of the associated economic input: energy efficiency improvements imply less demand for fuels, and thus lower emissions, not lower emissions per unit of fuel use. However, in some cases the environmental input per unit of economic activity can also decrease, especially when the environmental pressure is not linked to a specific input in production, but a by-product of the production process. A typical example is end-of-pipe measures to reduce the release of air pollutants per unit of production. In the latter case, the environmental factor reduces over time.

Greenhouse gas emissions in ENV-Linkages encompass the three main GHGs, CO₂, CH₄ and N₂O. These originate from fossil fuel combustion, industrial processes, and agricultural activities. Emissions are tied to economic variables through sector-, region- and time-specific emission factors on fossil fuel use for combustion emissions, sectoral output for industrial processes and fugitive emissions, and production factors. Emission abatement happens through different mechanisms: changes in the prices of fuel, other production factors and output (including due to carbon pricing) affect the least-cost production methods and affect both the composition of production inputs and level of activity related to emissions, while emission factors related to process emissions can also decrease for CH₄ and N₂O as well as process CO₂ following marginal abatement cost curves from the literature (U.S. Environmental Protection Agency (2019^[286]), complemented by other sources). Changes in the climate system are then recovered using the MAGICC model (Meinshausen et al., 2020^[287]; Meinshausen, Raper and Wigley, 2011^[288]).

ENV-Linkages includes air pollutant emissions, comprising BC, OC, other fine particles (particulate matter lower than 2.5 µm, Other PM_{2.5}), carbon monoxide (CO), NH₃, NO_x, SO₂ and non-CH₄ volatile organic compounds (NMVOC). These air pollutants combine to projections for PM_{2.5} as well as tropospheric ozone. The modelling of air pollutant emissions in ENV-Linkages is similar to GHGs: emissions are tied to economic variables: fossil fuel demand for combustion emissions, sector output for process emissions and production factors for agricultural activities. Abatement of air pollutant emissions are operated through activity reduction based on fuel, factors and output prices, as well as emission factors reductions based on the GAINS model outputs (Amann et al., 2011^[289]). Changes in air pollutant concentration, as well as impacts, are ultimately evaluated using the JRC TM5-FASST model (Van Dingenen et al., 2018^[290]).

Modelling materials use in ENV-Linkages in a demand-based approach allows for capturing the effects of structural changes as well as modifications of consumption and trade patterns, which drive changes in materials demand. The projections cover 60 materials, grouped in 4 categories: metals (e.g. Iron, Copper or Aluminium ores), non-metallic minerals (e.g. sand, gravel and crushed rocks, limestone), fossil fuels (e.g. oil, natural gas and various coal types) and biomass (e.g. about 15 crops, grazed biomass, fish). Including materials in the modelling toolbox requires three main steps: (i) including the extraction of primary

materials in the model, (ii) modelling recycling and secondary material processing, and (iii) modelling the substitution between primary and secondary materials, when possible. Physical material flows are linked to the economic flows in the ENV-Linkages model (OECD, 2019^[291]), based on physical material flows (UNEP IRP, 2024^[292]). Material flows are either directly linked to the economic output of the corresponding extraction sector (e.g. coal extraction or sugar cane and beet cultivation) or to the economic activity of the downstream processing sectors (e.g. iron ores is linked to the demand for mining products by the iron and steel sector).

The ENV-Linkages modelling framework is also used to calculate plastic flows along their lifecycle, encompassing use, waste generation and management as well as leakage. ENV-Linkages has been enhanced to include data on plastics use, waste and end-of-life treatment (see (OECD, 2022^[293]) for more details). The projections encompass 14 polymer groups, 14 applications, 4 waste treatment options. Plastics use is modelled by linking it to economic activities. Plastics are considered not only as a final good for consumption, but also as a production input for each sector, taking into account the complexity of the interactions across sectors and regions and along the plastic lifecycle. The generation of waste depends on the average lifespan of each plastic product. International trade in plastic goods and waste is also modelled. The ENV-Linkages model has also been enhanced to distinguish the end-of-life fates of plastics, which heavily depend on the waste management capacities and regulations of the location where plastic waste is generated and handled. Four end-of-life fates are modelled: waste can be recycled, incinerated, landfilled (in sanitary landfilling), or mismanaged (which includes uncollected litter). The recycling of plastics physical flows is then linked back to the economic flows represented in the economic sectors in ENV-Linkages.

Annex 1.D. The IMAGE model framework

Overview

IMAGE is an integrated assessment modelling framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere, and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The model can be used to explore long-term pathways for future environmental and sustainable development problems as well as possible response strategies. It has representations of the energy, agriculture, land use, and climate systems. Typical outputs include projections of energy supply and demand, agricultural production, land use and land cover change, emissions of GHGs and other pollutants, and demand for water and material resources. The model is calibrated to datasets of energy supply and demand (International Energy Agency) and agricultural production and land cover (Food and Agricultural Organisation). IMAGE participates in multiple model intercomparison projects covering energy transition, land use change and emission scenarios, and sustainable development trajectories. IMAGE is a hybrid systems dynamics model. It employs stylised optimisation techniques when meeting climate targets. The model simulates the human and natural environment from 1971 to 2100, with the 1971-2022 period acting as a calibration and spin-up period. The model works on an annual timestep.

Population and economic activity are key exogenous drivers. Assumptions (across the food and energy systems) on technology availability and development, behavioural and lifestyle choices are also inputs. The model can incorporate land protection, energy, and other quantifiable policies. Biophysical and land use are represented at a 0.5x0.5-degree grid, while socio-economic processes are modelled on the level of 26 regions.

Energy supply and demand

The energy system is modelled by the energy-system simulation model, *TIMER* (van Vuuren et al., 2007^[294]). This energy model includes fossil and renewable primary energy carriers (coal, heavy/light oil, natural gas, modern/traditional biomass, nuclear, concentrated/photovoltaic solar, onshore/offshore wind, hydropower, and geothermal). Primary energy carriers can be converted to secondary and final energy carriers (solids, liquids, electricity, hydrogen, heat) in order to provide energy services for different end-use sectors (heavy industry, transport, residential, services, chemicals and other).

The model projects future (useful) energy demand for each end use sector based on relationships between energy services and activity, the latter of which is related to economic growth. More details on the methods can be found in papers on the modelling of energy demand in heavy industry (van Ruijven et al., 2016^[295]), transport (Girod, van Vuuren and de Vries, 2013^[296]; 2012^[297]), the residential sector (Daioglou, van Ruijven and van Vuuren, 2012^[298]), chemicals (Daioglou et al., 2014^[299]) and other sectors (Stehfest et al., 2014^[300]).

For each demand sector, secondary energy carriers (including solid and liquid biofuels) compete based on relative costs with each other in order to meet the useful energy demand. A Multinomial Logit function is used to determine market shares of each energy carrier, where the cheapest option gets the largest market share, the 2nd cheapest the 2nd largest market share, and so on. Energy prices are based on supply curves of energy carriers (Rogner, 1997^[301]). For non-renewable sources, these are formulated in terms of cumulative extraction; while for renewable sources, these are formulated in terms of annual production (as explained above for biomass).

Land cover and use

Land use dynamics including agricultural activities and forestry are modelled at grid level in the IMAGE land component (Doelman et al., 2018^[302]). The agro-economic general equilibrium model MAGNET is soft-coupled to IMAGE and provides information on crop and livestock demand, trends in intensification and international trade (Woltjer, 2014^[303]). The land supply curve specifies the relation between total agricultural land supply and the real land price and depends on the constraints related to the availability of biophysically suitable land and institutional factors (agricultural and urban policy, conservation of nature) source. The land supply curve is constructed with land availability data provided by IMAGE (Dixon et al., 2016^[304]; van Meijl et al., 2006^[305]).

Crops, the carbon cycle and the hydrological system are represented through the *Lund-Potsdam-Jena managed Land* model (LPJmL). LPJmL is a global gridded model that describes the coupled carbon and water cycles (Schaphoff et al., 2018^[306]). It simulates natural vegetation growth, crop growth and hydrology. The human impacts to the hydrological cycle, such as irrigation water withdrawals, other water withdrawals, water supply and the operation of large dams and reservoirs, are included. The effect of water limitation on vegetation growth is simulated. This makes LPJmL a very suitable tool to study the interactions between water and food production. The model is validated against discharge measurements, carbon fluxes and vegetation patterns, and calibrated against crop yields at country level. LPJmL is run fully coupled to IMAGE. This means that it gets annually gridded data on climate, non-agricultural water use, land use from IMAGE, and sends back annual info on crop yields, agricultural water withdrawals, water availability, natural vegetation growth and the carbon cycle to IMAGE. The LPJmL model represents all biophysical processes at 0.5x0.5-degree grid, but water balances are calculated with subgrid variability. Crop management parameters are calibrated at country level. The model output can subsequently be aggregated to any regional level.

Biodiversity

The GLOBIO model quantifies local terrestrial biodiversity intactness, expressed as the Mean Species Abundance (MSA) indicator as a function of climate change, atmospheric nitrogen deposition, land use, roads, and hunting (tropical regions). The impact of habitat fragmentation, resulting from both land use and roads, is also included. The impact of the different pressures on MSA is quantified for plants and vertebrates separately, and then combined into one overall MSA value. In this study, we applied version 4 of the GLOBIO model. GLOBIO 4.0 is based on pressure-impact relationships established through meta-analytical approaches based on empirical data in combination with data on pressure levels. Regression equations for each independent pressure factor are estimated using generalised linear mixed models.

Population changes and economic activity are key exogenous factors driving land use change, climate change and nutrient pollution. These pressures are exogenous input for the GLOBIO model and were for this study provided by OECD (based on (United Nations, 2022^[307]) and Environmental Outlook modelling toolbox; see also Annex 2.A. on socioeconomic trends for more details in Chapter 2). Additional assumption on nature protection and the level of protection, land use configuration and the level of infrastructure use can be adapted to address scenario assumptions and policies. Global road data are from the GRIP database (Meijer et al., 2018^[308]). To quantify hunting pressure in tropical regions, the distance to settlements is required. We obtained locations of settlements from OpenStreetMap (<http://download.geofabrik.de>), the Humanitarian Data Exchange (www.data.humdata.org) and national databases.

Nutrient flows and pollution

The *Global Nutrient Model* (GNM) is a global distributed, spatially explicit model using hydrology from PCRGLOBWB as the basis for describing nitrogen (N) and phosphorus (P) delivery²⁴ to surface water, transport and in-stream retention in rivers, lakes and reservoirs in the IMAGE model. GNM is hard-linked to the integrated assessment modelling framework IMAGE. IMAGE-GNM uses the land use information and nitrogen deposition from IMAGE and the associated agricultural production (grass, crop and animal production) to estimate the N and P fertiliser use for cropland and grassland. Human protein consumption is used to estimate the delivery of human and industrial sewage to the rivers. Also, the delivery of nutrients from natural land to the rivers is estimated. The load is transported by the rivers to the coastal seas, taking into account the in-stream loss processes in the river. The model can be used to explore the long-term pathways for future environmental and sustainable development problems as well as possible response strategies. Typical outputs include projections of nutrient delivery to the rivers and the export of nutrients to the coastal seas including the distribution of the different nutrient sources.

IMAGE-GNM is a global distributed, spatially explicit model. The model works on an annual timestep while taking into account the historical loads. The model starts in 1900. This is needed to incorporate the storage of nitrogen in groundwater and storage of phosphorus in the soil pools. The model is validated on long term time series of observed nitrogen and phosphorus concentrations in several river basins (e.g. Mississippi, Rhine, Meuse, Yangtze).

Alongside the data that is used from IMAGE, there are other assumptions that are not provided by the IMAGE model. Nitrogen use efficiency is used as the main driver to calculate future nitrogen fertiliser use. The phosphorus fertiliser use is determined by the phosphorus content of the soil and the phosphorus availability for the plant. The recycling of manure and soil conservation in the agricultural sector are policy options which can lead to a more sustainable sector. Assumptions on the number of people connected to a sewage system and the efficiency of the sewage treatment plants can improve the population health and the water quality. The production of aquaculture is another direct source of nutrients in rivers and is one of the scenario assumptions.

Annex 1.E. Regional details of the modelling framework

The analysis in this report has global coverage and provides regional details. Throughout the report, results are presented at the global level, or disaggregated into three or nine regions.

Annex Table 1.E.1 shows how these regions map onto the 26 regions of the IMAGE modelling framework. Outputs at these levels of aggregation are complemented with more detailed maps where possible.

Annex Table 1.E.1. The regional aggregation used in the modelling toolbox

3-region aggregation	ENV-Linkages aggregation draft Baseline	IMAGE regions
Higher-income region	North America	USA
		Canada
	Europe	Western Europe
		Central Europe
		Türkiye
	Japan, Korea and Oceania	Oceania
		Japan
		Korea region
Middle-income region	East Asia	China region
	Middle East and North Africa	Middle east
		Northern Africa
		Ukraine region
	Eurasia	Central Asia
		Russia region
		Mexico
		Rest of South America
	Central and South America	Central America
		Brazil
Lower-income region	South Asia	India
		Southeastern Asia
		Indonesia region
		Rest of South Asia
	Sub-Saharan Africa	Western Africa
		Eastern Africa
		Rest of Southern Africa
		South Africa

Note: The 3-region aggregation is based on the average income level in 2050 of the 9 aggregate regions included, not on the income level of individual countries. Thus, individual countries are first grouped geographically (e.g. Haiti in Central America) and then allocated to the income aggregate of that region (in this case the Middle-income region).

Source: Authors' own elaboration.

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Notes

¹ Brownfield land is abandoned land that was previously developed, and which may be polluted.

² The socioeconomic interlinkages are discussed more extensively in Chapter 2.

³ There remains considerable ambiguity over the importance of genetic evolution versus plastic responses.

⁴ See, for example, smaller fish sizes recorded in IISD's Experimental Lake Areas (IISD, 2015^[314]).

⁵ According to the International Union for Conservation of Nature (IUCN) and the Convention on Biological Diversity, "invasive alien species" refer to a subset of alien species that have harmful impact on the economy, environment or health.

⁶ See for instance eChemPortal (OECD, 2024^[311]) for information on chemical properties.

⁷ Nutrient load refers to the total amount of nutrients, such as nitrogen or phosphorus, entering a system or environment such as water bodies over a specific time period.

⁸ The surplus of nitrogen and phosphorus is calculated as the difference between nutrient inputs (such as manure, synthetic fertilisers, atmospheric deposition and biological nitrogen fixation) and the amount of nutrients taken up in plant biomass. This surplus leads to nutrient buildup in soils and runoff into water bodies.

⁹ The N:P ratio is a measure of nutrient balance, expressing the relative availability or concentration of nitrogen relative to phosphorus, typically expressed in molar terms.

¹⁰ The meta-analysis includes studies on 471 different pesticide active ingredients, which also include both those banned and currently in use.

¹¹ Under the Stockholm Convention, the POPs are defined as organic chemical substances that have a "combination of physical and chemical properties such that, once released into the environment, they (i) remain intact for exceptionally long periods, (ii) become widely distributed throughout the environment as a result of natural processes involving soil, water and, most notably, air; (iii) accumulate in the living organisms including humans, and are found at higher concentrations at higher levels in the food chain, and (iv) are toxic to both human and wildlife" (UNEP, n.d.^[313]). On a subgroup of PFAS, see also (Secretariat of the Basel, Rotterdam and Stockholm Conventions, 2022^[312]).

¹² For instance, while suspended solids rely on physical processes of sedimentation and filtration from the substrate, organic matter and nitrogen removal occur through microbiological degradation stimulated by plants (Brisson et al., 2020^[309]).

¹³ Ground-level ozone is formed through photochemical reaction of precursors (NO_x and VOCs) with heat and solar radiation.

¹⁴ The spray drift depends on the application techniques. For instance, upward spraying results in greater release compared to downward spraying.

¹⁵ Tailings are a mixture of crushed rock and fluids that remain after the extraction of resources such as metals and minerals (Kossoff et al., 2014^[156]).

¹⁶ The Kigali amendment of the Montreal Protocol, implemented in 2019, commits the Parties to reduce the production and consumption by more than 80% to limit GHG emissions.

¹⁷ Aerosols vary in shape and size and depending on their characteristics, they can either scatter or absorb radiation. Sulphates, nitrates and ammonium are examples of scattering aerosols, while BC is an absorbing aerosol (Li et al., 2022^[197]).

¹⁸ Radiative forcing is the disruption to the energy balance of the earth-atmosphere system; in the context of air pollution and climate change, for instance, it represents the net balance between the warming and cooling impacts of the changes in concentrations of different pollutants.

¹⁹ NbS are not new; for instance, Article 5 of the Paris Agreement highlights the importance of conserving and enhancing natural reservoirs of GHGs including forests.

²⁰ NbS are defined as “actions to protect, conserve restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” (UNEP, 2022^[203]).

²¹ The nine planetary boundaries are: (1) climate change, (2) novel entities, (3) stratospheric ozone depletion, (4) atmospheric aerosol loading, (5) ocean acidification, (6) modification of biogeochemical flows, (7) freshwater change, (8) land system change, (9) biosphere integrity (Rockström et al., 2009^[310]).

²² Drivers can be classified differently in various analyses. For an overview, see Annex 1.B.

²³ While the scope of materials can vary depending on contexts, for instance including only raw materials or including transformed materials as well, including or not water, in this report materials use refers to the primary raw materials as detailed in (OECD, 2019^[291]), and encompassed in the updated UNEP-IRP (2024^[292]) materials database. These materials pertain to four groups: metals, non-metallic minerals, biomass and fossil fuels.

²⁴ Nutrient delivery reflects the transport of nutrients to the water system. It differs from nutrient application, which is the nutrient content of e.g. fertiliser or manure put on the ground.

2 Historical and future drivers of the triple planetary crisis

This chapter starts with a view on the direct drivers of climate change, biodiversity loss and pollution, their underlying socio-economic trends, and interactions under current policies. The chapter then unpacks these drivers and provides quantifications of past and future trends of key drivers from a supply- and demand-side perspective, revealing the critical role of efficiency and related resource use. Finally, it provides a unified outlook on the evolution of key indicators that drive the triple planetary crisis in the absence of more stringent policies.

2.1. Introduction

This chapter explores the common underlying drivers of the triple planetary crisis and their evolution over time under current policies. It builds on the general analytical framework of driver-pressure-state-impact-response (DPSIR) described in Chapter 1 and applies it to assess how the pressures on the environment can be explained by changes in their drivers.

The drivers of the triple planetary crisis are multifaceted. Some drivers are direct: for example, driving a car with an internal combustion engine emits greenhouse gases (GHGs) and contributes to air pollution. Other drivers are indirect: population growth increases demand for food and other commodities, and the production of these goods leads to increased pressures on the environment. To unpack these drivers, it is helpful to distinguish between broad socioeconomic trends and specific drivers. Socioeconomic trends – such as population growth – are the primary drivers for changes in economic activity, which in turn affect environmental pressures (Figure 2.1).¹ These links are further influenced by several crosscutting aspects, such as resource use. Figure 2.1 presents the links explored in this chapter, as represented in the Environmental Outlook modelling toolbox.²

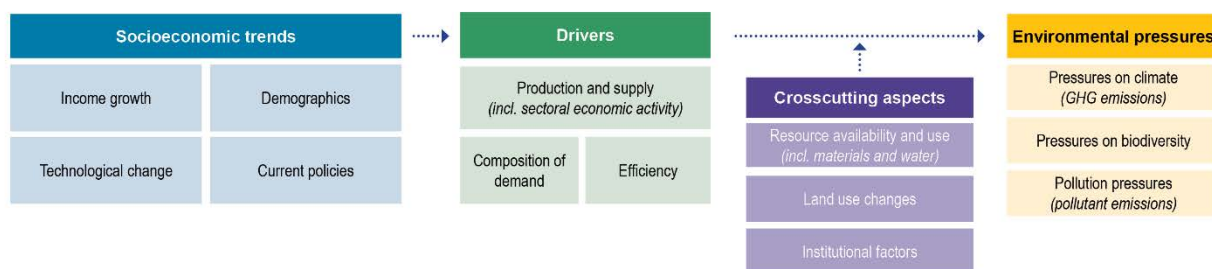
As is also considered in certain strands of the literature (e.g. Riahi et al (2017_[1])), and as detailed in Chapter 1, the projections provided in this chapter exclude feedback effects of environmental degradation. These projections form the reference point against which assessments of impacts can be made. The modelling in this report provides projections of how drivers affect pressures, and subsequently states, impacts and responses. Assessing feedbacks from environmental degradation is important for cost-benefit analysis of environmental policy, but the indirect effects of feedbacks on environmental pressures and thus states is much more limited.

Under current environmental policies, and in the absence of feedback effects of environmental degradation on these trends and drivers, the projected global evolution of these main socioeconomic trends can be summarised as:

- Populations continue to grow in many countries, albeit at a slower global pace than in the past.
- Per capita income levels converge partially, although major differences between regions persist.
- Labour productivity growth differs by sector and continues to drive economic growth across all regions.
- Services become an increasing part of the global Gross Domestic Product (GDP).
- Current environmental – and related – policies continue affecting the links between economic activity and environmental pressures, i.e. environmental pressures do not scale proportionally with economic activity.

The key data sources used to make these projections are summarised in Annex 2.A.

Figure 2.1. Linking socioeconomic trends, drivers and crosscutting aspects to environmental pressures



Note: The projections presented in this chapter are under current policies and thus exclude feedback effects of environmental degradation. Therefore, feedbacks from environmental degradation from pressures are not shown in this infographic.
Source: Authors' own elaboration.

The economic drivers of environmental pressures can be grouped into three aspects: (i) production and supply, (ii) composition of demand (including trade), and (iii) efficiency (or productivity). Quantifying these aspects entails determining the scale of economic activities, the structure of these activities and the intensity with which they lead to environmental pressures (this is usually done through decomposition of changes in pressures, see e.g. (Kaya and Yokobori, 1997^[2]; Grossman and Krueger, 1991^[3]). Efficiency is largely driven by technological change and is sometimes referred to as a technique effect.

While all economic activity results in some degree of environmental pressure, two key sectors have significant impacts across climate change, biodiversity loss and pollution: (i) energy and (ii) agriculture and land use. Other economic activities also contribute to the pressures, including, for example, polluting mining activities, production and use of plastics and other chemicals, and industrial processes that emit GHGs beyond fossil fuel combustion. Therefore, the following sections explore the production, composition and efficiency aspects at the sectoral level. It should be noted that underlying economic and institutional factors, including market failures, influence the evolution of environmental pressures, although these are difficult to quantify and project, as discussed in Box 2.1.

Box 2.1. Underlying economic and institutional factors that influence trends

While analysing the socioeconomic trends and specific drivers described above is critical to identifying the causes of and solutions to the triple planetary crisis, considering underlying economic and institutional factors behind these drivers is also essential.

Economic systems can over-exploit limited resources and fail to supply adequate public goods in cases of market failures. Negative externalities such as the damages caused by particulate matter (PM) emissions and positive externalities such as the ecosystem services provided by natural habitats need to be accounted for. If negative externalities are not correctly priced, the associated economic activities do not reflect the full cost of their use leading to emissions of pollutants (and other environmental pressures) and therefore environment degradation at a cost for society.

Some polluting activities benefit from public subsidies to achieve a particular socio-economic outcome, like protecting jobs. Environmentally harmful subsidies, like certain types of support to livestock or reduced taxation of fossil fuels, can worsen environmental pressures (Lankoski, Nales and Valin, 2025^[4]; OECD, 2022^[5]; Iovino, 2023^[6]). Better pricing of carbon emissions could contribute to reduce carbon emissions at a level that is consistent with limiting global warming to well below 2°C by 2050.

Other market failures are due to the public or common good nature of planetary systems. A stable climate is a global public good, everyone has access to it and the use by one individual does not affect its availability for others. Free riding can undermine global climate change mitigation efforts as the implementation of carbon mitigation policies in a group of countries benefits other countries as well. As mitigating climate change comes at a cost, free riding incentivises countries to let other countries incur this cost while still benefitting from mitigation. International agreements can help countries to work together towards common goals and combat free riding.

Biodiversity is closely linked to the global commons, including oceans and tropical rainforests, that provide global benefits but are de facto open access resources and very hard to manage sustainably. Some are international by definition (e.g. high seas, polar regions, pristine boreal area), while others are under national jurisdiction where national rather than global objectives determine the way they are exploited. The unsustainable overexploitation of fish stocks in international waters illustrates the potential complexities to manage shared resources and the need for international co-operation.

Another important market failure comes from the fact that policies that mitigate climate change, conserve biodiversity and reduce pollution often deliver benefits and costs over long periods of times. For example, if a tonne of carbon dioxide (CO₂) is emitted now into the atmosphere, it will stay in the atmosphere and impacts the global climate for many years (IPCC, 2021^[7]). Current generations may favour immediate rewards and heavily discount future payoffs beneficial for future generations. This leads to current policies that are not ambitious enough and postpone a problem that is getting worse over time.

This chapter presents projections to 2050 for the drivers of climate change, biodiversity loss and pollution. Section 2.2 unpacks the different drivers, focusing especially on energy, agriculture and land use and other key sectors including plastics and other chemicals. It does this in three steps, in line with the middle part of Figure 2.1: (i) the evolution of total production (reflecting the overall size of these economic activities), (ii) the composition of demand (reflecting changing preferences and structural change), and (iii) the role of efficiency (including technological change) that decouples economic activity from environmental pressures. Section 2.3 then links these discussions on drivers to the cross-cutting aspects of resource use (material resources and water). In order to identify the importance of the different drivers for changes in environmental pressures, Section 2.4 brings the various elements together to provide a unified outlook on biodiversity loss, climate change and pollution.

2.2. Unpacking the drivers of the triple planetary crisis

While the main drivers of the triple planetary crisis have been studied individually (see for instance reports from the IPCC (2023^[8]) or the IPBES (2024^[9])), the purpose of this section is to look at cross-cutting perspectives common to or linking the aspects of the triple planetary crisis. Sectoral emphases allow to disentangle the effects of the overall size of economic activity (total production and supply), the composition of demand (including structural change), and technology factors, i.e. efficiency.

Several key dynamics, often sectoral, are chosen to highlight the interlinkages among each aspect of the triple planetary crisis. These include a focus on (i) agriculture and land use, including urbanisation, (ii) energy, including the reliance on fossil fuels and electrification and (iii) other key sectors including chemicals and plastics. These sectoral emphases make it possible to disentangle the effects of the overall size of economic activity (total production and supply), the composition of demand (including structural change), and technology factors, i.e. efficiency. The following subsections are structured accordingly, going through these three effects (production and supply, composition of demand and the pivotal role of efficiency) for each of these three sectoral focuses. The choice to focus the analysis on a broad sectoral perspective rather than on a global lifecycle assessment is explained in Box 2.2.

The evolution of the triple planetary crisis is fundamentally driven by a number of socioeconomic trends, including population and income growth, technological developments and current policies. Together, these socioeconomic trends have consequences for the evolution of environmental pressures that are the result of multiple, opposing trends, even under a business-as-usual scenario. These trends – and their underlying factors – are described in more detail in Annex 2.A. The world population is expected to continue to grow and reach 8.5 billion by 2030 and 9.6 billion by 2050. Global economic activity, measured through GDP, is projected to grow substantially faster than population: on average by 2.7% per year, versus 0.7% for population. Thus, global GDP (at constant prices) is projected to grow from USD 126 trillion (tln) in 2020 to USD 283 tln in 2050. Productivity increases lead to changes in the structure of GDP, as measured by the contribution of value added generated in the different sectors to economy-wide value added generated. For least developed countries, agriculture represents a large share, while production in emerging economies is characterised by industrialisation, including a significant growth in construction to support infrastructure development. Sectoral shares are more stable in developed economies, with high levels of services and relatively low levels of agricultural production. As countries reach different stages in their developments, the structure of the economy evolves accordingly, taking into account the countries' specificities.

Box 2.2. The usefulness and limitations of lifecycle assessments

Lifecycle assessments (LCAs) are methods used to quantify the net impacts of products throughout their lifecycles (from materials extraction to production and then transport, use and end of life). LCAs enable direct comparisons of environmental impacts per “functional unit” of products within the context of the triple planetary crisis (Hellweg et al., 2023^[10]).

For instance, LCA analysis allows to compare the environmental impacts of grocery bag alternatives. Considering a functional unit, such as grocery items carried per bag, one can assess which grocery bag type is least damaging in terms of climate change, biodiversity loss and pollution. Paper bags emit five times more GHGs than single-use plastic bags (Meng, Brandão and Cullen, 2024^[11]). While this means that paper bags are more harmful for climate change, improper disposal of plastic bags contributes significantly to global pollution (OECD, 2022^[12]). The number of times the bags can be reused also alter their environmental impacts. Adding more complexity to the analysis, other alternatives such as biobased plastic bags require more land to be produced, contributing to biodiversity loss through deforestation (OECD, 2022^[12]). Similarly, Tacket et al. (2025^[13]) estimate that 68% of the considered alternatives to polyethylene packaging on the European market emit more GHG emissions (while 26% emit less).

Although LCAs offer a critical toolkit to identify synergies and trade-offs in product and material choices, they are more useful at a granular level. At the global level, the LCA of a given product is limited by data availability and current scientific knowledge. With countless product varieties, gathering data on each stage of the product lifecycle may not be feasible at the global scale. In the grocery bag example for instance, there is limited scientific knowledge on the impacts of plastic ingestion and entanglement by affected species (Woods et al., 2021^[14]). Also, the same product can be produced using different processes. For instance, transport emissions associated to wood used in the production of paper bags will vary depending on the distance between the production plant and the wood source. As a result, estimates of transport emissions for the same product could vary drastically within and across countries. This observation can be generalised for any lifecycle stage and impact evaluated.

While previous OECD reports such as the Global Materials Resources Outlook to 2060 (OECD, 2019^[15]) and the Global Plastics Outlook (OECD, 2022^[12]) adopted global LCAs to evaluate selected material and plastic polymer lifecycles, a full LCA is beyond the scope of this report due to lack of data to make a robust assessment. Nevertheless, conceptually, the modelling tools used in this chapter can

be interpreted as top-down LCAs as they offer evidence-based and multi-dimensional insights into the environmental consequences of different stages of production lifecycles. Environmental impacts from materials extraction, production, transport and end of life are modelled at sector and region levels within the modelling toolbox developed for this Outlook.

2.2.1. Production and supply of goods and services

Agriculture, forestry and other land uses

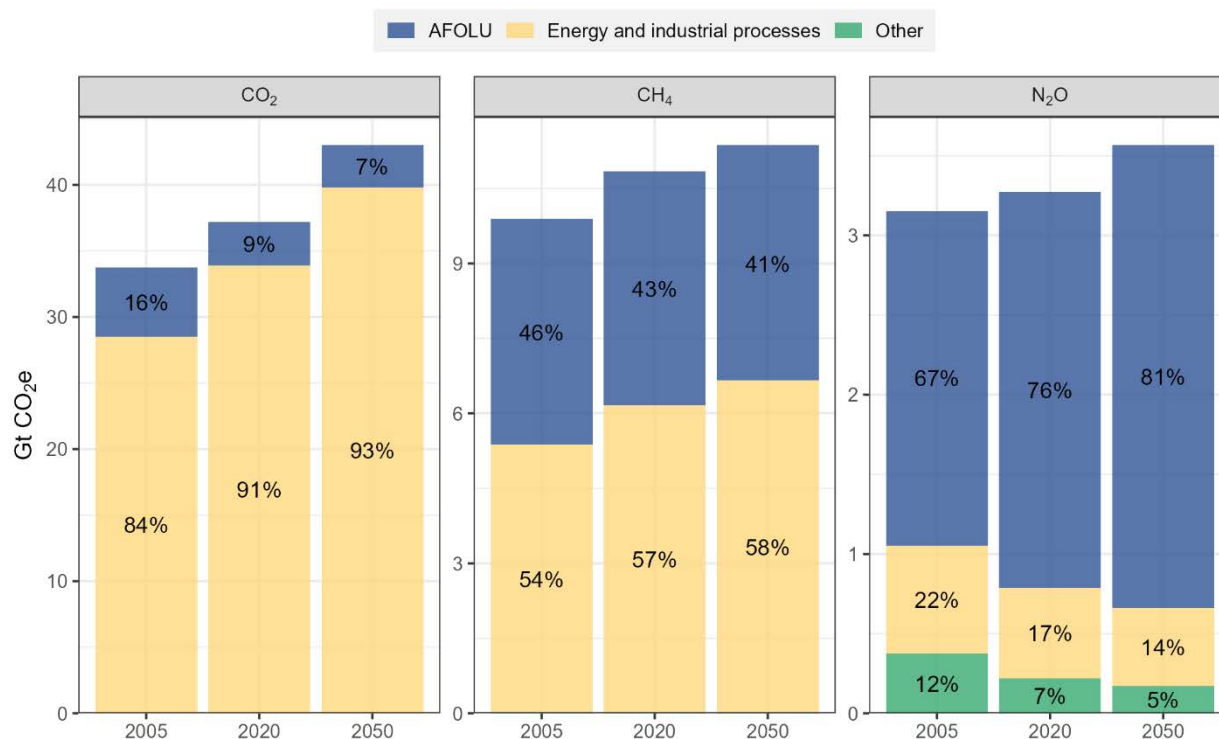
Agriculture occupies a complex and important role for climate change, biodiversity loss and pollution. While it remains essential for human systems, providing food to a growing population and offering jobs and livelihoods to over a billion people (FAO, 2023^[16]), agriculture also generates sizeable negative externalities. It is the largest source of methane (CH₄) and nitrous oxide (N₂O) emissions, the main contributor of nutrient pollution in water bodies, and the primary driver of land use changes, which in turn drives terrestrial biodiversity loss. Agriculture development is closely linked to land use change, cropland expansion in particular. Beyond land, agriculture also consumes substantial resources, including water and energy, further straining ecosystems and natural resources. But the sector also holds considerable mitigation potential, such as through reduction of deforestation, improved livestock practices and carbon sequestration options (IPCC, 2023^[8]), which remain untapped under current policies. Moreover, agriculture is highly dependent on healthy ecosystems and natural processes, making it particularly vulnerable to environmental degradation.

Current policies won't unlock the potential positive contribution of agriculture, forestry and other land uses

Agricultural activities are one of the main sources of global CH₄ emissions (43% of global emissions in 2020), mainly from enteric fermentation from livestock and rice cultivation, and the main source of N₂O emissions (76% of global emissions in 2020), due to fertiliser use and manure management (Figure 2.2). More generally, Agriculture, Forestry and Other Land Uses (AFOLU) are responsible for one-fifth of all GHG emissions, mainly CO₂, CH₄ and N₂O. At the same time, the mitigation potential from agricultural activities is estimated to be large. Reduction in non-CO₂ emissions from agriculture, particularly CH₄, is key but costly (OECD, 2025^[17]). The potential for carbon sequestration is larger and mainly arises from carbon management in croplands and grasslands, as well as agroforestry. The IPCC (2023^[8]) finds that AFOLU activities have the largest potential to reduce emissions or to sequester carbon, estimated at 8-14 gigatonnes of carbon dioxide equivalent (Gt CO₂e) per year (for a carbon price below USD 100 per tonne CO₂e). Through the deployment of nature-based solutions with safeguards (e.g. bioenergy plantations and afforestation) over a third of the required climate change mitigation required to keep climate warming below 2°C can be achieved (IPBES, 2019^[18]). Other negative impacts include pollution from pesticide use, water pollution, air pollution and water resource depletion (Lankoski, Nales and Valin, 2025^[4]).

Current policies are expected to be unable to unlock the potential for emissions reductions and sequestration from AFOLU activities.³ Emissions are projected to continue increasing, particularly CH₄ and N₂O in the middle-income region, due to a high growth in ruminant production (OECD/FAO, 2024^[19]). However, with current policies, the overall emission intensity is projected to decrease, with agricultural production growing faster than emissions, through the improvement of management practices and technology. The emission intensity is expected to decline more significantly in production systems that are currently more emissions intensive, compared to systems and regions where substantial efforts have already been made.

Figure 2.2. GHG emissions by sector

Global emissions in Gt CO₂e

Note: Emissions from AFOLU are net emissions. Scales differ by panel.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/ku2l6i>

The use of synthetic fertilisers – in addition to improved farm management practices – to boost crop production can help limit agricultural land expansion and the associated environmental impacts.⁴ However, fertiliser use also contributes significantly to the negative externalities generated by agriculture (see also Chapter 6). Beyond emitting GHGs, fertilisers are also the main source of nutrient pollution in water bodies (see also Chapter 3). When more nutrients are applied on the land than can be taken up by plants (nutrient uptake), this generates a nutrient surplus that often leaks into the surrounding environment (for example through runoff into water bodies), generating nutrient pollution.

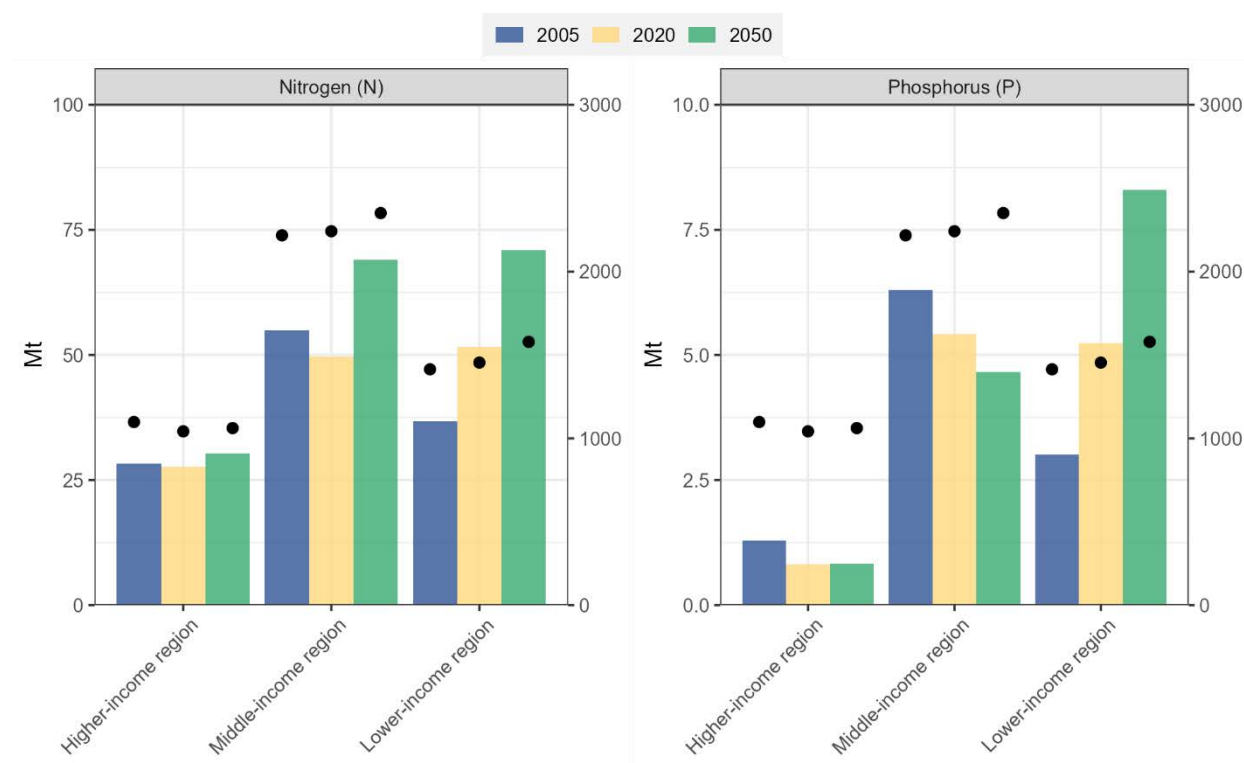
Under current policies, both nitrogen and phosphorus surpluses are projected to increase by 2050. In 2020, global nitrogen and phosphorus surpluses on all agricultural land, i.e. including both cropland and grassland, amounted to 129 and 11 million tonnes, respectively, with over 78% of nitrogen and 92% of phosphorus surplus reported in the middle- and lower-income regions (Figure 2.3).⁵ Fertiliser intensity (fertiliser use per hectare) was lower in these regions compared to the higher-income region, as the total agricultural land is also significantly higher than in the higher-income region (around 1.5 bln ha in lower-income, 2.2 bln ha in middle-income and 1.0 bln ha in higher-income region). Nonetheless, nutrient surpluses remained high. This reflects differences in agricultural area and in nutrient use efficiency, which are affected by factors such as agronomic practices, soil conditions and access to agricultural technologies. Agricultural areas in the higher-income region are roughly stable and increasing in the middle- and lower-income regions (to 1.6 and 2.4 bln ha in 2050 respectively). These regions also face a pressing need to increase yields to meet future food demands, which adds complexity. Under current policies, nitrogen surpluses are expected to increase by 2050, particularly in the lower- and middle-income regions (38% for nitrogen compared to 2020), while phosphorus surpluses are projected to increase by 59% in the lower-income region.⁶ In parallel, in many high-income countries, nutrient surpluses have

decreased over the past decades, and despite a slowdown, there is no expectation that the trend would reverse (OECD, 2025^[20]). The overall future trend of rising fertiliser use underscores the need for further policies promoting efficient nutrient use to boost crop production while protecting the environment (as discussed in Chapter 6). Other limiting factors should be addressed to optimise crop production, such as efficient water use (irrigation) and soil conditions (e.g. micronutrients and organic matter).

Along with other actions such as reducing food loss and waste as well adopting lower-impact consumption patterns such as moving towards plant-based diets (FAO, 2020^[21]), intensification (i.e. increasing agricultural production per hectare) remains key in reducing the conversion of natural land into agricultural land, while continuing to produce food for a growing population. Although limiting land expansion is key for agriculture, intensification of production should not come at the expense of other sustainability objectives, which highlights the importance of the concept of sustainable productivity growth (OECD, 2024^[22]).

Figure 2.3. Nutrient surpluses in agriculture

Million tonnes of nutrients on agricultural land (bars, left axes) and million hectares of agriculture land (dots, right axes)



Note: Scales for nutrient surpluses (on the left axes) differ for nitrogen and phosphorus. Agricultural land includes cropland and grassland.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/f1x4bo>

Land use change, driven by agricultural land expansion, is the main driver of biodiversity loss

Land use and land use change are the main drivers of biodiversity loss, as well as both a large source and sink of GHG emissions, and underpin food production. Winkler et al. (2021^[23]) estimate that land use change has affected almost a third of the global land area in just six decades (1960-2019). These changes result from geographically diverging processes, with afforestation and cropland abandonment in the Global North and deforestation and agricultural expansion in the South.

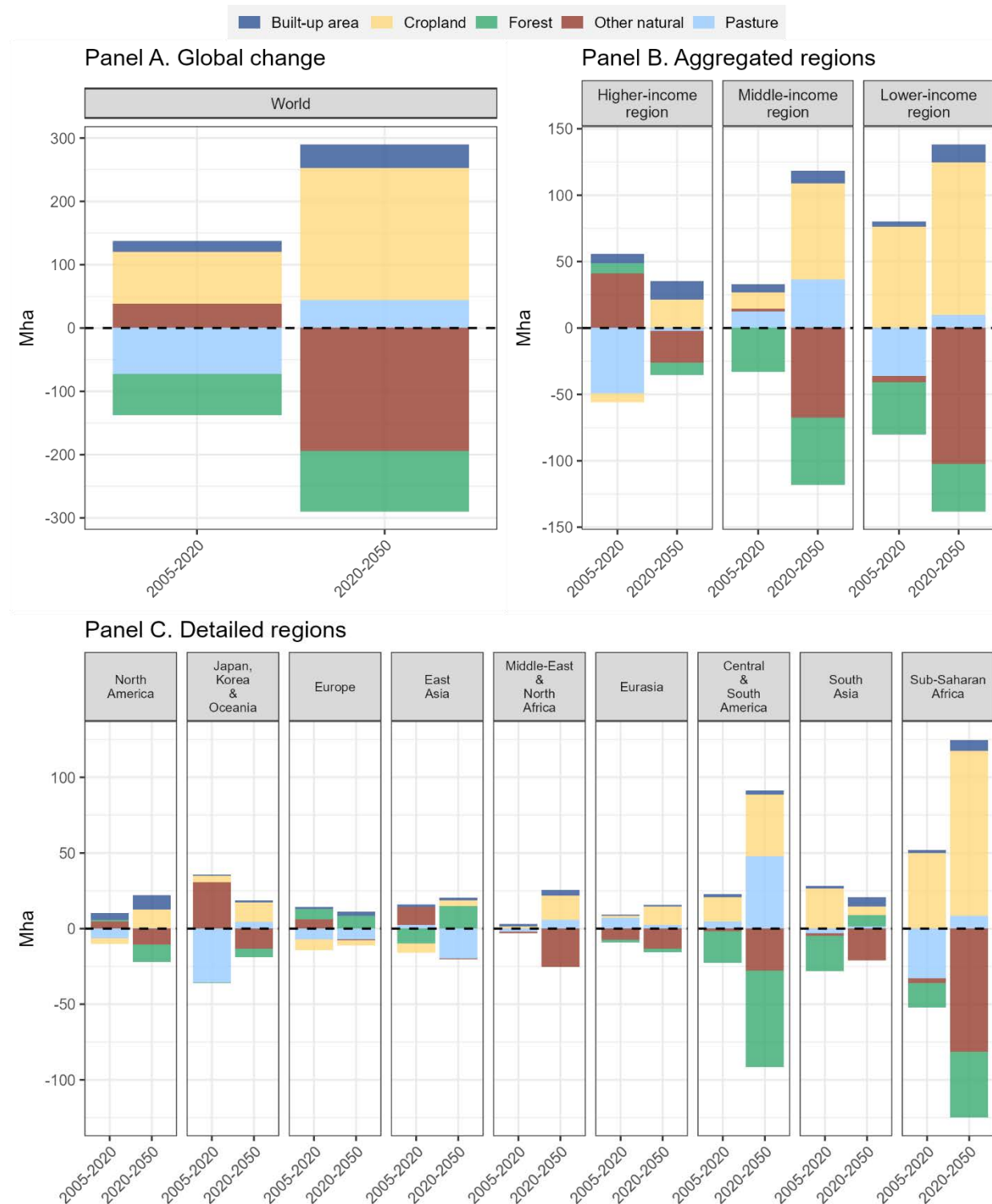
Precise measurement of land use changes is challenging, and measures of land covers are not unanimous (Li et al., 2018^[24]). Overall, the trends are clear, but not their order of magnitude: between 1992 and 2015, databases confirm that global forested area significantly decreased, while cropland expanded. Li et al. (2018^[24]) report a decrease in global forested areas by around 600 million hectares (Mha), close to estimates by Hurtt et al. (2011^[25]), while other sources find a decrease which is double or more, larger than 1200 Mha (Houghton and Nassikas, 2017^[26]; Hansen et al., 2013^[27]). Thus, current deforestation rates could range from 1.6% to 3.1% compared to an estimated at over 3800 Mha in 2020. More recently, FAO (2024^[28]) find an 80 Mha cropland expansion whilst forest land area decreases by 100 Mha between 2001 and 2022. Over time, FAO (2024^[29]) observes that deforestation rates have declined from 15.8 Mha per year in 1990-2000 to 10.2 million hectares per year in 2015-2020. These aggregate numbers are net impacts. For instance, between 2000 and 2012, Brazil's well-documented reduction in deforestation was offset by increasing forest loss in Indonesia, Malaysia, Paraguay, Bolivia, Zambia, Angola, and elsewhere, according to Hansen et al. (2013^[27]).

Striking a balance between intensification and extensification, linking to the debate between land sparing (minimising demand for farmland by increasing yields) and land sharing (favouring biodiversity on cultivated land but decreasing yields), is central to limiting the degradation of nature.⁷ Under current policies, with no increase in protected areas, agriculture is projected to remain the main driver of land expansion between 2020 and 2050, accounting for 87% of the increase in land use (Figure 2.4) through cropland and pasture expansion. However, the increase in agricultural land (meaning in cropland and pasture) remains small in relative terms (+5%), indicating an overall intensification of agricultural production, which reduces pressure on natural land but brings its own environmental impacts locally.

Regional differences in land use change, measured in Mha, are important (Figure 2.4). From 2005 to 2020, the higher-income region generally reduced agricultural land (i.e., cropland and pasture), while in other regions, agricultural land expanded at the expense of forest and other natural land. Between 2020 and 2050, agricultural land – mainly cropland – is projected to increase in the lower-income region (+124 Mha, representing +9% compared to 2020), replacing forests and, primarily, other natural land. Sub-Saharan Africa is projected to see the largest expansion, with an increase of 117 Mha, which is driven by an increase in demand for food and feed due to population growth. Yields are expected to increase as well, but not enough to prevent agricultural expansion into forests and other natural land. In the middle-income region, agricultural land is also projected to grow by 109 Mha (+5%), with pasture expansion playing a significant role, particularly in Central and South America, driven by a continued increase in international demand for both crops and animal products from this region. In the higher-income region, the availability of natural land suitable for agricultural expansion is limited, and growth in food production continues to rely on intensification.

Figure 2.4. Main drivers of land use change

Change in land cover in Mha



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/l1omn0>

While agricultural land use is the dominant driver of land use change, other factors such as urbanisation also contribute to land use change. Urbanisation has a lower impact on land use in terms of area (less than 1% of global land use), but it could constitute an opportunity to reduce environmental impacts, provided it is sustainably managed, as discussed in Box 2.3.

Box 2.3. The environmental effects of urbanisation

The share of urban population has increased significantly over the last decades in all regions of the world, reaching around 80% in Northern and Latin America, between 75% and 70% in Europe and Oceania, 50% in Asia, and 43% in Africa (UN, 2022^[30]).

Overall, urbanisation tends to decrease energy consumption and emissions in more mature and highly developed areas (IPCC, 2022^[31]), however it has complex environmental impacts. By attracting people to cities, rural areas recover, and biodiversity is enhanced in previously pressured areas (IPBES, 2019^[18]). Agglomeration economies also promote resource efficiency and energy savings (UNEP, 2019^[32]). However, as cities expand, they may replace natural land with infrastructure, reducing carbon sinks, biodiversity and increasing impervious surfaces, which exacerbate heatwaves and flooding (Lemonsu et al., 2015^[33]; Zhang et al., 2018^[34]). As cropland is lost to urbanisation, productive land can be replaced with intensification and expansion on less productive land (Bren d'Amour et al., 2016^[35]).

Urban expansion can lead to natural habitat conversion and degradation (van Vliet, 2019^[36]; McDonald et al., 2020^[37]) but also to natural habitat fragmentation (Haddad et al., 2015^[38]; Liu, He and Wu, 2016^[39]), which is a major driver of biodiversity loss. Urban expansion often occurs through urban sprawl and low-density development patterns that have a significant environmental footprint per capita (OECD, 2018^[40]). Urban land grew at almost double the speed of the global population between 1975 and 2015 and is projected to triple in 2030 relative to the 2000 cover (UNEP, 2019^[32]). This will result in loss of natural habitats in key biodiversity hotspots, although land cover of human settlements remains small compared to agricultural land (Seto, Güneralp and Hutyra, 2012^[41]).

Urban expansion has large impacts on biodiversity loss at both global and local levels. Globally, it is estimated that urban expansion has caused about a 50% loss of local within-site species richness and a 38% loss of total abundance of species in intensively used urbanised areas (Newbold et al., 2015^[42]). In local areas, urban expansion has resulted in more than 80% of natural habitat loss (Ke et al., 2018^[43]).

In terms of climate change global urban expansion led to a net loss in carbon sinks estimated at 22.4 Mt CO₂e per year between 2000 and 2010 (Liu et al., 2019^[44]). This loss is equivalent to 0.7% of the 3.4 Gt CO₂e absorbed by land ecosystems every year globally (IPCC, 2021^[7]). Low density suburbs contribute more GHG emission per person than cities. Urban areas that are more compact, walkable, and co-located can reduce future urban energy use by 20–25% in 2050, while providing a corresponding mitigation potential of 23–26% (IPCC, 2022^[31]).

As for the impacts of climate change, urbanisation processes generate vulnerability and exposure which combine with climate change hazards to drive urban risk and impacts (IPCC, 2022^[45]). Urban flooding risks increase with urban expansion and land use changes, which enlarge impermeable surface areas, impacting floodwater drainage and causing sewer overflows. Urban development in coastal cities exposes them to high risk of sea level rise impacts (IPCC, 2022^[45]).

In terms of air pollution, a 1% increase in cities' density is associated with a 0.3% reduction in per capita emissions of CO₂ and PM_{2.5} (Castells-Quintana, Dienesch and Krause, 2021^[46]). Large metropolitan regions with high urban sprawl experience 60% more high ground-level ozone days than more spatially compact metropolitan regions (Stone, 2008^[47]). Fragmentary urban patterns with many urban patches are positively linked with rising PM_{2.5}, PM₁₀, ground-level ozone and NO₂ concentrations (McCarty and Kaza, 2015^[48]; Cárdenas Rodríguez, Dupont-Courtade and Oueslati, 2015^[49]).

Energy supply is projected to continue to be dependent on fossil fuels

Energy production and use contribute significantly to both GHG emissions and air pollutant emissions. Indeed, a large share of GHG emissions originate from energy use, which includes the combustion of fossil fuels by end-users and for electricity generation. Combustion of fossil fuels is also the source of most air pollutants, with the exception of ammonia (NH₃) and non-methane volatile organic compounds (NMVOC). In 2020, combustion accounted for 8% of total NH₃ emissions and 33% of NMVOC emissions, shares that are decreasing over time. For other air pollutants, the contribution of combustion ranges from 60% for carbon monoxide to 94% for sulphur dioxide (SO₂) in 2020. In all cases, this share decreases over time, indicating that emissions from industrial processes are being abated less than those from combustion.

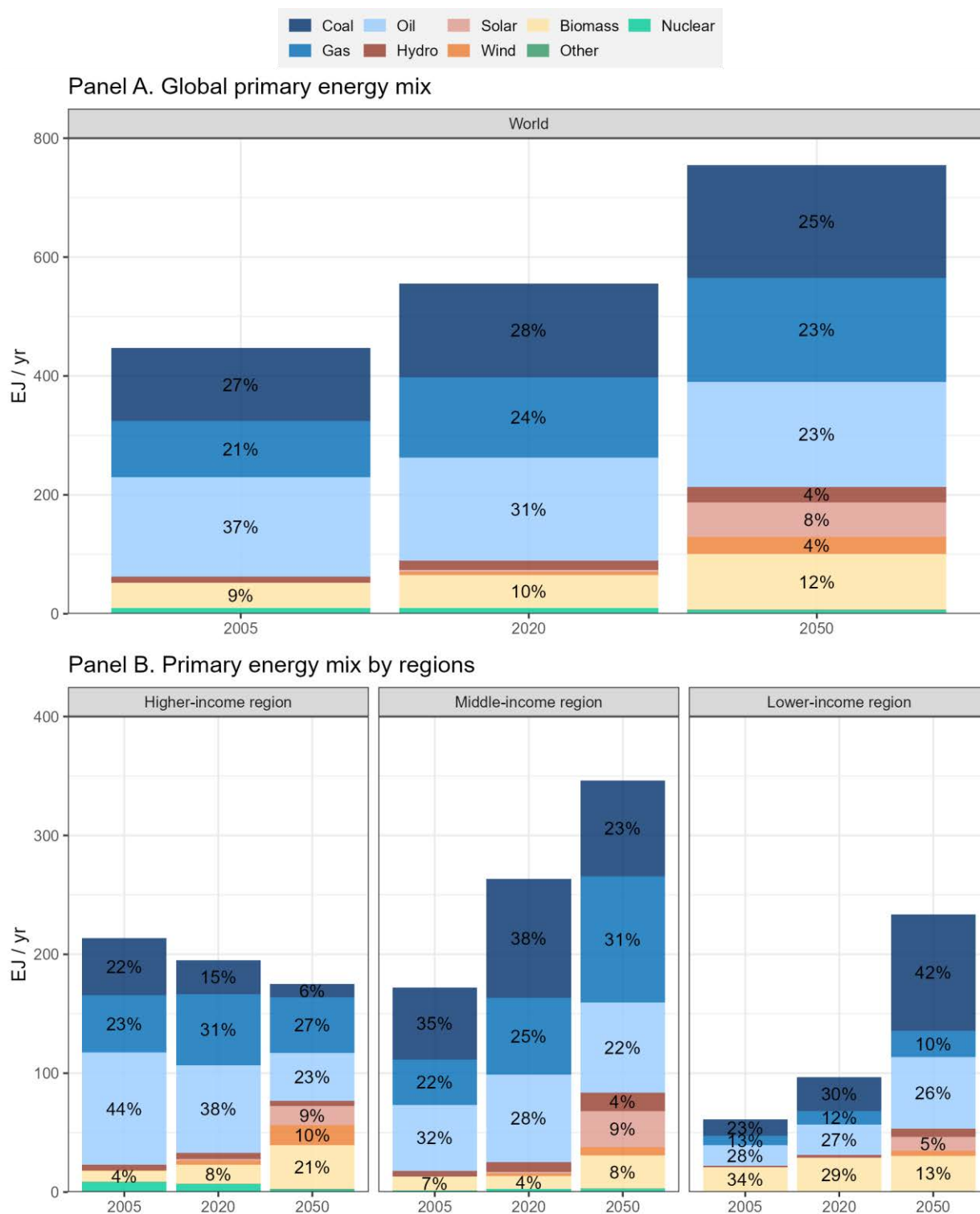
Current policies embedded in the baseline scenario result in a continuation of past trends. Overall, total primary energy supply (TPES) is projected to grow, driven largely by increased affluence and improved access to energy services, especially in the middle- and lower-income regions. While the deployment of renewable energy is expected to accelerate, it will not be sufficient to offset the continued reliance on fossil fuels. More specifically, TPES is projected to reach 755 exajoules (EJ) by 2050, a 36% increase compared to 2020 (Figure 2.5). By mid-century, slightly more than one-quarter of this supply will come from renewable sources, up from 14% in 2020 (and 12% in 2005), reflecting a 2.6-fold increase in renewable energy supply over 30 years. However, despite this substantial growth, fossil fuels are still projected to remain the dominant energy source under current policies, reaching 541 EJ in 2050, a 16% increase relative to 2020.

The aggregate evolution of TPES hides contrasting regional patterns. While TPES in the higher-income region is projected to decrease by 10% between 2020 and 2050, TPES is projected to more than double in the lower-income region and increase by 31% in the middle-income region in the same time period. The reduction in TPES in the higher-income region is driven by absolute reductions in fossil fuel supply with coal, oil and gas supply decreasing by 61%, 45% and 22% respectively. Much of the growth of TPES in the middle-income region is driven by a shift towards gas whose share increases from 25% to 31% and solar whose share rises from less than 1% to 9%. In parallel, the middle-income region is projected to decrease its reliance on coal, whose share decreases from 38% to 23%. In the lower-income region, TPES growth is driven by an absolute and relative increase in coal whose share in total TPES increases from 30% in 2020 to 42% in 2050 an absolute increase of 241%.

The reliance on fossil fuels is projected to decrease in the higher-income region but remain in the middle-income region and even grow in the lower-income region. The TPES evolutions leads to a projected decrease in the share of fossil fuels in TPES from 84% in 2020 to 56% in 2050 (corresponding to an absolute decrease from 162 EJ to 98 EJ) in the higher-income region, from 91% to 76% in the middle-income region (while supply still increases from 238 EJ to 262 EJ). In the lower-income region, the share of fossil fuels in TPES is projected to increase from 69% to 78%, corresponding to an increase in fossil fuel supply from 66 EJ to 180 EJ.

Figure 2.5. Primary energy supply

Energy supply in EJ/yr



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/rx92yb>

The energy system continues to electrify, with a continued dependence on fossil fuels and the emergence of renewables

Global electricity production is projected to rise substantially by mid-century, faster than the growth of primary energy demand, indicating an increased electrification of energy services. While a growing share of this production will be met through wind and solar power, fossil fuels, particularly gas and coal, are expected to continue playing a significant role under current policies. Power generation is projected to more than double between 2020 and 2050, globally increasing from 96 EJ to 220 EJ in 2050. The majority of these 124 extra EJ will be generated in the middle-income region (59 EJ) and the lower-income region (53 EJ). Further details on regional electrification rates by sector are provided in Section 2.2.2. In 2020, solar and wind together made up less than 13% of the power mix in the higher-income region, and less than 8% in other regions. The contribution of solar and wind is expected to increase markedly, reaching 37% of global electricity generation in 2050 (60% in the higher-income region, 34% in the middle-income region and 24% in the lower-income region). Nevertheless, gas and coal remain key components of the power system under current policies: the use of gas and coal to produce power will continue to expand in absolute terms, albeit at a slower pace than lower-carbon sources, resulting in a reduced relative contribution to the overall power mix.

The increase in emissions of both air pollutants and GHGs from energy use is moderated by greater electrification and the expansion of solar and wind. At the same time, the rapid development of renewable energy technologies can affect resource use and potentially have impacts on biodiversity, as discussed in Chapter 6. Carefully designed policies will be crucial to minimise these negative trade-offs and ensure that the energy transition support all dimensions of the triple planetary crisis.

Other sectors, including plastics and other chemicals

Beyond agriculture and energy, other economic sectors also contribute significantly to environmental pressures. For example, the environmental impacts of mining are well documented (Macklin et al., 2023^[50]), and certain industrial processes, such as cement production, directly emit GHGs. The rapid growth of digital services has driven a surge in the number of data centres, which causes rising energy use and adds pressure on land use. Additionally, electronic waste is becoming an increasingly urgent issue: in 2022 alone, 62 million tonnes of electrical and electronic waste were generated globally (Baldé et al., 2024^[51]). The following paragraphs provide details on the future trends of selected key sectors that play a substantial role in fuelling the triple planetary crisis. These include the chemicals sector, including plastics, followed by a broader perspective on materials use, and concluding with key developments in waste generation and management.⁸

The chemicals sector encompasses a broad range of products, including plastics and pharmaceuticals, that are used in a wide variety of applications, both as inputs in production (e.g. fertilisers and pesticides in agriculture, plastics in car manufacturing) and as consumer products (e.g. cleaning products, paints). The sector represents a major area of economic activity. Some substances, often labelled as chemicals of concern, have significant adverse effects on human health, ecosystems and pollution levels (Landrigan et al., 2018^[52]). The cumulative impact of continued exposure to multiple chemicals is increasing over time, raising growing concern about chemical pollution (OECD, 2023^[53]). In recent years, widespread environmental contamination and human exposure to “forever chemicals”, i.e. PFAS (per- and polyfluoroalkyl substances), has drawn heightened attention (Goldenman et al., 2019^[54]). Beyond PFAS, many hazardous chemicals and pharmaceutical pollutants, as well as artificial fertilisers and plastics, are released in large quantities and contribute significantly to environmental degradation (UNEP, 2019^[55]). In this context, the consumption, trade, production and use of these substances can be considered as drivers of climate change, biodiversity loss and pollution.

Chemical production is a major industry. Including pharmaceuticals, the chemical industry was the second-largest manufacturing sector globally in 2017, with total sales reaching USD 5.7 trillion (tln). Asia is currently both the largest producer and consumer of chemicals (UNEP, 2019^[55]). By 2030, global chemical sales are projected to double, with particularly rapid expansion expected in middle-income countries. The production of a wide range of chemicals, including fertilisers, pesticides, pharmaceuticals, perfluorinated chemicals, flame retardants and nanomaterials, is increasing across many regions, with production of petrochemicals (including plastics) growing even faster.

Industrial use of plastics is expected to continue increasing to 2050, leading to a consistent stream of plastic waste that countries will need to manage. The low cost and versatility of plastics are expected to drive demand up, with little change in plastic intensity. As plastic waste closely follows plastics use (albeit with a delay), this growth raises concerns about leakage to the environment, particularly where waste is not managed in a manner that is protective of human health and the environment (OECD, 2022^[56]). With a significant share of global plastics use projected to take place in regions with underdeveloped waste management systems by 2050, plastic leakage can increase if plastic waste fails to be collected, sorted and treated in an environmentally sound manner, resulting in additional plastic pollution.

More broadly, resource extraction, including the mining of metals and mining and quarrying of non-metallic minerals, is highly energy-intensive and thus causes high GHG emissions as well as significant air, soil and water pollution (Macklin et al., 2023^[50]; Coelho, Teixeira and Gonçalves, 2011^[57]; Dietler et al., 2021^[58]). Downstream material refining and processing further contributes to emissions. In total, more than half of all GHG emissions can be directly or indirectly attributed to “materials management”, although the share attributed to the extraction of non-fossil fuels remains a minority (OECD, 2019^[15]). Recycling materials is generally less energy intensive than extraction (OECD, 2019^[15]). For instance, producing the most commonly used metals by recycling metallic waste and scrap needs 60% to 97% less energy than producing them from mined material.

2.2.2. Composition of demand for goods and services and structural change of the economy

Agriculture and land use: the impact of the nutrition transition on agricultural demand and environmental sustainability

The nutrition transition refers to the link between rising income and changing diets. It typically involves an increase in overall calorie consumption, a shift away from starchy staples, and a significant rise in calories from animal products, fats, and sweeteners. This shift has a considerable impact on future agricultural demand.

The growing demand for animal-based calories, driven by income growth (particularly from low- and middle-income regions), plays a key role in increasing the environmental impact of the agricultural sector. Global meat consumption increased from 231 Mt in 2010 to 300 Mt in 2024 as demonstrated in Table 2.1 (OECD/FAO, 2025^[59]). This represents an average annual growth rate of 2%. Between 2010 and 2024, average annual growth in meat consumption was particularly high in Asia and Africa which recorded increases of 2.7%. Gouel and Guimbard (2018^[60]) estimate that, under current policies and historical trends, by 2050, demand for animal-based calories will double compared to 2010, while food demand for starchy staples is projected to rise by just 19%.

Table 2.1. Meat consumption by world region, 2010-2034

Quantities of meat in million tonnes (Mt)

	2010	2024	Average annual growth (2010-2024)	2034 projections	Projected average annual growth (2024-2034)
Africa	13.3	19.0	2.7%	25.2	3.2%
Asia	102.6	144.2	2.7%	164.6	1.5%
Europe	44.8	49.1	0.7%	50.1	0.2%
Latin America	34.8	44.9	2.0%	51.3	1.5%
Northern America	32.9	39.3	1.4%	42.1	0.8%
Oceania	2.5	3.2	1.9%	3.5	1.1%
World	230.8	299.7	2.0%	336.9	1.3%

Note: The regions in this table differ from the rest of the chapter as they are based on data availability.

Source: Authors' own calculation based on data from OECD/FAO (2025^[59]). Tonnes of carcass weight equivalent converted to edible weight equivalent using conversion factors 0.67 for beef and veal, 0.73 for pig meat and 0.66 for sheep meat.

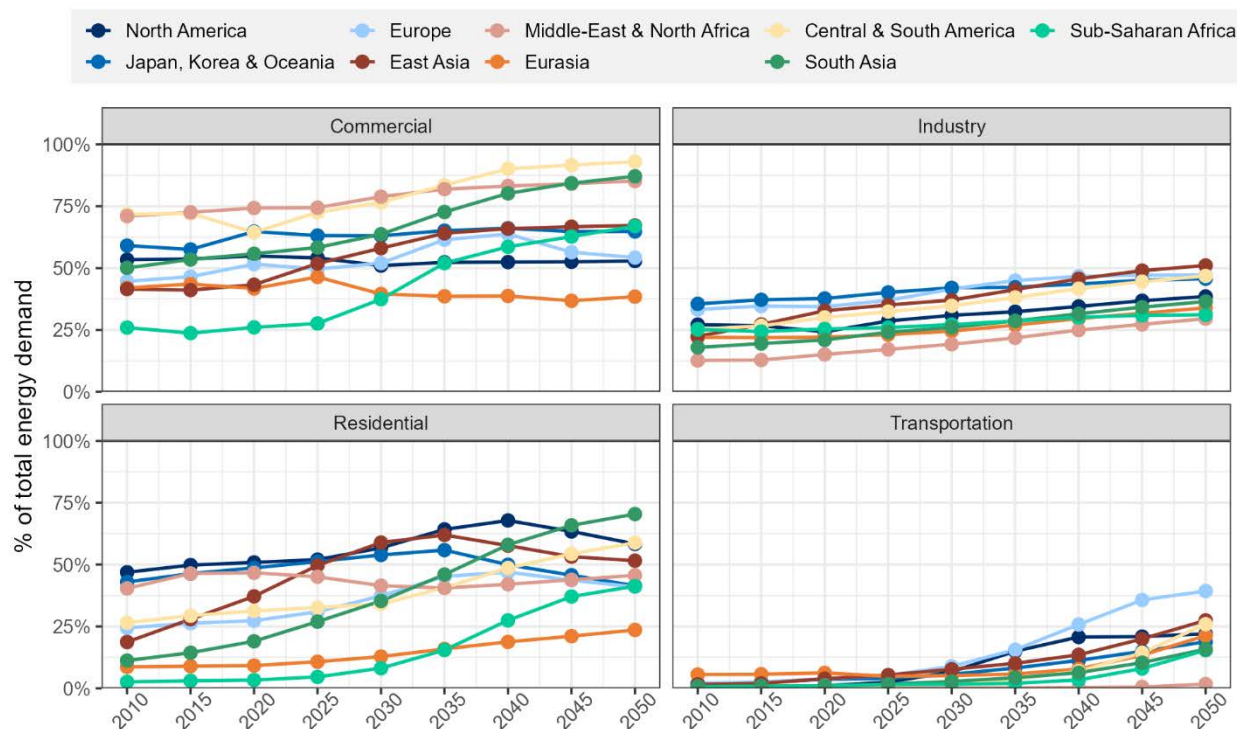
This dietary shift towards animal-based calories drives the environmental impact of agriculture. Current production practices for animal products in many places can have detrimental effects on biodiversity, increase pollution and contribute negatively to climate change. While the environmental impacts of animal production practices can vary 50-fold depending on producers, even the impacts of the lowest-impact animal farming products often exceed those of vegetable substitutes (Poore and Nemecek, 2018^[61]). Livestock activity can affect hydrological inflows (such as infiltration and soil moisture) and outflows (such as runoff, sediment) although the situation varies across many dimensions including climate, herbivore types and soil textures (Eldridge, Ding and Travers, 2022^[62]). Additionally, meat production is a major source of GHG emissions, notably from ruminants due to enteric fermentation and manure. Livestock systems with cattle, buffaloes, sheep, goats, pigs and chickens collectively contributed to 6.2 Gt CO₂e emissions in 2015 approximately 12% of all anthropogenic GHG emissions (FAO, 2023^[63]) and half of all GHG emissions from AFOLU (IPCC, 2022^[31]). Manure runoff also contributes to nutrient pollution, while enteric fermentation leads to ground-level ozone formation (Benton et al., 2021^[64]). Furthermore, livestock production is closely linked to land-use changes and biodiversity loss, as increased demand for feed crops expands agricultural land, and newly deforested areas are in some regions primarily driven by cattle grazing needs (Campbell et al., 2017^[65]; IPBES, 2019^[18]). Moreover, the livestock sector increases the pressure on water scarcity by using an equivalent of 11 900 km³ of freshwater annually or approximately 10% of the estimated annual global water flows. The livestock sector impacts the whole water cycle as 2 290 km³ of green water and 370 km³ of blue water was attributed to feed production on cropland in 2010 (FAO, 2019^[66]).

Energy: the role of electrification in facilitating the transition towards clean energy

Electricity contributes more to the increased final energy use than other energy sources, resulting in larger electrification in 2050 compared to 2020 in all key sectors. In commercial buildings, the share of electricity in total energy demand is already larger than 50% in 2020 in six of the nine regions and continues to increase over time (Figure 2.6). Sub-Saharan Africa, which has the lowest share in 2020 around 25%, shows a rapid catch-up over time. Residential energy follows a similar pattern, with increased electrification over time and a catch-up of Sub-Saharan Africa. Industry, although less electrified than commercial or residential buildings, continues to electrify its energy use over time at a steady pace. Through electrification, industry can decrease process emissions, such as with the replacement of blast furnace by electric arc furnace, which decrease the use of fossil energy (coal) as well as CO₂ process emissions.

Figure 2.6. Electrification rates of key sectors

Electrification rate in key sectors: transport, buildings, and industry, % of final energy demand



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/qcusk4>

In 2020, the share of electricity in transport final energy demand was less than 7% in all regions (Figure 2.6). This share is projected to increase over time, although at different speeds. In Europe, transport is projected to have the fastest electrification (39% of its energy demand electrified by 2050). East Asia, Eurasia, Central & South America and North America are projected to have slower uptakes than Europe by 2050, ranging between 21% for Eurasia to 27% for East Asia. Other regions are projected to have electrified less than 20% of total energy demand by 2050 with the Middle East & North Africa projected to have electrified less than 2% of their total energy demand.

Other sectors, including plastics and other chemicals: recycling can alleviate the transition to lower impacts of materials

Further to the GHG impacts of industrial sectors, some industrial activities lead to other environmental impacts. Many of these impacts can be linked to materials extraction and transformation (OECD, 2019^[15]). Recycling is a solution to reduce the potential impacts of materials, and therefore of industrial sectors. Recycling reflects an increase of the efficiency of raw materials use, as the same materials are not discarded but can be used again (often after some form of re-processing), thereby increasing production volume per unit of materials input over time.

However, recycling is not equally possible for different materials. Secondary materials (the result of processing recyclable waste into raw materials that can be used again) currently make up a modest part of total materials use, while having lower environmental impacts across a range of LCA indicators. Many metals have substantial recycling rates, and scrap metals are used as secondary material. The share of secondary lead has surged in recent years to above 50%, while secondary steel has gradually declined to below 30%. Secondary shares for aluminium, zinc and copper are even lower. Recycling – and hence secondary materials use – is rare for non-metallic minerals; concrete for example is often used as low-value road filler. The use of both primary and secondary materials is projected to rise with current policies. Given the projected technology trends and unchanged policies, the supply of secondary materials is insufficient (or too expensive) to meet the demands of a growing economy.

Increased recycling can allow for a decrease in the (primary) resources used for production. For instance, OECD (2022^[56]) projects that the growth of virgin plastics will be partly dampened even with current policies, as the share of recycled plastics doubles to 12%. This shift towards more circular economies can allow materials to be used more efficiently and decrease the exploitation of natural resources, for instance metals mining or fossil fuels inputs for plastics, although substitution away from specific materials towards other inputs always requires careful consideration of the net environmental impacts (as projected by LCA). Combined with policies to curb demand for materials, the resulting reduction in virgin materials can lessen the pressures on the triple planetary crisis.

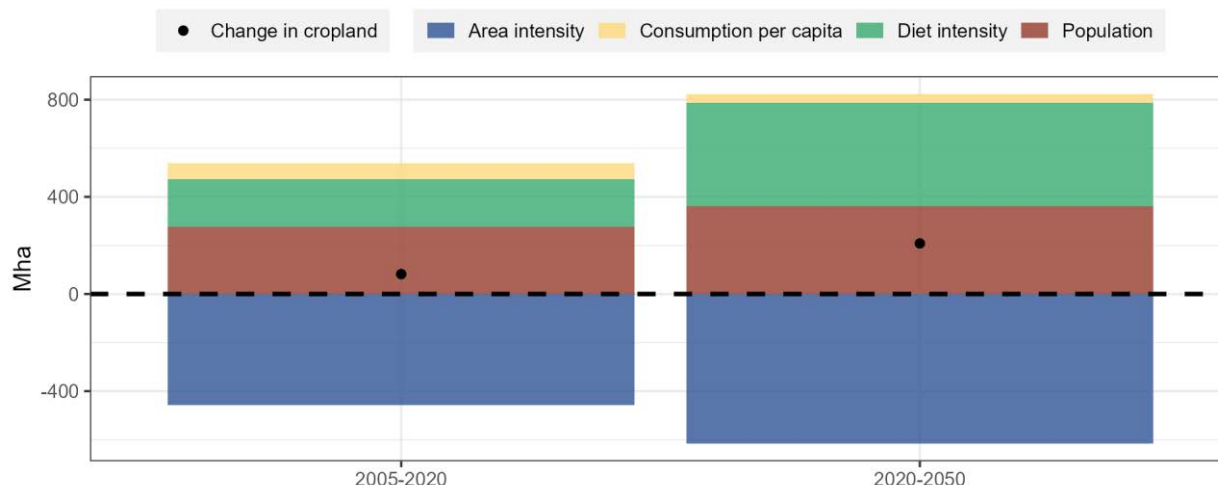
2.2.3. Efficiency improvements in production of goods and services

The intensification of agricultural practices can reduce land use change

The decomposition of the drivers of changes in cropland illustrates the key role played by intensification and the need for sustainable intensification of agricultural production. Based on the methodology proposed in Huber et al. (2014^[67]), Figure 2.7 decomposes the change in cropland expansion into different drivers. On the demand side, the increase in population, combined with the increase in per capita consumption drive a *scale* effect (see Section 2.2.1); in parallel, the change in diets modifies the types of agricultural goods that are consumed, driving a *composition* effect (see Section 2.2.2). On the production side, the increase in yields, i.e. a decrease in the area intensity of cropping, counteracts the impact of these two effects, limiting cropland expansion. This reflects the *efficiency* effect: more food can be produced on the same land. While scale effects accounted for 63% of cropland expansion between 2005 and 2020, diet intensity is projected to account for over 50% of global cropland expansion between 2020 and 2050 demonstrating the increasing importance of the composition of diets for cropland change. At the global level, while agricultural demand increases, yields also rise, but not sufficiently to fully fulfil the larger demand, resulting in cropland expansion. Nonetheless, the projected cropland expansion is only about a quarter of what it would be without the yield improvement, reflecting the importance of efficiency effects.

Figure 2.7. Drivers of changes in area dedicated to cropland (2020-2050)

Global cropland expansion (in Mha) and contribution of identified factors of change.



Note: The variables are calculated as follows. Area intensity of crop production is the ratio of cropland area (in million ha) to crop production (in million tonnes dry matter), reflecting the inverse of crop yields and cropping intensity through fallow or multi-cropping (ha/ tonne dry matter). Diet intensity describes the intensity of the diet, namely the ratio of crop use for food and feed (in million tonnes dry matter) to consumption (in million kcal) and describes how much crops are used per unit of consumption (tonne dry matter / kcal). Per capita consumption is measured as the ratio between food demand over population per year (in kcal/capita). Population is reported in billion people.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/uri9d4>

Energy efficiency mitigates the growth of energy demand

The continuous increase in kilometers travelled by road, air and maritime transportation leads to a significant increase in energy demand. Efficiency improvements (detailed in Annex Figure 2.A.7) can only partially compensate this. All modes included, the increase in transport activity only results in a 23% global increase in energy demand for transport (compared to 60% increase in freight transport and 122% in passenger transport), showing that efficiency improvements partially decouple the increase in the economic service provided from the underlying polluting economic activity, thereby avoiding significant emissions of e.g. GHGs and air pollutants.

Similarly, residential buildings show significant efficiency improvements but no reduction in energy demand. The floor space for residential buildings increases significantly, though the associated energy demand is almost completely offset by increased efficiency in the energy use for heating (by switching to heat pumps for example). Floor space for residential buildings is projected to increase by 53% between 2020 and 2050, while energy demand for residential buildings only increases by 3% over the same period, showing large improvements in energy efficiency over time.

Industrial value added more than doubles between 2020 and 2050, increasing in all regions. Indeed, global industrial value added increases by 131% between 2020 and 2050. Over the same period, energy demand by industry only increases by 31%, again demonstrating increased efficiency in energy use.

Other sectors: efficiency can allow to reduce environmental impacts

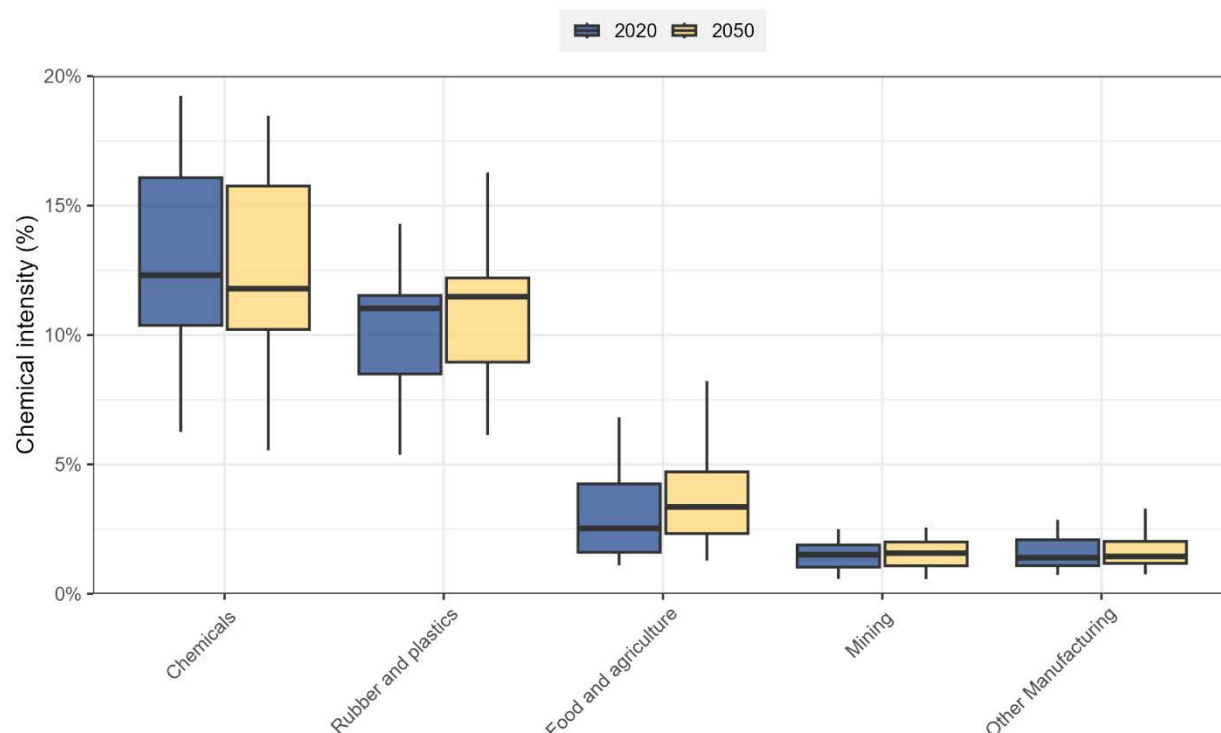
Improved efficiency translates into a reduction in the use of inputs, leading to decreased environmental impacts (for a given production level). In addition to recycling (discussed in Section 2.2.2), improved technology can increase the efficiency of use of raw (e.g. metals and non-metallic minerals) and synthetic materials (e.g. plastics and chemicals) in their production processes.

This trend of efficiency improvements is visible for plastics: the global plastic intensity (the amount of plastics used that accompanies the generation of a dollar of GDP) is projected to fall by 12% by 2050. The reduction in plastic intensity allows to dampen the growth of plastics use and the implied environmental impacts, especially stemming from waste mismanagement. This decrease in plastics use intensity to the 2050 horizon is observed in most sectors and regions, highlighting the key role of improvements of technologies (OECD, 2022^[12]). Exceptions include the food products and construction sectors in developed economies which increasingly use plastics, reflecting a shift towards commodities that use more plastics rather than a decline in efficiency, i.e. the shift in the composition of sectoral economic activity more than compensates for the decline in plastic demand in each individual sector. Economy-wide servitisation, i.e. increased use of services in manufacturing, drives a large part of plastics use increases, reflecting the central role of packaging plastics, which make up 40% of total plastics use.

In contrast, chemical intensity, that is the ratio of the value of chemicals used in the production to the gross output value, is projected to remain relatively stable between 2020 and 2050 as shown in Figure 2.8.⁹ In other words, current policies do not lead to a significant improvement in the efficiency in which chemicals are used in production, and thus the associated environmental impacts remain unabated. The projected changes in sectoral chemicals intensity are negligible compared to the variation in chemical intensity for the same sector across regions. This points to the potential need for further policy action to reduce chemical pollution.

Figure 2.8. Chemical intensity by sector in 2020

Chemical intensity expressed in %



Note: Chemical intensity is the ratio of the value of chemicals used during the production process to the gross output value, computed for each sector in each region. These values are measured in 2020 in the blue boxes and 2050 in the yellow boxes, and expressed in constant 2017 USD bln. The boxplots illustrate the distribution of chemical intensities across regions, for each sector. The top and bottom values of the boxes correspond to the first and third quartile of the distribution. The upper and lower whiskers extend from the hinge to the largest (resp. lowest) value no further than 1.5 times the inter-quartile range. The bar within the plot corresponds to the median value. Sectors with a median intensity lower than 1% in 2020 or 2050 are not represented in the figure. For instance, the chemicals sector displays a median chemical intensity of 11.8%, with a distribution ranging from 5.5% to 18.5% in 2020.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/7xiu6j>

2.3. The role of resource use in driving environmental pressures

Material and water resources represent the physical foundations of human life and thus are at the core of the triple planetary crisis. The way material and water resources are extracted, used and disposed of throughout the economy and human life impact the evolution of the pressures on and state of the environment. Together with the demand for the various services provided by the environment, including food, drinking water, energy and goods, the evolution of the way these services are provided shape anthropogenic pressures to the environment. They thus combine with the drivers outlined above as crosscutting aspects.

2.3.1. Use of (raw) material resources

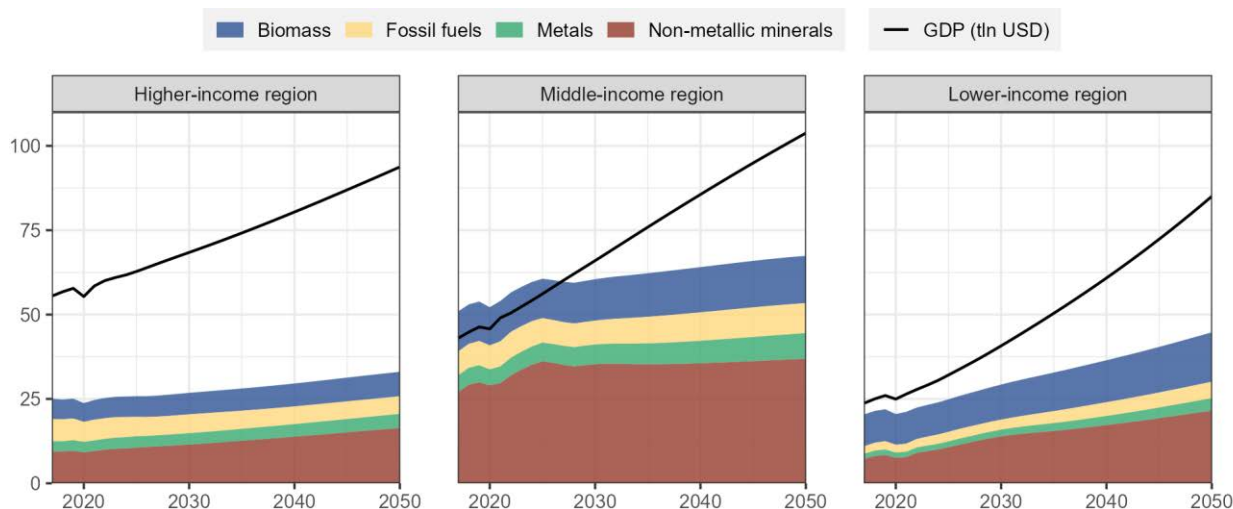
The extraction and processing of (raw) material resources¹⁰ – biomass, fossil fuels, non-metallic minerals and metals – is a key common driver of climate change, biodiversity loss and pollution. UNEP (2024^[68]) find that the extraction of material resources is responsible for over 60% of climate impacts (including land use change) alone whilst the combination of extraction and processing accounts for 40% of health impacts due to emissions of particulate matter (half of which is due to non-metallic minerals). Biomass (agricultural crops and forestry) also accounts for approximately 60% of the total land use related biodiversity loss and water stress although sustainable land and forest management can reduce some of these impacts (FAO, 2024^[29]).

All mining on land has increased dramatically and has significant negative impacts on biodiversity, emissions of highly toxic pollutants, water quality and water distribution, and human health (IPBES, 2019^[18]). Surface mining leads not only to deforestation (Giljum et al., 2022^[69]) but also to other landscape transformations including opening of pits, vast amounts of toxic waste and changes in freshwater streams, all detrimental to biodiversity (Macklin et al., 2023^[50]). Subsequent processing of fossil fuels, ores and minerals also releases CO₂, SO₂, CH₄, particulate matter, mercury and other heavy metals, generating acid rain and raising the bioavailability of mercury and other heavy metals (IPBES, 2019^[18]). While material extraction of fossil fuels, metal ores and non-metallic minerals is not a major driver of water stress at the global level, it can consume more freshwater than what is naturally available at the local level (Meißner, 2021^[70]).

In the baseline scenario, the use of primary materials is projected to increase roughly by half from 96 Gt in 2020 to 145 Gt in 2050. The increase in materials use applies to all material groups considered in the analysis (biomass, fossil fuels, metals and non-metallic minerals) and all regions in the world. Non-metallic minerals remain the largest material group in the three regions. The sustained use in the middle-income region supports strong infrastructure growth. A more gradual ramp-up of infrastructure and minerals use similarly occurs in the lower-income region.

Figure 2.9. Projections of total materials use

Materials use in Gt and GDP in tln USD



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/al580d>

As the economies of fast-growing countries mature and build up infrastructure, factories and housing, their use of materials (mostly non-metallic minerals and metals) increases strongly. After the investment boom, materials use tends to stabilise and is directed mostly at investment that replaces existing infrastructure, which tends to involve less intense use of materials.

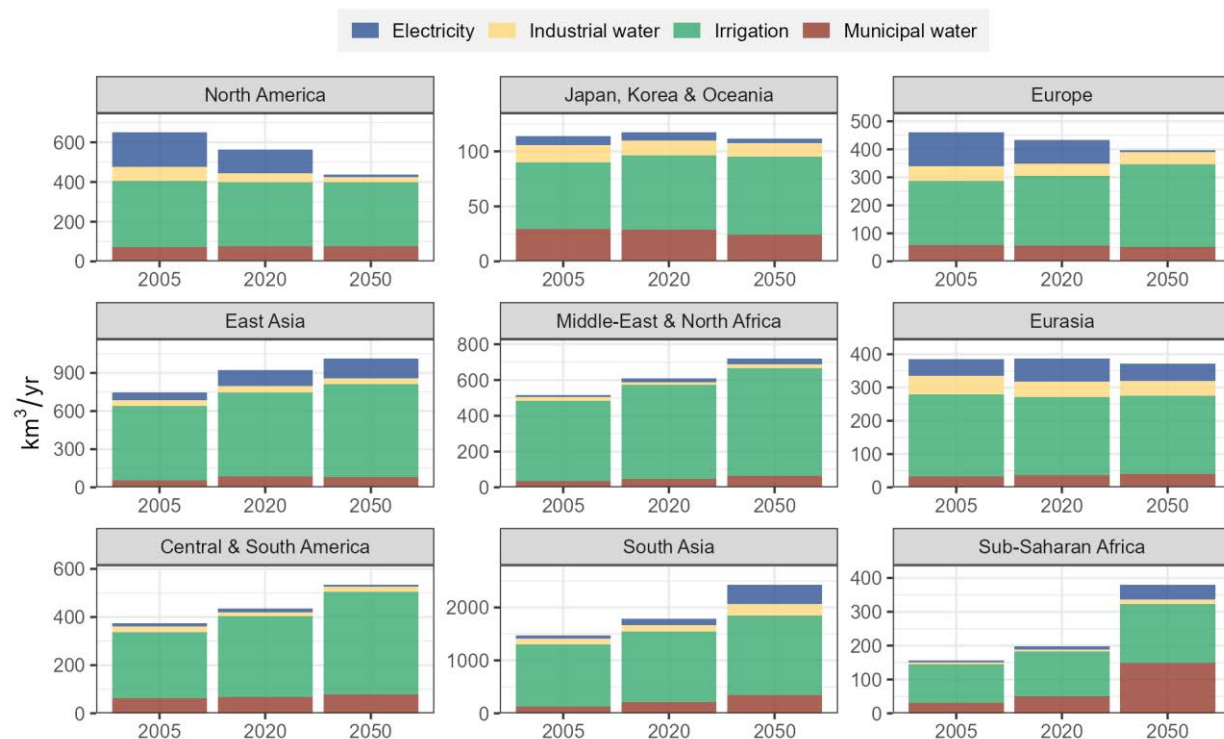
Despite a projected relative decoupling between economic activity and materials use between 2020 and 2050, materials use is projected to continue rising. The increasing share of services in manufacturing, household and government demand, alongside trends such as digitalisation and an increase in R&D, increases the importance of service sectors in the economy. Since services are less material-intensive than agriculture and industry, this structural shift leads to a decline in global material intensity over the projected period. This “relative decoupling” does not imply a reduction in total materials use. On the contrary, material-intensive sectors continue to expand in absolute terms through 2050, resulting in a substantial overall increase in global materials use. In other words, while each unit of economic output uses fewer materials (including energy), the total volume of materials used still rises due to continued economic and population growth. For instance, under current policies (for example on food loss and waste), global demand for food and agricultural goods is projected to increase by about 38% by 2050 over 2020 levels.

2.3.2. Water use

Water withdrawal is projected to increase by 17%, in line with increasing demand trends for other resources. Water withdrawal constitutes the freshwater taken from ground or surface water sources, either permanently or temporarily.¹¹ Thus water withdrawal differs from the related concept of water consumption (water use). Water withdrawal includes water uptake by economic activities that is later returned to the environment.¹² Figure 2.10 details the main applications for water. The largest user of water continues to be the agricultural sector through irrigation: despite some increases in efficiency, total water use for irrigation is projected to increase between 2020 and 2050 as total agricultural land area equipped for irrigation grows. The largest increases in water withdrawal are projected in demand from households and in the industry sector. This is in line with the growing population, increasing affluence and higher consumption that cannot be compensated by increases in water use efficiency (the ratio between water withdrawal and consumption). The demand for water for energy generation is projected to decrease, as renewable electricity sources increase and traditional fossil-fired and nuclear power plants decrease. The latter technology requires large amounts of cooling water while wind and solar electricity do not need this.

Changes in water withdrawal from 2020 to 2050 differ substantially between, but also within, world regions (Figure 2.11). Strong increases are projected in specific parts of South Asia, Middle East, Sub-Saharan Africa, Latin America and the Mediterranean. This is partly due to expansion of irrigated agricultural lands but also to growing populations and increased economic activity, causing higher water demand for households, industry and energy purposes. Substantial decreases in demand are observed in the urban areas of Northern America, Europe and Eurasia, which is related to increased water use efficiency in water demand for industry and households and decreasing demand for energy generation due to shifts towards more renewable energy sources.

Figure 2.10. Regional water withdrawal by sector

Water withdrawal in km³/yr

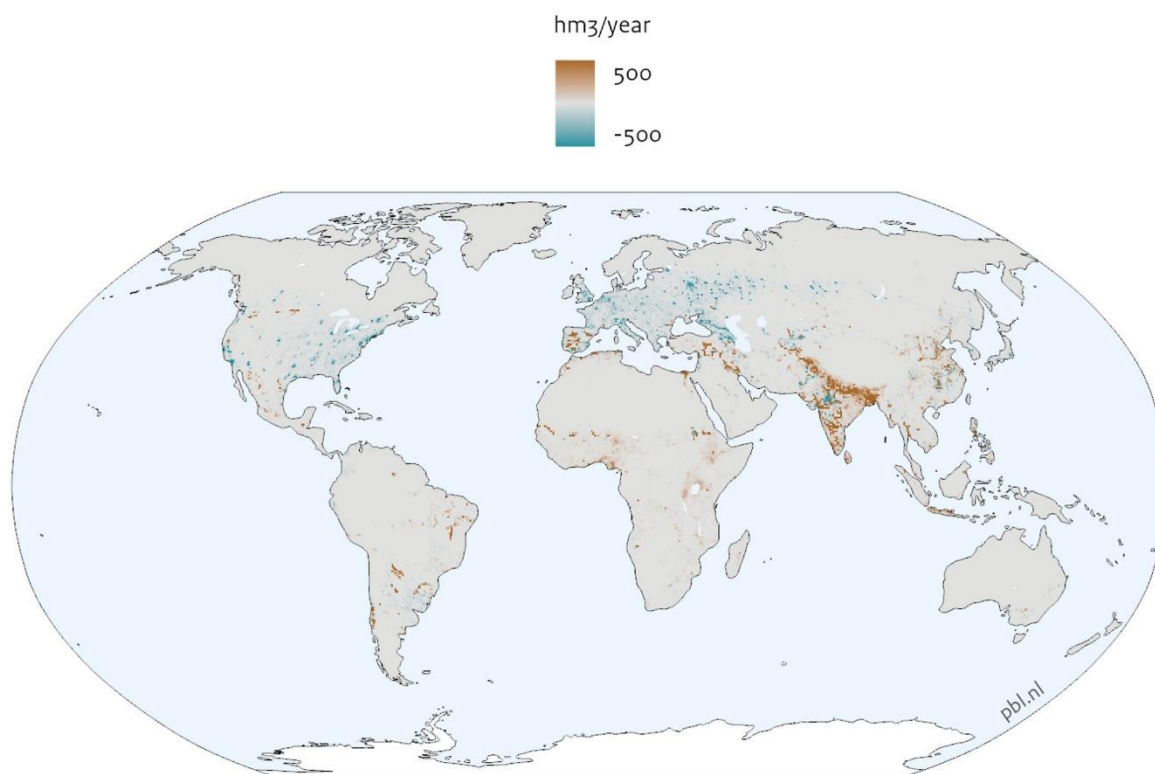
Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/clmg9b>

Water intensity, i.e. water withdrawals as ratio to GDP, are projected to decrease across all regions and converge towards levels similar to current levels for North America, Europe and Japan, Korea & Oceania; from a global average of 47 m³/kUSD in 2020 to 24 m³/kUSD in 2050. For comparison, water consumption per capita converges from a global average of 696 m³/cap in 2020 to 659 m³/cap in 2050.

Figure 2.11. Global map of the evolution of water withdrawal

Change in water withdrawal in cubic hectometres per year (hm^3/year) between 2020 and 2050



Source: Environmental Outlook modelling toolbox.

2.4. A unified outlook on the multifaceted drivers of the triple planetary crisis

To understand and address the future challenges of the triple planetary crisis, the key trends outlined above can be brought together. The current section presents a coherent dashboard of the main trends and drivers in an easily accessible manner. This can support a holistic understanding of the dynamics fuelling environmental degradation and help guide more effective and integrated policy responses. Annex 2.B further decomposes trends in environmental pressures into the contributions of different socioeconomic trends and specific drivers.

The proposed dashboard shows key socio-economic trends and the evolution of a selected set of drivers behind the environmental pressures contributing to the triple planetary crisis (cf. Figure 2.12). A central message of this chapter is the importance of examining cross-cutting issues that drive the crisis, going beyond economic growth and demographics. These transversal drivers relate to agriculture and land use, production and use of energy, and the use of resources, such as materials and water. Accordingly, the dashboard is structured around four categories of indicators. The first category includes GDP and total population. The second category focuses on total final energy use, primary energy use from fossil fuels, and coal use for electricity generation. The third category relates to agriculture, including total food demand, meat and dairy products demand, and fertiliser use. The fourth category captures resource use through water consumption, materials and plastics uses.

Interlinkages are key. First, each single driver contributes to multiple environmental pressures. For example, drivers related to energy production and use are primarily associated with emissions of GHGs

and air pollutants, which are environmental pressures that contribute simultaneously to climate change, biodiversity loss and pollution. Similarly, agricultural drivers influence land use, emissions of CH₄, N₂O, and NH₃, as well as nutrient pollution and pesticides use (not shown in the dashboard). Second, the indicator groups are not independent of each other. For instance, food production requires significant water inputs; fossil fuels and food are counted within materials use (alongside with metals and non-metallic minerals); and both the production and transportation of food require energy. These examples illustrate the complex interdependencies that exist even at the level of the drivers, reinforcing the need for an integrated understanding of the forces behind climate change, biodiversity loss and pollution.

Overall, the analysis shows a degree of relative decoupling between the drivers of environmental degradation and economic activity, but pressures to the environment are projected to continue to grow. Figure 2.12 presents the projected growth of the selected indicators from 2020 to 2050 (and the evolution in 15-year increments between 2005 and 2050). At the global level, and under current policies, both economic activity and population are expected to grow significantly between 2020 and 2050 as shown in Figure 2.12, Panel A. Real GDP at purchasing power parity (PPP) and Population bars indeed extend beyond the circle representing an index 100% for the level in 2020 (see also Section 2.2 and Annex 2.A). GDP is projected to more than double, while the global population is expected to increase by 24%. These trends reflect increasing incomes and living standards, accompanied by greater access to energy and food. However, this trajectory may raise environmental concerns. To limit negative impacts, economic growth must become more sustainable, curbing overconsumption and increasingly relying on cleaner energy sources and cleaner sectors, which will require significant technological progress. In other words, to prevent further environmental degradation, or, ideally, to improve the state of the crisis, composition and technique effects must outweigh scale effects. Overall, global projections indicate that, under current policies, this is unlikely to occur. All the selected drivers of climate change, biodiversity loss and pollution are expected to increase, albeit at a slower pace than GDP. This implies a degree of relative decoupling from economic activity, but not absolute decoupling, meaning environmental pressures will continue to rise, but not as rapidly as the economy.

A key takeaway of this chapter is that improved efficiency plays a crucial role in moderating the rising pressures driven by multiple socio-economic and sectoral trends. As the bar representing the evolution of GDP is longer than the ones representing materials use and water use in Figure 2.12, Panel A, materials use and water use efficiency are projected to improve. This means that less water and materials will be required to produce each dollar of GDP in 2050 than in 2020. However, under current policies, these efficiency gains are not sufficient to offset the overall scale of economic and population growth. Efficiency improvements enable a relative decoupling, which helps slow the increase in energy, food, materials, and water demand, but are not sufficient to halt their continued rise at the global level in the coming decades. Thus, efficiency improvements need to be combined with upstream policies to curb demand and downstream policies to deal with environmental burdens.

Most drivers shown in the dashboard exhibit an upward trend in per capita terms. Notable exceptions include water consumption and use of fossil fuels to produce primary energy. Although global water consumption (not to be confused with water withdrawal, which includes water temporarily withdrawn from the environment but returned later) is projected to rise by 22%, per capita water consumption is expected to decline slightly by 1%. Similarly, while the use of fossil fuels for primary energy increases by 16%, per capita use declines by 6%, driven by greater energy efficiency, increased electrification of transport, and the growing share of renewables. However, coal use for electricity generation stands out: it is projected to increase substantially, by 86% in absolute terms and 50% per capita, despite a 17% decline in its intensity relative to GDP.

While still showing growth, comparing the bar lengths in Figure 2.12, Panel A with Panel B illustrates a slight slowdown for the projected 2020-2050 evolution of climate change, biodiversity loss and pollution compared with 2005-2020. Some drivers (e.g. plastics use) show limited signals of slower growth in the future. Coal-fired electricity generation, on the other hand, is set to grow faster in the 2020-2050 period.

Global aggregates mask significant regional heterogeneity. To provide a more detailed perspective, Figure 2.13 shows the same set of indicators as in Figure 2.12 but disaggregated across nine regions, covering the world. Two additional elements enrich the regional plots: a black dot, which shows the evolution of the global average for each indicator (as in Figure 2.12), and bar colours, which reflect the relative intensity of each indicator in 2050 compared to the region with the highest value. For example, GDP per capita in 2050 is highest in North America (represented in black) and lowest in Sub-Saharan Africa (indicated in light blue), where it amounts to about 8% of North America's level.

The evolution of key socio-economic indicators varies significantly across regions. GDP is projected to grow between 2020 and 2050 in all regions, with the fastest growth occurring in lower-income regions (see the length of the bar beyond the circle in the South Asia and Sub-Saharan Africa panels of Figure 2.13).¹³ Population growth is more uneven: it is expected to be more rapid in South Asia, Sub-Saharan Africa and in the Middle East and North Africa, while remaining stable or declining in Europe, East Asia, Eurasia and in Japan, Korea, and Oceania. While the global analysis does not reveal any cases of absolute decoupling in the coming decades, regional-level data show a few such instances. In such instances, the bars in Figure 2.13 are lower than the outer grey line meaning that the level of the indicator is below its value in 2020. Absolute decoupling cases are mostly related to the energy transition, with total energy and fossil energy use, as well as coal-based electricity supply all projected to decline in Europe (by -10%, -50% and -45% respectively), North America (-14%, -28% and -100%), and Japan, Korea, and Oceania (-9%, -50% and -63%). Another example is the projected 11% decrease in nitrogen fertiliser use in Europe. Nonetheless, such instances of absolute decoupling remain exceptions, with most regions continuing to experience rising trends across the drivers of climate change, biodiversity loss and pollution.

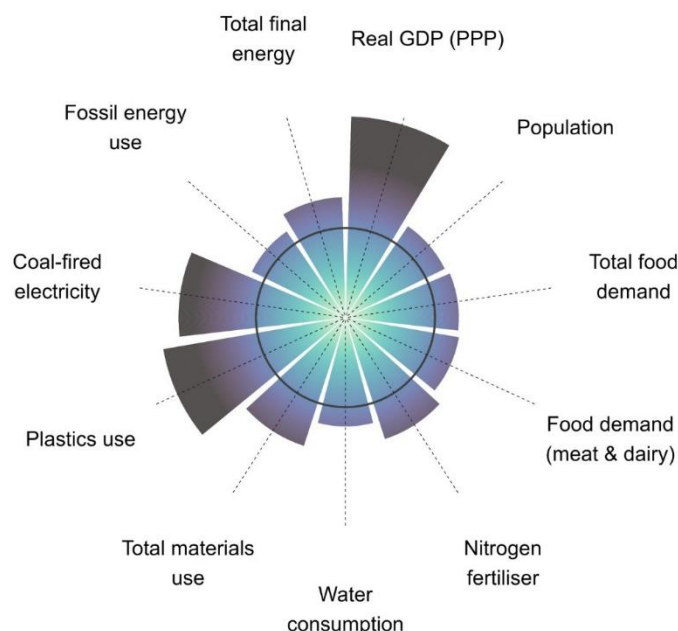
The majority of indicators show increasing trends across all regions. As incomes and access to energy improve, energy use more than doubles in South Asia and the Middle East and North Africa, and rises by more than 70% in Sub-Saharan Africa. These increases are largely met by expanded use of fossil fuels and coal-fired electricity. South Asia, in particular, stands out for showing sharp growth across all energy-related indicators. Sub-Saharan Africa also displays high projected growth in total energy demand, fossil fuel consumption, coal use in electricity generation, plastics, materials, and food demand. However, as indicated by the colour scale in Figure 2.13, the intensity of these indicators in both South Asia and Sub-Saharan Africa remains among the lowest globally, even by 2050. Conversely, several region-indicator pairs combine both high growth rates and high per capita levels in 2050, posing particular concerns. These include plastics use in North America and Japan, Korea and Oceania, and coal-fired electricity generation in East Asia. Such combinations of high intensity and strong growth suggest heightened environmental pressures, reinforcing the triple planetary crisis.

In addition to the major trends already discussed, such as the absolute increase in key drivers of the triple planetary crisis, relative decoupling from GDP and gains in efficiency, the proposed dashboard also highlights notable sectoral developments projected under current policies. In the agricultural sector, current production and consumption patterns and their projected trends suggest the sector will not reduce its adverse impacts on the environment. As a consequence, the related emissions of GHGs and pollutants, as well as biodiversity loss, are expected to increase. Without shifts in production technologies, farm practices and food consumer behaviours, the climate mitigation potential of the agricultural sector will remain untapped. The projected continued reliance on fossil fuels is incompatible with efforts to address the triple planetary crisis. The transition to electrification powered by renewables, implemented in ways to minimise potential risks such as increased pollution and biodiversity loss (see Chapter 6), is a key component to mitigate the challenge. In parallel, total materials use and water consumption are also projected to grow, continuing to follow an unsustainable trend and adding further strain on ecosystems and natural resources. However, under current policies, the pace and scale of this transition are insufficient.

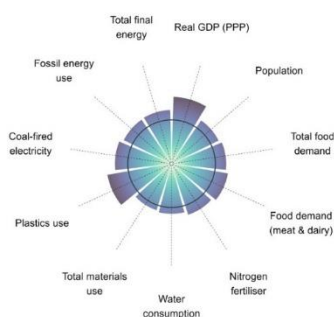
Figure 2.12. Evolution of drivers and socio-economic trends behind environmental pressures

Global evolution for selected drivers

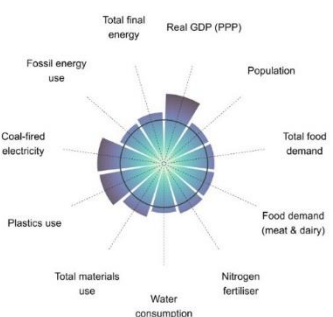
Panel A. 2020-2050



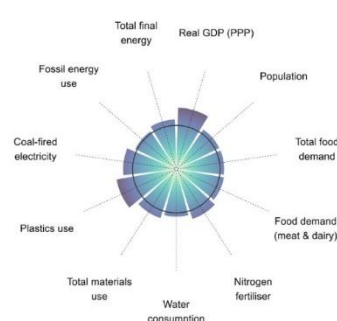
Panel B. 2005-2020



Panel C. 2020-2035



Panel D. 2035-2050



Indicators	Explanation: from drivers to pressures
Real GDP (PPP)	Growing income & economic activity (incl. of polluting sectors) affect the drivers of the triple planetary crisis.
Population	Demographic trends, incl. population growth, affect the demand for goods and services (e.g. food, energy).
Total food demand	Meeting the demand for food drives agricultural production and associated inputs (incl. land) and emissions.
Food demand: Meat & dairy	Animal-based agriculture is a driver behind environmental pressures (emissions, land) from food production.
Nitrogen fertiliser use	Inefficient use of nitrogen fertiliser can lead to excess nutrient load and pollution, affecting biodiversity.
Water consumption	Unsustainable water use can lead to environmental degradation and can put ecosystems at risk.
Total materials use	The extraction, processing, use and disposal of materials lead to a range of environmental consequences.
Plastics use	The entire lifecycle of plastics, from production to disposal, has a variety of environmental impacts.
Secondary energy: coal	The mining and combustion of coal for electricity generation causes significant emissions & environmental impacts.
Primary energy: fossil	The extraction, production, and use of fossil fuels is a key driver behind climate change and air pollution.
Total final energy	Depending on the source, the extraction, production and use of energy is associated with land use & emissions.

Note: The length of the bars represents evolution over time (between the two dates in each panel). For instance, for Panel A, the circle indicates the 2020 level indexed to 100%, against which to compare the evolution in the bar. For example, plastics use is projected to increase by 106% over the 2020-2050 period at the global level. Annex 2.C provides details on the values and the units of reported indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/c1x9ju>

Figure 2.13. Regional differences in the evolution of drivers behind environmental pressures

Regional evolution for selected drivers, 2020-2050



Note: The length of the bars represents the evolution from 2020 to 2050. The circle indicates the 2020 level. The colour indicates the relative intensity of a given indicator in each region (e.g. per capita GDP in 2050) compared to the region with the highest intensity in 2050. For example, the light blue bar for Real GDP (PPP) in Sub-Saharan Africa shows that GDP per capita in this region will be the lowest in 2050, relative to other regions. In contrast, the dark bar for North America indicates that GDP per capita will be the highest in this region. Black dots represent evolution over time at the global level. Values are capped at +140% above 2020 levels for visual appearance (a triangle effect is present when values exceed this threshold). Annex 2.C provides details on the values and the units of reported indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/n6qiyx>

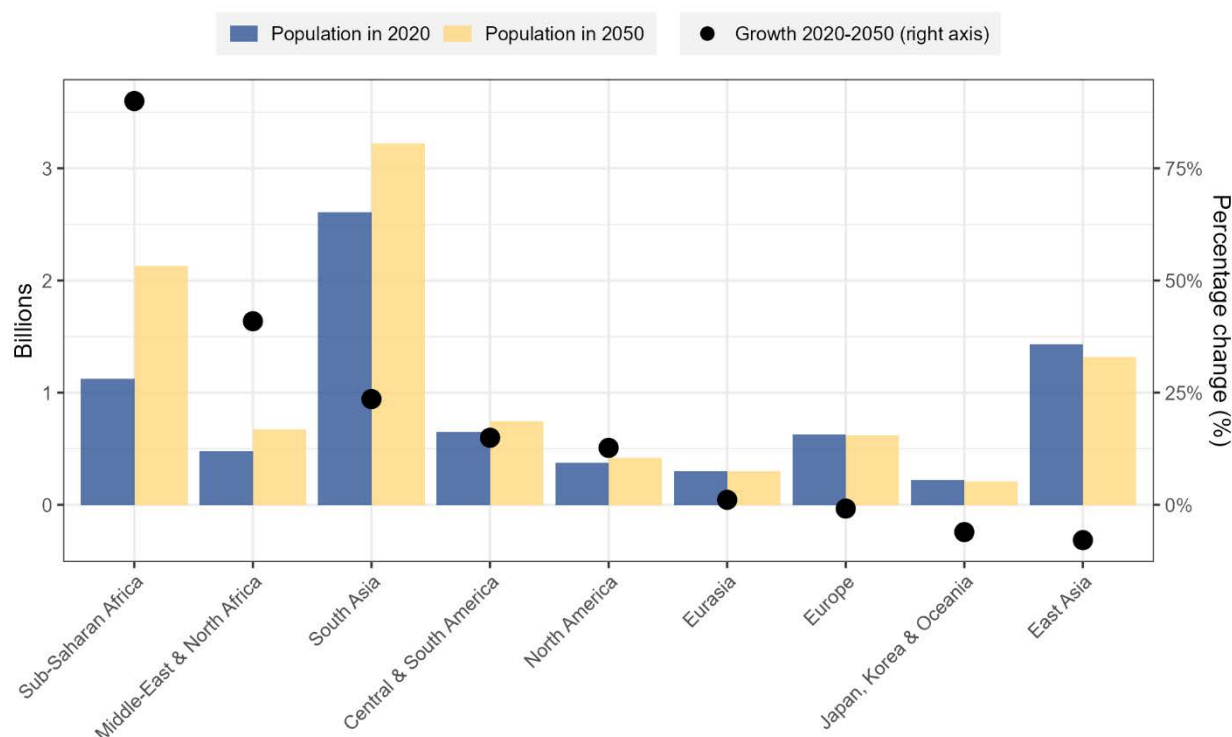
Annex 2.A. Socioeconomic trends

Demographics

The world population is expected to continue to grow and reach 8.5 billion by 2030 and 9.6 billion by 2050 (Annex Figure 2.A.1). The global population growth *rate* is projected to decline gradually, implying a peak population level somewhere in the third quarter of the century. The decline in population growth applies to all countries. Yet the total population in lower-income regions is projected to continue to rise significantly in the coming decades, reaching more than 5 billion by mid-century. Average population growth in the coming decades is projected to be highly heterogenous across countries, ranging from population declines in East Asia to sustained growth above 2% in many less-developed Sub-Saharan African countries.

Annex Figure 2.A.1. Regional population growth ranges from negative to nearly 100% from 2020 to 2050

Population in billion people in 2020 and 2050, and total growth between 2020 and 2050



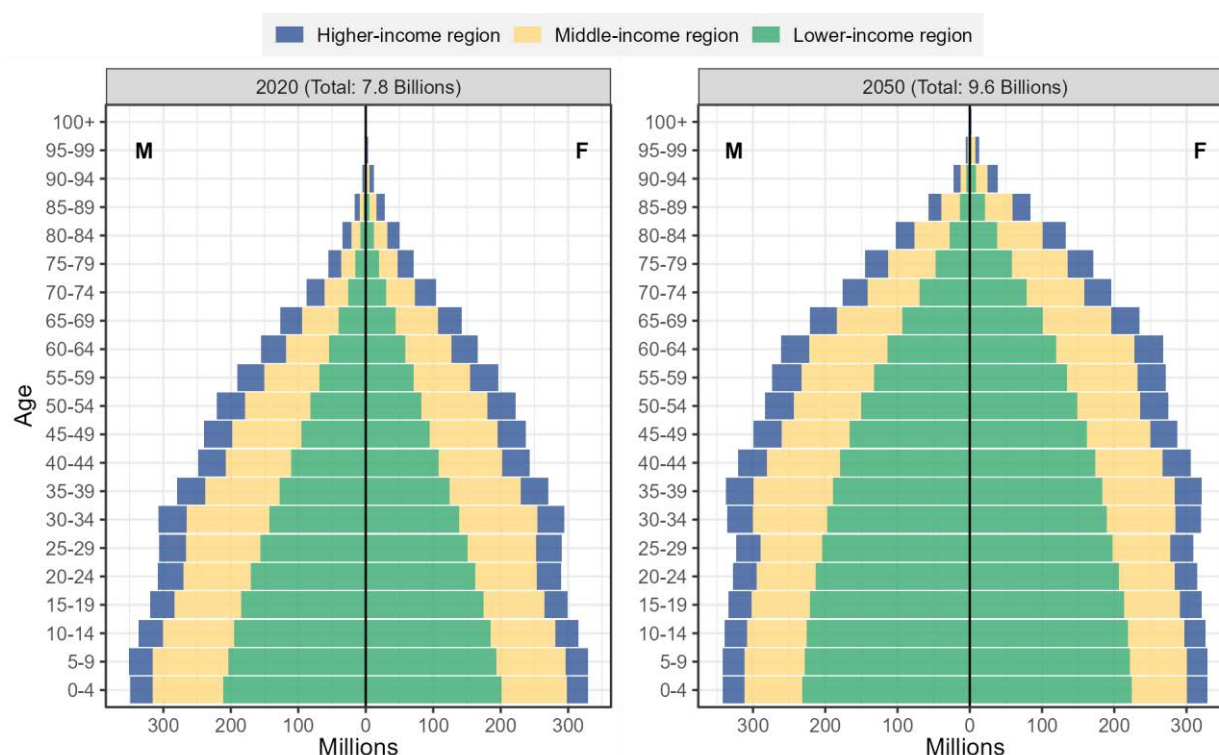
Source: Central projection from UN (2022_[30]).

StatLink  <https://stat.link/dfvgpj>

Furthermore, the composition of populations changes over time, with significant aging in many countries in the higher- and middle-income regions, leading to an increased share of elderly people (Annex Figure 2.A.2). This has a wide range of consequences, including different consumption patterns, among which an increased demand for health care services (de la Maisonneuve and Oliveira Martins, 2014^[71]) and a reduction in the ratio of working age population to total population (and thus labour supply).¹⁴ In contrast, in many less-developed countries populations are significantly younger. Education levels are projected to continue to converge (see e.g. (KC and Lutz, 2017^[72])). Education – and especially female education – in turn affects birth rates and thus future population size (Adhikari, Lutz and Kebede, 2024^[73]).

Annex Figure 2.A.2. Life expectancy continues to grow for both men and women

Global population in million people by sex and age cohort



Note: M stands for male population, F for female population.

Source: Central projection from UN (2022^[30]).

StatLink  <https://stat.link/6npbhl>

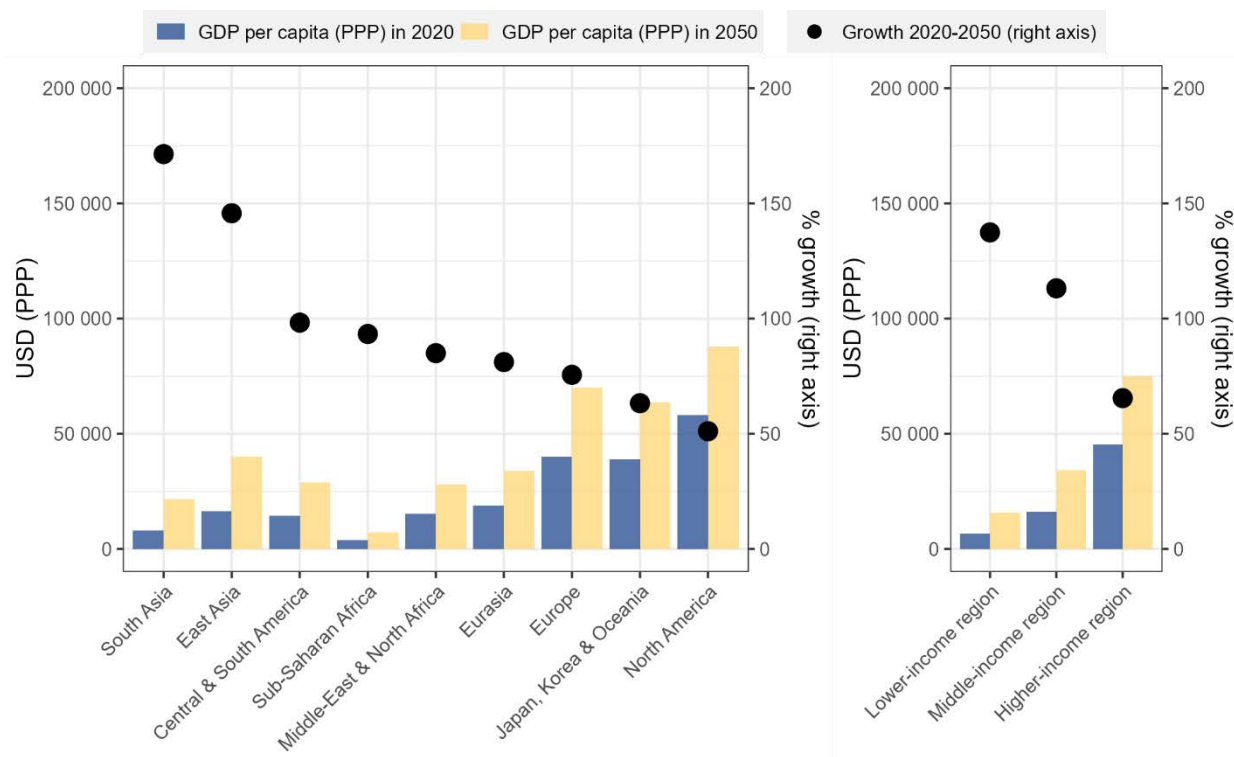
Economy

Global economic activity, measured through GDP, is projected to grow substantially faster than population: on average by 2.7% per year, versus 0.7% for population (Annex Figure 2.A.3). Thus, global GDP, at constant prices, is projected to grow from USD 126 trillion in 2020 to USD 283 trillion in 2050. There is significant regional variation, with steady but rather low growth in higher-income region, a declining growth rate in the middle-income region (not least related to a fast decline in annual growth in the People's Republic of China), and faster growth in lower-income regions. The latter is a combination of fast growth in a number of emerging economies in the short run, not least India, plus increasing growth rates in many developing countries, including in Sub-Saharan Africa.

The average (per capita) income of the lower-income region in 2020 equalled USD 6 700; by 2050, this is projected to rise to USD 15 900; a 2.4-fold increase (Annex Figure 2.A.3). For the middle-income region, income is projected to increase from USD 16 000 on average in 2020 to USD 34 100 on average by 2050 (a bit more than doubling). Finally, for the higher-income region, growth is slower but starts from a higher level: from USD 45 300 in 2020 to USD 75 000 in 2050 (a growth of 65%). As with population, the income growth projections are fairly similar to those in the literature, and especially SSP2.

Annex Figure 2.A.3. Per capita income grows fastest in the lower- and middle-income regions

Per capita gross domestic product by region, levels in 2020 and 2050, and total growth between 2020 and 2050



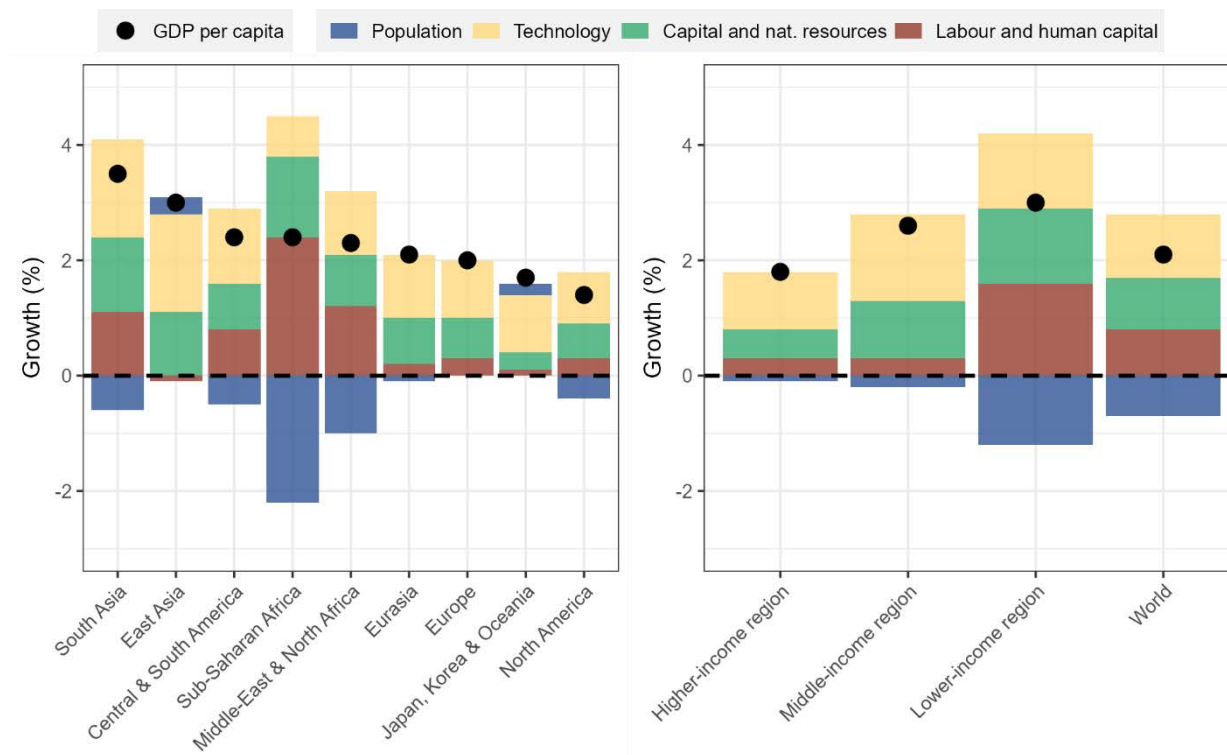
Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/95a2sj>

The faster income growth in emerging and developing economies (Annex Figure 2.A.4) is in line with the concept of conditional convergence: countries that are further from their technology frontier will grow faster, as they catch up in technology to more developed economies (Johansson et al., 2013^[74]; Dellink et al., 2017^[75]). Population growth influences income in two distinct ways: *per capita* income lowers with higher population (resources are shared across more people), but more people in the working age population leads to higher labour supply, which is a component of GDP. This is most clearly seen in Sub-Saharan Africa: the currently young population implies a rapid increase in the working age population in the coming decades, and thus fast growth of labour supply. But total population grows almost as fast and dampens growth of income (GDP per capita). Investments and capital growth and technological developments have a positive effect on income growth. Emerging economies, such as the South Asia region, can sustain fast growth with a significant contribution from technological progress as they catch up. In the higher-income region, the contribution of the demographic factors is rather small, and both capital and technology drivers dominate overall income growth.¹⁵

Annex Figure 2.A.4. Global income growth is driven in roughly equal parts by labour, capital and technology

Average annual income growth between 2020 and 2050 and contribution of the various drivers



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/nis3kz>

Technological and structural change

As explained in the previous section, economic growth is driven by a combination of using more inputs (more labour, more capital) and increasing the production outputs that can be made with the same amount of inputs.¹⁶ The latter aspect, technological improvements, includes efficiency improvements in the use of specific production inputs, e.g. energy efficiency, as well as improvements in output per unit of primary inputs, especially labour, i.e. labour productivity growth (e.g. from learning-by-doing). These technology effects can differ substantially between sectors, and between regions. Generally, productivity growth is relatively fast in industrial sectors compared to agriculture and services, and faster in fast-growing emerging economies as their technology levels catch up to the most developed countries.

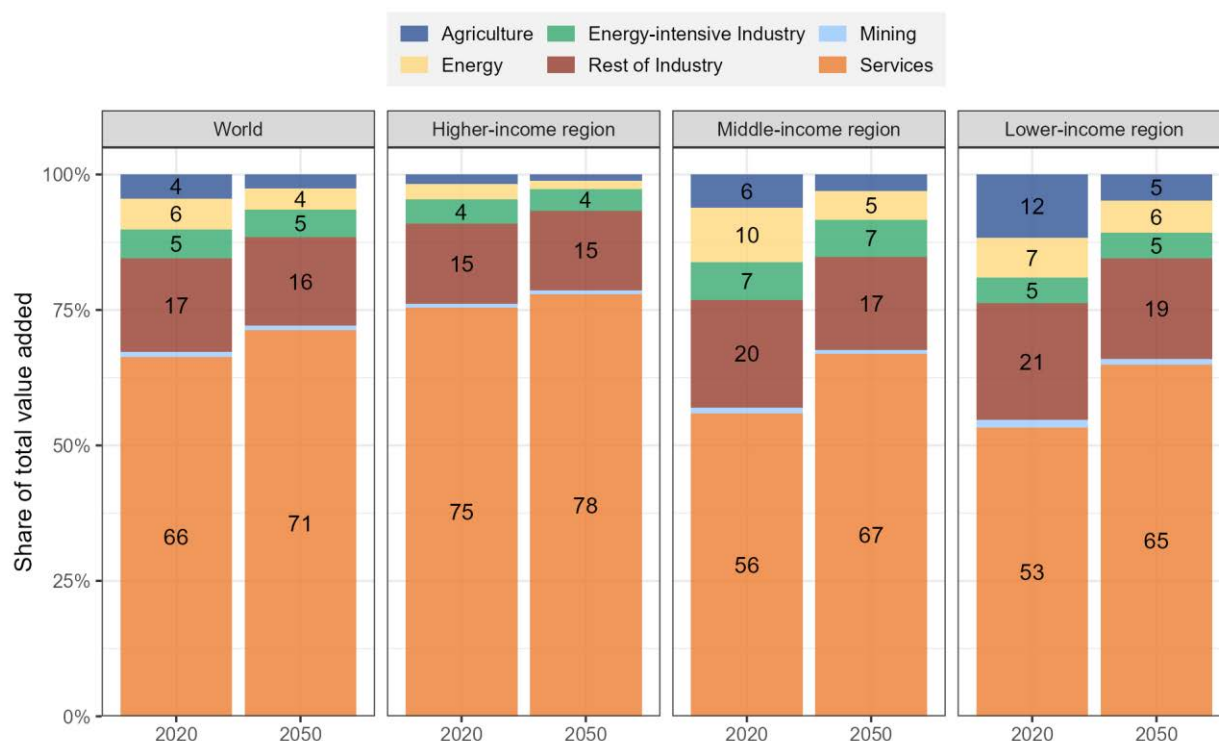
These productivity increases give rise to a change in the structure of GDP, as measured by the contribution of value added generated in the different sectors to economy-wide value added generated, i.e. GDP. For least developed countries, agriculture represents a large share, while production in emerging economies is characterised by industrialisation, including a significant growth in construction to support infrastructure development. Sectoral shares are more stable in developed economies, with high levels of services and relatively low levels of agricultural production. Consumption patterns do not have to follow these same trends, and the transformation of consumption patterns often lags behind transformation of production, as countries engage in international trade (see below) to specialise production where they have a comparative advantage, while consumer preferences gradually evolve as incomes rise.

In all three regions services make up the majority of value added generated, even more so in 2050 than in 2020 (Annex Figure 2.A.5). As expected, the share is lowest in the lower-income group, but even that group contains several countries that have fairly diversified economies. This domination of the services sector is linked to a range of socioeconomic trends: (i) the income elasticity of services tends to be higher than for most other commodities, and thus rising income leads to a rising share of household consumption spent on services; (ii) aging populations lead to increased demand for healthcare services; (iii) productivity growth is on average lower than for industry, and thus in relative terms expenditures on services need to rise compared to expenditures on goods to keep a balanced basket of consumption; (iv) manufacturing tends to be increasingly “servitised” (Pilat and Nolan, 2016^[76]), and finally (v) digitalisation of the economy, including a switch to e-commerce, imply less need for physical commodities and more for services. Digitalisation contributes significantly to the servitisation of both industrial production and consumer demand, induces a shift away from equipment towards electronics, reduces international transport while simultaneously lowering the cost of international trade, and e.g. increases energy use for data centres (OECD, 2019^[77]; OECD, 2024^[78]).

In contrast, the share of agriculture in total production declines over time – food is an essential good and food demand rises only modestly as incomes increase. The share of value added generated in energy declines as well, reflecting continued energy efficiency improvements. The decline in energy value added is especially pronounced in the middle-income region, which contains many of the fossil fuel exporting countries. These shifts in the structure of the economy are much less pronounced in the higher-income region, whose countries tend to have more diversified economies and more stable demand structures.

Annex Figure 2.A.5. Services are the largest economic sector, and become even more important by 2050

Sectoral composition of value added (in constant 2017 USD), in shares of total value added



Source: Environmental Outlook modelling toolbox.

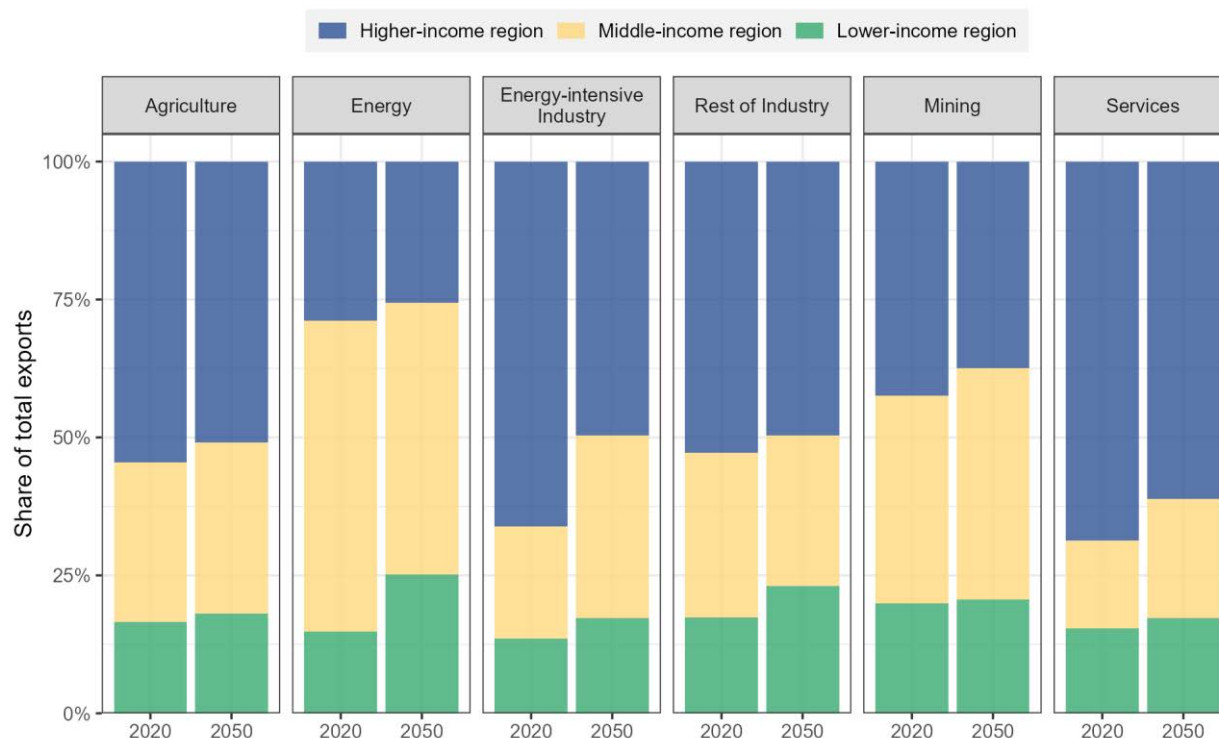
StatLink  <https://stat.link/ljr8d0>

The faster population and economic growth in the middle- and lower-income regions also implies a shift in consumption towards those regions. Thus, the share of the higher-income region in global production and consumption is projected to decline over time. This also affects the balance of trade: in 2020, the largest trade flow occurs within the countries in the higher-income region, representing more than one-third of total trade. But this share declines over time, with exports by especially the lower-income region expanding (from 16% in 2020 to 20% in 2050); most of that expansion involves the rapidly increasing trade between countries in the lower-income region (from less than 4% in 2020 to 6% in 2050).

As the structure of the economy differs across regions, different countries have different trade specialisations. Thus, the increase in exports by the lower-income region does not extend proportionately to all commodities. Rather, the biggest increases in the share of the global market are projected for energy – relatively easy to achieve as export prospects for the fossil fuels are rather weak and thus there is very little growth of the traditional fuel trade flows – as well as industry, matching the theory on economic development. Specifically, industrial production in the lower-income region increases more rapidly than consumption, and development of export opportunities is a key part of the development strategy of many countries.

Annex Figure 2.A.6. Export shares of lower-income regions increase for energy and industrial commodities

Share of regions in global exports by commodity group



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/s3unq2>

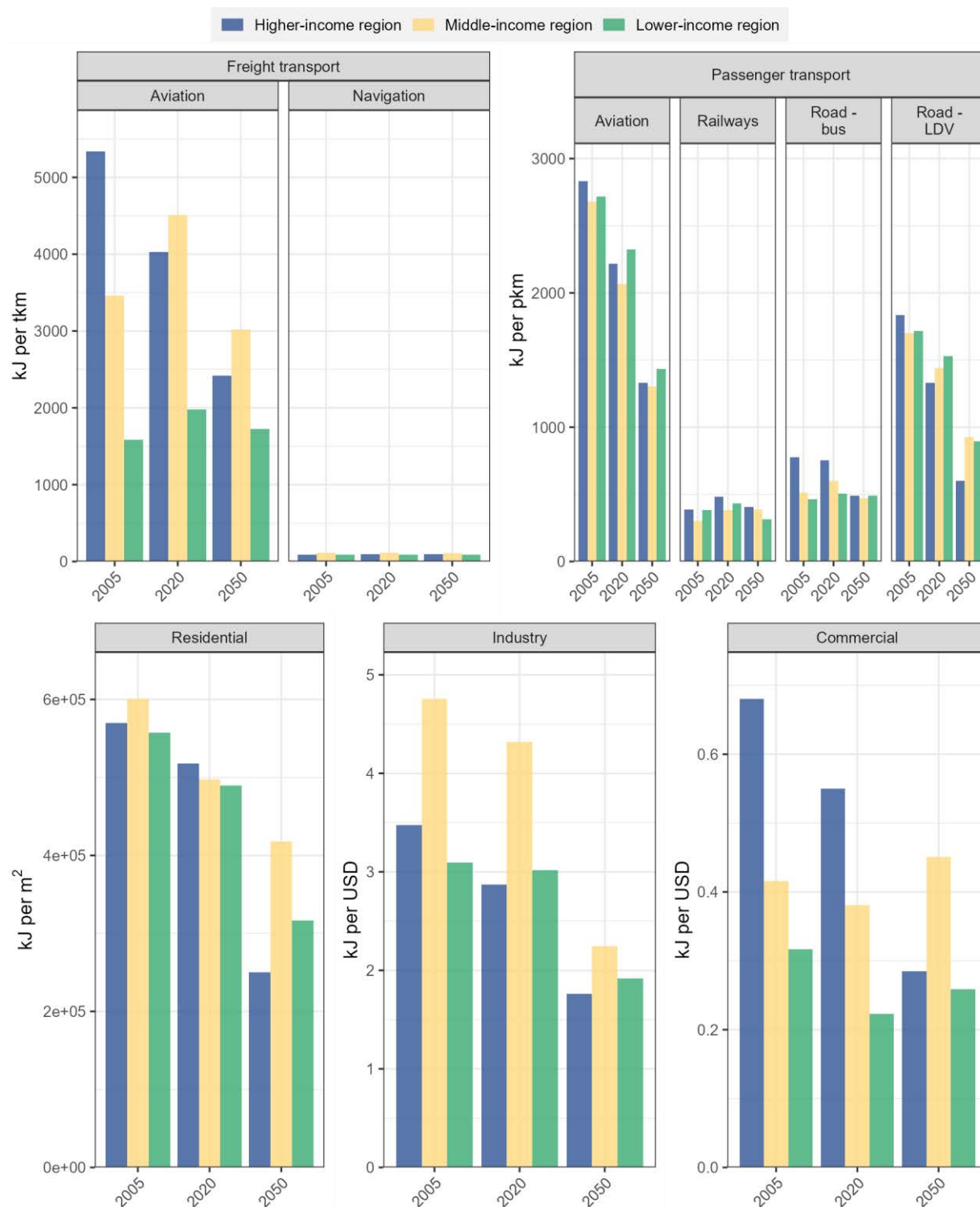
International trade thus plays a key role in reconciling trends on the production side and trends on the consumption side. However, long-term imbalances on the trade balance, with a significant surplus on the current account, put pressure on exchange rates and in most cases such surpluses are projected to fade – though not necessarily fully disappear.

Technological and structural change also impact energy efficiency. Energy efficiency for freight and passenger transport is projected to improve as shown in Annex Figure 2.A.7. For instance, between 2020 and 2050, the energy intensity of aviation for freight transport (the amount of kilojoules (kJ) required to transport a tonne of freight by one kilometre (tkm)) is expected to fall by over 30% in the higher- and middle-income regions and 12% in the lower-income region. Similar improvements are also observed for the energy intensity of aviation for passenger transport (the amount of kJ required to transport a passenger by one kilometre (pkm)) with all regions projected to undergo reductions above 35%. The energy intensity of light-duty vehicles also falls by 36% (in the middle-income region) to 55% in the higher-income region. Most regions are projected to also have energy intensity reductions for buses, navigation and railways, although these are much smaller.

Residential, industry and commercial energy intensity is projected to decrease in all regions between 2020 and 2050. This is most pronounced for residential energy intensity (measured in kJ by m²) which decreases by approximately 50% in the higher-income region. This could be explained by the developments in building standards made in higher-income regions such as the standardisation of modern insulation methods. Industry and commercial energy intensity is projected to drop in all regions with the exception of commercial energy intensity in the lower-income region, in link with the development of services in this region.

Annex Figure 2.A.7. Energy intensity changes within key sectors

Changes in energy intensity of key sectors: transport, buildings, and industry



Note: Freight transport energy intensity is the ratio of energy use in kilojoules (kJ) to tonne-kilometres travelled (tkm). Passenger transport energy intensity is the ratio of energy use in kJ to passenger-kilometres travelled (pkm). Residential is the ratio of energy use in kJ to m², Industry and Commercial are measured as the ratio of energy use in kJ to value added in 2010 USD.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/bpx2nd>

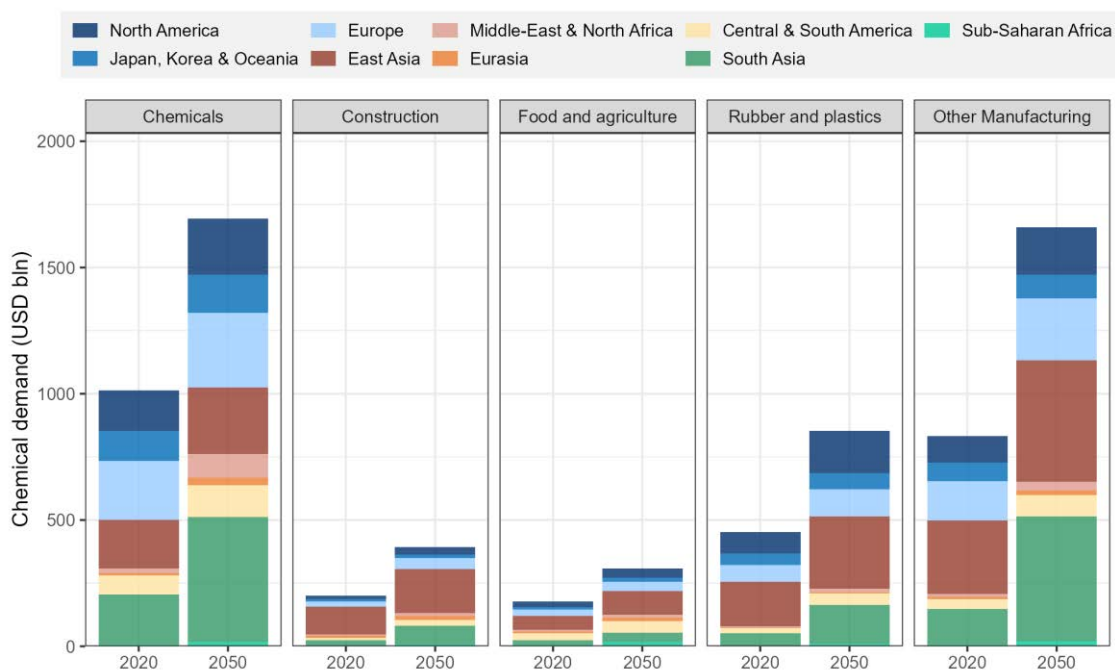
Other sectors, including plastics and other chemicals: regional and sectoral shifts in economic growth drive demand

The structure of the economy is changing over time. Such changes happen more rapidly for fast-developing countries that industrialise and diversify their economies than for more developed countries that already have relatively mature, diversified economies. Nonetheless, there is a trend towards servitisation (the increased reliance on services in manufacturing as an input or as bundled output) in all countries, with services making up a larger share of final consumption, e.g. health expenditures for health care in an aging population, but also increased use of services in industry, either by bundling outputs (a service contract combined with the purchase of a good) or through leasing commodities. These economic dynamics affect environmental pressures and are captured in the analytical framework through their effect on structural change and thus on the composition of total demand.

As the global economy grows between 2020 and 2050, the sectoral composition of chemical demand is projected to evolve. Around 60% of chemical demand is projected to continue to be driven by chemicals, other manufacturing and rubber and plastics by 2050, as illustrated in Annex Figure 2.A.8. The chemicals sector itself is projected to continue to be the leading consumer of chemical products (here excluding pharmaceuticals, rubber and plastics), accounting for over USD 1 trillion in 2020 and USD 1.7 trillion in 2050. While in 2020, over half of chemical demand by the chemicals sector is concentrated in North America, Europe, and Japan, Korea and Oceania, most of the projected growth in chemical demand to 2050 is driven by other regions. South Asia (+149%), Eurasia (+253%) and the Middle East and North Africa (+381%) see the highest growth rates driving growth in chemical demand by the chemicals sector. By 2050, an increasing proportion of chemical demand will be accounted for by other manufacturing increasing from 16% in 2020 to 18% in 2050 in contrast to the chemicals sector which will account for 27% in 2050 relative to 31% in 2020.

Annex Figure 2.A.8. Chemical demand by sector

Chemical demand in USD bln



Note: Chemical demand represents the intermediate demand for chemicals (excluding rubber, plastics and pharmaceuticals) by sector (excluding services) in each region. Chemical demand is expressed in constant 2017 USD bln for both 2020 and 2050. Only sectors with a share higher than 2% in 2020 are shown.

Source: Environmental Outlook modelling toolbox.

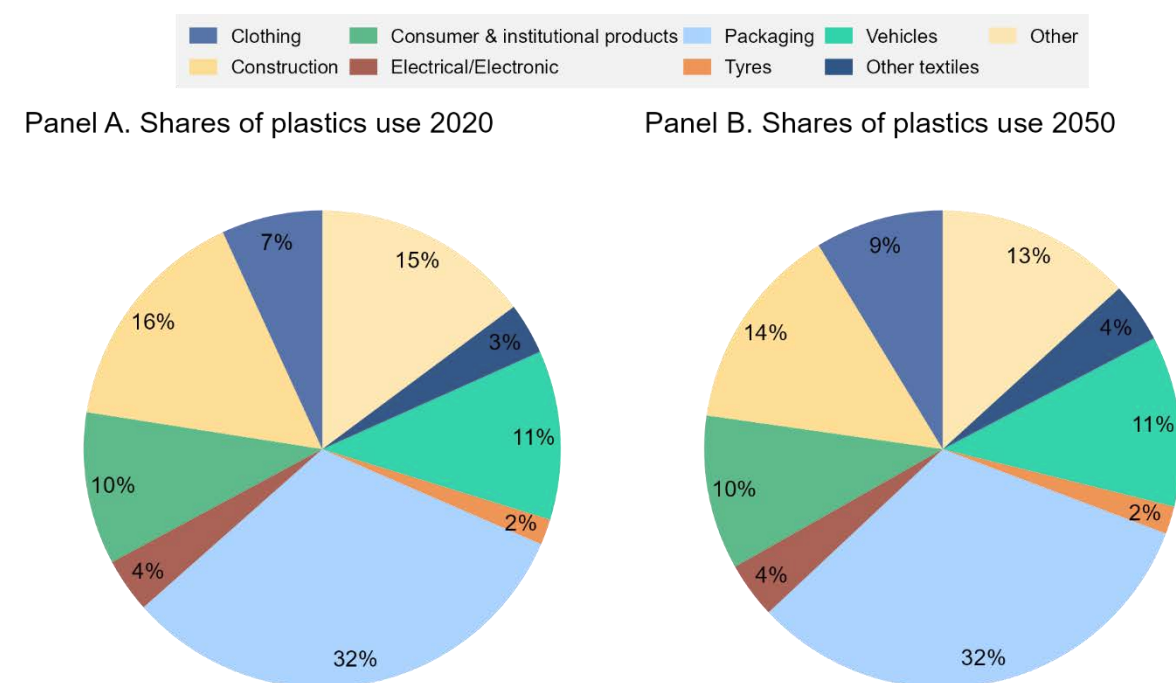
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Another example of the structural shifts occurring in the baseline scenario can be drawn with plastics. Three main applications account for approximately 60% of plastics use: packaging, construction and vehicles, which includes transport equipment (Annex Figure 2.A.9, Panel A). With limited substitution away from plastics foreseen under current policies, plastics use follows increases in economic activity across the economy and is thus projected to increase for all sectors (Annex Figure 2.A.9, Panel B). The largest increases in plastics use are for packaging, construction, transportation and consumer products, linked to soaring demand for consumer goods and transportation as economies develop. With the digitalisation and electrification trends, plastics use dedicated to electrical and electronic products increase strongly as well.

Despite the services sector having a relatively low plastic intensity (the amount of plastic per unit of output), the shift towards a service-based economy will result in the services sector using the most plastics. This trend manifests with the growing use of plastic products in service industries, such as packaging and consumer items (e.g., takeaway food containers, healthcare and medical products, art supplies, credit cards, and luggage). The rise in plastics used for packaging indicates that current policies are inadequate to counteract the increased plastics use by key sectors dependent on packaging, including business services, food products, and trade.

The increase of plastics use for other applications is slower. The growth of the textile sector in middle- and lower-income economies drive plastics use for clothes. In those countries, investment in infrastructure lead construction activities to use plastics, as necessary to economic development (OECD, 2019^[15]). Plastics use for industrial sectors and machinery undergoes a slower growth, following the structural shifts away from industry towards services.

Annex Figure 2.A.9. Plastics use by application in 2020 and 2050



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/a43nz9>

Policies

The projections include (mostly implicit) policies included in the macroeconomic projections and (mostly explicit) environmental policies in each of the domains of the triple planetary crisis and beyond. Annex Table 2.A.1 summarises the policies included in these two domains by wide issues.

Annex Table 2.A.1. Summary of policies included in the baseline

	Domain	Type of policies	Implementation	Source
Environment	Climate change	Economy-wide emission reduction policies (e.g. emission reduction fund programmes, Kigali Amendment signatories, emissions pricing programmes)	Explicit	Nascimento et al. (2024 ^[79])
	Energy	- renewable capacity targets, - renewable share in the electricity mix, - power plant standards, - vehicle emission standards, - electric vehicle targets	Explicit	Nascimento et al. (2024 ^[79])
	Biodiversity	Terrestrial protected areas	Explicit	UNEP-WCMC (2020 ^[80])
	Deforestation	Reducing Emissions from Deforestation and Forest Degradation (REDD+)	Explicit	Nascimento et al. (2024 ^[79]); Nascimento et al. (2023 ^[81])
	Afforestation	Goals for forest expansion as specified in national policies	Explicit	Nascimento et al. (2024 ^[79]); Nascimento et al. (2023 ^[81])
	Air pollution	Stylised improvements of emission factors representing pollutant end-of-pipe control	Implicit	
	Plastic pollution	Trends derived from current policies.	Implicit	OECD (2022 ^[56])
	NP pollution	Stylised improvements of N and P use efficiencies	Implicit	
Macroeconomy & wider policies	Materials	Trends derived from current policies.	Implicit	OECD (2019 ^[15])
	Demography & education	Trends based on current policies.	Implicit	UN (2022 ^[30])
	Labour	Trends based on current policies.	Implicit	ILO (2022 ^[82])
	Economy	Trade, monetary, structural, and growth trends based on current policies	Implicit	- OECD (2023^[83]) for OECD countries - IMF (2023^[84]) for other countries - completed when needed with World Bank (2023^[85])

Source: Authors' own elaboration.

Environmental policies

Policies related to mitigating climate change are based on implementation of specific sectoral targets directly on appropriate model variables or appropriate proxies (renewable energy targets, efficiency improvements, etc.). Targets on decarbonisation rates are emulated through sectoral carbon prices, which result in a target emission level over a given time horizon. The carbon price, imposed on all GHG emissions, induces a response of the energy system where investments in energy efficiency, fossil fuel substitution and additional investments in non-fossil options increase (van Vuuren et al., 2017^[86]). These carbon prices are differentiated at regional and sectoral levels. Land based climate change mitigation efforts are represented in the model by afforestation and reduced deforestation and forest degradation policies. Only policies that are currently embedded in national laws were taken into account and only countries with considerable AFOLU emission reductions were considered, including Brazil, Canada, the People's Republic of China, European Union, India and Indonesia (Nascimento et al., 2023^[81]).

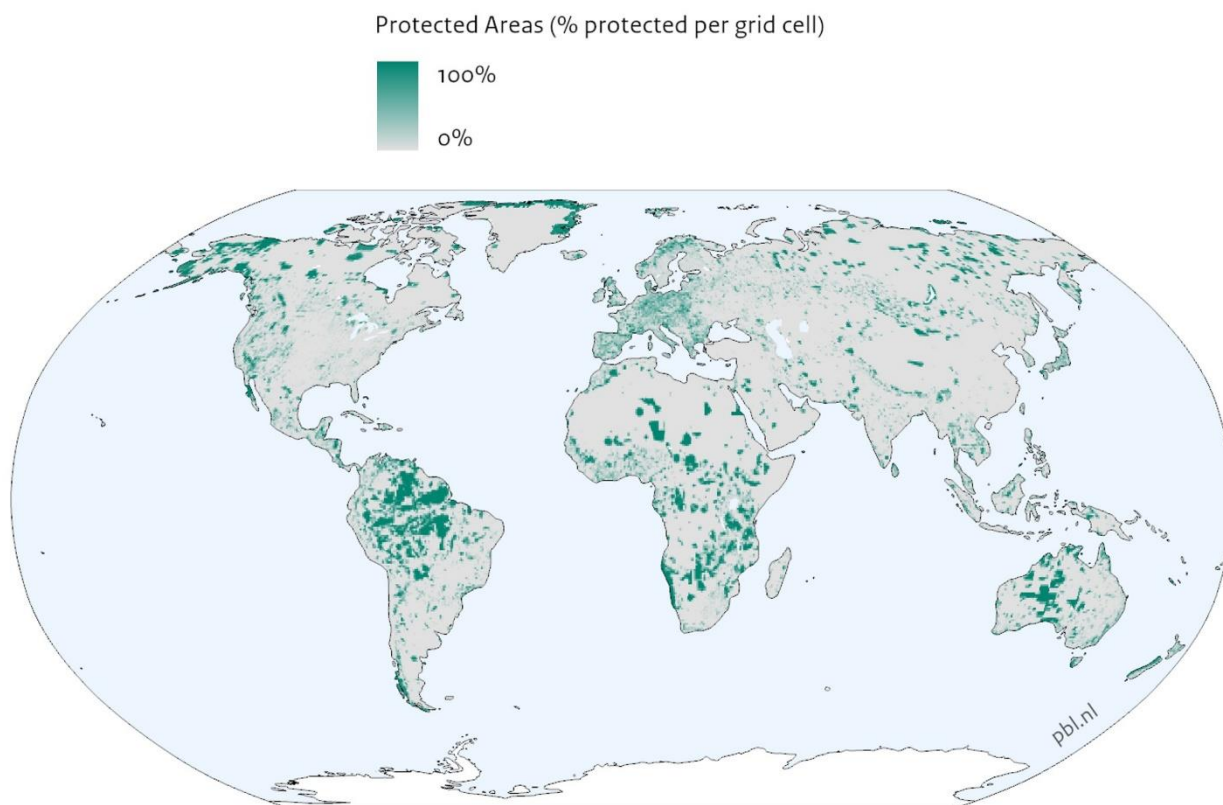
The energy policies are specified by sector. In the electricity sector, policies implemented explicitly include capacity targets for power technologies, renewable energy supply targets as a percentage of the total electricity production, electricity capacity caps, coal phase out policies, and efficiency goals on existing and new power plants. Policies in the transport sector include fuel efficiency car standards, targets for the share of biofuels and electric vehicles, fuel taxes and subsidies. Regulations on CH₄ fugitive emissions and F-gases are applied. In the building sector, energy efficiency is improved via imposing a premium factor on building insulation levels, providing subsidies for insulation of buildings, imposing appliance standards, and regulations for residential PVs and/or heat pumps uptake.

Current policies are implemented until 2030, after which they are continued at that level. The year 2030 was chosen since that is the target year for almost the whole policy ensemble implemented in the IMAGE model. Post 2030 it is assumed that policies remain constant, with sectoral policy targets maintained at the current policy level where applicable, using the following methods: All (sectoral) carbon prices, fuel prices, subsidies, premiums on power production etc. are kept at the same level until the end of the century. Policies that have a certain target level for a certain year, i.e. renewable capacity targets for power supply technologies, are treated as the minimum threshold in the model. Thus, if in the post-2030 period the endogenous model solution leads to an outcome that is more ambitious than the current policies, the model adopts the improved outcome.

Policies related to combatting pollution link to three elements in this report: air pollutants, plastic leakage, and nutrient pollution. First, policies related to reducing outdoor air pollution are implicitly represented through improvements in emission factors. The underlying assumption is improvements in pollutant end-of-pipe control, growing more ambitious up to 2100: emission factors assume efficient implementation of current environmental legislation (CLE) and thus describe a scenario of pollution control where countries implement all planned legislation until 2030 with adequate institutional support. The CLE emission factors are “fleet average” values that are the aggregate emission factor of all ages of equipment operating in the given year (Rao et al., 2017^[87]). The higher- and middle-income regions implement CLE in 2030, reaching 2030 West Europe emission factors by 2100; the lower-income region implements Western Europe factors increased by 10% in 2030, reaching 2030 West Europe emission factors by 2100). Second, policies related to plastic leakage to the environment are represented through improvements in waste management infrastructure, leading to less waste, as well as explicit bans on some microplastics use. Third, policies related to fertiliser use are implicitly represented through improvements in nitrogen and phosphorus use efficiencies.

Policies to protect biodiversity in the baseline take the form of protected areas. The baseline projections include the assumption that current protected areas are stable and effectively protected until 2050, represented on a map in Annex Figure 2.A.10. Terrestrial protected areas in IMAGE and GLOBIO are based on the World Database on Protected Areas (UNEP-WCMC, 2020^[80]). Agricultural expansion cannot occur in any type of protected area (Van der Esch et al., 2022^[88]), but already existing agricultural land inside protected areas can remain. These protected areas represent 17% of the global land area (Kok et al., 2023^[89]), while pressure on land increases at the expense of (unprotected) natural areas in the baseline scenario.

Annex Figure 2.A.10. Protected areas per category



Source: Environmental Outlook modelling toolbox.

Other policies

The macro-economic projections include a number of policies other than environmental policies, directed towards several domains including economic, labour, education, monetary, trade. These trends, which policies underlie, are used to project the drivers of growth to produce long run macro-economic projections.

The demographic projections include the policies geared towards population and education from the UN database (UN, 2022^[30]). The labour policies are implicitly taken onboard from (ILO, 2022^[82])'s active population prospects and OECD Labour Force Statistics and Projections (2022).

The economic projections include all the policies described in the short- and medium-term forecasts (from OECD Economic Outlook (OECD, 2023^[83]), the World Economic Outlook database (IMF, 2023^[84]), and World Bank (2023^[85])). These sources reflect the forecast of economic growth to 2028 as of late 2023. The projections further build on the long-term macroeconomic projections provided in (OECD, 2023^[83]).

Annex 2.B. Decomposing the evolution of the various drivers

Decomposing the key factors of environmental pressures behind climate change, biodiversity loss and pollution is a complex endeavour, but a vital one to understand the underlying dynamics at play. The previous sections examined the various drivers in the form of the scale, composition and efficiency effects and provided sectoral perspectives. This Annex brings together the underlying socioeconomic trends and specific drivers of the triple planetary crisis to identify how specific indicators of environmental pressures are affected by the various aspects.

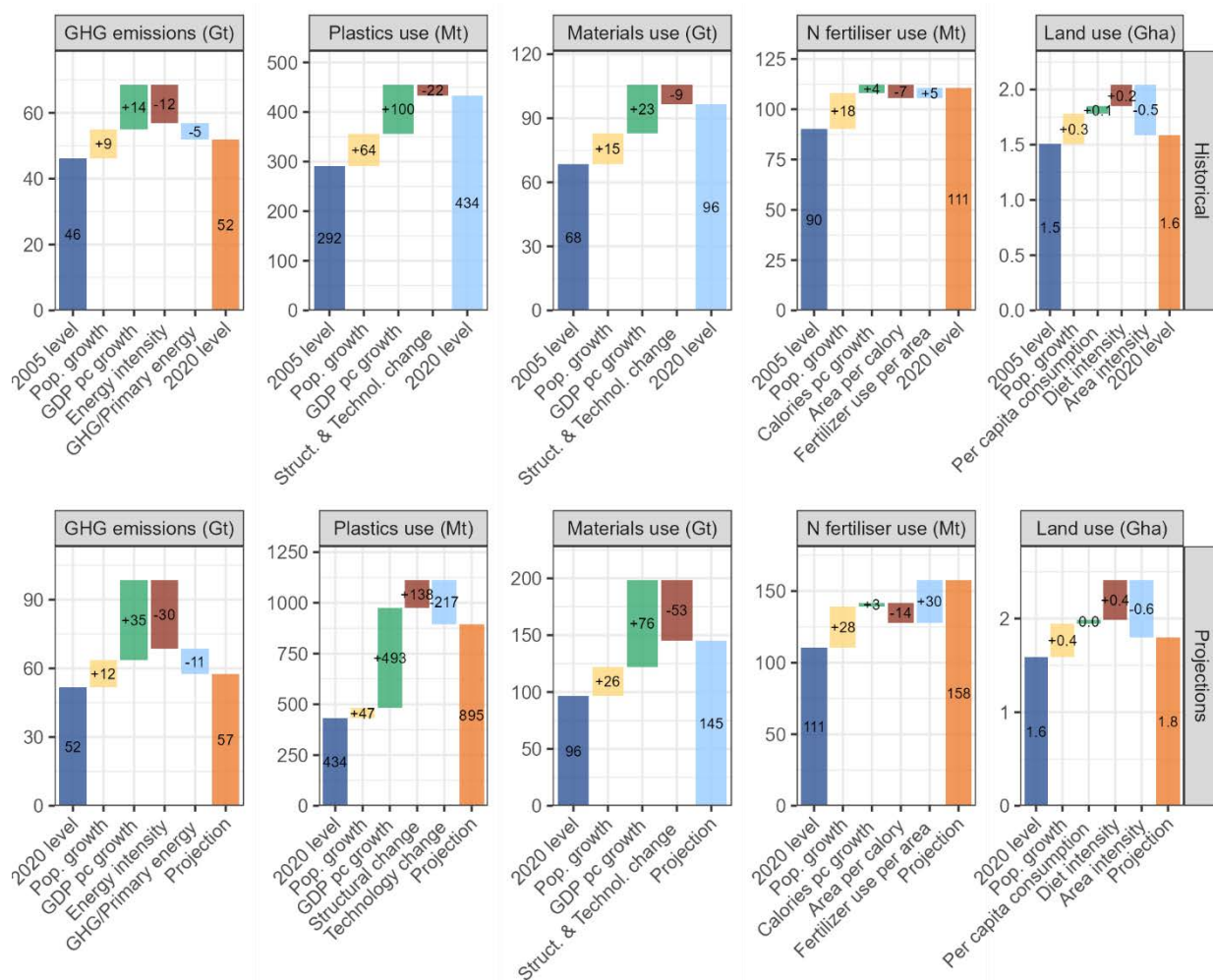
Decomposition of drivers

The scale of environmental pressures has been growing and is projected to continue growing. In almost all cases, this is (and has been) only partially compensated by composition and efficiency effects, with the former having an ambiguous effect depending on the specific changes in economic structures and geography of production, but especially the latter alleviating environmental pressures. These trends for the drivers of environmental pressures are consistent with most of the literature (UNEP, 2024^[68]). Annex Figure 2.B.1 presents decompositions of the major environmental pressures discussed in this chapter, using the basic decomposition into scale, composition and efficiency effects as discussed throughout the chapter. This decomposition is challenging for biodiversity loss, as climate change and pollution are among the key drivers of biodiversity loss (see also Chapter 3). For GHG emissions, plastics, and materials use, a similar story emerges: population and GDP per capita growth (the scale factors) increase the pressures, while structural change (the composition factor) and technology change (the efficiency factor) alleviate environmental pressures both in 2020 and in 2050. The overall impact of structural change for plastics between 2020 and 2050 is positive.¹⁷ The contribution of structural change to plastics use growth reflects the evolution of growth projections, the pervasiveness of plastics in sectors that continue to grow, in particular industrial sectors and demand for packaging. In the case of GHG emissions, structural change and technology change are measured by primary energy over GDP (the amount of energy to produce one dollar of value added) and the ratio of GHG to primary energy (the amount of emissions for each GWh of energy used).

The drivers of land and fertiliser use show different dynamics, where specific drivers take precedence. For example, for fertilisers, it is more insightful to take land use as the basic unit rather than agricultural production. Population growth remains a positive driver across all decompositions shown in the figure. The largest driver of both fertiliser use and land use depicts (in opposite directions) the current trend of intensification of agriculture, where the land-saving efficiency is increased through an increase in fertiliser. However, this dynamic does not constitute a free arbitration as the expansion of land is constrained by its availability. Finally, for land use, the largest projected driver of land use expansion corresponds to diet intensity between 2020 and 2050, revealing the efficiency of the food transformation industry as well as the evolution of diets towards more meat.

Annex Figure 2.B.1. Decomposing the evolution in drivers

Contribution of the various factors (in the unit of the indicator) to the 2005-2020 (upper panel) and 2020-2050 (lower panel) evolution of indicators



Note: Scales differ by panel. The term pc stands for per capita.

Source: Environmental Outlook modelling toolbox.

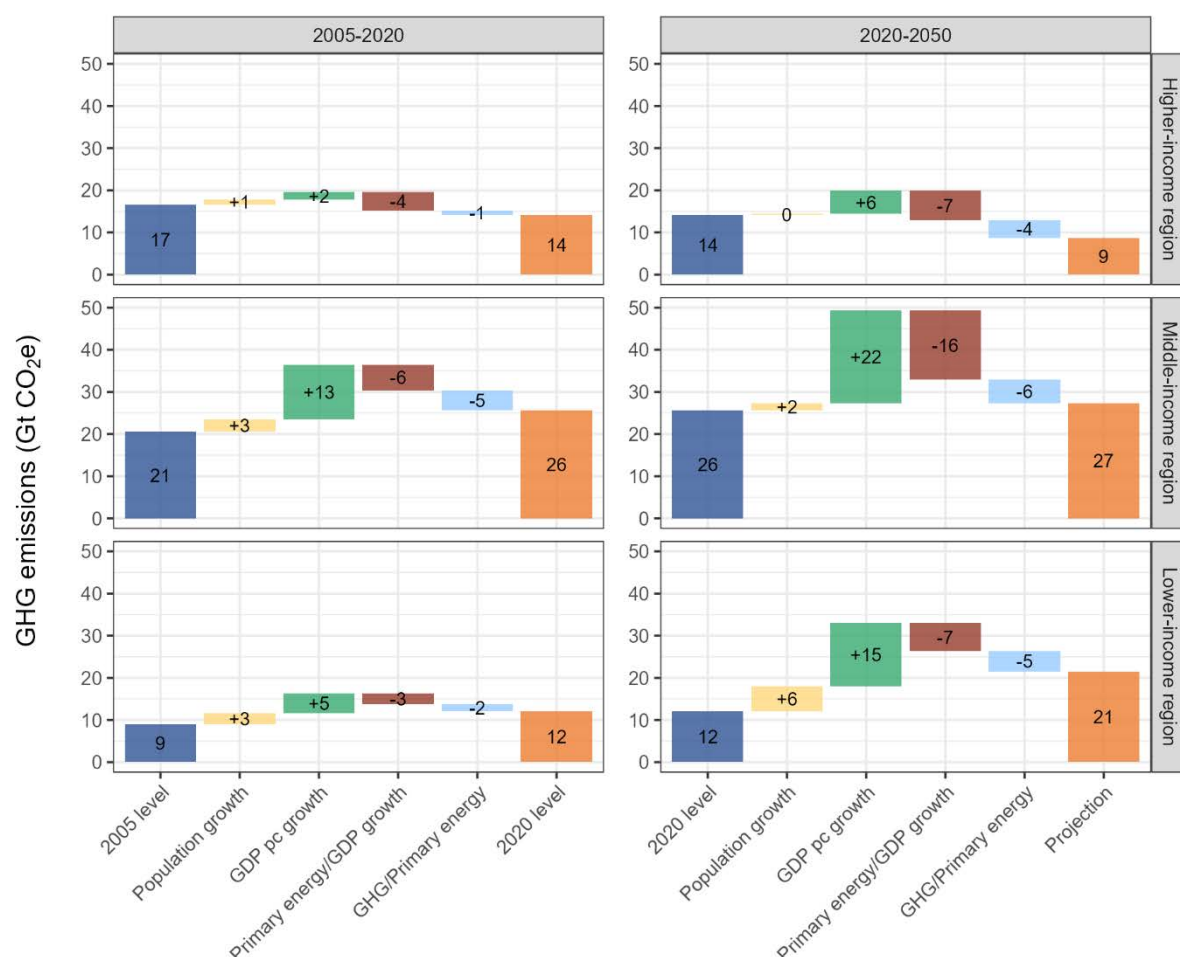
StatLink  <https://stat.link/865q17>

The global story hides significant regional disparities as illustrated in Annex Figure 2.B.2 for GHG emissions. While scale (population growth) and income effects (GDP per capita growth) increase GHG emissions, composition (Primary energy/GDP growth) and technology effects (GHG/Primary Energy) reduce GHG emissions in all regions, although regional differences in the relative magnitude of the drivers are large. For instance, higher-income regions have negligible increases in GHG emissions from population growth. In contrast, population growth in lower-income regions is high, putting upward pressure on the drivers of environmental impacts and therefore GHG emissions. Whilst the population of middle-income regions also grows, their main increase in environmental impacts is driven by economic growth. Economic growth is also a main driver of environmental impacts in lower-income regions, although their growth effect is lower than in middle-income regions. GDP per capita growth drives emissions up in higher-income countries but to a lesser degree than other regions as the economy and consumption turns to more services. Structural change (primary energy to GDP ratio) and technological change (GHG to primary energy ratio) both slow emission growth in all regions. The wealthier regions show stronger decoupling

through structural change, increasingly specialising in services, while the less wealthy regions show a larger influence of technological change (illustrating the switch from cheap carbon-intensive energy carriers used for fast economic growth towards a more sustainable energy system, which is already much more advanced in wealthier economies).

Annex Figure 2.B.2. Regional decomposition of the drivers of GHG emissions

Contribution of the various factors (in Gt CO₂e)



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/5a23ic>

This decomposition is useful to paint broad strokes but has limitations. For instance, a caveat of the analysis for GHG emissions is that this decomposition mostly shows the influence of energy, when other sector-specific emissions (i.e. from agriculture and industrial processes) also contribute to total emissions, whose drivers do not appear in the current graph. The more diverse the system, the harder it becomes to show synthetic indicators.

Decoupling

Overall, the comparisons of GDP growth and drivers of environmental pressures paint a stark picture of the challenge to overcome: in most regions and for most indicators, the environmental pressures continue to rise in the coming decades. This should however be seen in a context of continued economic growth. Most regional dynamics follow a relative decoupling, i.e. environmental degradation continues at a slower pace than that of economic growth.¹⁸ This implies that under current policies the pressures on the environment continue to increase, even if the pressure per unit of economic activity declines over time. Consequently, the risks of crossing important tipping points also continue to increase, even if the environmental degradation trend is lower than that of economic growth.

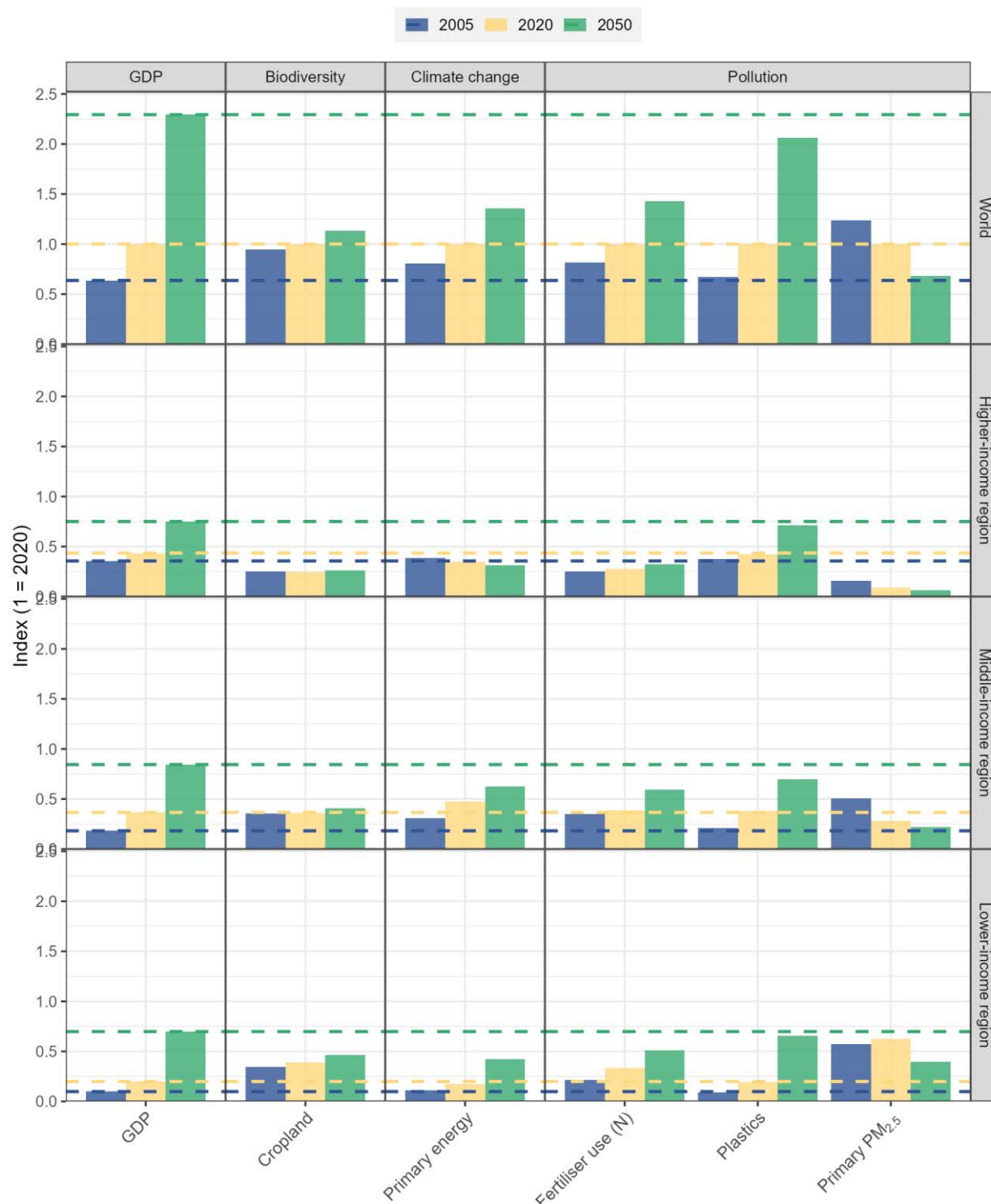
Most drivers of environmental pressures are projected to reach a relative decoupling, with primary PM_{2.5} emissions projected to show absolute decoupling (a decrease from 2020 to 2050). The first line of Annex Figure 2.B.2 shows the evolution of the indexes of the main drivers of climate change, biodiversity loss and pollution (with a global value of 1 in 2020). The indicators related to biodiversity loss, climate change, and plastic and nutrient pollution show an increase by 2050, at various degrees, but lower than that of GDP. This implies a relative decoupling. However, the degree of this relative decoupling varies by indicator: land use growth is small (13%), being very constrained, primary energy grows by 36%, nitrogen (N) fertiliser use grows by 43%, while plastic pollution more than doubles (+106%), almost on par with GDP. In contrast, the index for primary PM_{2.5} shows an absolute decrease globally.

This result overall holds over the 3 aggregate regions presented in this report. The second to fourth lines of Annex Figure 2.B.2 shows the evolution of the indexes of these main drivers (the initial value in 2020 representing the share in the global driver, the lines comparing to GDP). However, primary energy shows an absolute decoupling in the higher-income region. As at the global level, PM_{2.5} decrease occurs in all regions.

The largest increases for these drivers of environmental pressures are shown for the lower-income region. In that region, cropland increases by 18%. Plastics use more than triples, while primary energy more than doubles and nitrogen fertiliser increases by 52%. The only decrease occurs for PM_{2.5} (-36%).

Annex Figure 2.B.3. Projections of relative decoupling in the drivers of environmental pressures

Index 1 for the global value in 2020 (for each indicator)



Note: Initial value for other regions represents the share in the global value, growth is by region compared to GDP growth (compared to line).
Source: Environmental Outlook modelling toolbox.

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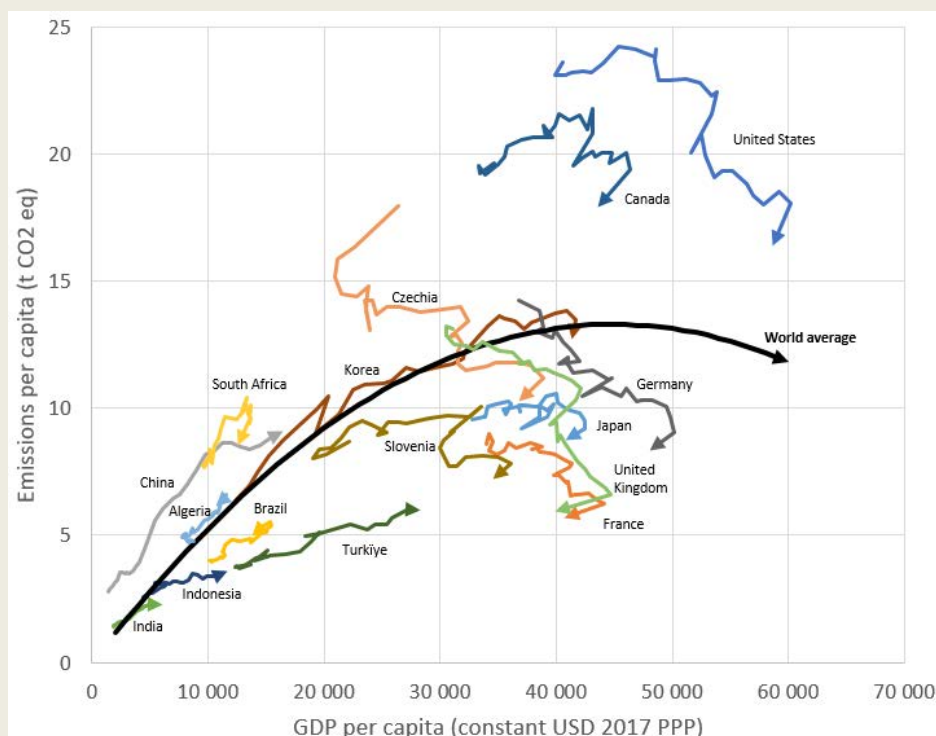
Annex Box 2.B.1. Environmental Kuznets Curve – the example of GHG emissions

The main implications of economic growth, at least since the industrial revolution, have been growing demand for fossil fuels and other resources, significant land use changes and larger generation of waste. However, in the long run, higher GDP per capita could lead to larger willingness to pay to reduce environmental impacts as basic needs are being fulfilled and poverty reduced. The relationship between environmental outcomes and income has been studied for decades. Notably, it was empirically investigated by Grossman and Krueger (1991^[3]) and described later as environmental Kuznets curves (EKC) by Panayotou (1993^[90]). The traditional model of EKC is an inverted U-shaped curve where environmental impacts tend to grow as income levels rise, reaching a peak, and subsequently declining after exceeding a certain income threshold.

GHG emissions per capita and GDP per capita follows an inverted U-shaped curve as illustrated by Annex Figure 2.B.2 based on country level data on the period 1990-2020. This result for GHG is consistent with the majority of previous work (Shahbaz and Sinha, 2019^[91]; Wang, Wang and Jiang, 2024^[92]). Each country follows its own path and has a specific initial position but on average, GHG emissions per capita rapidly surge then decelerate then stop increasing at USD 45 000 2017 PPP per capita, after which they decrease.

The shape of the EKC depends very much on the environmental impacts and pollutants analysed as illustrated by Grossman and Krueger (1995^[93]) for urban air pollution, oxygen regime, faecal contamination, heavy metal contamination and nutrients in rivers using data at the city-country level. Another example of how EKC are pollutant dependent is plastic leakage. While macroplastic leakage increases with GDP per capita and then rapidly decreases after USD 10 000 per capita, microplastic leakage continues to grow with GDP per capita with decreasing marginal increases (OECD, 2022^[12]). For biodiversity conservation, the evidence of an inverted U-shape relation with income is mixed and inconclusive (Dietz and Adger, 2003^[94]; McPherson and Nieswiadomy, 2005^[95]; Mills and Waite, 2009^[96]).

Annex Figure 2.B.4. GHG emissions per capita and GDP per capita, 1990-2020



Note: Total GHG emissions in Gt of CO₂ equivalent are composed of CO₂ totals excluding short-cycle biomass burning (such as agricultural waste burning and savanna burning) but including other biomass burning (such as wildfires, post-burn decay, peat fires and decay of drained peatlands), all anthropogenic CH₄ sources, N₂O sources and F-gases (HFCs, PFCs and SF₆). The world average curve is estimated using a quadratic function and using data from all countries via an OLS regression including country and year fixed-effects. The right shift in income observed for various countries in 2020 is due to the covid-19 crisis.

Source: Authors calculation based on data from the World Development Indicators 2022 (<https://data.worldbank.org/products/wdi>) and from the ENV-Growth model.

Environmental Kuznets curves are seen more as tools to visualise the joint evolution of environmental outcomes and income. However their main limitation is that they do not provide clear information on the causal effect of income as stressed by Stern (2004^[97]; 2017^[98]) nor on interlinked drivers behind this evolution, which is highly important for analysing the triple planetary crisis. For example, the reduction in domestic environmental impacts can be either due to the adoption of stricter environmental policies, cleaner technologies or the outsourcing abroad of economic activities that have high environmental impacts, all correlated with higher income.

Annex 2.C. Increasing drivers affect all aspects of the triple planetary crisis simultaneously: Underlying data

Figure 2.12 and Figure 2.13 are based on several indicators reporting the global level and the regional intensities of selected drivers of environmental changes. Annex Table 2.C.1 summarises the units of these indicators, and Annex Table 2.C.2 provides the values of these indicators.

Annex Table 2.C.1. Units of the indicators summarising the evolution of the drivers

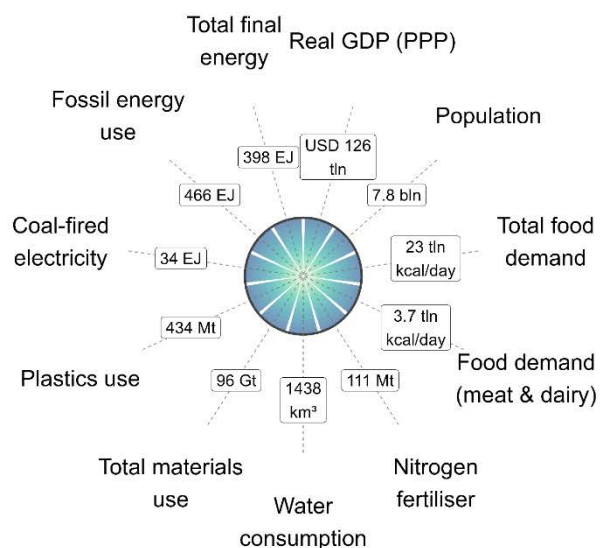
Level		Intensity	
Indicator	Unit	Indicator	Unit
GDP	USD 2017 trillion (PPP)	GDP per capita	USD 2017 per person
Population	Million people	Population intensity	Thousands of people per hectare
Food demand	Trillion kcal per day	Food availability	kcal per day and per person
Nitrogen fertiliser use	Million tonnes of N	Nitrogen fertiliser per harvested area	Tonnes per ha
Water consumption	km ³	Water consumption per capita	m ³ per person
Materials use	Billion tonnes	Materials use per capita	Tonnes per person
Plastics use	Million tonnes	Plastics use per capita	kg per person
Secondary energy (coal)	EJ	Secondary energy per capita	GJ per person
Primary energy (fossil)	EJ	Primary energy per capita	GJ per person
Final energy (all sources)	EJ	Final energy per capita	GJ per person

Note: Indicators on the level of the pressures determine the length of the bars, while indicators on the regional intensity determine the colour shade of the bars in regional plots.

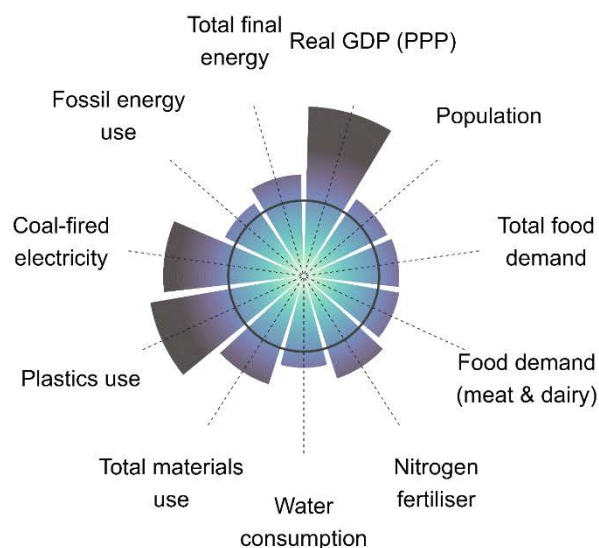
Annex Figure 2.C.1. Evolution of drivers and socio-economic trends behind environmental pressures compared to 2020 values

Global evolution for selected drivers

Panel A. 2020



Panel B. 2020-2050



Note: The length of the bars represents evolution over time indexed at 100% in 2020. For instance, for Panel A, the circle indicates the 2020 level indexed to 100%, against which to compare the evolution in the bar in Panel B. For example, plastics use is projected to increase by 106% over the 2020-2050 period at the global level. Annex 2.C provides details on the values and the units of reported indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/07vetu>

Annex Table 2.C.2. Detailed values of the indicators summarising the evolution of pressures

Indicator	Value in 2020	Value in 2050	Relative change in 2050	Intensity in 2050	Indicator	Value in 2020	Value in 2050	Relative change in 2050	Intensity in 2050
North America					Japan, Korea & Oceania				
Real GDP (PPP)	21.7	37.0	70.3	164082	Real GDP (PPP)	8.7	13.3	53.3	122664
Population	374	421	12.7	0.23	Population	222	208	-6.1	0.24
Total food demand	1.4	1.6	8.5	3700	Total food demand	0.7	0.63	-9.1	2895
Food demand (meat & dairy)	0.4	0.46	16.8	1098	Food demand (meat & dairy)	0.12	0.12	2.6	567
Nitrogen fertiliser	15.0	21.4	42.6	0.15	Nitrogen fertiliser	2.4	2.7	9.2	0.07
Water consumption	158	158	0.4	376	Water consumption	32.5	32.6	0.3	149
Total materials use	9.9	13.7	38.3	32.4	Total materials use	5.1	6.8	33.6	32.4
Plastics use	88.1	156	77.6	371	Plastics use	20.0	29.7	48.5	136
Coal-fired electricity	3.2	0.0	-100	0	Coal-fired electricity	2.4	0.91	-62.6	4.2
Fossil energy use	78.9	56.7	-28.0	135	Fossil energy use	30.1	15.2	-49.6	69.2
Total final energy	70.9	61.3	-13.6	145	Total final energy	23.5	21.4	-8.8	97.9
Europe					East Asia				
Real GDP (PPP)	25.0	43.5	74.1	70196	Real GDP (PPP)	23.4	52.9	126	40112
Population	625	620	-0.8	1.1	Population	1432	1320	-7.9	1.2
Total food demand	2.2	2.2	-2.2	3499	Total food demand	4.6	4.4	-4.2	3296
Food demand (meat & dairy)	0.62	0.63	2.4	1010	Food demand (meat & dairy)	0.78	0.8	3.4	596
Nitrogen fertiliser	13.3	11.8	-11.0	0.11	Nitrogen fertiliser	22.4	34.4	53.6	0.19
Water consumption	130	142	9.7	228	Water consumption	214	240	12.2	178
Total materials use	8.8	12.6	42.9	20.4	Total materials use	32.4	35.9	10.8	27.2
Plastics use	75.9	123	61.5	198	Plastics use	96.8	164	69.1	121
Coal-fired electricity	2.0	1.1	-44.5	1.7	Coal-fired electricity	18.3	24.1	32.2	17.9
Fossil energy use	53.2	26.5	-50.2	42.3	Fossil energy use	135	123	-8.8	91.4
Total final energy	55.8	49.9	-10.5	79.9	Total final energy	93.3	118	26.4	87.5
Middle East & North Africa					Central & South America				
Real GDP (PPP)	7.3	19.0	161	28109	Real GDP (PPP)	9.5	21.6	128	28829
Population	479	674	40.9	0.62	Population	651	748	14.9	0.37

Total food demand	1.4	2.1	51.0	3162	Total food demand	2.0	2.5	23.4	3290
Food demand (meat & dairy)	0.16	0.28	78.0	412	Food demand (meat & dairy)	0.44	0.58	30.4	772
Nitrogen fertiliser	3.1	5.5	78.1	0.09	Nitrogen fertiliser	11.3	18.5	64.3	0.09
Water consumption	166	201	21.1	298	Water consumption	123	164	33.6	220
Total materials use	5.7	10.1	76.9	14.9	Total materials use	10.0	16.0	60.2	21.3
Plastics use	19.3	44.9	132	66.6	Plastics use	32.0	66.5	108	88.8
Coal-fired electricity	0.17	0.0	-99.0	0.0	Coal-fired electricity	0.29	0.36	22.1	0.48
Fossil energy use	40.7	72.4	78.0	107	Fossil energy use	22.7	28.7	26.4	38.3
Total final energy	28.8	59.7	107	88.4	Total final energy	23.5	37.9	61.3	50.6
Eurasia					South Asia				
Real GDP (PPP)	5.6	10.3	83.2	34040	Real GDP (PPP)	20.7	69.5	235	43074
Population	300	303	1.1	0.14	Population	2606	3220	23.6	3.2
Total food demand	0.95	0.98	3.6	3294	Total food demand	6.5	8.6	32.0	2706
Food demand (meat & dairy)	0.23	0.26	9.4	859	Food demand (meat & dairy)	0.78	1.2	53.8	377
Nitrogen fertiliser	5.9	7.2	20.9	0.05	Nitrogen fertiliser	34.0	48.2	41.8	0.12
Water consumption	116	123	6.6	413	Water consumption	441	599	35.8	188
Total materials use	4.2	5.5	32.6	18.2	Total materials use	15.4	34.0	120	10.5
Plastics use	17.1	27.7	61.7	91.2	Plastics use	66.1	215	226	67.6
Coal-fired electricity	1.1	1.4	33.3	4.8	Coal-fired electricity	5.9	33.2	463	10.4
Fossil energy use	39.7	38.0	-4.2	127	Fossil energy use	55.9	150	169	47.2
Total final energy	29.8	31.2	4.7	105	Total final energy	52.7	121	129	38.0
Sub-Saharan Africa					World				
Real GDP (PPP)	4.2	15.6	267	7318	Real GDP (PPP)	126	283	124	29298
Population	1121	2130	90.0	0.89	Population	7810	9645	23.5	0.74
Total food demand	2.7	5.5	109	2522	Total food demand	22.5	28.5	26.7	2940
Food demand (meat & dairy)	0.17	0.39	132	179	Food demand (meat & dairy)	3.7	4.7	28.1	487
Nitrogen fertiliser	3.2	8.1	156	0.02	Nitrogen fertiliser	111	158	42.7	0.1
Water consumption	58.4	93.3	59.8	42.5	Water consumption	1438	1754	22.0	181
Total materials use	5.1	10.8	112	5.1	Total materials use	96.5	145	50.5	15.1

Plastics use	18.3	68.4	274	32.1	Plastics use	434	895	106	92.8
Coal-fired electricity	0.79	2.4	204	1.1	Coal-fired electricity	34.1	63.5	86.3	6.5
Fossil energy use	9.9	30.3	207	13.8	Fossil energy use	466	541	16.1	55.7
Total final energy	19.4	33.5	72.7	15.3	Total final energy	398	534	34.2	54.9

Note: Values for 2020 and intensities for 2050 are reported in the units listed in Annex Table 2.C.1, while the relative change in 2050 compared to 2020 is presented as a percentage. For example, in the Central & South America region, the GDP in 2020 was USD 9.5 trillion (2017 USD); this is projected to increase by 128% by 2050, resulting in an intensity indicator measured as GDP per capita of USD 28 829 (2017 USD) per person in 2050. In Figure 2.12, the length of the bars represents the relative change between 2020 and 2050, while in Figure 2.13, the colour shading of the bars reflects the intensity in 2050.

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Notes

¹ Socioeconomic trends can also affect environmental pressures through indirect effects. For instance, landscape fragmentation and climate change are major drivers of biodiversity loss. Clarifying these indirect relations is fundamental in mapping out the synergies and trade-offs between climate change, biodiversity loss, and pollution. However, as they involve interactions between environmental states rather than drivers, they are addressed in the next chapters.

² Figure 1.3 in Chapter 1 provides the fuller picture, including the feedback effects of environmental degradation.

³ The challenge for agricultural policymaking is to address multiple challenges simultaneously: supporting the food system and ending hunger, while addressing several global issues such as environmental degradation and distortions in international markets (OECD, 2022^[5]).

⁴ Agricultural systems with lower input use often have better overall environmental performance per hectare (e.g. lower pollution to water bodies). However, these systems typically have lower yields as well. This implies that all else equal, more land would be needed to produce the same amount of output.

⁵ These numbers differ from e.g. those by FAO (Ludemann et al., 2024^[99]) that focus on nutrient surpluses for croplands, not accounting for grassland surpluses.

⁶ These aggregate results show overall trends, but extract from the variability at the country level and even further when looking at spatial results. Parts of Africa in particular can show negative phosphorus surplus, in line with the current scientific findings (Ludemann et al., 2024^[99]). While all numbers are subject to uncertainty, the contribution of grasslands to phosphorus surpluses is highly uncertain because the uptake of grass is not very well known.

⁷ Such practices, and other land use changes, can also have mixed effects – and thus trade-offs – on different ecosystem services; for instance between carbon storage and plant diversity.

⁸ This selection of sectors does not imply that the environmental impact of other economic activity is negligible. Rather, they are meant as illustrative for the link between economic activity and the pressures on the environment, highlighting a number of salient issues. When considering substitution to alternatives to the highlighted commodities, a full LCA is required to ensure that the overall outcome improves; in some cases, the environmental profile of substitutes is better, but in other cases it may be worse.

⁹ While chemical intensity is an imperfect measure (being based on monetary values, a small intensity can simply reflect relatively high output unitary prices), it provides useful comparative insights when interpreted alongside other indicators.

¹⁰ While biomass and fossil fuels are partly covered in the section on agriculture and energy, material resources include all materials, including these categories. In this section, these categories have a broader scope: fossil fuels include all resources used (and not just energy), including chemicals and plastics. Similarly, biomass include textiles, grazed biomass, fishing in addition to conventional agricultural commodities. This definition of material resources is in line with the literature on the topic (OECD, 2019^[15]; UNEP, 2024^[68]).

¹¹ See <https://www.oecd.org/en/data/indicators/water-withdrawals.html> for more information.

¹² A typical example is water withdrawal for cooling of nuclear power plants.

¹³ As the visual depiction of growth factors is capped at 140%, Figure 2.13 does not fully represent the scale of the growth factors in lower-income regions.

¹⁴ Increases in the retirement age, as implemented recently in some countries, can alleviate this, but in most cases life expectancy continues to outpace increases in retirement age. Furthermore, longer schooling means young people enter the labour market at a later age.

¹⁵ In a long-term balanced growth path, capital accumulation would adjust to match growth in labour and technology. This only happens when countries are at the technology frontier and when capital supply is not limited. The fact that the contribution of technology growth is higher than that of capital even in higher-income countries shows that for the coming decades, all regions are still in transition towards such a (very) long-term balanced growth path.

¹⁶ Sustainable economic growth achieves this by not increasing the associated environmental inputs, nor the environmental pressures associated with production. This subsection does not aim to calculate an environmentally-adjusted productivity growth but rather presents the economic drivers such that later subsections can illuminate the associated environmental aspects.

¹⁷ This shows a slight change in trends since the Global Plastics Outlook (OECD, 2022^[54]) which highlights that plastics are used in a wide variety of economic sectors with differing growth patterns.

¹⁸ Sometimes decoupling can be described in the form of Environmental Kuznets Curve, illustrated in Annex Box 2.B.1 based on GHG emissions.

3

The current and future state of the triple planetary crisis

This chapter provides a detailed overview of the present and future trajectories of indicators for each dimension of the triple planetary crisis. A select set of key indicators is chosen to create a dashboard that allows for a quick, clear overview of the state of the environment at both global and regional levels. This dashboard also highlights how the different dimensions of the crisis are interconnected and mutually reinforcing. Additionally, the chapter addresses the challenges of assessing the economic impacts of environmental degradation, offering some estimates based on existing literature.

3.1. Introduction

This chapter links socioeconomic trends and specific drivers (Chapter 2) to the evolution of environmental pressures and subsequently changes in the state of climate change, biodiversity loss and pollution to 2050. Section 3.2 emphasises how pressures simultaneously contribute to dimensions of the triple planetary crisis, thus highlighting trade-offs and synergies. The following Sections 3.3 through 3.5 examine the current and projected future state of each dimension individually – climate change, biodiversity loss, and pollution – before integrating them in a comprehensive assessment in Section 3.6. Where available, projections of selected impacts and cross-cutting topics such as health, water, and adaptation are presented to provide further insight into the anticipated consequences of ongoing environmental pressures.

3.2. Evolution of environmental pressures

The socioeconomic trends and specific drivers of climate change, biodiversity loss and pollution, as discussed in Chapter 2, are associated with multiple environmental pressures as part of the driver-pressure-state-impact-response methodological framework outlined in Chapter 1. For instance, providing food for a growing population drives an increase in agricultural production, which puts pressure on the environment in terms of emissions, land use change, and nitrogen and phosphorus pollution. Adding to the complexity, one environmental pressure can affect more than one dimension of the triple planetary crisis. Methane (CH₄), for example, is a greenhouse gas (GHG), and at the same time is a precursor for ground-level ozone; CH₄ emissions thus connect climate change and air pollution.

Encompassing a broad range of indicators is therefore essential to understand the evolution of the environmental pressures behind climate change, biodiversity loss and pollution. This section aims to offer such a view, focusing on the evolution of these pressures between 2020 and 2050. It draws on carefully selected indicators that, while not being exhaustive, provide an informative snapshot, enabling a high-level overview of the evolution of key factors behind the crisis (see Annex 3.A) and especially their interactions.¹ Together, these indicators describe a wide set of pressures on air, land, water and soil that lead to environmental degradation. The set of indicators used in the modelling toolbox is presented in Table 3.1 (see Annex Table 3.A.1 for the associated units).

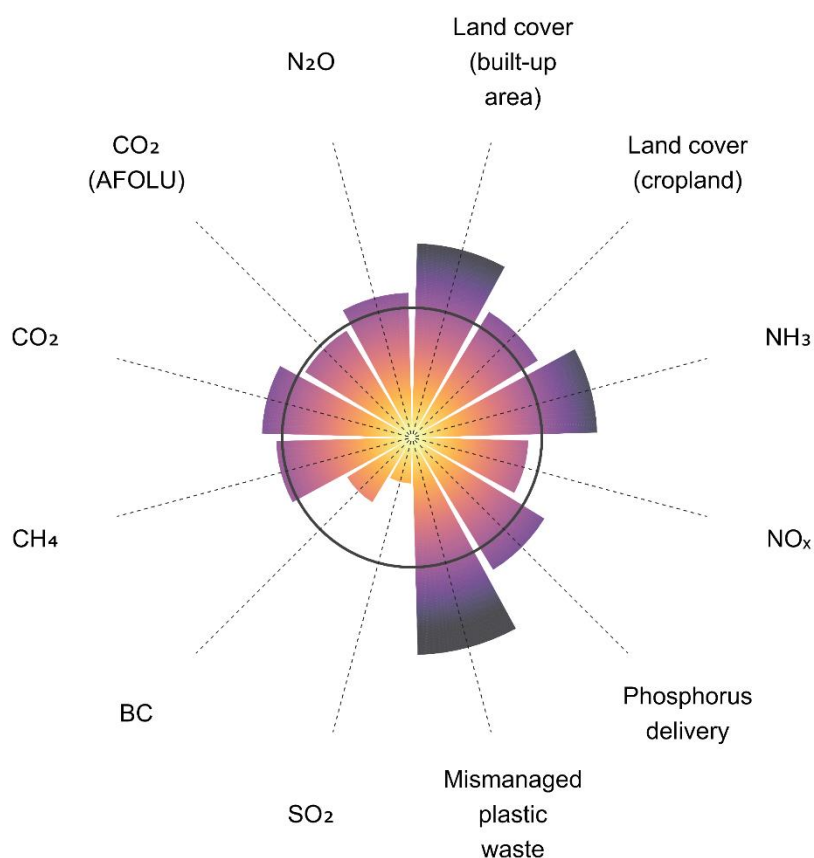
Table 3.1. Overview of the indicators used to describe environmental pressures

Environmental pressure	Detailed indicator
<i>Air</i>	
CO ₂ emissions	Carbon dioxide (CO ₂) emitted mainly from energy use, is a key greenhouse gas that causes climate change.
CO ₂ emissions: AFOLU	Emissions from AFOLU contribute to climate change and can be associated with pressure on biodiversity, e.g. from deforestation.
CH ₄ emissions	Methane (CH ₄) is a short-lived climate pollutant that contributes to ozone air pollution and to climate change.
N ₂ O emissions	Nitrous oxide (N ₂ O), emitted mainly by agricultural activities, is a greenhouse gas that causes climate change.
BC emissions	Black carbon (BC) is a short-lived climate pollutant that contributes to particulate matter (PM _{2.5}) air pollution and to climate change.
SO ₂ emissions	Sulphur dioxide (SO ₂) emissions contribute to PM _{2.5} air pollution and have a cooling effect on global temperature.
<i>Land</i>	
Land Cover: Built-up Area	Expansion of built-up areas puts pressure on habitats and terrestrial biodiversity.
Land cover: Cropland	Expansion of cropland on natural land puts pressure on habitats and terrestrial biodiversity.
<i>Water and soil</i>	
NH ₃ emissions	Ammonia (NH ₃) emissions contribute to PM _{2.5} air pollution as well as land and water pollution, with potential impacts on biodiversity.
NO _x emissions	Nitrogen oxides (NO _x) emissions contribute to PM _{2.5} and ozone air pollution, as well as to pollution and acidification of water bodies and soils through rainfall (acid rain), with potential impacts on biodiversity.
Phosphorus delivery	Phosphorus (P) delivery from agriculture to water can lead to eutrophication and aquatic biodiversity loss.
Mismanaged plastic waste	Mismanaged plastic waste risks leaking into the environment.

Combined, the selected indicators paint a mostly worsening picture at the global level. Under current policies, global environmental pressures are projected to rise between 2020 and 2050 across most dimensions, i.e. most bars extend beyond the circle that represents the 2020 value in Figure 3.1. This implies current policies are insufficient to safeguard human and planetary health. Pressures primarily related to air pollution (emissions of BC, SO₂ and NO_x) are the exception.

Figure 3.1. Evolution of selected environmental pressures

Global evolution of selected indicators of environmental pressures, 2020-2050



Note: The length of the bars represents the evolution from 2020 to 2050. The circle indicates the 2020 level. For instance, under current policies, NH₃ emissions increase by 43% globally over the 2020-2050 period, while NO_x emissions are expected to decrease by 10%. Annex 3.A provides detailed values and units for the reported indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/9bd78q>

Mismanaged plastic waste and land covered by built-up area exhibit the most significant projected increases over the 2020-2050 period, rising by 68% and 49%, respectively. The growth in mismanaged plastic waste is substantial, driven by a doubling of global plastics use by 2050 (see Chapter 2). Although modest improvements in waste management are projected under current policies, plastic leakage to the environment continues to grow. The expansion of built-up area, while still representing a relatively small proportion of total land, is also projected to be considerable. Urbanisation tends to contribute to deforestation (Hosonuma et al., 2012^[1]) and disrupts local ecosystems and wildlife in complex ways (see Box 2.3 in Chapter 2 for details). More broadly, land use change is one of the leading drivers of biodiversity loss and is projected to continue playing this role under current policies. Cropland area, in particular, is expected to increase globally by 13% by 2050, adding further pressure on pollution and biodiversity. Despite this expansion, current policies aimed at limiting deforestation and promoting re- and afforestation – driven by both climate change and biodiversity goals – are projected to drive a 4% reduction in CO₂ emissions from Agriculture, Forestry and Other Land Use (AFOLU) over the same period.

Global emissions of air pollutants BC and SO₂ are projected to decline significantly (by 42% and 64%, respectively), while NH₃ emissions are expected to rise sharply, increasing by 43% globally, not least due to increases in livestock. These contrasting trends reflect differences in underlying drivers and the uneven adoption of new technologies. BC and SO₂ are primarily associated with energy use, and their decline is largely due to the increasing uptake of renewables and improved (end-of-pipe) emission control technologies, related to current policies to reduce pollutant emissions. These advances also contribute to a global reduction in NO_x emissions (-10%). In contrast, NH₃ emissions are mainly linked to agricultural activities, particularly fertiliser use and livestock farming, and are not expected to benefit from advances in the energy system. Other agriculture-related indicators, including CH₄, N₂O and phosphorus delivery² also show projected increases, even if more moderate (5%, 11 and 20% respectively).

Meanwhile, global CO₂ emissions are projected to continue rising over the coming decades under current policies, despite a reduced contribution by AFOLU. Although technological improvements reduce emissions intensity at the sectoral level, they are insufficient to counterbalance the overall increase in fossil energy use (as projected in Chapter 2), unlike the more favourable trends seen for several air pollutant emissions.

Significant regional variations in environmental pressures are apparent (Figure 3.2). The global trend, as shown in Figure 3.1, is depicted by a black dot and serves as a reference point for comparison. To further aid interpretation, the figure also includes a colour scale indicating the regional intensity of each indicator in 2050, ranging from dark purple indicating for the highest intensity across the regions to yellow for the lowest.³ This dual representation allows for a nuanced comparison, capturing both the magnitude of regional change between 2020 and 2050 and the relative intensity of each indicator in 2050 compared to other regions. For instance, built-up land area is projected to more than double in Sub-Saharan Africa from 2020 to 2050, marking the largest increase among all regions (as shown by the bar extending well beyond the 2020 circle and the global average dot at 49%). However, built-up area per capita in 2050 remains among the lowest in the world, as indicated by the yellow shading, and is projected to be five times smaller than in Europe by that time.

Some trends are observed across regions. The increase of land covered by built-up area and NH_3 emissions increase in all nine regions, signalling widespread challenges in reversing these pressures. Other indicators closely linked to agriculture also show rising environmental pressure across most regions. Cropland area is projected to expand in all regions except Europe, while N_2O emissions and phosphorus delivery increases in six of the nine regions considered. Agriculture-related environmental pressures are projected to rise particularly in Sub-Saharan Africa, which records the highest relative increases in cropland area (+41%) and phosphorus delivery (+62%), and the second largest in CO_2 emissions from AFOLU (+40%). Nonetheless, the intensity of these indicators remains among the lowest compared to other regions. Central and South America stands out as the region with the largest increase in land dedicated to pastures (+9%, equivalent to 48 million hectares) and the most significant decrease in area dedicated to forests (-64 million hectares), corresponding to annual deforestation rates comparable to those observed in recent years (FAO, 2024^[21]). As a consequence, this region contributes to approximately half of global emissions of CO_2 from AFOLU in 2050. While indicators strongly linked to land use and agriculture are generally projected to incur rising pressures, some regions show signs of progress over time, albeit modest in certain cases. Europe and (to some extent) East Asia experience declining pressures in terms of phosphorus delivery and N_2O emissions. In addition, these two regions are projected to become net sinks of CO_2 emissions from AFOLU in 2050, having been net emitters in 2020.

The results further illustrate that global progress on air pollution is not uniformly reflected in all regions. Emissions of BC and SO_2 are projected to decrease in all regions. NO_x emissions also show decreasing trends in most regions, with Sub-Saharan Africa and South Asia being the two exceptions. These regional differences reflect the energy drivers discussed in Chapter 2, which highlight growing fossil energy use and continued coal-based electricity generation in both regions, driven at least partially by relatively low income levels in many countries in these two regions. CO_2 emissions are projected to decrease in Europe (-46% in 2050 relative to 2020), Japan, Korea and Oceania (-42%), North America (-33%) and East Asia (-18%, following a peak in 2030). They remain roughly stable in Eurasia over the period. In contrast, no peak in CO_2 emissions is observed in the other regions; South Asia and Sub-Saharan Africa, in particular, more than double their CO_2 emissions in 2050 with respect to 2020. The decrease in five of nine regions is not sufficient to offset increases in the remaining four regions. As a result, under current policies, global CO_2 emissions are projected to increase, placing the goal of net zero emissions by 2050 out of reach. In per capita terms, the lowest CO_2 emissions in 2050 are projected for Sub-Saharan Africa, Europe, and South Asia.

Figure 3.2. Regional evolution of selected environmental pressures

Regional evolution for selected indicators of environmental pressure, 2020-2050



Note: The length of the bars represents the evolution from 2020 to 2050. The circle indicates the 2020 level. The colour indicates the relative intensity of the considered indicator in each region (e.g. per capita CO₂ emissions) compared to the region with the highest intensity in 2050. Black dots represent evolution at the global level. Region-indicator pair bars extending beyond the dot, imply that the region experiences faster growth than the global average over the 2020-2050 period. Environmental pressure indicators are defined in Figure 3.1. For readability, bars related to CO₂ AFOLU have been truncated for East Asia and Europe. Annex 3.A provides detailed values and units for the indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/jxm47n>

3.3. Current and projected future state: Climate change

3.3.1. Climate-induced temperature changes

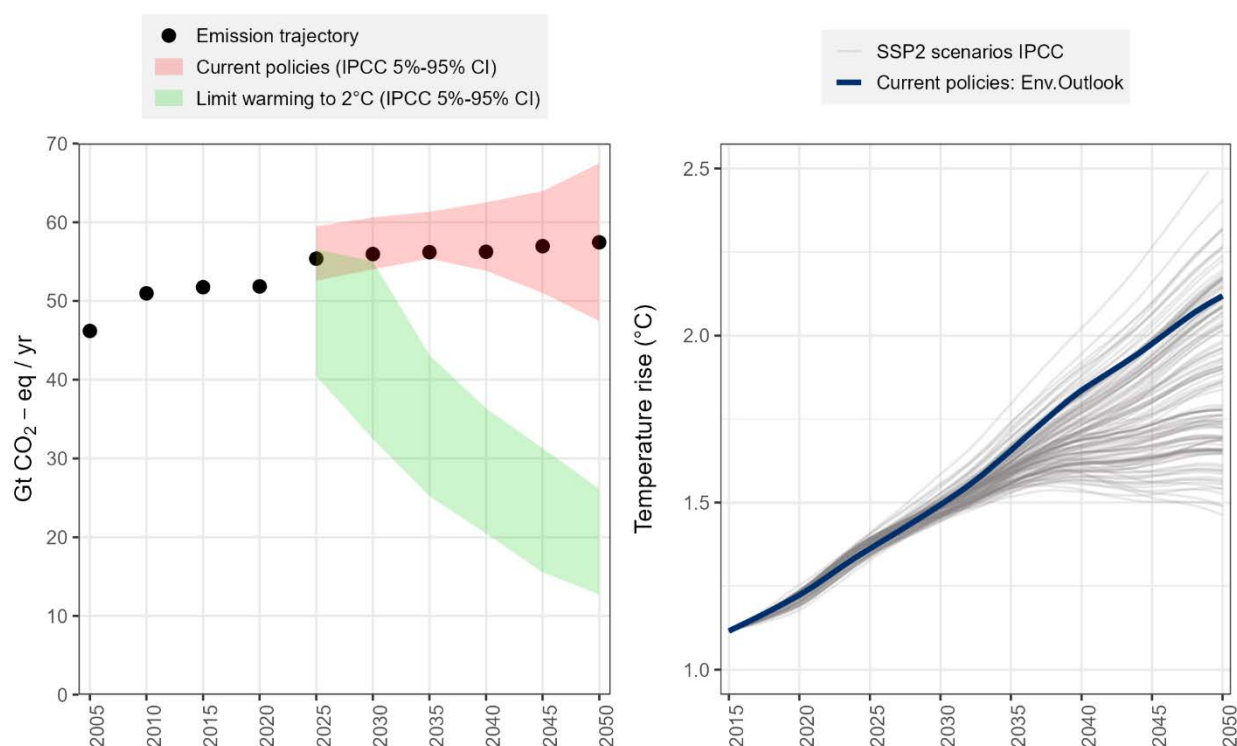
Global surface temperatures have been increasing rapidly since 1970, outpacing any other 50-year period in at least the last 2000 years (IPCC, 2023^[3]). While the warming effect of GHGs is partially offset by the cooling influence of aerosol emissions, the overall trend remains one of significant heating. In addition to global surface warming, (upper) oceans have also warmed since the 1970s. As a result of this warming in the climate system, global mean sea levels are rising at an accelerating rate. Hot extreme weather has become more frequent and more intense across most land regions since the 1950s, while cold extreme weather has become less frequent and less severe. Marine heatwaves have doubled since the 1980s. The observed frequency and intensity of heavy precipitation events have increased since the 1950s (Calvin et al., 2023^[4]).

Future GHG emissions trajectories are projected to lead to an increase in the global mean temperature of approximately +2.1°C by 2050, relative to pre-industrial levels (Figure 3.3, right panel). As climate change is a long-term phenomenon with long-lasting impacts of current emissions, it is also important to look at climate effects beyond the model horizon of 2050. Assuming a continuation of current policies beyond 2050, the projected temperature increase by 2100 is projected to be +3.4°C, in line with IPCC (2023^[3]). These temperature increases far exceed the Paris Agreement's goal of limiting "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels". They also contradict the goal of achieving carbon neutrality by 2050.

Temperature increases are projected to be unevenly distributed, with mean annual temperature increases varying between +0.3°C and +4.2°C from 2020 to 2050. North-western Europe and the southern parts of South America are projected to experience the lowest increases in mean temperature, while the highest increases will occur near the North Pole, particularly in northern Europe and around the Bering Strait (Figure 3.4). Other regions of the world will also see varying degrees of warming, with three notable hot spots in mountainous areas: the Himalayas, the Ethiopian Highlands, and the Andes. As a result, by 2050, the warmest regions are expected to remain around the Equator, the Sahel, and South-East Asia, where average annual temperatures will reach 30°C. The lowest average annual temperatures are likely to remain in Greenland and Siberia, though they are projected to no longer drop below -29°C.

Foreseen global warming under current trajectories likely increases the probability of the occurrence of climate tipping-points significantly. Under a warming of more than 3°C, tipping points such as the East Antarctic Subglacial Basins collapse, the Sahel greening, or the Boreal Forest southern dieback could be breached (OECD, 2022^[5]). Each of these tipping points could trigger cascading effects, such as intensifying warming or rising sea levels.

Figure 3.3. Projected GHG emissions and temperature trajectory under current policies



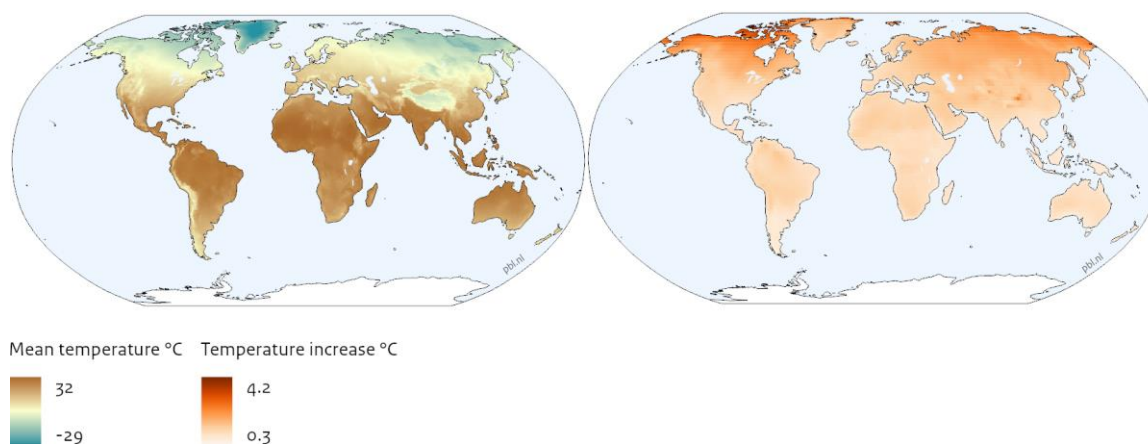
Note: In the left panel, the dots represent global emissions under current policies, as projected by the Environmental Outlook modelling toolbox. The red shaded area provided for 2025-2050 reflects the 5%-95% confidence interval of all "Current policies" scenarios from the IPCC AR6 database (Byers et al., 2022^[6]). The green shaded area represents the corresponding interval of scenarios aiming to limit warming to 2°C in the IPCC AR6 database. In the right panel, the blue line shows the global temperature increase projected by the Environmental Outlook modelling toolbox. The grey lines represent increases projected for SSP2 baselines and scenarios in the IPCC AR6 database, which includes scenarios with stringent mitigation efforts.

Source: IPCC (2023^[3]) and Environmental Outlook modelling toolbox.

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Figure 3.4. Regional average temperatures and projected temperature changes

Mean annual temperature in 2050 (left) and temperature increase 2020-2050 (right)



Source: Environmental Outlook modelling toolbox.

The economic consequences of these temperature increase, and the associated changes in water systems outlined below, are projected to be severe (OECD, 2015^[7]). A brief discussion of the recent literature on this topic is provided in Annex 3.B.

3.3.2. *Climate-induced changes in water systems*

Beyond temperature increase, changes in the climate portend changes to global water cycles. Changes in global temperature patterns and their distribution will continue to induce significant alterations in the climate system, particularly through shifts in the precipitation patterns. Most regions will experience a decrease in precipitation, except for some already wet areas, such as monsoon and mid-latitude wet regions, which will see further increases. Seasonal variance is also projected to rise globally by 2050, with more extreme dry and wet days (IPCC, 2023^[3]).

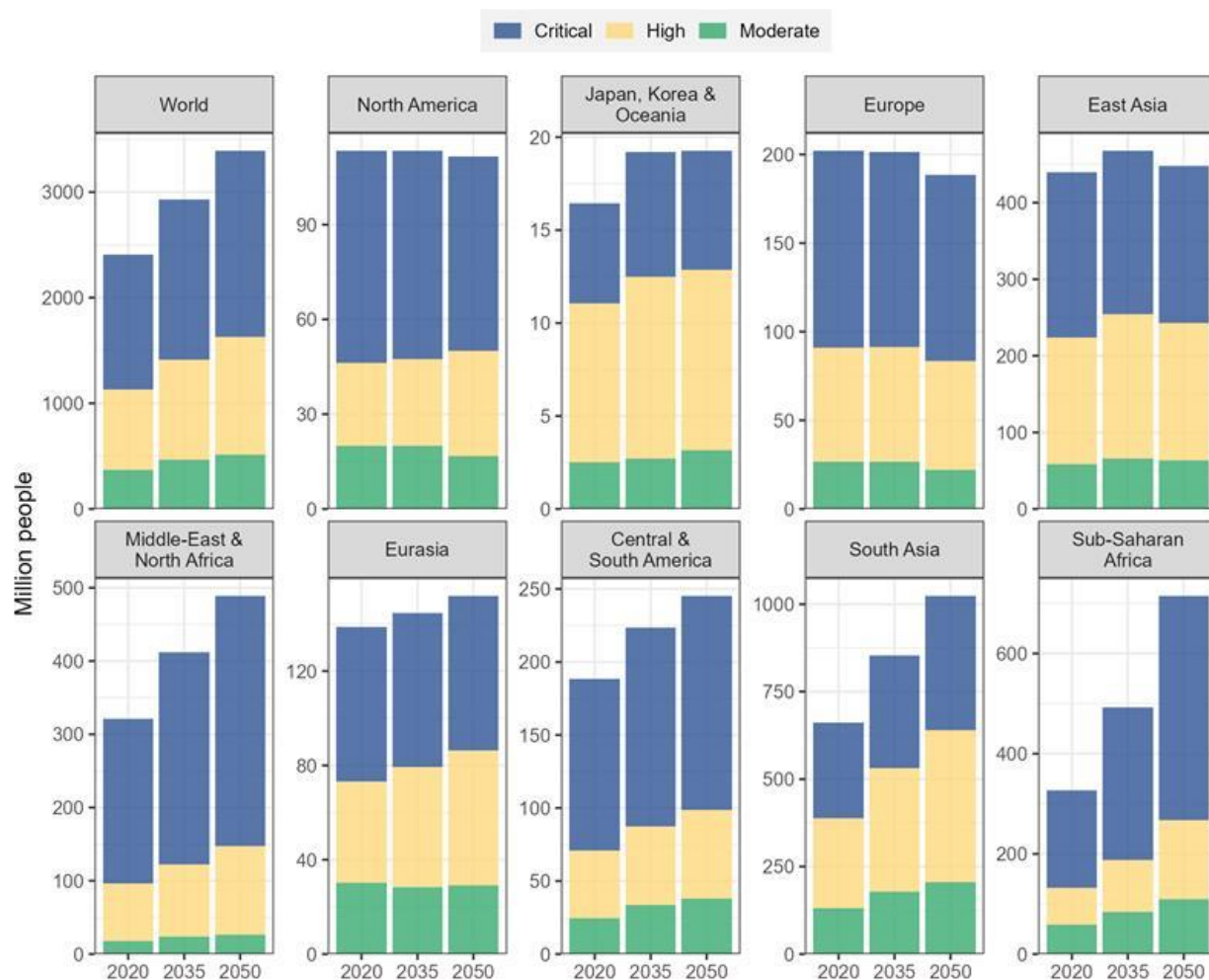
As a result of temperature increases and precipitation changes, the distinction between arid and humid land is projected to become more pronounced by 2050. Arid land expands around the Mediterranean Sea, in North America, Western South America, Western Europe, Caucasus, around the Gobi Desert and in Australia. On the contrary, the northern parts of the northern hemisphere and equatorial regions will see a decrease in aridity.

Along with changes in precipitation patterns, water demand will also increase, mainly from the energy and industry sectors, as well as from households. Global irrigation demand is projected to increase less than water demand because increased water use efficiency is foreseen to offset some of the increase in the irrigated area, at least at a global level (there can be significant variations across regions though that may cause bottlenecks).⁴ The combination of these two drivers results in significant changes in river dynamics. In the worst cases, increased demand can lead to water flows that are unsustainable, even ending in rivers drying up. This has already happened in the Colorado river (Fleck and Udall, 2021^[8]) and the Aral sea (Micklin et al., 2020^[9]).

Water stress is another key water-related indicator, reflecting the number of people living in areas that are at risk of water shortage. The population at risk of water stress is projected to rise significantly, by over 40% between 2020 and 2050, amounting to around 1 billion additional people (Figure 3.5).⁵ The impacts of water scarcity vary across sectors: it can reduce energy generation (including from hydropower, as well as from coal, gas or nuclear power plants with significant cooling water needs), restrict domestic water use, and limit irrigation, thereby decreasing crop yields. Under current policies, the area at risk of water stress shows a negligibly small projected increase by 2050. This is the result of spatially diverse trends, with some areas experiencing more stress while others see a reduction, due to changes in water withdrawal and varying precipitation patterns. This underscores the concern that regions already vulnerable to water shortages are likely to see much faster population growth, further intensifying the risks.

Figure 3.5. Water stress

Population at risk of water stress in million people



Note: Water stress is defined by the share of water withdrawal per 30 arc-min grid cell that needs to be obtained from non-renewable sources (i.e. no surface water or renewable groundwater, e.g. deep aquifers or desalinisation). Population is classified according to the severity of water stress based on the percentage of non-renewable water needed: moderate (> 10%), high (> 25%) and critical (> 50%).

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/fyp9qh>

Approximately 3.3 to 3.6 billion people live in locations that are highly vulnerable to climate change (IPCC, 2023_[10]). Among those, people with considerable development constraints, such as Indigenous Peoples, small-scale food producers and low-income households, are more vulnerable to climatic hazards. Increasing weather and climate-related extreme events have exposed millions to acute food insecurity and reduced water security, with the largest adverse impacts observed in Africa, Asia, Central and South America and the Arctic. Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with low vulnerability.

3.4. Current and projected future state: Biodiversity loss

Humanity has always modified the ecosystems it inhabits. However, at global level human-induced drivers of environmental change have accelerated dramatically in recent years, which directly affect biodiversity.⁶ Although the complexity of biodiversity makes it challenging to measure comprehensively, indicators used to monitor changes in different dimensions of biodiversity all show a clear continuing loss. This section draws on a selected set of key biodiversity indicators (see Box 3.1) to provide an overview of past and projected changes in ecosystem structure, the composition of natural communities, and the state of certain species populations, particularly their persistence and size. Projections for biodiversity loss are restricted to the terrestrial realm.⁷ In addition, estimates of changing provision of ecosystem services are also presented in this section, as are the strong interconnections among the different dimensions.

Box 3.1. Biodiversity indicators

Biodiversity can be defined as the variability among living organisms from terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part, including diversity within species, between species and of ecosystems (United Nations, 1992^[11]). The multidimensionality of biodiversity has consequences for how it can be measured and monitored. In particular, assessments focusing on a single biodiversity indicator are likely to underrepresent the full meaning of the biodiversity concept. Furthermore, capturing this multidimensionality with a limited number of indicators is challenging, yet crucial for informing and assessing policies.

The modelling toolbox used in this Environmental Outlook projects changes in different species populations indicators to assess biodiversity change: Mean Species Abundance (MSA) and Living Planet Index (LPI). MSA is an indicator of local biodiversity intactness, ranging between 0 and 1, and relates to the naturally occurring species in affected ecosystems compared to an undisturbed situation. When the species assemblage is fully intact MSA is equal to 1; when all original species are locally extinct, MSA equals 0 (Alkemade et al., 2009^[12]; Schipper et al., 2019^[13]). LPI measures the mean relative change in population size (number of individuals) compared to a reference year (1970). LPI values lower than 1 indicate that most populations have declined, whereas values higher than 1 indicate increases in population size of most species relative to the reference year (Collen et al., 2009^[14]). It is important to note that, in this report, the projected MSA covers terrestrial warm-blooded vertebrates (birds and mammals) and plants, while projected LPI covers terrestrial mammals only.

The Red List Index (RLI) is another indicator that is widely used in the literature. RLI shows trends in overall extinction risk for species. An RLI value of 1 indicates that all species qualify as Least Concern (i.e. not expected to become Extinct) whereas an RLI value of 0 equates to all species having gone Extinct. If RLI remains constant over time this indicates no change in the extinction risk of the group of species analysed (Butchart et al., 2004^[15]).

To facilitate the reading and interpretation of these three indicators, this Outlook follows the approach used by IPBES (2019^[16]) and presents the numbers as an index by presenting the value on a scale of 0-100. For example, MSA in 2020 was estimated at 0.597 globally, i.e. the index equals 59.7.

3.4.1. Losses in terrestrial biodiversity

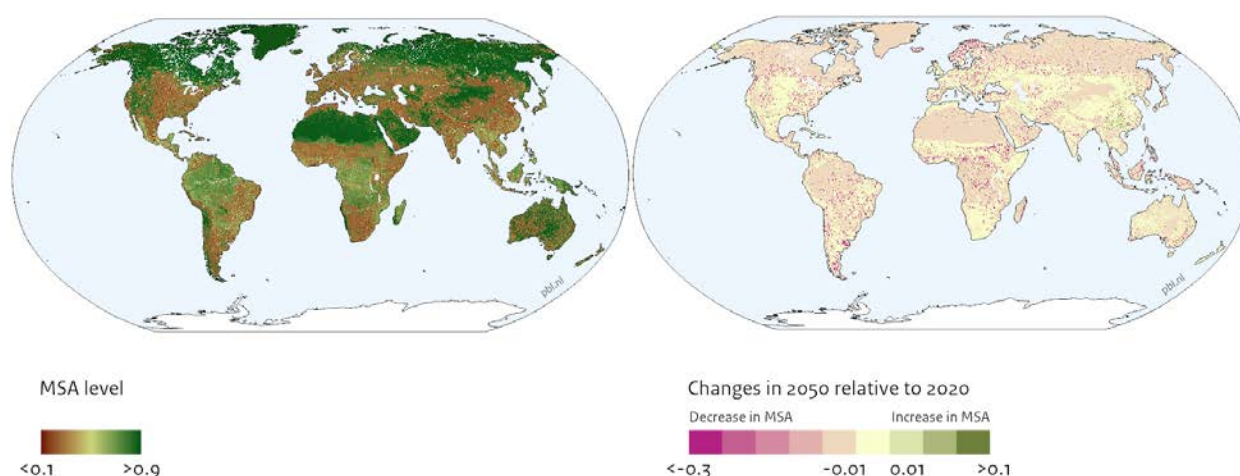
Most global indicators show a steady deterioration in ecosystem integrity. For instance, high-biodiversity tropical forests continue to decline, albeit at a slower rate than between 1990 and 2000 (FAO, 2024^[2]). Forests covered about 4.1 billion ha of the global land surface in 2020, a more than 10% decline from 1990 levels. While forest loss continues, the net rate of loss has halved since the 1990s, largely due to net increases in temperate and high latitude forests. IPBES (2019^[16]) estimates that more than one in eight animal and plant species already face global extinction, and about one quarter of animals, plants and non-insect invertebrates are now threatened with extinction (Díaz and Malhi, 2022^[17]).

Since 1970, the composition of natural communities has changed dramatically in many regions. The global MSA index considers both the number of species and the size of their populations. As calculated using the Environmental Outlook modelling toolbox, MSA for warm-blooded vertebrates and terrestrial plants has declined by approximately 1 point each decade, to an estimated value of 59.7 in 2020 (Box 3.1). This decline is more pronounced in areas with both exceptional concentrations of endemic species and significant loss of habitat (Myers et al., 2000^[18]). The decrease in original species has occurred alongside the addition of already widespread species to ecological communities, including through the influx of invasive alien species. These two processes have contributed to the erosion of differences between ecological communities in different places. This homogenisation of natural communities is now well established and may jeopardise ecosystem integrity (IPBES, 2019^[16]).

Terrestrial MSA is projected to decline in all regions by 2050, with the impact of future climate change playing an increasingly important role (Figure 3.6). Regions expected to experience the greatest biodiversity loss include Sub-Saharan Africa, South Asia, Central and South America, as well as Europe (see also the discussion on the drivers of regional biodiversity loss in Section 3.4.4 below).⁸

Figure 3.6. Global Mean Species Abundance (MSA): Patterns in 2020 and changes by 2050

Terrestrial Mean Species Abundance in 2020 (left) and absolute changes by 2050 (right)



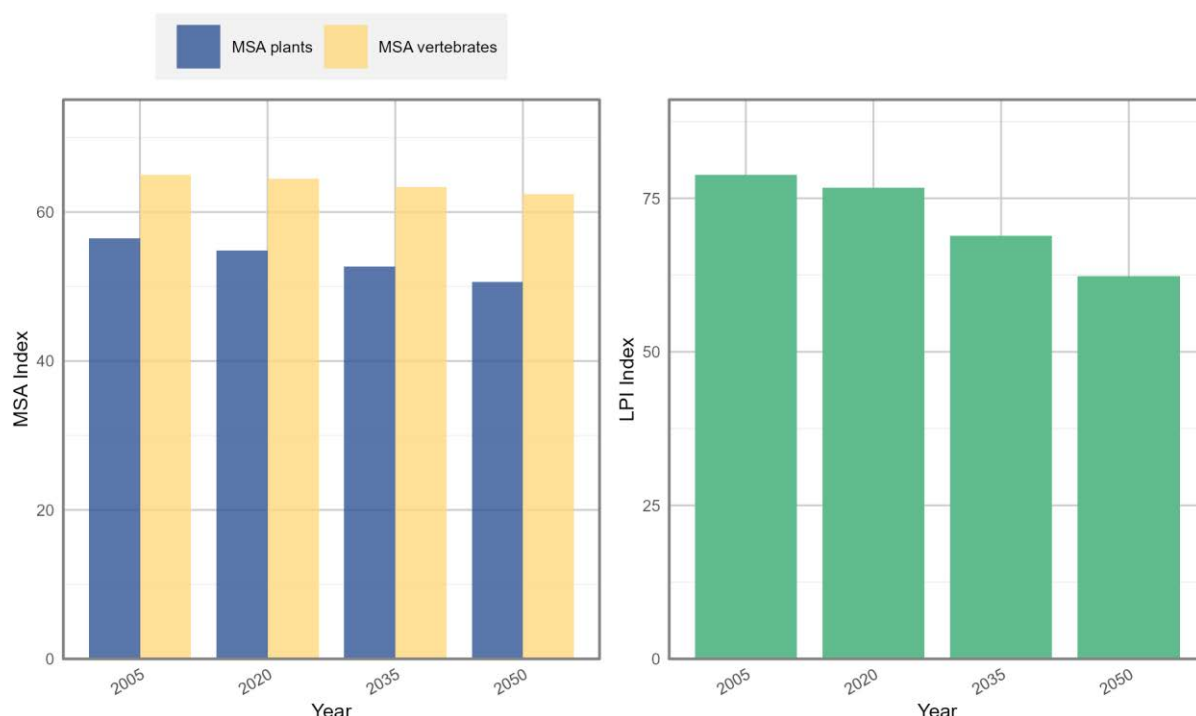
Note: MSA levels are projected against a local “pristine state” baseline and is thus not relevant to compare biodiversity richness across regions. Source: Environmental Outlook modelling toolbox.

These results for the MSA index are confirmed by other indicators (Figure 3.7):

- The state of biodiversity is projected to continue deteriorating over the next three decades. Under current policies, MSA for both warm-blooded vertebrates and terrestrial plants is projected to decline. Plant biodiversity is expected to be more severely affected than that of vertebrates: the MSA for plants is projected to decline to reach 50.6 by 2050 (4.3 points less than in 2020), while the MSA for warm-blooded vertebrates is expected reach 62.4 (2 points less than in 2020). In other words, global plant biodiversity is projected to be almost halved on average by 2050. The relative vulnerability of plants may be related to the complete removal of vegetation due to intensive land use and land conversion. Overall, by 2050, the global remaining terrestrial MSA index is projected to be 56.5, 3.2 points lower than in 2020. At first glance, this reduction may appear modest. However, a decline of 2 to 6 points in the MSA index corresponds to the conversion of approximately 2.5 to 8 million km² of pristine habitat into areas where all the original species have been lost, i.e. where all the native biodiversity has been destroyed (Schipper et al., 2019^[13]). The projected decline is equivalent to the conversion of pristine habitat of more than 4 million km² into an area where all the original species have been lost.
- The LPI measures the state of global biodiversity based on population trends of vertebrate species from terrestrial, freshwater, and marine habitats (mammals, birds, fish, reptiles and amphibians). The Living Planet Report (WWF, 2024^[19]) looks at field data for a subset of populations for selected species and finds a 73% decline in the average size of monitored wildlife populations between 1970 and 2020. For mammals, Kok et al. (2023^[20]) report a decline more limited than the average, using a model-based approach. In line with the methodology of Kok et al. (2023^[20]), the LPI index calculated in the Environmental Outlook modelling toolbox is expected to fall from 68 in 2015 to 62.3 by 2050, indicating that most species are projected to decline in their extent of occurrence or extent of suitable habitat (Figure 3.7). The projection of the LPI provides a clear message of continuous declines resulting from important drivers such as land use and climate change.
- The RLI tracks trends in the survival probability of the species listed in the International Union for Conservation of Nature and Natural Resources (IUCN) Red List of threatened species. In 2015, it stood at 75% of the value it would have been without human impacts, having decreased by an average of 4% per decade between 1970 and 2015. Species living exclusively in forested areas (the so-called forest specialists) displayed the lowest RLI index in 2015, at 72, not least due to deforestation causing permanent forest cover loss (although temporary loss of forest cover from e.g. wildfires also play a role). Meanwhile, species used for food and medicine experienced the largest per-decade rate of change in their RLI (-1.7%). Kok et al. (2023^[20]) suggest that the RLI could decrease by over 6 points by 2070 at the global level. Population sizes are projected to continue declining for 70% of threatened mammal species, with rates of decline exceeding 50% for around 30% of the species. Only 5% of threatened mammal species are expected to experience an increase in population size in the coming decades.

Figure 3.7. Biodiversity over time through the lens of MSA and LPI

Global MSA and LPI index values in 2005, 2020, 2035 and 2050



Note: The left panel presents MSA index values which measure the local biodiversity intactness. Values below 100 indicate that some local species have become extinct. MSA values are presented for both plants and vertebrates. The right panel presents LPI values which measure the relative increase/ decline in populations since 1970. Values lower than 100 indicates a decline in populations whereas values greater than 100 indicate growing populations. LPI values contain both plants and vertebrates.

Source: Environmental Outlook modelling toolbox.

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3.4.2. Losses in aquatic biodiversity

Inland waters and freshwater ecosystems show among the highest rates of degradation of their structures (IPBES, 2019^[16]). Coastal marine ecosystems are among the most productive globally. Their loss and deterioration diminish their ability to protect shorelines – and the people and species that rely on them – from storms, as well as their capacity to support sustainable livelihoods (IPBES, 2019^[16]).

Inland waters – such as rivers, lakes, marshes, peatlands and other wetlands – are particularly rich in biodiversity and underpin essential ecosystem services. For example, peatlands, covering only 3% of the planet's surface, store twice as much carbon as the world's forests (Beaulne et al., 2021^[21]). Furthermore, rivers and their riparian habitat (such as riverbanks and floodplains) also provide vital connectivity between different freshwater, terrestrial and marine ecosystems, supporting habitat heterogeneity essential for riverine fish abundance and diversity. Inland waters are, compared to marine and terrestrial ecosystems, the most threatened ecosystems. This is because lakes around the world are warming faster than the atmosphere and the oceans and the flow regime of entire river systems is shifting amongst other reasons. Estimates of threats to freshwater species suggest that nearly one in three species is threatened with extinction. According to the 2024 LPR (WWF, 2024^[19]), in 2020, monitored populations of freshwater species had declined by 85% on average compared to 1970, a much faster rate than in marine and terrestrial realms.

With the oceans containing around 80% of the earth's biodiversity, marine biodiversity and its ecosystem services are a particularly important contributor to food security, nutrition, and poverty reduction. Marine populations have declined by 56% in 2020 relative to 1970, as measured by the 2024 LPI (WWF, 2024^[19]). Although most indicators of marine biodiversity have declined less than terrestrial or inland water biodiversity, the marine index is dominated by fish species, many of which are managed to control the level of fishing pressure. Overall, the fraction of marine fishery stocks within biologically sustainable levels decreased to 62.3% in 2021, 2.3% lower than in 2019 (FAO, 2024^[22]). Unmanaged fish stocks such as sharks and rays continue to show critical levels of decline. Apart from fishing, threats to marine biodiversity include a more than 30% fall in the ocean pH since the industrial revolution (IPBES, 2019^[16]). Increasing nutrient pollution and eutrophication affect particularly coastal regions that make up only a relatively small area but contain around 90% of ocean animal life (Deutsch, Penn and Lucey, 2024^[23]). Beyond animals, aquatic plants are also affected.

There is greater uncertainty in quantifying the future changes in aquatic biodiversity relative to terrestrial biodiversity. Inland water biodiversity is projected to decline further in the future. Focusing on freshwater MSA, OECD projections suggest a major decline for Africa in 2050 compared to 2000 (Janse et al., 2015^[24]; OECD, 2012^[25]), with declines also in Asia, Latin America and Eastern Europe. A modest improvement is projected in parts of the USA, central Asia and Europe, due to an assumed stabilisation of agricultural area and eutrophication abatement.

When it comes to marine biodiversity, climate change alone is projected to decrease ocean net primary production (i.e. the uptake of carbon dioxide through photosynthesis by phytoplankton) by between 3 and 10%, and fish biomass by between 3 and 25% (in low and high warming scenarios, respectively) by the end of the century (IPBES, 2019^[16]). Most marine organisms are cold-blooded and have the same temperature as the surrounding water. Therefore, variations in water temperature and marine heatwaves directly impact their functioning, including reproduction, migration and survival (Payne, 2024^[26]; OECD, 2025^[27]).

Most studies agree that climate change will shift the location of marine species (García Molinos et al., 2015^[28]; Jaureguiberry et al., 2022^[29]; Meyer et al., 2024^[30]). While climate change is expected to have an impact on potential habitat areas, the size and even sign of the overall effects on marine habitats is still unclear (Chen et al., 2024^[31]; Meyer et al., 2024^[30]; Santana-Falcón et al., 2023^[32]). In addition, further research is needed to use potential habitat predictions to predict realised species distribution (where species actually are found) as well as the extent to which they are found. Beyond temperature, pH and other abiotic variables can also limit the colonisation of newly suitable thermal habitats, while ocean currents can function as biogeographic barriers or facilitate access to habitats. Marine biodiversity also depends on the interaction between invasive and resident species (Araújo and Luoto, 2007^[33]). Immigrating species can introduce new predators, pathogens and competitors, disrupting trophic interactions and causing the decline of resident species (Meyer et al., 2024^[30]).

3.4.3. Ecosystem services

Nature and biodiversity contribute to human well-being in a variety of ways. In recent decades, economists have developed a conceptual landscape to take into account that environmental systems play a fundamental role in determining a country's economic output and social well-being. In this framework, a nation's wealth is grounded in four core stocks of capital: manufactured capital, human capital, social capital and natural capital (whether renewable or not). Natural capital describes the stock of natural assets. These assets produce a flow of services, called ecosystem services (MEA, 2003^[34]). Methods for measuring the values of these assets and flows are still being refined (see Box 3.2), and frameworks for natural capital accounting and assessment are being developed but are considered to still be in their early days (Dasgupta, 2021^[35]).⁹

Box 3.2. Challenges and approaches to valuing biodiversity and ecosystem services

Several studies have attempted to assign a value to biodiversity and ecosystem services, but the methodologies and valuation efforts remain a work in progress. Given the resulting uncertainties and challenges, the main text focuses on indicators that measure the state of biodiversity and ecosystem services in physical units. This box offers a brief overview of ongoing efforts to value natural capital and ecosystem services, while also highlighting the limitations of these exercises.

The economic consequences of biodiversity loss have received less attention than those of climate change and pollution. While growing evidence highlights the value of biodiversity and the costs associated with its decline (TEEB, 2010^[36]), significant gaps remain.

Biodiversity loss is typically assessed through a narrow focus on a select number of species or ecosystem services, such as pollination, timber, marine fisheries, and carbon sequestration. Recent studies have demonstrated the high economic value of nature's ecosystem services in specific contexts, for example sanitation services provided by vultures in India (Ishwar and Das, 2024^[37]). The decline of these species has led to human health impacts with economic costs estimated in USD billions. Ranger et al. (2023^[38]) find lower-bound nature-related economic risks of USD 5 trillion for five analysed ecosystem services. The wide range of estimates is also reflected in Constanza et al. (2014^[39]), who estimate that between 1997 and 2011 the world lost an estimated USD 4-20 trillion per year in ecosystem services owing to land use change, depending on which unit values are used.

Valuing non-marketed ecosystem services – those essential to human well-being – would likely increase damage estimates. Efforts like the Gross Ecosystem Product, GEP (Ouyang et al., 2020^[40]), attempt to address this by monetising nature's inputs where markets do not exist, but GEP only measures current flows and not depletion of natural stocks. Similarly, the World Bank (2021^[41]) valued renewable natural capital—forests, mangroves, fisheries, agricultural land, and protected areas—at USD 35 trillion in 2018, excluding many regulating services, which Dasgupta (2021^[35]) notes are large but difficult to capture in economic terms. Despite uncertainties (OECD, 2019^[42]), estimates such as those by Constanza et al. (2014^[39]), which amount to USD 125-145 trillion in 2011, i.e. well over one and a half times the size of the world's GDP that year, underscore the vast economic value of biodiversity.

Beyond the challenges of valuation, non-linearity of ecosystems and tipping points are also important to consider. Ecosystems that are pushed too far can collapse abruptly and irreversibly, posing a severe risk to the economy and human well-being (OECD, 2021^[43]). For instance, Johnson et al. (2023^[44]) project a loss in global GDP of USD 2 trillion in the case of a partial ecosystem collapse, several orders of magnitude larger than the loss estimated when assuming that tipping points are not reached. Overall, Dasgupta (2021^[35]) argues that the biosphere's value lies not in its sheer economic worth but in the fact that, without it, life as we know it could not exist.

Ecosystem services are grouped in three main categories, following the Common International Classification for Ecosystem Services (CICES): (i) provisioning services encompass the material outputs produced by ecosystems, such as food and water; (ii) supporting and regulating services are related to the ecological processes that maintain the functioning of ecosystems, for example, pollination, carbon sequestration, erosion and flood control, as well as genetic diversity; (iii) cultural services cover the benefits that people derive from their relationship with ecosystems, including inspiration and recreation, among others. Since ecosystem services stem from the overall state of nature, they are not tied to a single dimension of the environmental crisis. Changes in ecosystem services capture the impacts of the broader degradation of the environment on what nature can contribute to human societies. With this respect, they serve as good indicators of the impact of the triple planetary crisis.

Over the past 50 years, a clear trade-off has emerged between provisioning services and regulating services (Pereira et al., 2024^[45]). While material outputs from nature (e.g. food, timber and energy) have increased due to agricultural expansion and land transformation, these changes have led to the loss of natural habitats such as forests and grasslands. Combined with pollution and climate change, this has resulted in declines in supporting and regulating services, including a global decrease in pollinator abundance and diversity (IPBES, 2019^[16]). This underscores the extent to which man-made capital ultimately relies on the integrity of natural capital, which also provides the essential ecological functions that underpin long term productivity and resilience.

Under current policies, the trade-off between provisioning and regulating services is expected to continue. By 2050, global agricultural production is projected to increase by over 60% (measured in terms of dry matter and excluding feedback from environmental degradation). In contrast, most regulating services are expected to decline, with the notable exception of carbon removal by AFOLU, which is projected to increase by around 0.5 Gt CO₂ in 2050, thanks to policies aiming at improving carbon storage from forests for climate change mitigation purposes. This increase is 8% larger than the one in total GHG emissions. Conversely, Kok et al. (2023^[20]) project declines in other key regulating services: the area of cropland under natural pest control, the share covered by pollinators, and the area protected from erosion by natural vegetation are projected to fall by 4.4%, 1.1%, and 10.5%, respectively.

These trends are marked by substantial regional disparities. For instance, carbon capture by AFOLU in East and South Asia is projected to more than triple between 2020 and 2050. In stark contrast, it is expected to fall significantly in Central and South America and in Sub-Saharan Africa. East Africa is projected to see large declines across all regulating services: -35% in natural pest control, -36% in soil erosion protection, and -12% in pollinator coverage. Similarly, in Indonesia, pest and erosion control services are expected to fall by over 30%. Even small declines in ecosystem services, while seemingly modest at the global level, could have severe impacts on human societies. Beyond a certain threshold, even minor changes in ecosystems can push them past a 'tipping point', leading to a new, potentially less favourable equilibrium.

Aquatic inland ecosystems also provide substantial ecosystem services (Moberg et al., 2024^[46]). These ecosystems are vital for a wide range of functions, including the provision of drinking water, irrigation, water quality regulation, pollution control, support for food security through freshwater fishes and other species, health and well-being, climate mitigation and adaptation – for example through the reduction of flood damage by natural floodplains and riparian vegetation. Freshwater ecosystems, a subcategory of inland waters excluding saline and some brackish systems, cover only around 2% of the planet yet are home to about (and probably more than) 12% of known species, one-third of known vertebrate species and more than half of all fish species (Moberg et al., 2024^[46]).

Complementing the critical role of inland waters, marine ecosystems also underpin major ecological and economic functions. In 2022, 62% of aquatic animals were harvested in marine areas, with 69% originating from captures fisheries – i.e. 43% of the total, amounting to approximately 80 million tonnes – and 31% from marine aquaculture (FAO, 2024^[22]). According to FAO estimates, around 16 million people were employed worldwide in the primary sector of marine fisheries in 2022. Beyond their importance for food security and livelihoods, marine ecosystems also play a key role in climate change mitigation and adaptation, sequestering and storing a significant part of CO₂ emissions from human activities (Rohr et al., 2023^[47]).

3.4.4. Decomposing biodiversity loss

Historically, land and sea use change have been the most significant human-induced direct cause of change in the global state of biodiversity, accounting for 30% of the overall human impact. This is followed by direct exploitation (23%), climate change (14%), pollution and invasive species (IPBES, 2019^[16]). In the coming decades, climate change will overtake land use change as the main cause of biodiversity loss. The

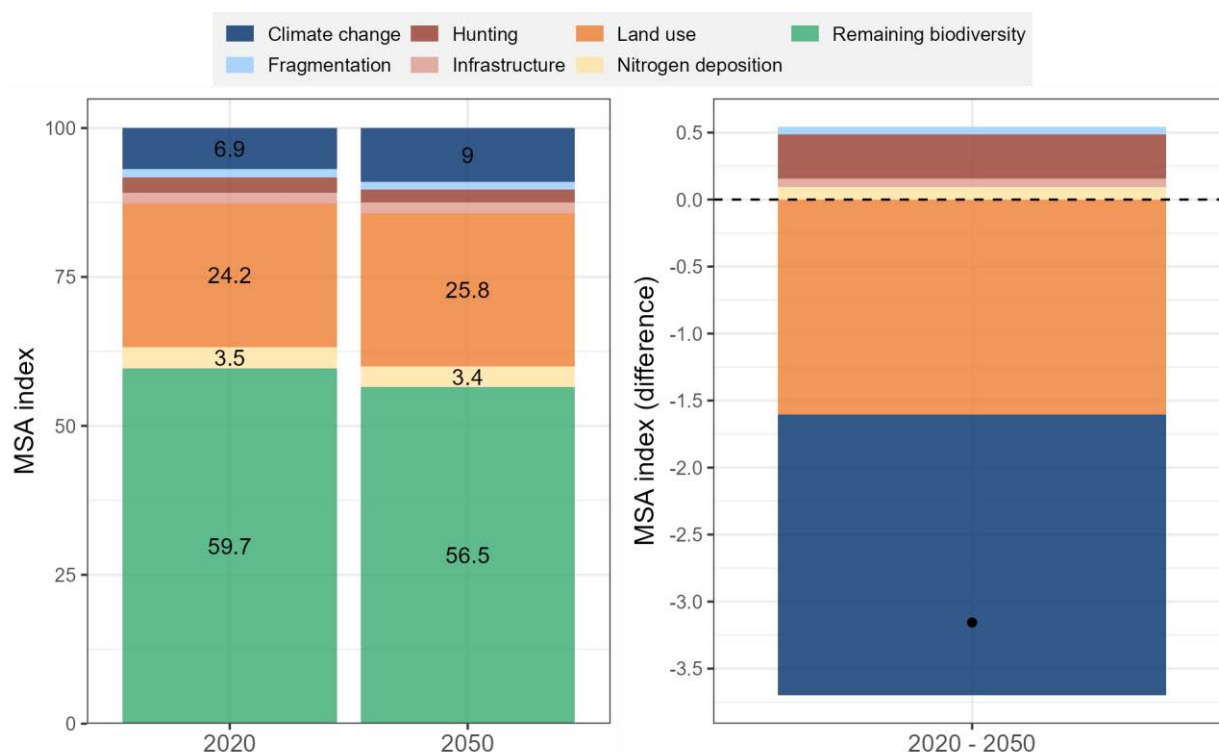
global MSA index is expected to decrease by 3.2 between 2020 and 2050, with climate explaining two thirds of the decline (Figure 3.8).¹⁰ Damaged ecosystems show reduced ability to act as carbon sinks, especially forests and oceans (see Section 1.3 of Chapter 1). Meanwhile, habitat fragmentation, infrastructure expansion, hunting, and nitrogen deposition are projected to have a declining impact, as a result of changing habits and current policies to protect natural areas. However, the reduction in harm from these sources is insufficient to counterbalance the growing losses associated with climate change and land use transformation.

From a regional perspective, the developments in South Asia are particularly concerning, as the region already exhibited one of the lowest MSA indexes in 2020 (48.5) and faces one of the largest decreases, driven by both climate change and land use impacts (Figure 3.9). East Asia is expected to remain the region with the lowest MSA by 2050, dropping to 43.5. In Europe, the projected biodiversity decline is primarily driven by land-use changes, including a 22% expansion of built-up areas and continued agricultural land expansion. Although biodiversity recovery is occurring on abandoned croplands and in young forests, this regeneration takes time to become fully effective and is insufficient to compensate for the losses by 2050.

The decomposition of the drivers of biodiversity loss also alludes to the fact that while the (direct) causes of climate change and pollution are local – even if climate change is global – the main driver of future MSA loss is global climate change. This will have implications for policymaking, where local action can mitigate global environmental change that feeds back to local effects.

Figure 3.8. Decomposing the evolution of global biodiversity loss

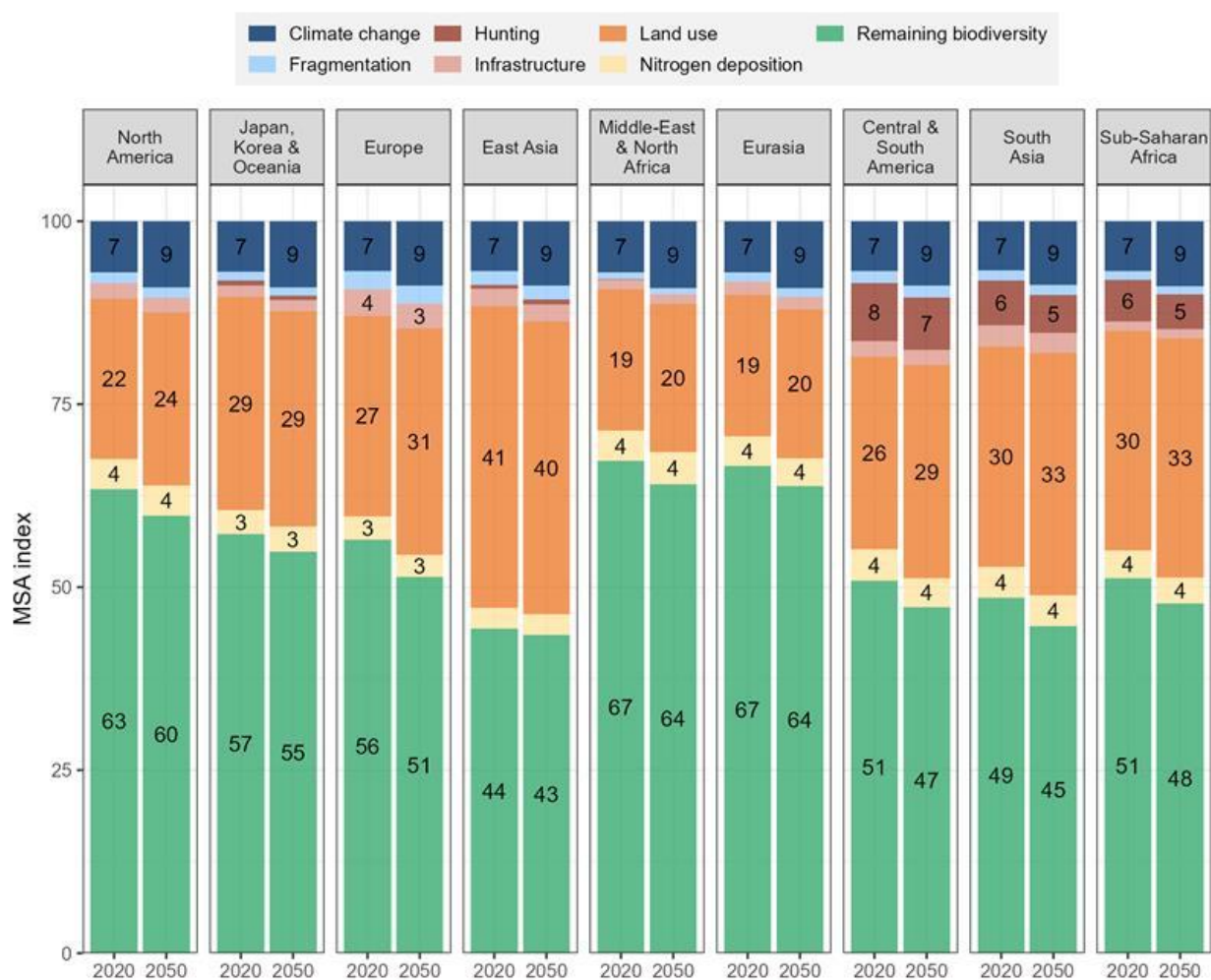
Global biodiversity (expressed in MSA index): contribution of the main causes to biodiversity loss



Note: The left graph presents the remaining biodiversity and the contribution of the different causes of biodiversity loss. The right graph zooms in the change in the MSA index between 2020 and 2050, breaking down the contribution of each cause to this projected change. The black dot reflects the net result on the overall MSA index.

Source: Environmental Outlook modelling toolbox.

Figure 3.9. Effects of different pressures on regional terrestrial MSA, in 2020 and 2050



Note: Values smaller than 3 are not reported in the figure.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/sqwd9g>

3.5. Current and projected future state: Pollution

The pollution crisis is multifaceted, involving the release of various substances into the environment across several media (air, water, and soil). Its impact on both human health and wildlife is significant, with pollution responsible for an estimated 9 million deaths annually, equivalent to one in six deaths worldwide (Fuller et al., 2022^[48]). This section examines pollution from particulate matter and ground-level ozone (air pollution), nutrients, chemicals and plastics.

As outlined in earlier chapters, there are clear, direct (yet complex) links between air pollutants and climate change. The links between pollution and biodiversity loss are less known, but are also pronounced. Among species at risk of extinction, 18.2% are affected by pollution, with 4.7% facing it as the primary driver of their decline (Hogue and Breon, 2022^[49]). A recent assessment by Jaureguiberry et al. (2022^[29]) ranks pollution as the third most significant driver of biodiversity loss, up from fourth in the 2019 IPBES report (IPBES, 2019^[16]). Especially freshwater fauna species are threatened by pollution. A recent study found that more than half of the threatened species are impacted by pollution (Sayer et al., 2025^[50]).

3.5.1. Air pollution

Both outdoor and indoor air pollution are major public policy concerns since they cause premature mortality and illness. Particulate matter and tropospheric ozone concentrations result from the emissions of various compounds and their chemical interactions in the atmosphere.¹¹ Air quality is therefore affected by emissions of several pollutants, originating from the combustion of fossil fuels and biomass (including wildfires), animal-based agriculture, and manufacturing and extracting industries, which also emit heavy metals.

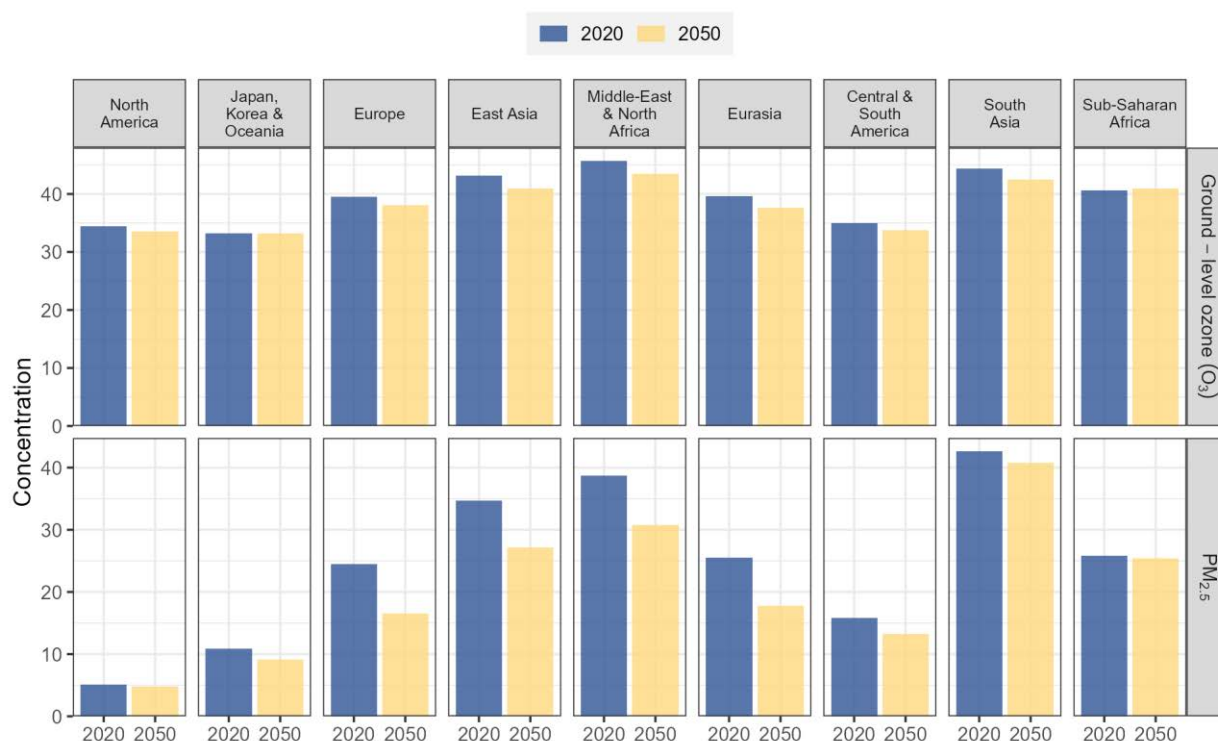
Air pollution has been acknowledged as an important environmental and health issue at least since around 400 BC (Fowler et al., 2020^[51]). Recently, the combination of policy measures and technological progress have led to reductions in air pollution exposure in many countries. Exposure to indoor air pollution, primarily due to the burning of solid fuels for cooking and heating in countries in the lower-income region, has been decreasing as the take-up of modern technologies rises with growing incomes. Policies such as enhanced technology standards for the combustion of fossil fuels have contributed to limiting exposure to outdoor air pollution, although strong variation persists across countries.

Within countries, there is evidence from the Netherlands and the United Kingdom that outdoor air pollution affects low-income households more (Fecht et al., 2015^[52]). Data for Europe shows that groups of lower socio-economic status tend to be more negatively affected by environmental health hazards (EEA, 2018^[53]). Such results likely extrapolate to other regions, which is particularly concerning for lower-income, high pollution exposure regions.

Population-weighted fine particulate matter concentrations are projected to decline further in most regions in the 2020-2050 period (Figure 3.10). In line with strong emission reductions, projections indicate large air quality improvements between 2020 and 2050 in several regions, especially East Asia, Middle East and North Africa, and Eurasia, for both fine particulate matter and ground-level ozone. While air quality is set to improve in most regions, projections also indicate PM_{2.5} in Sub-Saharan Africa as an exception.

Figure 3.10. Population exposure to ground-level ozone and fine particles

Population-weighted concentrations of ground-level ozone (parts per billion volume, ppbV) and fine particles 2.5 (micrograms per cubic meter, $\mu\text{g}/\text{m}^3$) in 2020 and 2050



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/5y06ez>

Another air pollutant of interest is SO_2 . Exposure to ambient SO_2 has been associated with all-cause and respiratory mortality, conditional on particulate matter exposure (Orellano, Reynoso and Quaranta, 2021^[54]) and with morbidity impact such as asthma and chronic bronchitis. Like nitrogen compounds, SO_x can react with other compounds in the atmosphere to form particulate matter detrimental to health. Moreover, SO_2 emissions also have impacts on ecosystems. For example, SO_2 contributes to acidification of surface water, reducing biodiversity and killing fish (US EPA, 2002^[55]). Acidification also damages forests through direct impacts on leaves and needles, contributing to soil nutrient depletion. Thanks to technical progress, SO_2 emissions are expected to significantly decrease in all regions (Figure 3.2), decreasing by 64% on average at the global level (Figure 3.1).¹²

Air pollution is a key risk factor behind environment-related premature deaths, with an estimated 6.7 million lives lost annually, 4.1 million of which are from outdoor air pollution and the rest from exposure to indoor air pollution (Fuller et al., 2022^[48]), making it the fifth ranking mortality factor (Cohen et al., 2017^[56]).¹³ The increase over the last 15 years reflects a growth in the population exposed in developing countries as well as some increases in concentrations. During this period most developed countries have seen a decline in death rates, whereas some emerging economies have seen an increase, particularly India.

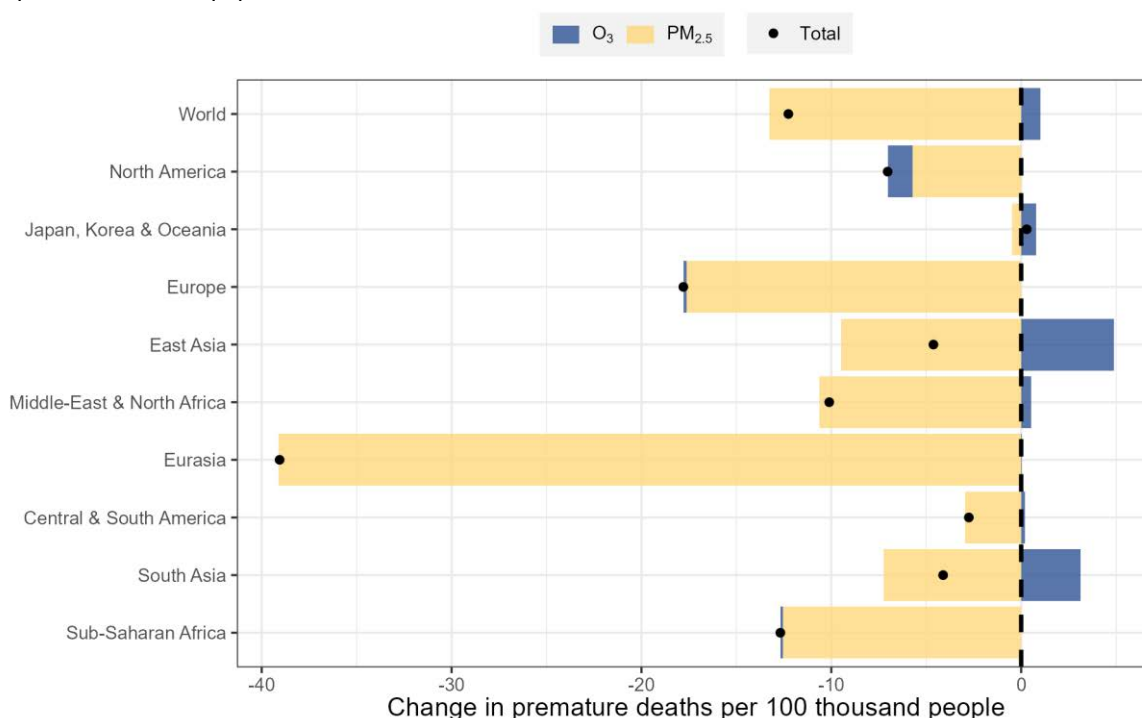
The number of premature deaths due to $\text{PM}_{2.5}$ are projected to decline over time in all regions (Figure 3.11). Declines in $\text{PM}_{2.5}$ mortality rates are particularly strong in Eurasia and Europe, largely due to strong implementation of current policies to improve air quality and reduce emissions of air pollutants, including $\text{PM}_{2.5}$. For example, in the EU, the National Emission Reduction Commitments Directive sets national

reduction commitments for five pollutants including PM_{2.5} (European Parliament and Council, 2016^[57]). These ambitious emission standards contribute to driving down air pollution.

While PM (and specifically PM_{2.5}) accounts for the highest share of deaths from outdoor air pollution, the overall share of global premature deaths due to ground-level ozone is projected to increase over time (Figure 3.11), mainly because of higher temperatures and projected increases in urban population. Premature deaths due to ground-level ozone rise especially for regions where high numbers of premature deaths due to ground-level ozone already take place, in particular South Asia, in line with rising emissions of NO_x and NH₃ (Figure 3.2). In addition to levels of air pollution, the evolution of demographic characteristics contributes to the changes in incidence of air pollution-related diseases over time.

Figure 3.11. Air pollution-related mortality projections

Change in the number of deaths caused by PM_{2.5} and ground-level ozone outdoor air pollution between 2020 and 2050, per 100 thousand population



Source: Environmental Outlook modelling toolbox.

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3.5.2. Chemical pollution

Chemical pollution is a critical component of the broader pollution crisis, especially in light of the projected increase in global chemical production and use (see Chapter 2). Releases of manufactured chemical products to the environment can occur at every step of their global value chain, from raw materials extraction, to manufacture, use and disposal. Large volumes are released as waste materials during production stages, and unintentional leaks, spills and fugitive emissions produce other significant releases. Major sources of hazardous chemicals include mining, agriculture, wastewater treatment, energy generation, chemical production, and product manufacturing, use and disposal (United Nations Environment Programme, 2019^[58]).

According to WHO (2021^[59]), more than 2 million deaths in 2019 could have been prevented through better management and reduction of environmental chemical exposures. Of these, 45% were attributable to lead exposure,¹⁴ 44% to occupational exposure to hazardous chemicals, and the remainder to acute poisonings, 20% of which were self-inflicted. Alarmingly, the full extent of the disease burden from chemical pollution is likely underestimated due to limited toxicity testing and the growing complexity, diversity, and volume of chemicals, which outpace scientific and regulatory capacity (Carney Almroth et al., 2022^[60]). Additional health impact estimates are available for specific substances. For instance, recent estimates indicate that lead exposure causes 5.5 million premature deaths globally each year (Larsen and Sánchez-Triana, 2023^[61]). Moreover, between 14 and 19 million artisanal and small-scale gold miners are at risk of occupational exposure to mercury (Landrigan et al., 2018^[62]). Despite regulatory actions at both national and international levels, the market for most heavy metals (including lead and mercury) is stable or growing (United Nations Environment Programme, 2019^[58]).

In addition to well-known hazardous substances, a number of emerging chemical concerns have gained prominence in recent years and are expected to become increasingly important. Endocrine-disrupting chemicals, including phthalates, dioxins and some pesticides, interfere with hormonal systems in both humans and wildlife, disrupting physiological functions even at very low doses. The disease cost attributable to endocrine-disrupting chemicals has been estimated at EUR 163 billion annually in the European Union (Duh-Leong et al., 2023^[63]).

Another major concern is the persistence of certain chemicals, particularly Per- and polyfluoroalkyl substances (PFAS), known as "forever chemicals". PFAS have been detected in drinking water, soils, food, and household products across many countries (Wee and Aris, 2023^[64]). Efforts to track, assess, and regulate PFAS, as well as to identify safer alternatives, have been underway for over two decades (OECD, 2015^[65]; OECD, 2024^[66]; OECD, 2024^[67]; OECD, 2023^[68]). In early 2023, the Forever Pollution Project, a consortium of 16 European newsrooms, reported that nearly 23 000 sites in Europe are contaminated with PFAS, with a further 21 500 sites likely contaminated due to industrial activity (The Forever Pollution Project, 2025^[69]). While certain PFAS have already been linked to adverse health outcomes, the long-term effects of chronic, low-dose exposure remain poorly understood. Cumulative impacts and low-dose chronic exposure are key concerns when considering PFAS and endocrine-disrupting chemicals.

Chemicals pose a significant and growing concern for wildlife and biodiversity. For example, while pesticides have contributed to agricultural productivity—helping sustain rapid population growth (Tudi et al., 2021^[70])—a recent study estimates that around 75% of global agricultural land is at risk of pesticide pollution, with serious implications for biodiversity-rich and water-scarce regions (Tang et al., 2021^[71]; Tang et al., 2021^[71]). Major environmental risks are associated with the run-off of pesticides from agricultural land in soils and water systems.

Chemical pollution poses a multifaceted threat to ecosystems through both direct and indirect pathways (Sigmund et al., 2023^[72]). Direct impacts include acute toxicity leading to mortality, and sub-lethal effects such as developmental, physiological, and behavioural alterations that compromise individual fitness and population viability. For example, psychoactive substances and metals can alter animal behaviour, increasing predation risk (Brodin et al., 2013^[73]; McIntyre et al., 2012^[74]), while even low, chronic exposures can drain energy reserves critical for survival and reproduction. Moreover, the development of chemical tolerance may reduce genetic diversity, weakening long-term resilience. Environmental assessments often overlook these complex dynamics, focusing narrowly on a few toxicity indicators like survival and reproduction.

Indirect effects of pollution emerge through ecological interactions, such as altered food webs, disrupted social behaviours, or imbalanced predator-prey dynamics. Chemical pollutants can modify microbial communities and trophic structures, with consequences that depend on context-specific interactions. Persistent organic pollutants like certain PFASs, polychlorinated biphenyls (PCBs), and dichlorodiphenyltrichloroethane (DDT), due to their longevity and global spread, accumulate in organisms

and magnify up food chains, often with irreversible consequences. Even chemicals that are not inherently persistent—such as diclofenac—can become "pseudo-persistent" due to continual use, harming non-target species and triggering ecosystem-wide cascades (Green et al., 2004^[75]).

3.5.3. Nutrient pollution

Nutrients are elements that are essential for plant growth. They include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) and silicon (Si). However, excessive application of nutrients, particularly nitrogen and phosphorus, leads to water pollution. In large quantities, the leaking of these nutrients to the environment can act like fertilisers, promoting excessive algae growth, a process known as eutrophication. Severe algae blooms can block sunlight needed by aquatic plants, such as seagrass, causing them to die. Their decay depletes oxygen levels in the water, leading to death of aquatic animals. Beyond eutrophication and the resulting threat to biodiversity, nutrient pollution also degrades water quality, potentially making it unsuitable for drinking.

More generally, human activities are causing an imbalance in the nitrogen to phosphorus (N:P) ratio in the biosphere, an issue that has received less attention but warrants increasing concern (see also Chapter 6). This growing N:P imbalance can have significant consequences, not only for natural ecosystems but also for crop production, food security, and ultimately human well-being (Peñuelas and Sardans, 2022^[76]).

Nutrient pollution originates from both natural processes and human activities. Natural sources include nitrogen fixation in vegetation and the weathering of rocks and soils. Human inputs exceed natural ones, primarily from wastewater, fertiliser runoff from agricultural land (see also Section 2.2.1 of Chapter 2), and aquaculture activities. At the global level, according to the historical data gathered in the Environmental Outlook modelling toolbox, in 2020 agriculture accounted for 53% of global nitrogen delivery, followed by natural sources (26%), wastewater (19%), and aquaculture. A similar ranking applies to phosphorus delivery, though the scale differs: at the global level, nitrogen delivery amounted to 68 Mt in 2020, compared to 10 Mt of phosphorus delivery. This ranking is projected to remain consistent to 2050, although absolute numbers will change. However, these global figures conceal regional variations. In countries in the higher-income region, where agriculture is more intensive and wastewater treatment more widespread, agriculture contributes an even larger share of nitrogen delivery (61% in 2020), while wastewater accounts for 15% of nitrogen delivery. In contrast, in the middle-income region, wastewater and agriculture are responsible for 21% and 49% of all nitrogen delivery, respectively.

By 2050, nitrogen and phosphorus delivery (the transfer of nutrients to ground- and surface water) are projected to rise respectively by 22% and 20% globally. However, with global GDP expected to more than double between 2020 and 2050, nutrient intensity per unit of economic output is set to decline significantly. This relative decoupling is anticipated across all regions, with phosphorus delivery in the higher-income region expected to experience absolute decoupling. The largest increases in nutrient delivery will occur in the lower-income region, where nitrogen and phosphorus delivery are expected to grow by 41% and 40%, respectively. This is primarily driven by population and economic growth, along with the expansion and intensification of agricultural activities. The agricultural sector in these regions is anticipated to expand crop and livestock production, leading to a 55% growth in overall value added. Under current policies, this expansion will necessitate higher fertiliser applications and increased manure production, contributing to a 41% rise in nitrogen delivery.

Decoupling between economic activity and nutrient delivery is even stronger in higher- and middle-income regions. In the higher-income region, phosphorus delivery is projected to stabilise, and nitrogen delivery is projected to increase by 4%. The primary driver of this near-complete decoupling is improvements in wastewater treatment, which will reduce delivery by 43% for nitrogen and 27% for phosphorus, respectively, while the population remains largely stable. In the middle-income region, however, nutrient delivery is expected to increase by 18% and phosphorus delivery by 14%, largely driven by agricultural activity.

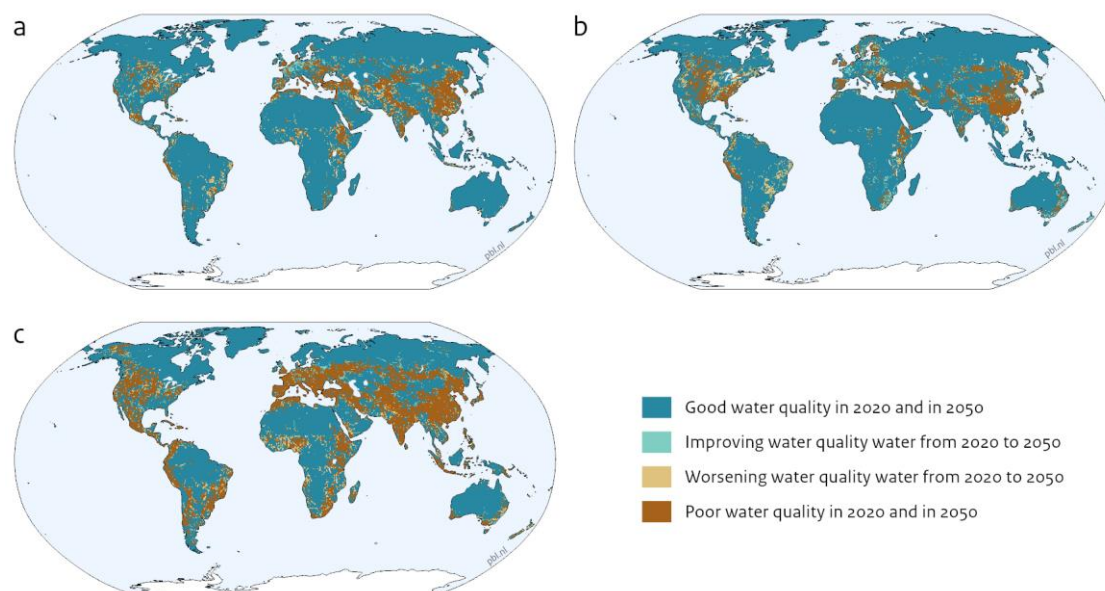
Nutrient delivery indicates potential risks to water quality and biodiversity, but do not necessarily translate into environmental problems or water quality concerns for local populations, except in locations where nitrogen concentrations exceed critical standards. In 2020, the global area with groundwater concentration of nitrogen exceeding the WHO standard for drinking water reached around 5 million km² (Figure 3.12). In 2020, over 17% of Europe's total area exceeded critical thresholds for nitrogen concentrations in groundwater (followed by almost 17% in the Middle East and North America, and 15% in East Asia). Europe also is the region with the highest share of area (48%) exceeding critical thresholds for nitrogen concentration in surface water in 2020, followed by East Asia (41%) and South Asia (21%).

By 2050 under current policies, the global area with poor-quality groundwater is expected to increase by 22%, reaching around 6 million km². The biggest increases are projected for the Americas, Sub-Saharan Africa, and Middle East and North Africa, and South Asia. In contrast, the area with poor-quality groundwater is projected to decrease in Europe (-14%) and in Japan, Korea and Oceania (-7%), due to ongoing improvements in wastewater treatment and a modest reduction in agricultural production. However, at the global level, this small improvement is counterbalanced by significant increases in the area where groundwater is unsuitable for drinking, in the lower-income region (+37%) and middle-income region (+28%).

The water quality indicators related to phosphorus suggest that in 2020 most of Europe (70%) exceeded critical thresholds for phosphorus concentrations in surface water, followed by East Asia (66%) and South Asia (57%). Water quality indicators related to phosphorus are expected to remain poor due to the slow turnover of phosphorus in soils leading to long-term effects of historical over-application.

Figure 3.12. Change in areas where water pollution exceeds standard thresholds

Change in areas exceeding critical thresholds for a) nitrogen concentration in surface water, b) nitrogen concentrations in groundwater, c) phosphorus concentrations in surface water



Note: The critical threshold for nitrogen in groundwater considered is the standard for drinking water set by the World Health Organization, 11.3 mg N/L. For nitrogen and phosphorus in surface water, thresholds of 2.5 mg N/L and 0.1 mg P/L, respectively, are considered, based on a literature review, as proposed by Bouwman et al. (2024^[77]).

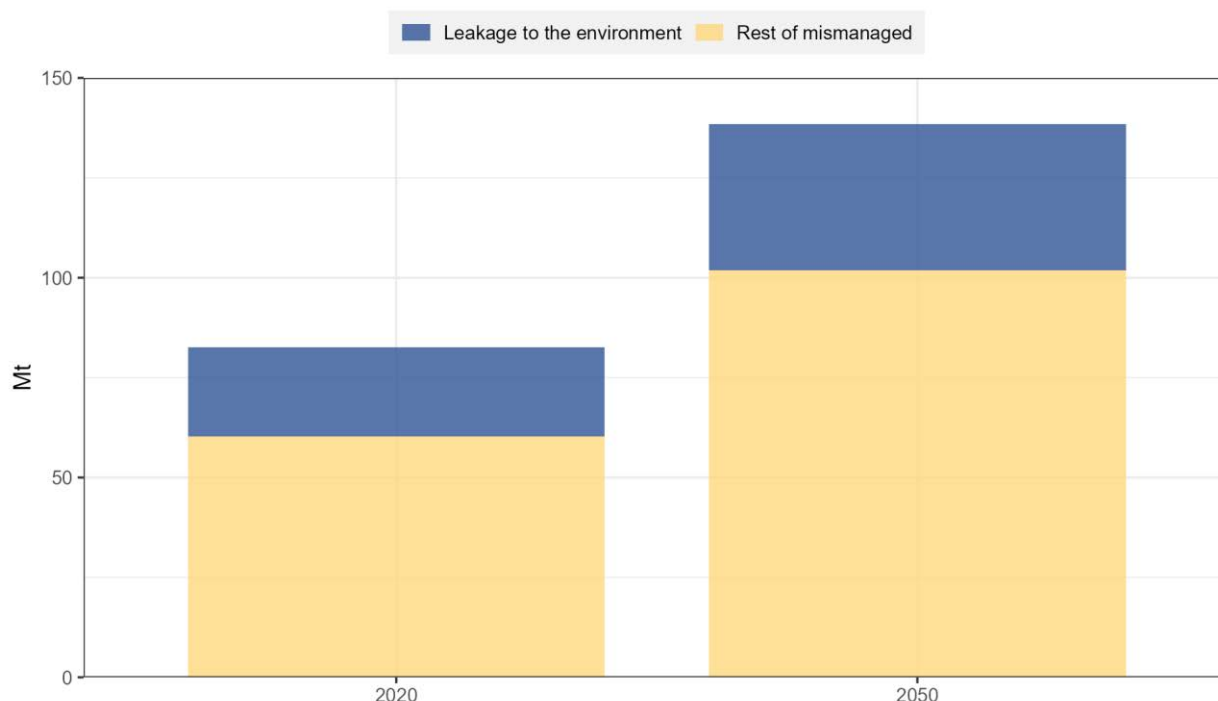
Source: Environmental Outlook modelling toolbox.

3.5.4. Plastic pollution

In 2020, 83 Mt of plastic waste was estimated to be mismanaged globally, as shown in Figure 3.13, significantly more than what is recycled.¹⁵ A substantial portion of mismanaged waste (21%; 22 Mt) leaked into terrestrial and aquatic environments. The remainder consisted mostly of non-sanitary landfills and dumpsites (42% of mismanaged waste in 2020) and open burning (31%).

Figure 3.13. Mismanaged plastic waste and leakage to the environment

Mismanaged plastic waste and plastic leakage in Mt in 2020 and 2050



Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/5e19zn>

Under current policies, annual mismanaged plastic waste is expected to increase by 66% (to 138 Mt) by 2050 from 2020 levels. This increase is despite a decreasing share of total waste being mismanaged; all regions are assumed to improve their waste management systems over time, driven by income growth. Consequently, annual plastic leakage is projected to continue to grow by two-thirds in the absence of new policies, from 22 Mt in 2020 to 37 Mt in 2050, while almost 900 Mt of plastics are projected to accumulate in the environment over the same period. Plastic leakage is more pronounced in countries currently lacking advanced waste collection and management systems, as discussed in earlier OECD reports (OECD, 2022^[5]; OECD, 2024^[78]; OECD, 2025^[79]). Macroplastic leakage is projected to remain at or decline to near zero levels in the higher-income region with advanced waste management infrastructure. In contrast, macroplastic leakage continues to increase in regions currently lacking comprehensive waste management. This increase is further exacerbated by fast projected GDP growth in those regions. For instance, the volume of macroplastic leakage in Non-OECD Asia is projected to grow by more than 80% between 2020 and 2050, and by more than 150% in Sub-Saharan Africa, well above the global average of 64%. Despite a relatively low growth rate, China remains the country with the highest plastic leakage, projected to rise to 6.8 Mt in 2050. A major risk for the coming decades is the significant increase in plastic waste that is generated (see also Chapter 2), which could overwhelm waste collection, sorting and treatment capacities.¹⁶

A substantial share of plastics that leak to the environment reach aquatic environments, where they accumulate in rivers, lakes and oceans (OECD, 2022^[5]). Some of the accumulated plastics eventually degrade into smaller macroplastics and microplastics, which can also travel through the aquatic environments. Given the transboundary nature of rivers and oceans, plastic pollution can reach countries different from where the leakage occurred. Large stocks of plastics have already accumulated in the aquatic environment (mostly in rivers), and continued plastic leakage implies these stocks continue to build up. Projections for Southeast and East Asia show that especially the lower-middle income ASEAN countries are vulnerable to plastic pollution (OECD, 2025^[79]). In contrast, recent data suggests that plastic leakage on European coastlines may have reduced by approximately 29% in recent years (Hanke et al., 2025^[80]), highlighting that advanced policy frameworks can be effective in reducing aquatic plastic leakage.

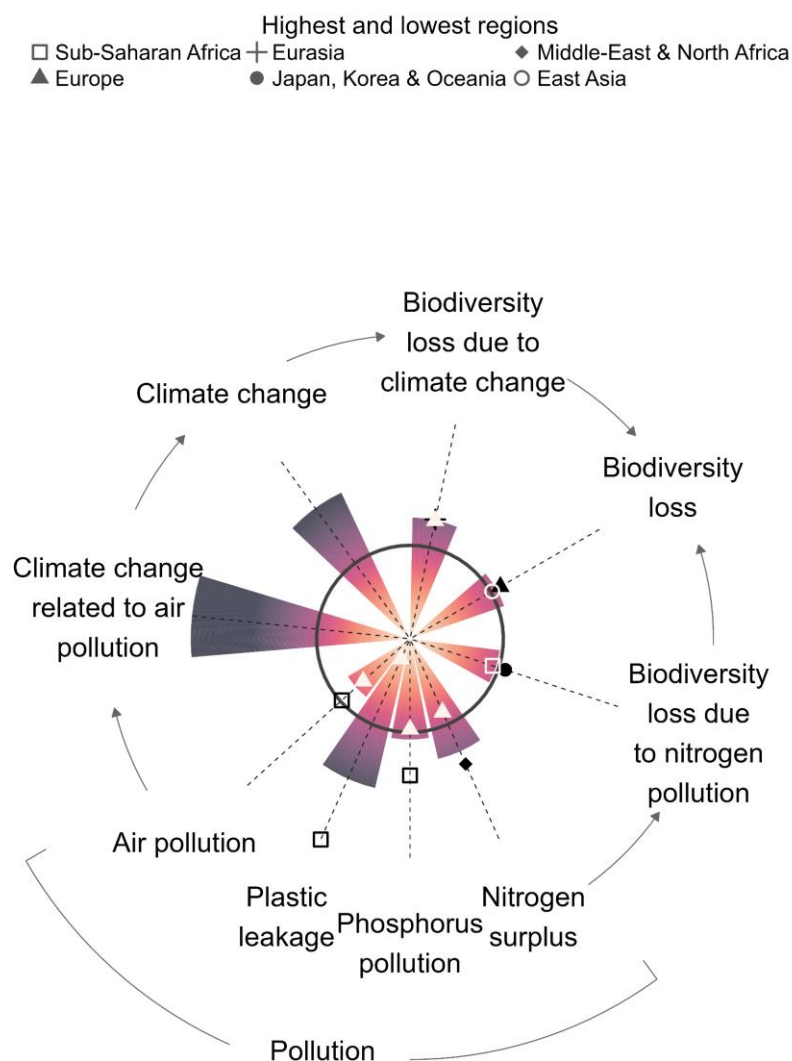
3.6. Mutually reinforcing aspects of the triple planetary crisis

Climate change, biodiversity loss and pollution are connected through shared drivers, interacting pressures, and compounding impacts. Consequently, both a comprehensive understanding and the development of effective solutions require moving beyond siloed approaches. As shown in the previous subsections, the state of each dimension can be assessed using a range of indicators. A dashboard for tracking the evolution of each dimension can therefore take multiple forms. Throughout this report, a wide array of detailed indicators has been presented to reflect the complexity of the challenges, drawing on the quantitative modelling toolbox described in Chapter 1. A synthetic dashboard, based on selected key indicators, can summarise how the developments in the state of climate change, biodiversity loss and pollution interlink. As above, the selection is not exhaustive but is intended to underscore the interdependencies between the three dimensions, in particular how the state of one dimension can influence the others.

The dashboard brings together a set of “headline indicators” for each of the dimensions of the triple planetary crisis. For climate change, it tracks global temperature change relative to pre-industrial levels. Terrestrial biodiversity loss is measured through MSA of plants and warm-blooded vertebrates. Pollution is represented through several indicators: population-weighted PM_{2.5} concentration for air pollution, leakage of plastic waste into the environment for plastic pollution, area of surface water exceeding critical phosphorus concentration thresholds, and nitrogen surplus from agriculture for nutrient pollution. In addition, the dashboard also includes “interaction indicators” that illustrate how the three dimensions are interlinked: air pollutants and SLCP influence global warming; climate change leads to biodiversity loss; and nitrogen pollution acts as a further driver of biodiversity decline. While not an exhaustive list, this combination of quantified indicators offers a valuable first insight into the overall trajectory of the triple planetary crisis and its interconnections. Figure 3.14 displays the evolution of all selected indicators at the global level. As in Figure 3.1, the length of each bar indicates the change over time (2020-2050). For indicators with a strong local component (all indicators except climate-related ones), the regions with the fastest and slowest growth (or decline) are marked.

Figure 3.14. Projections of intensifying and mutually reinforcing environmental degradation

Global evolution towards 2050 for selected indicators of the state and interactions of biodiversity, climate change and pollution



Environmental state	Detailed indicator
Biodiversity loss due to climate change	Loss in Mean Species Abundance caused by climate change
Biodiversity loss	Loss in Mean Species Abundance
Biodiversity loss due to nitrogen pollution	Loss in Mean Species Abundance
Nitrogen surplus	Nitrogen surplus in agriculture (Mt)
Phosphorus pollution	Area (km ²) with surface water pollution above the WHO P threshold (0.1 mg P/L)
Plastic leakage	Leakage of plastic waste into the environment (Mt)
Air pollution	PM _{2.5} concentration (µg/m ³)
Climate change related to air pollution	Effective radiative forcing of short-lived climate forcers (BC, CH ₄), aerosols, and ozone (W/m ²)
Climate change	Global surface temperature change relative to pre-industrial times (°C)

Note: The length of the bars represents the evolution from 2020 to 2050. The circle indicates the 2020 level. For the sake of readability, the bar for the Climate change related to air pollution is truncated. Annex 3.A provides detailed values and units for the reported indicators.

Source: Environmental Outlook modelling toolbox.

StatLink  <https://stat.link/r1v4u3>

Once again, the overall picture sends a clear signal: current policies are insufficient to reverse environmental degradation. Compared to 2020, most dimensions are projected to worsen by 2050 under the continuation of existing policy efforts. Global temperatures rise from around 1.2°C in 2020 to 2.1°C by 2050. Biodiversity continues to decline, with MSA falling from 59.7 in 2020 to 56.5 in 2050. As mentioned in Section 3.4, this reduction may appear modest but actually is equivalent to the conversion of several million km² of pristine habitat into areas where all the original species have been lost. Plant biodiversity fares even worse than that of warm blooded vertebrates, dropping from 55 to less than 51 over the same period. In other words, by 2050, nearly half of the global plant biodiversity is projected to be lost. Clearly, current policy measures (see Annex 2.A for details) fall short of halting and reversing biodiversity loss, as agreed under the Kunming-Montreal Global Biodiversity Framework.

Various forms of pollution also follow a rising trend. Plastic leakage into the environment is expected to increase by 64% between 2020 and 2050, undermining efforts to meet the global ambition to end plastic pollution. The nitrogen surplus indicator shows a smaller but still notable increase, reaching a 32% rise over the same period. A more positive development is the projected global decline of 21% in population-weighted PM_{2.5} concentrations by 2050 relative to 2020.

These projections further illustrate that climate change, biodiversity loss and pollution mutually reinforce each other, with several interaction effects expected to intensify over time. Climate change emerges as the dominant driver of future biodiversity loss, overtaking land use change, which has historically been the primary cause. This shift highlights the deepening interlinkage between these two dimensions. In turn, even if not visible from our dashboard, biodiversity decline is expected to limit climate change mitigation by reducing the ability of ecosystems to act as carbon sinks, especially forests and oceans (IPBES, 2024^[81]). In parallel, the contribution of air pollutants and SLCPs to climate change is growing significantly in proportional terms. Historically, the combined effective radiative forcing of SLCPs, aerosols, and ozone has been negative, exerting a net cooling effect on the climate system. By 2020, however, this effect has diminished, turning into a small warming effect that is projected to grow over time. While rising CH₄ emissions contribute to this trend, the principal driver is the decline in emissions of aerosols, SO₂ and, to a lesser extent, BC, thereby reducing the offsetting cooling influence they previously exerted. Finally, nutrient pollution will continue to pose a threat to biodiversity loss. Although terrestrial biodiversity loss linked specifically to nitrogen pollution shows a slight decrease by 3% at the global level between 2020 and 2050 under current policies, this global average masks significant regional disparities. In some regions, nitrogen-driven biodiversity loss increases, up to 7%, reflecting uneven mitigation efforts and differing agricultural intensities. More generally, pollution, not limited to nutrients, is projected to remain one of the key five drivers of biodiversity loss and, in response, biodiversity decline is expected to exacerbate water pollution, not least through diminished pollution filtering (IPBES, 2024^[81]).

Local and global scales are closely interconnected. While climate change is inherently a global phenomenon, since greenhouse gas emissions contribute to planetary warming regardless of their origin, its physical manifestations, such as temperature and precipitation changes, vary significantly across regions. In contrast, biodiversity loss and pollution are often more localised in nature, with their drivers, pressures and impacts being tightly linked to specific geographies (albeit with global consequences). The projections presented in this chapter underscore the growing importance of global factors, particularly climate change, in accelerating biodiversity decline. Similarly, while air pollution is largely shaped by regional trends in emissions, resulting in varied air quality outcomes across the world, cross-border and transboundary dynamics remain important. Biophysical and economic channels—including international trade, atmospheric transport of pollutants, and other spillover effects—establish strong linkages between countries and regions, reinforcing the need for co-ordinated global action alongside locally tailored solutions.

There is substantial regional variation in the evolution of all dimensions (Figure 3.14). For example, while the leakage of plastic waste into the environment is projected to increase by 64% globally between 2020 and 2050, regional trends diverge sharply, from very small leakage rates in most OECD countries to more than a doubling (155%) in Sub-Saharan Africa. Other indicators also illustrate contrasting trends: for instance, nutrient pollution is expected to rise in some regions while declining in others. Biodiversity loss due to climate change increases by approximately 30% in all regions, while biodiversity losses caused by nitrogen pollution differ substantially across regions increasing in four out of nine regions and decreasing in the remaining five. Despite these differences, all regions are expected to experience an increase in biodiversity loss, ranging from 2% to 12%, with a global average of 8%. These trends highlight that maintaining protected areas alone, as modelled under our current policies scenario, is insufficient to reverse biodiversity loss, and more systemic, integrated actions are needed to "bend the curve". PM_{2.5} concentrations are projected to decrease in all regions, but at different speeds, from -32% in Europe to -4% in South Asia, where it remains the highest in 2050.

The outlook presented in this chapter sends a clear signal that current trends are unsustainable, and environmental degradation is set to exacerbate in the coming decades. Projections show that the state of climate change, biodiversity loss and pollution is likely to diverge even more from pathways aligned with global goals and ambitions, underscoring the urgent need calling for stronger and more co-ordinated policy action. The increasing impacts associated with each dimension also heighten the costs and complexity of adaptation efforts, as the biophysical and economic consequences affect current and future health, wealth, and overall well-being through multiple channels. Notably, the overlapping nature of the three dimensions of the triple planetary crisis puts stress on the same systems, creating compound impacts that may make effective adaptation even more challenging.

At the same time, the analysis reveals that progress is possible: several region-indicator pairs show positive trends, suggesting that well-designed and ambitious policy measures can reverse negative developments and steer economies toward more sustainable trajectories.

It is important to note that the projections presented here do not account for government pledges that have yet to be translated into concrete policy measures, as is the case for e.g. many Net Zero targets for climate change mitigation announced in Nationally Determined Contributions and Action Plans set in National Biodiversity Strategies. This reinforces the urgent need to convert high-level ambitious targets into comprehensive and actionable policy packages. The complex interlinkages—spanning drivers, pressures, state, and impacts—highlight the critical importance of integrated and aligned policy responses across environmental domains.

Annex 3.A. Detailed indicators of environmental pressure

This chapter focuses on a selected set of environmental pressures, related to air, land, water and soils; together these give an informative snapshot of projected trends, without being exhaustive. The first set of selected indicators covers the environmental pressures that are emitted to the air, thereby affecting climate change and pollution, particularly air pollution. These include emissions of carbon dioxide (CO₂), CH₄, and nitrous oxide (N₂O). In addition to GHGs – the primary drivers of climate change – this set also includes emissions of other gases that influence global temperatures. Short-lived climate pollutants (SLCPs) such as black carbon (BC), contribute to global warming (through positive effective radiative forcing, especially when deposited on snow), while also causing fine particulate matter (PM) air pollution. Conversely, gases such as sulphur dioxide (SO₂) contribute to air pollution but have a negative effective radiative forcing, exerting a net cooling effect on the planet. CH₄, a potent GHG, is also a precursor for the formation of ground-level ozone, a harmful air pollutant. The emission of these gases therefore represents pressures on climate change and (air) pollution and often stem from common drivers. For example, coal-fired electricity generation results in emissions of CO₂, BC, and SO₂ (and some other gases) simultaneously.

A second set of indicators capture pressures associated with land use. Land use change, especially when it involves deforestation, can contribute to net GHG emissions – as well as to emissions of air pollutants – and is one of the five main causes of biodiversity loss (IPBES, 2019^[16]). For example, healthy forests and peatlands act as carbon sinks by absorbing CO₂ and serve as vital reservoirs of biodiversity. Conversely, the expansion of agricultural land threatens biodiversity through habitat destruction and fertilised soils and livestock are major sources of N₂O and CH₄ emissions. Deforestation in tropical forests leads to increased CO₂ emissions, while simultaneously endangering biodiversity, especially when it occurs in biodiversity hotspots. The combination of several indicators – CO₂, N₂O, and CH₄ emissions, and cropland area increases – reflects the fact that Agriculture, Forestry and Other Land Use (AFOLU) activities are a shared driver of both climate change and biodiversity loss. This set of integrated indicators provides a more comprehensive view of the environmental pressures than a fragmented focus on individual indicators or domains.

A third group of environmental pressures is related to pressures to water and soil (and directly or indirectly in some cases also the air) that link biodiversity loss and pollution. Emissions of ammonia (NH₃) and nitrogen oxides (NO_x) contribute to air pollution through the formation of fine particulate matter (PM) and, in the case of NO_x, ground-level ozone – but as part of a complex nitrogen cascade (see Chapter 6) these emissions also lead to nitrogen deposition, which adversely affects biodiversity. Phosphorus pollution – and mining of phosphorus rock – is similarly associated with ecological degradation and biodiversity decline. For instance, nutrient pollution in water bodies increases the risk of eutrophication, causing significant harm to aquatic ecosystems. SO₂ emissions also contribute to PM air pollution and, together with NO_x, can cause acidification, impacting both terrestrial and aquatic ecosystems. The expansion of built-up areas can result in biodiversity loss through habitat destruction or fragmentation and can be associated with waste streams that exacerbate pollution and localised sources of nutrient pollution. Finally, mismanaged plastic waste is a major pollution concern in its own right but also intersects with climate change and biodiversity loss. As most plastics are currently produced from fossil fuels, their production and processing contribute to greenhouse gas emissions. Once released into the environment, plastic waste can damage natural ecosystems and poses a threat to biodiversity.

Figure 3.1 and Figure 3.2 in the main text reported the global level and the regional intensities of selected environmental pressures. Annex Table 3.A.1 provides the units of these indicators and Annex Table 3.A.2 summarises their values. Similarly, Figure 3.14 shows indicators on the state of the environment: Annex Table 3.A.3 lists the units of these indicators and Annex Table 3.A.4 details their values.

Annex Table 3.A.1. Units of the indicators summarising the evolution of environmental pressures

Level		Intensity	
Indicator	Unit	Indicator	Unit
Land Cover (Built-up Area)	Million hectares	Share of total land dedicated to built-up area	Percentage points
Land Cover (Cropland)	Million hectares	Share of total land dedicated to crops	Percentage points
NH ₃ (ammonia)	Million tonnes of NH ₃	Emissions of NH ₃ per capita	kg of NH ₃ per person
NO _x (oxides of nitrogen)	Million tonnes of NO ₂ equivalent	Emissions of NO _x per capita	kg per person
Phosphorus delivery	Million tonnes of Phosphorus (P)	Share of delivery in total load at the river mouth	Percentage points
Mismanaged plastic waste	Million tonnes	Mismanaged waste per capita	kg per person
SO ₂ (sulfur dioxide)	Million tonnes of SO ₂	Emissions of SO ₂ per capita	kg of SO ₂ per person
BC (black carbon)	Million tonnes of BC	Emissions of BC per capita	kg of BC per person
CH ₄ (methane)	Million tonnes of CH ₄	Emissions of CH ₄ per capita	kg of CH ₄ per person
CO ₂ (carbon dioxide)	Billion tonnes of CO ₂	Emissions of CO ₂ per capita	Tonnes of CO ₂ per person
CO ₂ (AFOLU)	Million tonnes of CO ₂	Emissions of CO ₂ per capita	kg of CO ₂ per person
N ₂ O (nitrous oxide)	Million tonnes of N ₂ O	Emissions of N ₂ O per capita	kg of N ₂ O per person

Note: Indicators on the level of the pressures determine the length of the bars, while indicators on the regional intensity determine the colour shade of the bars in regional plots.

Annex Table 3.A.2. Detailed values of the indicators summarising the evolution of environmental pressures

Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050	Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050
North America					Eurasia				
Land cover (built-up area)	22.3	32.0	43.3	1.8	Land cover (built-up area)	4.1	5.1	25.2	0.24
Land cover (cropland)	204	216	5.9	12.0	Land cover (cropland)	206	218	5.9	10.3
NH ₃	4.9	6.2	26.5	14.8	NH ₃	2.3	3.3	43.1	11.2
NO _x	8.8	4.3	-51.3	10.2	NO _x	7.9	4.2	-46.8	14.1
Phosphorus delivery	0.57	0.62	9.8	43.8	Phosphorus delivery	0.97	1.0	6.6	42.6
Mismanaged plastic waste	2.8	1.4	-49.0	3.4	Mismanaged plastic waste	5.1	6.1	18.9	20.2
SO ₂	2.5	0.43	-82.5	1.0	SO ₂	8.6	1.5	-82.7	5.0
BC	0.17	0.05	-70.1	0.12	BC	0.24	0.07	-69.7	0.24
CH ₄	37.7	23.0	-39.0	54.6	CH ₄	41.1	66.8	62.6	224
CO ₂	5.3	3.5	-33.4	8.3	CO ₂	2.8	2.7	-3.0	9.0
CO ₂ (AFOLU)	111	82	-26.3	195	CO ₂ (AFOLU)	169	254	50.2	852
N ₂ O	1.4	1.3	-2.8	3.1	N ₂ O	0.61	0.80	31.4	2.7
Japan, Korea & Oceania					Central & South America				
Land cover (built-up area)	3.9	5.3	36.9	0.61	Land cover (built-up area)	8.5	11.6	35.3	0.57
Land cover (cropland)	39.4	52.3	33.0	6.0	Land cover (cropland)	179	220	22.6	10.8
NH ₃	1.4	2.6	84.0	12.1	NH ₃	9.8	14.0	42.5	18.6
NO _x	5.1	2.5	-51.5	11.3	NO _x	11.9	9.6	-19.5	12.8
Phosphorus delivery	0.27	0.27	-1.5	51.8	Phosphorus delivery	1.8	2.2	18.9	42.9
Mismanaged plastic waste	0.49	0.34	-31.6	1.6	Mismanaged plastic waste	12.5	15.3	22.4	20.5
SO ₂	2.3	1.3	-40.8	6.1	SO ₂	6.7	2.5	-63.7	3.3
BC	0.21	0.18	-18.0	0.8	BC	1.0	1.0	-3.2	1.4
CH ₄	11.1	11.2	1.3	51.2	CH ₄	51.3	48.7	-5.1	65.0
CO ₂	1.9	1.1	-41.7	5.0	CO ₂	2.0	3.5	69.6	4.6
CO ₂ (AFOLU)	-200	-23.8	88.1	-109	CO ₂ (AFOLU)	596	1522	155	2033
N ₂ O	0.34	0.42	21.1	1.9	N ₂ O	1.8	2.0	12.8	2.8

Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050	Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050
Europe					South Asia				
Land cover (built-up area)	12.5	15.3	22.3	2.7	Land cover (built-up area)	7.4	13.7	85.4	1.4
Land cover (cropland)	148	144	-2.4	25.2	Land cover (cropland)	354	360	1.6	36.1
NH ₃	4.8	5.4	12.6	8.7	NH ₃	19.4	29.3	50.6	9.2
NO _x	7.8	3.2	-59.7	5.1	NO _x	25.7	29.7	15.6	9.4
Phosphorus delivery	0.82	0.78	-4.5	55.3	Phosphorus delivery	2.1	2.8	32.2	57.0
Mismanaged plastic waste	4.0	0.99	-75.0	1.6	Mismanaged plastic waste	21.5	50.1	133	15.6
SO ₂	5.7	1.1	-81.1	1.7	SO ₂	22.0	15.3	-30.5	4.8
BC	0.29	0.08	-72.3	0.13	BC	2.3	1.2	-48.3	0.37
CH ₄	25.9	18.9	-26.9	30.3	CH ₄	78.8	90.1	14.4	28.3
CO ₂	3.5	1.9	-46.0	3.0	CO ₂	5.8	12.8	119	4.0
CO ₂ (AFOLU)	38.3	-56.1	-246	-89.8	CO ₂ (AFOLU)	1535	367	-76.1	115
N ₂ O	1.1	1.0	-5.8	1.6	N ₂ O	2.5	3.2	27.5	1.0
East Asia					Sub-Saharan Africa				
Land cover (built-up area)	6.8	8.6	26.0	0.79	Land cover (built-up area)	5.6	13	130	0.54
Land cover (cropland)	128	131	2.7	12.1	Land cover (cropland)	267	375	40.8	15.6
NH ₃	8.8	9.8	11.1	7.3	NH ₃	6.9	12.5	80.9	5.7
NO _x	25.5	14.3	-43.6	10.6	NO _x	10.3	11.0	6.5	5.0
Phosphorus delivery	1.5	1.5	-0.19	53.6	Phosphorus delivery	0.78	1.3	62.4	32.3
Mismanaged plastic waste	19.1	26.8	39.9	20.3	Mismanaged plastic waste	10.5	26.6	154	12.5
SO ₂	14.8	2.3	-84.3	1.7	SO ₂	5.0	3.2	-35.8	1.5
BC	1.1	0.20	-80.6	0.15	BC	1.8	1.4	-23.9	0.62
CH ₄	52.8	30.6	-42.0	22.7	CH ₄	46.1	50.1	8.6	22.8
CO ₂	11.4	9.4	-17.8	6.95	CO ₂	1.8	3.7	101	1.7
CO ₂ (AFOLU)	57.4	-381	-763	-282	CO ₂ (AFOLU)	1020	1430	40.2	652
N ₂ O	2.1	2.0	-7.2	1.5	N ₂ O	1.3	1.5	10.6	0.67
Middle East & North Africa					World				
Land cover (built-up area)	4.3	8.0	85.6	0.73	Land cover (built-up area)	75.5	113	49.0	0.87

Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050	Indicator	Value in 2020	Value in 2050	Rel. change in 2050	Intensity in 2050
Land cover (cropland)	62.2	78.2	25.7	7.2	Land cover (cropland)	1587	1795	13.1	13.8
NH ₃	2.4	3.9	61.2	5.8	NH ₃	60.9	87.0	42.9	9
NO _x	9.3	7.5	-20.1	11.0	NO _x	129	116	-10.5	11.9
Phosphorus delivery	0.77	1.1	42.5	25.9	Phosphorus delivery	9.6	11.5	20.0	46.0
Mismanaged plastic waste	6.6	10.9	63.8	16.1	Mismanaged plastic waste	82.6	138	67.6	14.4
SO ₂	9.2	0.65	-92.9	0.96	SO ₂	81.7	29.4	-64.0	3.0
BC	0.32	0.18	-42.2	0.27	BC	7.4	4.3	-41.6	0.44
CH ₄	34.5	58.2	68.6	86.3	CH ₄	379	398	4.8	40.9
CO ₂	2.7	4.6	68.9	6.8	CO ₂	37.2	43.0	15.6	4.4
CO ₂ (AFOLU)	-3.6	-0.52	85.4	-0.77	CO ₂ (AFOLU)	3324	3194	-3.9	329
N ₂ O	0.38	0.60	59.0	0.89	N ₂ O	11.5	12.8	11.2	1.3

Note: Values in 2020 and 2050, as well as intensities for 2050 are reported in the units listed in Annex Table 3.A.1, while the relative change in 2050 compared to 2020 is presented as a percentage. For example, in the North America region, the built-up area in 2020 was 22.3 million hectares; this is projected to increase by 43.3% by 2050, reaching 32 million hectares. In 2050, this will represent 1.8% of the total land area in this region. In Figure 3.1 and Figure 3.2, the length of the bars represents the relative change between 2020 and 2050; in Figure 3.2, the colour shading of the bars reflects the intensity in 2050.

Source: Environmental Outlook modelling toolbox.

Annex Table 3.A.3. Units of the indicators summarising the evolution of the state of the environment

Indicator	Unit
Biodiversity loss due to climate change	index
Biodiversity loss	index
Biodiversity loss due to nitrogen pollution	index
Nitrogen surplus	Million tonnes of nitrogen (N)
Phosphorus pollution	Million hectares of polluted land
Plastic leakage	Million tonnes of plastics
Air pollution	µg/m ³
Climate change related to air pollution	Watts/m ²
Climate change	Degrees Celsius

Note: Indicators on the level of the pressures determine the length of the bars. Biodiversity indicators (based on MSA) are already indexes, without unit.

Annex Table 3.A.4. Detailed values of the indicators summarising the state of the environment

Indicator	Value in 2020	Value in 2050	Rel. change in 2050
World			
Biodiversity loss due to climate change	6.9	9.0	30.3
Biodiversity loss	40.3	43.5	7.8
Biodiversity loss due to nitrogen pollution	3.5	3.4	-2.6
Nitrogen surplus	129	170	32.1
Phosphorus pollution	4230	4606	8.9
Plastic leakage	22.3	36.6	64.0
Air pollution	22.9	18.0	-21.2
Climate change related to air pollution	-0.01	0.45	3187
Climate change	1.2	2.1	73.2

Note: Values in 2020 and 2050, as well as intensities for 2050 are reported in the units listed in Annex Table 3.A.3, while the relative change in 2050 compared to 2020 is presented as a percentage. For example, global increase in temperature (Climate change) was 1.2°C in 2020, it is projected to reach 2.1°C by 2050, corresponding to a 73.2% increase. In Figure 3.14, the length of the bars represents the relative change between 2020 and 2050.

Source: Environmental Outlook modelling toolbox.

Annex 3.B. The economic consequences of climate change

Climate change affects everyday life through many channels: extreme events, human health, labour productivity, crop yields, sea level rise, etc. Combined, their impact translates into economic damages, which are expected to increase significantly over time. It is important to note that the literature on macroeconomic damages from climate change provides a wide range of estimates. The lack of comparability between the methodologies used render an attempt of identifying a robust range of damage estimates from climate change challenging.¹⁷ Due to the long-term nature of climate change and the effect of emissions in the coming decades, it is essential to look at consequences through the 21st century.

Recent literature indicates high damages from climate change, although there is a lively debate about a plausible range of damages and the causes for the wide variety of estimates (Morris et al., 2025^[82]). An ongoing debate is whether climate damages should include effects on economic growth rates. Some statistical models assume that climate change impacts can reduce economic growth, not just levels. Nath, Ramey and Klenow (2024^[83]) highlight that this assumption influences end-of-century damage projections. Along with other recent studies, such as Bilal and Känzig (2024^[84]), they suggest that impacts persist over 10 years after a temperature shock but their shocks do not support permanent growth reductions. This partially bridges the gap in existing studies, which tended to assume either no effect of climate damages on growth rates at all (e.g. Barrage and Nordhaus (2024^[85])) or a full effect of damages on GDP growth rates Burke et al., (2015^[86]). Advanced structural models, such as the one used in OECD (2015^[7]) take an intermediate approach by assuming damages affect capital stocks, which in turn have an effect on growth rates by diminishing expansive investment rates (as more investments are needed to replace existing capital stocks).

Even at current levels of global warming, there is a wide span of damage projections. Since we lack a no-warming counterfactual, it is impossible to verify which estimate is correct. Bilal and Känzig (2024^[84]), for example, suggest that warming of 1°C lowers global output 12% below what it would have been without climate change. By 2100, they project that warming of 3°C could lower global output by almost half. Their impact estimate for a 1°C shock scales up the linear effect of smaller shocks (observed in the sample), implying extrapolations far beyond the sample. This implicitly assumes adaptation "as observed historically" but might underestimate adaptation in a future richer and high-warming world, as well as any non-linearities in the system.

These estimates contrast with recent structural modelling from the COACCH project (van der Wijst et al., 2023^[87]), which projects global damages from a 3°C temperature change by 2100 to range between 10% to 12% of GDP (medium estimate). Importantly, climate change impacts are not evenly distributed across the globe: regions such as Sub-Saharan Africa and South Asia are expected to experience damages (expressed as a share of GDP) up to 1.5 times higher than the global average, qualitatively in line with earlier OECD analysis (OECD, 2015^[7]). Despite the significant differences compared to the results from statistical modelling (Bilal and Känzig, 2024^[84]), the COACCH project represents a notable advancement by broadening the scope of quantified impacts. When aggregated at the global level, the COACCH low, medium and high damage estimates align closely with those from the damage functions in DICE (Nordhaus, 2014^[88]), Howard and Sterner (2017^[89]) and Burke, Hsiang and Miguel (2015^[86]), although regional results and underlying drivers of impacts vary significantly.

In addition to methodology, projections of future climate damages depend on the emissions and temperature trajectory used. Literature on future climate impacts covers a wide range of temperature scenarios, with IPCC AR6 projections for 2100 ranging from 1.4°C to 4.4°C. Many studies use the high-end RCP 8.5 pathway or its successor, SSP5-8.5 (Burke, Hsiang and Miguel, 2015^[86]; Nath, Ramey and Klenow, 2024^[83]), which projects more than 4°C warming by 2100, resulting from emissions that continue to rise rapidly throughout the century, well above the current policy trajectory projected in this Environmental Outlook. Such a high emissions trajectory is thus more of an upper bound of what could happen than a plausible current policies projection. According to the UNEP Emissions Gap report (United Nations Environment Programme, 2024^[90]), global warming by 2100 is projected to range from 1.9°C to 3.6°C, with a median forecast of 3.1°C, roughly in line with the pathway of this Environmental Outlook. Thus, climate risks are significantly lower for the median current policy emissions pathways than for no-policy upper-bound scenarios.

Temperature-related mortality risk

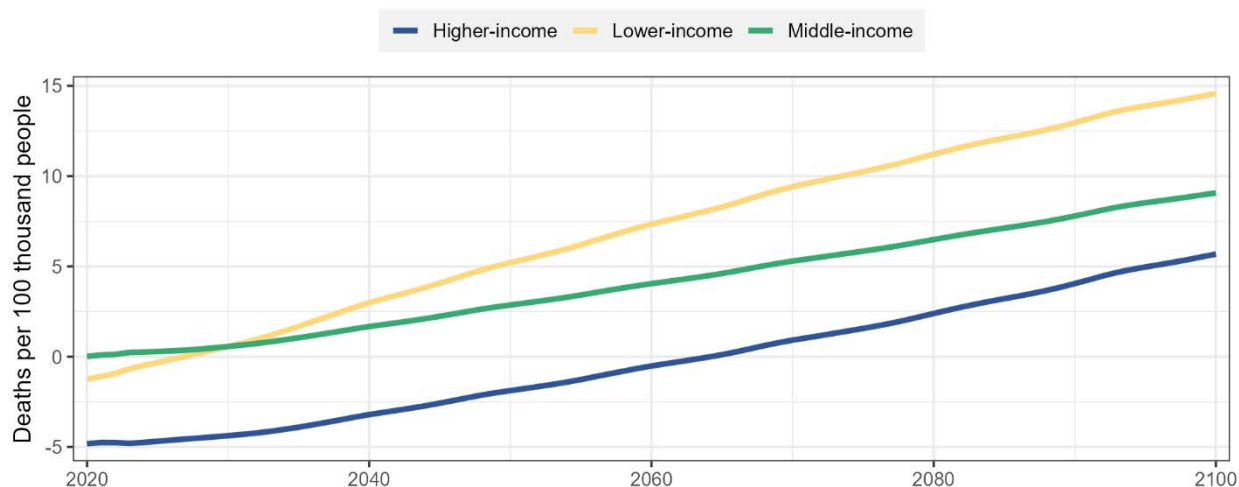
Not all economic consequences are easily expressed in terms of changes in economic output or GDP. In some cases, the biophysical impacts are important from a welfare perspective, even if they do not significantly affect macroeconomic activity. The key example of this is mortality (OECD, 2015^[7]). Uncertainty surrounding temperature-related mortality estimates is large. Some studies indicate that at a global level increased deaths from heat already outweigh reductions in cold-related mortality (Bressler et al., 2021^[91]; Gasparrini et al., 2017^[92]). However, other studies suggest that, at low levels of warming, the reduction in cold-related mortality in cold and temperate climates may still exceed the increase in heat-related deaths in hotter climates (Carleton et al., 2022^[93]; Zhao et al., 2021^[94]).

Using data from 43 countries, Zhao et al. (2021^[94]) estimate that, between 2000 and 2019, approximately 489 000 heat-related deaths occurred each year, 46% in Asia and 37% in Europe. Cold-related mortality is also large, with an average of 4.6 million deaths annually over the same period — about 52% of these in Asia and 26% in Africa (Zhao et al., 2021^[94]).

Under current policies, temperature-related mortality risk is set to rise in the coming decades, disproportionately affecting the lower-income region. Using projections from the Environmental Outlook modelling toolbox and the methodology of Carleton et al. (2022^[93]), estimates suggest that by 2050, the average temperature-related mortality risk will reach -1.9 deaths (increasing from -4.8 in 2020) per 100 thousand people in high income countries, 5.2 in upper-middle income countries, and 2.9 in low and lower-middle income countries (Annex Figure 3.B.1). By 2100, the corresponding mortality risk is projected to rise sharply to 5.7, 9.1 and 14.6 death per 100 000 people in higher income, upper-middle income and low and lower-middle income regions respectively.

Annex Figure 3.B.1. Temperature-related mortality risk of climate change is rapidly rising over time

Additional deaths per 100 000 people



Note: Projections under warming of around 2.1°C in 2050 and 3.4°C in 2100 using the Environmental Outlook modelling toolbox. Cost of climate adaptation included for full mortality risks following Carleton et al. (2022^[93]). Negative numbers reflect a reduction in mortality risk (i.e. current levels of warming have reduced cold-related mortality especially in countries in the higher-income regions with colder climates).

Source: Authors' own calculations based on damage functions provided by Carleton et al. (2022^[93]).

StatLink  <https://stat.link/vojmfx>

These increased mortality risks can be valued using different techniques to assess the welfare effects and thus make them comparable to other economic impacts. One measure that is often used to assess the economic values associated with increased mortality risks is the concept known as the value of an avoided fatality or the value of statistical life (VSL).¹⁸ Assuming a global average VSL of USD 2.7 million,¹⁹ the more than 340 000 additional deaths globally by 2050 would translate into a welfare loss of a little more than USD 925 billion (for comparison, this is equivalent to 0.3% of GDP in 2050).

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Notes

¹ In line with the approach used and explained in Chapters 1 and 2, feedback links from environmental degradation on environmental pressures are excluded from the modelling projections.

² Phosphorus delivery reflects the transport of phosphorus to the water system. It differs from phosphorus application, which is the phosphorus content of fertiliser or manure put on the ground, as it excludes e.g. plant uptake of applied phosphorus.

³ As explained in 0, these intensities are calculated differently for different indicators, e.g. where relevant in terms of per capita values; converting absolute values into intensities allows a cross-regional comparison that is not affected by the size of a region.

⁴ This is less beneficial than it may sound, as increased water use efficiency for irrigation means that less water is returned to rivers and aquifers, and more water is evapotranspired (Perry et al., 2023^[99]).

⁵ In contrast, the population in areas not at risk grows by 21% (around 1.1 billion additional people).

⁶ Clearly, this acceleration started earlier in some regions than others, and in some regions the degradation has recently slowed down.

⁷ The modelling toolbox used in this Environmental Outlook to produce projections focuses on terrestrial biodiversity and therefore the current and future states of terrestrial and aquatic ecosystems are discussed separately, the latter only qualitatively.

⁸ According to the modelling, the last large region in 2020 where biodiversity was least disturbed with respect to its pristine state was Greenland, with a MSA index higher than 92. By 2050, this will no longer be the case, due to climate change, which will drive Greenland's MSA down to 90. The regional uncertainty in the modelling toolbox does not allow to draw robust conclusions from this.

⁹ Natural capital will also be discussed in Chapter 6.

¹⁰ The relative importance of each cause varies considerably across biodiversity indicators. Since 1970, land use changes explain more than half of global losses in the Red List Index (RLI), while they account for 40% of the changes in Living Planet Index (LPI) and the MSA indicator calculated in (IPBES, 2019^[16]) (which has a different definition from the indicator calculated in the Environmental Outlook modelling toolbox. The IPBES MSA index has been particularly sensitive to climate change, which explains 30% of the overall losses. In contrast, for species population trends, direct exploitation is the second most significant factor, accounting for 30% and 25% of LPI and RLI losses, respectively (IPBES, 2019^[16]).

¹¹ Fine particulate matter, defined as particles with a diameter smaller than 2.5 µm (PM_{2.5}), includes both primary particles – such as BC, organic carbon (OC) and other directly emitted particles – and secondary particles formed through atmospheric reactions involving sulphur oxides (SO_x), NO_x, NH₃, CH₄ and non-methane volatile organic compounds (NMVOC). Tropospheric ozone, also known as ground-level ozone, is not emitted directly but forms through chemical reactions involving NO_x, CH₄, and NMVOC.

¹² As explained above, this has had the perverse effect of accelerating climate change, as SO_x act as a coolant.

¹³ While the two pollutants responsible for most of the impacts are PM_{2.5} and ground-level ozone, concern has also risen in recent years about the impact of NO_x. Global estimates for this pollutant are not available

but studies for the EU show that about 10 000 premature deaths annually can be attributed to NO_x emissions from diesel cars, vans and light commercial vehicles. This is part of a total of about 425 000 premature deaths in the EU, Norway and Switzerland from outdoor air pollution (IIASA, 2017^[96]). Concentrations of NO_x have declined considerably in these countries since 1990 (European Environment Agency, 2018^[95]), as the evidence of the health risks associated with air pollution grows (Harrison, 2018^[97]).

¹⁴ Many heavy metals are hazardous chemicals.

¹⁵ Note that significantly more plastic is collected for recycling than actually recycled; in 2020 57 Mt was collected for recycling, but only 34 Mt actually recycled. The rest was incinerated or landfilled.

¹⁶ Thus, curbing demand and designing for circularity remain cornerstones of an ambitious policy response (OECD, 2024^[78]).

¹⁷ Structural models focus on drivers, sectoral impacts and interactions, examining how specific biophysical changes (e.g. heatwaves) affect economic activities (e.g. labour productivity) (OECD, 2015^[7]). However, these models often provide incomplete estimates, as not all impacts can be quantified with confidence globally. Statistical models, by contrast, take a top-down approach but generally lack insights into underlying drivers and detailed impact categories.

¹⁸ The VSL represents the value a given population places on avoiding the death of an unidentified individual, such as reducing the number of deaths from air pollution or the number of traffic fatalities. As underlined in (OECD, 2012^[98]), the VSL is not the value of any individual person's life, but an aggregation of how individuals value small changes in mortality risk.

¹⁹ Based on ENV/EPOC/WPIEEP(2024)9/REV3. This uses 2023 PPP exchange rates.

4

The interactions between climate, biodiversity and pollution policy objectives: Conceptual overview

This chapter examines the interactions between the policy objectives of climate change mitigation and adaptation, biodiversity conservation and pollution prevention and control. By categorising a range of existing policies based on a broad set of policy objectives to which they contribute, it analyses how addressing one aspect of the interlocking challenge may affect the remaining two, and presents a conceptual overview of the potential synergies and trade-offs.

4.1. Introduction

There are interactions between policies for addressing climate change, biodiversity loss and pollution. Considering these interlinkages can provide a more holistic picture of the costs and benefits of policies as well as more accurate estimates of their impacts. Conversely, policies that do not consider these interlinkages may result in unintended trade-offs between otherwise coherent objectives of tackling these challenges together.

There are a wide array of policies and an even larger set of policy instruments that have been implemented to address each of these challenges around the world. It is beyond the scope of the current analysis to map each policy or instrument and review its potential interlinkages. Instead, this analysis investigates these interlinkages by thematically categorising representative sets of policies into broad clusters based on the overall objective to which they contribute. These are further divided into sub-clusters to provide more granularity while remaining generalisable across contexts. Figure 4.1 provides an overview of these thematic clusters.

Climate policy objectives are categorised into three broad clusters (i) energy; (ii) food and (iii) ecosystems. These clusters encompass both climate change mitigation and adaptation. This categorisation draws upon the classification used by Pörtner et al. (2023^[1]) in exploring the interlinkages between climate change and biodiversity.

Biodiversity policy objectives are categorised into three clusters of policies aiming to: (i) protect, (ii) manage and (iii) restore biodiversity, drawing on the classification used in Pörtner (2021^[2]).¹ The objectives considered also build upon the “mitigation hierarchy”² of: (i) avoidance, (ii) minimisation, (iii) restoration and rehabilitation and (iv) offset that provide a versatile yet coherent framework for unifying various conservation efforts at different scales (from project-level to international) (Arlidge et al., 2018^[3]). The hierarchy represents four sequential and iterative steps which puts avoidance of biodiversity loss at the top of the priority, followed by minimisation, restoration and rehabilitation, and finally offsetting of the remaining adverse impacts (OECD, 2024^[4]). Full application of the mitigation hierarchy therefore should result in no net loss at minimum, and preferably a net gain (Maron et al., 2025^[5]).

Pollution policy objectives are categorised into three clusters of policies that seek to: (i) prevent pollution at source, (ii) reduce leakage of pollutants into the environment and (iii) remediate pollution. This categorisation loosely mirrors the “waste hierarchy” concept which ranks waste management options from the most to the least preferred (i.e. prevention, reuse, recycling, energy recovery and disposal) (OECD, 2024^[6]) as well as existing policy frameworks such as the European Union’s Action Plan “Towards Zero Pollution for Air, Water and Soil” (European Commission, 2021^[7]).

Figure 4.1. Overview of policy objectives considered

	Energy	Food	Ecosystems
Climate	Increase clean energy supply Increase uptake of clean technologies	Reduce food-related GHG emissions Promote dietary change	Retain and enhance natural carbon sinks Improve capacity and effectiveness of climate adaptation
Biodiversity	Protect Enhance area-based conservation Control the introduction and spread of invasive alien species	Manage Support sustainable use of biodiversity Reduce food loss and waste	Restore Restore lost and degraded natural habitats Create biodiversity
Pollution	Prevent Limit emissions from polluting activities Restrict the use of harmful substances	Reduce leakage Minimise waste generation Enhance natural capacity to filter pollutants	Remediate Restore quality of polluted lands and water bodies

Source: Authors' own elaboration.

Though non-exhaustive and context dependent, the analysis provides a conceptual overview of the possible synergies and trade-offs between policy objectives, to inform an integrated policy approach to address the triple planetary crisis. The broad patterns of synergies and trade-offs identified through literature review are detailed in Sections 4.2, 4.3 and 4.4 and are visualised at the end of each in Figure 4.3, Figure 4.6 and Figure 4.7, respectively. Following this analysis outlining the possibility of synergies and trade-offs as a first step in improving the policy coherence across different objectives (OECD, 2021^[8]), the next two chapters examine the extent to which these policy interlinkages are currently considered in national documents (Chapter 5) and the manifestations, management and assessment (including quantification) of synergies and trade-offs at the implementation stage, using four deep dives as case studies (Chapter 6).

4.2. Climate policy objectives

4.2.1. Energy

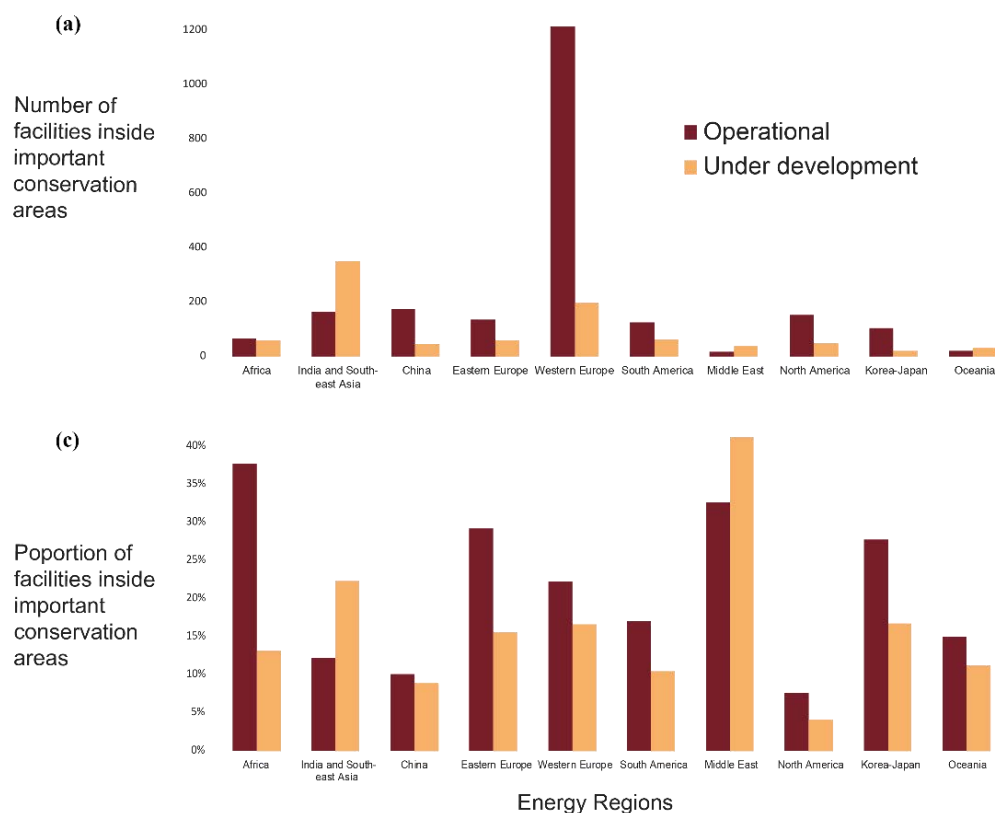
Increase clean energy supply

Reducing reliance on fossil fuel combustion as the primary source of energy is an integral part of climate change mitigation. Renewable energy, including solar and wind power, is considered among the key enablers of climate change mitigation (IEA, 2024^[9]). A decisive shift towards clean energy³ also brings considerable synergies for reducing air and water pollution and alleviating pressures on biodiversity from habitat degradation, destruction and fragmentation associated with the extraction of fossil fuels (OECD, 2024^[4]). In addition to reducing greenhouse gas (GHG) emissions, renewable energy outperforms fossil fuels on several other environmental parameters (see also Chapter 6.2, which provides a deep dive on the expansion of wind and solar energy). For instance, the impacts of the phase-out of fossil fuels and the expansion of renewable energy on air quality improvements have been extensively estimated, with many studies identifying significant reductions in emissions of sulphur dioxide (SO₂), nitrogen oxides (NO_x),

particulate matter with a diameter smaller than 2.5 micrometres (PM_{2.5}) and ground-level ozone (e.g. (Markandya et al., 2018^[10]; Sampedro et al., 2023^[11]; Millstein et al., 2017^[12])). Improvements in air quality confer more localised and immediate benefits and further strengthen the rationale for climate action (Vandyck et al., 2022^[13]).

Despite substantial benefits of replacing fossil fuels, renewable energy is also not entirely without environmental cost. Without careful consideration and management, there are risks that renewable energy infrastructure itself becomes a driver of biodiversity decline. From hydropower infrastructure impeding species' movements and dispersal across river basins to solar power infrastructure coinciding with species' natural habitats, there are cross-cutting risks relating to the spatial footprint of renewables' infrastructure which may result in habitat loss and fragmentation (Dhar et al., 2020^[14]; He, 2024^[15]). Furthermore, electricity transmission, distribution and energy storage infrastructure can pose a threat for biodiversity (OECD, 2024^[4]). As renewable energy is more diffuse compared to fossil fuels, there are additional concerns over energy sprawl at the cost of important areas for biodiversity conservation including protected areas.⁴ For instance, one study identifies over 2 200 existing renewable facilities within the boundaries of protected areas, Key Biodiversity Areas (KBAs)⁵ and distinct wilderness areas; a trend that appears set to accelerate in the coming decades and expand to a broader set of regions including Southeast Asia and Africa (Rehbein et al., 2020^[16]) (Figure 4.2).

Figure 4.2. Renewable energy facilities within important conservation areas under operation and development around the world



Note: The number (a) and proportion (b) of operational (red) and under development (orange) renewable energy facilities within important conservation areas (protected areas, KBAs and wilderness areas) by energy regions.

Source: Rehbein et al. (2020^[16]).

There are several land-sharing practices that can help mitigate these risks. For instance, in “agrivoltaics systems”, solar energy generation and agricultural production (food and energy crops) occur on the same land, helping to reduce land use pressures (Cogato, Marinello and Pezzuolo, 2023^[17]). These systems can also provide habitats for pollinators and shades for plants underneath solar panels, and therefore potentially contribute to retaining soil and water availability and quality (Hernandez et al., 2019^[18]; Cogato, Marinello and Pezzuolo, 2023^[17]), although the highly site- and crop-specific nature of agrivoltaics makes the optimisation of agricultural outputs and power generation challenging (Asa’a, 2024^[19]).

Similarly, it has also been suggested that competing uses for coastal zones can be balanced by co-locating offshore wind farms with low-trophic aquaculture (e.g. seaweed), which can also simultaneously contribute towards alleviating pressures on ecosystems from nutrient pollution (e.g. (Maar et al., 2023^[20])). However, there remains uncertainty over the viability of such approaches and careful management and monitoring is warranted. While it has been suggested that offshore windfarms can potentially act as *de facto* marine protected areas as they provide artificial habitats and refuges from fisheries activities (Ashley, Mangi and Rodwell, 2014^[21]), there are also concerns over the risk of adverse biodiversity outcomes, including the spread of invasive species that can exploit hard substrate of wind farms as their new habitat (Watson et al., 2024^[22]).

Impacts and the trade-offs can also differ among various types of renewable energy. Mortality risks of birds and bats species through collision with wind turbines are relatively well-documented (OECD, 2024^[4]). While bird mortality is relatively small in magnitude, wind turbine collision is identified as among the leading causes of collision mortality in bats (OECD, 2024^[4]). Furthermore, while far less water is needed for solar compared to fossil fuels, there are still water needs such as for cleaning the surface of solar PVs to maintain their efficiency (Aljaghoub et al., 2022^[23]). Some concentrated solar power plants also require water to be used as coolant, although dry cooling is an increasingly viable technology (Liqreina and Qoaider, 2014^[24]).

There remain considerable research gaps over the impacts of renewable energy infrastructure on marine and freshwater ecosystems, compared to uncertain yet relatively better-researched impacts on terrestrial ecosystems (OECD, 2024^[4]). Environmental impacts of various types of renewable energy generated using bodies of water are also relatively less understood, although existing evidence identifies some risks for biodiversity loss and pollution. For instance, hydropower infrastructure can lead to fragmentation in water bodies and change river sections from lotic (running) to lentic (standing), creating optimal conditions for phytoplankton growth and development of harmful algal blooms (He, 2024^[15]). Furthermore, hydropower reservoirs result in non-negligible carbon dioxide (CO₂) and methane (CH₄) as well as nitrous oxide (N₂O) emissions through the decay and degradation of organic matter (Lu et al., 2020^[25]). While still in its infancy, ocean energy harvesting technologies also raise concerns over disrupting marine ecosystems (Martínez et al., 2021^[26]).

Beyond the immediate impacts during the operation (electricity generation, transmission and distribution) of renewable energy infrastructure, it is also important to consider the lifecycle environmental impacts, ranging from extraction of materials and manufacturing to decommissioning. In particular, risks of trade-offs for biodiversity and pollution objectives can arise from the environmental pressures from obtaining material resources required to produce renewable energy technologies. As with the renewable infrastructure itself, there are risks that mining and processing activities partially undermine the effectiveness of protected areas for biodiversity conservation (Sonter et al., 2020^[27]). The manufacturing stage of renewable technologies can also result in various types of pollution which can harm human and planetary health. Manufacturing of solar PVs, for instance, is associated with the use of chemical compounds such as cadmium, arsenic and lead (Aman et al., 2015^[28]). End-of-life impacts of renewables can also result in trade-offs with biodiversity and pollution control objectives. For instance, due to their heavy weight and heterogeneity, wind turbine blades are not currently widely reused or recycled (Khalid et al., 2023^[29]).

Importantly, various impacts can accumulate, extending their reach beyond local sites. This makes the consideration of risks at multiple scales an imperative. Some impacts would be best addressed with cross-border collaboration, for instance, to consider the transboundary migratory patterns of certain species (e.g. birds and bats) (OECD, 2024^[4]). Additionally, flow regulation and thermal alteration from hydropower generation can have cumulative and cascading impacts that extend beyond a single river, necessitating local and regional collaboration to address the risks (He, 2024^[15]).

There are also risks of trade-offs associated with bioenergy (biomass and biofuels). Along with the concerns over the expansion of bioenergy for its potential impact on food security, the evolution of the debate over the role of bioenergy in decarbonisation of the energy system illustrates the need for the holistic consideration of environmental risks. Many mitigation pathways compatible with the 1.5°C goal feature the expansion of bioenergy, with some placing it on par with wind and solar energy (Rogelj et al., 2018^[30]). However, it is well-recognised that land use pressures associated with bioenergy can hinder its viability, as sourcing bioenergy from dedicated crops would lead to land use change (OECD, 2019^[31]; IEA, 2024^[9]) and may indirectly lead to an intensification of agriculture due to competition for land or nutrient pollution due to increased fertiliser use (Pörtner et al., 2021^[32]; Kanter and Brownlie, 2019^[33]).

The expansion of bioenergy plantations can also run counter to the climate mitigation objective itself, while posing a threat to biodiversity, especially when it comes at the cost of degradation of natural carbon sinks that are simultaneously biodiversity hotspots. For instance, while deforestation and peatland drainage for palm oil contributes to economic security of small holders due to the potential to achieve high yield per area, these activities also result in GHG emissions as well as biodiversity loss, while making the areas more fire-prone (Meijaard et al., 2020^[34]). Taxonomic diversity and species abundance are also found to be lower in crops for bioenergy compared to the natural ecosystems they replace (Núñez-Regueiro, Siddiqui and Fletcher, 2021^[35]). Furthermore, although there is uncertainty over its magnitude, crop types used for bioenergy also tend to have higher biogenic volatile organic compounds (VOCs) emissions, which are precursors to ground-level ozone (Rosenkranz et al., 2014^[36]).

The severity of the environmental risks from expanding bioenergy production varies depending on a number of factors such as the type of crops, scale of deployment and previous land use (IPCC, 2019^[37]). Some bioenergy requires dedicated land, while others can be produced from agricultural and industrial residues, including from sugarcane waste for ethanol. The biodiversity impact of bioenergy may be positive overall for a specific site under specific circumstances if, for instance, perennial bioenergy crops replace monocultural crops in agricultural landscapes (Landis et al., 2018^[38]). Second-generation bioenergy derived from non-food feedstocks such as agricultural and forest residues is generally considered more environmentally benign compared to dedicated production of bioenergy crops (Jeswani, Chilvers and Azapagic, 2020^[39]). Nonetheless, these solutions may come with their own risk of trade-offs. For instance, while using residues and organic waste as bioenergy feedstock can reduce pressures on land use change, they are limited in volume and may involve the removal of carbon and nutrient-rich residues that would otherwise remain on the ground and can reduce soil quality (IPCC, 2019^[37]).

Increase uptake of clean technologies

Together with increased supply of clean energy, improved energy use and efficiency through uptake of clean technologies are critical for curbing GHG emissions. However, there are also uncertain impacts associated with some of the technologies that are expected to play an important role in the transition towards carbon neutrality. Some clean technologies are cross-cutting, while others are aimed at electrifying their fossil fuel-based equivalents and have more sector-specific applications.

For sectors such as transport and buildings, electrification is an integral part of decarbonisation (see also Chapter 2 on the implications of electrification). Technologies for electrification can reduce emissions from numerous small sources (e.g. households) that add up to constitute a large share of total GHG emissions. Moreover, these technologies have the potential to deliver synergies including enhanced indoor and

outdoor air quality. Within the transport sector, policy attention has focused on the potential of electric vehicles (EVs). As EVs have no tailpipe emissions, incentivising their wider adoption can also help address air pollution. However, the purported benefits may be partially negated, as EVs typically weigh more compared to internal combustion engine vehicles due to the weight of the batteries and can therefore result in increased non-exhaust emissions (generated by the wearing down of brakes, tyres and road surfaces, as well as by the suspension of road dust) (OECD, 2020^[40]). Although there is relatively limited research assessing the impact of policies such as fiscal incentives for the purchase of EVs on air quality, emerging evidence substantiates pollution reduction benefits at a local level (Li and Zhang, 2023^[41]). Within the buildings sector, heat pumps and electrical devices that can convert energy from external sources to heat for residential and commercial buildings not only reduce GHG emissions, but can also improve indoor air quality (Gaur, Fitiwi and Curtis, 2021^[42]).

However, material requirements of many of these clean technologies – referred to as “critical raw materials (CRMs)” – remain both a bottleneck for their uptake and the source of potential trade-offs with biodiversity conservation and pollution control objectives across their lifecycle. Mining activities generate large volumes of waste including tailing, drainage water and slag, mismanagement of which can have adverse impacts on the water and soil (OECD, 2025^[43]). For instance, the production of clean hydrogen from renewable energy requires electrolysis, a process of splitting water into hydrogen and oxygen. “Electrolysers” for these production processes have high requirements for CRMs and their expansion can result in environmental pressures upstream (Eikeng, 2024^[44]). Similarly, inappropriate disposal of EV batteries can result in the release of toxic chemicals (Herbert-Read et al., 2022^[45]). Meanwhile, recycling of batteries, while important for material recovery, can also pose some environmental risks as they contain chemicals (including PFAS) that may break down during recycling, for instance, due to incomplete burning, potentially becoming an additional source of pollution (Rensmo et al., 2023^[46]). Without concomitant considerations of material recovery and resource efficiency, the accelerated deployment of these technologies could heighten the concerns over the expansion of unsustainable extraction from hitherto intact natural areas, such as the deep sea (e.g. lithium extraction from deep-sea brine pools (Herbert-Read et al., 2022^[45])).

“Clean” hydrogen produced with low carbon emissions (including through carbon capture and storage (CCS) technologies) can be a versatile energy carrier that can help decarbonise end-use sectors that use hydrogen as feedstock in industrial processes, such as production of steel and chemicals (Cordonnier and Saygin, 2022^[47]). Hydrogen can also help better integrate renewables in the electricity system as an option for storing intermittent wind and solar power, and their derivatives (e.g. ammonia) can become low-carbon alternatives for long-range shipping fuels (Hassan et al., 2024^[48]). However, expanding deployment of clean hydrogen carries potential risks for human safety and ecotoxicity due to its properties. Notably, hydrogen is flammable and can easily permeate, corrode and embrittle containment materials (Calabrese et al., 2024^[49]). Safeguards are therefore essential for the expanding use of clean hydrogen. Furthermore, if inadequately managed, ammonia used as a marine shipping fuel could result in nitrous oxide emissions that can compromise some of the climate mitigation benefits (UNEP/FAO, 2024^[50]), as well as create risks for acidification and eutrophication.

Water resource implications of hydrogen deployment also warrant attention (Shen et al., 2024^[51]). Although water requirements are substantially lower compared to fossil fuels,⁶ the source of water remains an important consideration for limiting the wider environmental footprint of producing clean hydrogen (Woods, Bustamante and Aguey-Zinsou, 2022^[52]). For instance, desalinating seawater is a viable option for meeting the water demand, but results in by-product brine which is harmful to aquatic species (Zhou, Chang and Fane, 2013^[53]). However, there are emerging technologies for the production of hydrogen that may deliver co-benefits for pollution, such as those that enable the simultaneous treatment of wastewater and production of hydrogen (Merabet, Kerboua and Hoinkis, 2024^[54]).

Reducing emissions from point sources through carbon capture and storage (CCS) and carbon capture and use (CCU), referred together as CCUS,⁷ is also increasingly a key component of tackling GHG emissions. While the majority (60%) of currently operational CCUS facilities are natural gas processing

facilities, they are also being established in other industrial sectors (Fajardy, 2025^[55]). A review of lifecycle assessments of CCUS technologies identifies some risks to the environment, finding that burying and storing captured emissions deep underground may adversely affect biodiversity and exacerbate pollution (Cuéllar-Franca and Azapagic, 2015^[56]). CCS deployed on-site within power and industrial facilities can also impact ecosystems through water footprint as well as water discharge, which risks causing acidification of aquifers (OECD, 2017^[57]; Mikunda et al., 2021^[58]). Regulatory frameworks that ensure geological storage sites are properly chosen, designed and managed can help address the risks associated with CCS. CO₂ storage in properly selected and managed geological reservoirs suggests it is likely to remain secure over time (IPCC, 2023^[59]),⁸ which is an advantage compared, for instance, to nature-based storage methods that can be more susceptible to the risks of extreme weather events.

Another set of cross-cutting technologies that can be deployed for climate mitigation is “negative emissions technologies” or carbon dioxide removal (CDR) technologies, which can contribute to addressing residual emissions or potentially enabling net-negative emissions (Smith et al., 2024^[60]).⁹ CDR entails an array of methods and options including bioenergy with carbon capture and storage (BECCS), mineral carbonation (e.g. enhanced weathering) or direct air capture.¹⁰ These technologies vary widely in certainty with which technical feasibility, scalability and effects on biodiversity and pollution can be estimated. Concerns over the adverse impacts on biodiversity have led to the COP10 CBD decision X/33, adopted in 2010 and widely interpreted as a non-binding moratorium, which urges caution on geoengineering activities that may affect biodiversity (Smith et al., 2024^[60]). Nonetheless, CDR options such as BECCS and direct air capture feature in several limited temperature increase scenarios (IPCC, 2023^[59]). Additionally, the carbon neutrality targets set in many countries rely implicitly on negative emissions technologies as part of their policy packages. Around 40 countries have specified quantifiable CDR contributions in their long-term climate strategies to 2050 (Lamb et al., 2024^[61]) and facilitate the deployment through various policies including dedicated research funding (e.g. Australia, Canada, the European Union, Japan, Norway and the United Kingdom) and certification frameworks (e.g. EU’s Carbon Removal Certification Framework (European Commission, 2024^[62])).

BECCS entails converting biomass into energy, capturing the CO₂ released during the process, compressing it into liquid and storing it underground. This can potentially be a powerful option to achieve net-zero emissions, as the negative emissions from this technology can offset hard-to-abate emissions from other processes (not least food production). BECCS can pose several environmental risks, ranging from increased fertiliser use, water use and chemical runoff and the risks of monoculture expansion, soil degradation and ecosystem fragmentation as large-scale BECCS requires vast amounts of land and water for growing and processing feedstock (Geoengineering Monitor, 2021^[63]; Williamson and Bodle, 2016^[64]). Further, while BECCS can contribute towards diversification and increase in rural incomes, it can also expose smallholders to global market fluctuations as large-scale deployment could create competition for resources (including land) and may increase food prices (Stoy et al., 2018^[65]). These risks can be managed better through governance of land use, including effective conservation measures and policies that account for biodiversity protection, water and nitrogen use, and land-use competition. The use of second-generation biomass feedstocks, such as agricultural and forest residues or dedicated cellulosic crops, combined with land management strategies that internalise environmental trade-offs, can help align BECCS deployment with broader sustainability objectives (IPCC, 2018^[66]).¹¹

CDR from the atmosphere, such as through direct air capture, typically requires the use of solvents and chemical sorbents and can result in local water and air pollution (Dooley, Harrould-Kolieb and Talberg, 2021^[67]). Meanwhile, poorly managed mineral carbonation processes could have a comparable environmental impact to large-scale surface mining operations (IPCC, 2005^[68]). For instance, while enhanced weathering (an approach that involves spreading select finely ground rocks at large scale over land to chemically bind atmospheric CO₂) can improve soil fertility (and lower the need for fertiliser application) and sequester carbon, the risks of habitat degradation and destruction and water and soil

quality deterioration associated with intensive mining of rock material, transport, and application processes also need to be carefully considered (Bach et al., 2019^[69]; Williamson and Bodle, 2016^[64]).

4.2.2. Food

Reduce food-related GHG emissions

Agriculture is vulnerable to climate change, yet at the same time, the sector is also a major driver of climate change (OECD, 2022^[70]) due to CH₄ emissions from livestock, N₂O emissions from fertiliser applications, as well as land conversion for cropland and grassland (OECD, 2022^[70]). In total, agricultural direct (i.e. on-farm; excluding land conversion) emissions contribute to 11% of global GHG emissions, a figure that doubles when considering land use change and increases further to about a third of global GHG emissions when considering the rest of the supply chains within the food system as a whole (OECD, 2023^[71]; OECD, 2025^[72]). At the same time, agricultural land can contribute to mitigating GHG emissions and act as a carbon sink depending on the agricultural practices deployed. In this context, agricultural policies can encourage farmers, landowners and managers to adopt practices that can improve soil health to reduce reliance on applications of agricultural inputs such as fertilisers and provide appropriate environmental safeguards.

Existing research suggests that agricultural practices that reduce GHG emissions generally can confer localised synergies for biodiversity and pollution. In particular, measures that can be implemented without creating demand for additional land can help alleviate pressures on biodiversity caused by habitat fragmentation and destruction (Smith et al., 2020^[73]). These practices range from precision agriculture (e.g. enabling targeted application of fertiliser and pesticides) to improved crop management, such as high carbon input practices (e.g. through crop rotation) that help sequester carbon. Other examples include reduced tillage, which also facilitates carbon storage. Increased soil carbon content through these practices also helps improve soil structure, regulate water flow and improve filtering capacity of pollutants.

However, poorly targeted policies to reduce agricultural GHG emissions can unintentionally incentivise unsustainable intensification of land use and increased fertiliser use to maintain yields, which can negatively affect biodiversity and exacerbate water pollution (OECD, 2022^[70]). These risks can be better managed by promoting sustainable agricultural productivity growth, which is essential for balancing the need for increased food production to feed the growing global population with the imperative to reduce environmental impacts through more efficient resource use (OECD, 2024^[74]). Progress towards sustainable agricultural productivity growth requires appropriate economic incentives to encourage shifts in farming practices, as well as investment in research, innovation and extension services (OECD, 2024^[74]). Governments – alongside farmers and researchers – can play a key role in promoting specific farming practices that strike the balance between several factors, including impacts on yields, costs, socio-economic outcomes and environmental impacts. For instance, research on “regenerative agriculture” has identified a number of practices that synergistically deliver positive biodiversity and climate outcomes (The Food and Land Use Coalition, 2023^[75]) – see also Section 4.3.

Furthermore, there are concerns that various farming practices that enhance carbon sequestration may require more nitrogen applications to maintain the gains in soil carbon and increase nitrogen pollution (Almaraz et al., 2021^[76]). Although these concerns have not been substantiated for many agricultural practices and are on average synergistic in terms of reduction in N₂O emissions and nitrate leaching in soil, there is some evidence that reduced and no-tillage practices can incur leaching and may increase nitrate in water (Almaraz et al., 2021^[76]). Similarly, while no-tillage practices can considerably reduce the particulate (attached to soil particles) phosphorous concentration, they can also lead to increased dissolved phosphorus in water, which are key elements of the eutrophication process of aquatic ecosystems (Daryanto, Wang and Jacinthe, 2017^[77]). The viability and cost-effectiveness of farming practices that are widely considered environmentally beneficial can vary depending on climate, soil texture

and topography (e.g. slope), underscoring the importance of tailoring practices to specific sites and contexts (Macrae et al., 2021^[78]).

Mitigating emissions from livestock production and grazing land management can also deliver synergies for biodiversity. Advancements in technologies that improve productivity and sustainably enhance livestock food production could reduce land requirements, which can in turn help protect wildlife (Lamb et al., 2016^[79]). There are a range of examples of techniques and technologies related to dietary management that improve feed conversion efficiency and limit CH₄ emissions during digestion (OECD/FAO, 2025^[80]). Direct interventions for limiting CH₄ emissions from enteric fermentation such as feed additives (CH₄ inhibitors) are increasingly deployed or considered (OECD, 2022^[70]) – see also Chapter 6 on nutrient management for examples. Further, use of nitrification inhibitors in stored livestock manure is already widespread. Although nitrification inhibitors can reduce N₂O emissions and prevent nitrate leaching, their application requires precision, as they may pose ecotoxic risks to both aquatic and terrestrial species (Kösler et al., 2019^[81]).

Promote dietary change

Promoting dietary change is a complementary objective to making the food system more environmentally sustainable. In particular, animal-based products such as red meat and dairy overall have an outsized impact on climate change, primarily due to pasture and land required for feed crops, as well as CH₄ emissions from enteric fermentation from ruminants and N₂O emissions from manure (OECD, 2022^[70]).¹² Higher intake of plant-based foods and lower consumption of animal-based products therefore have the potential to contribute towards climate change mitigation (IPCC, 2019^[37]).

In addition to mitigating GHG emissions, large-scale dietary shifts towards more plant-based diets are estimated to have substantial potential to offer a number of synergies, including alleviating air, soil and water pollution (Bonnet and Coinon, 2024^[82]). For instance, a modelling-based study suggests that substituting half of global consumption of the main animal products (pork, chicken, beef, and milk) with plant-based alternatives can lead to 31% reduction in GHG emissions by 2050 compared to a reference scenario of no dietary change (Kozicka et al., 2023^[83]). This shift could also yield additional synergies, including reduced water use and nitrogen applications (Kozicka et al., 2023^[83]). Similarly, another study that explores the impact of excluding animal-based products from diets suggests that such a shift could also reduce eutrophication by half (Poore and Nemecek, 2018^[84]).

Reduced consumption of meat and increased adoption of plant-based alternatives can also contribute towards protecting biodiversity, although its impact both on climate mitigation and biodiversity depends on how the animal-based food are substituted and how sustainably they are produced (FAO, 2023^[85]). Most of the synergies for biodiversity conservation stem from reduced pressure for land conversion of species-rich areas into pasture for grazing and arable land for animal feed crops production (Godfray et al., 2018^[86]). For instance, land conversion of ecosystems including rainforests for pasture is estimated to constitute almost 70% of land-use change in Latin America (De Sy et al., 2015^[87]). There are also more indirect synergies for biodiversity conservation; for instance, reduced livestock production can reduce pressures on plant diversity, as grazing pressure tends to exceed that of wild herbivores, although impacts are significantly affected by various climatic variables such as precipitation patterns and ecosystem characteristics (Filazzola et al., 2020^[88]). It may also help curb the decline of wild species' populations, which are commonly targeted by farmland owners seeking to prevent interactions between wildlife and their livestock (Machovina, Feeley and Ripple, 2015^[89]).

However, the current trend of increased consumption of animal-based calories along with economic development is projected to continue, particularly in low- and middle-income countries (see also Chapter 2). It can additionally be challenging to promote dietary change due to cultural norms, societal habits and personal significance (Hassett et al., 2025^[90]). The acceptability and uptake of plant-based alternatives to meat and dairy products vary. Despite improved availability, plant-based meat alternatives still constitute

a small share of food consumption (OECD/FAO, 2025^[80]). In contrast, plant-based dairy substitutes (e.g. soy milk) have become increasingly established in many regions (OECD/FAO, 2025^[80]).

Furthermore, while plant-based alternatives may facilitate the sustainable transition of the food systems in the interim, it is also important to consider the agricultural practices and site-specific impacts of their production (IPCC, 2019^[37]). For example, livestock production can have both negative (e.g. through land-use change) and positive (e.g. through improving the structural heterogeneity) impacts on biodiversity (Gordon, 2018^[91]). Low-intensity livestock farming can potentially play a role in maintaining or even enhancing biodiversity in rangelands used for livestock grazing (Neilly, Vanderwal and Schwarzkopf, 2016^[92]) and low-intensity grazing is also associated with increased soil carbon sequestration (Zhou et al., 2017^[93]), although overall effects would depend on counterfactual scenarios (i.e. how the land would otherwise be used and if there was no land use change).

There is the considerable heterogeneity in environmental footprints across different producers, even for the same commodity produced within a country (Deconinck, Jansen and Barisone, 2023^[94]). Nonetheless, available evidence based on LCAs suggest that the lowest-impact animal-based products typically have higher environmental impacts than plant-based substitutes (Poore and Nemecek, 2018^[84]). Realising and amplifying the potential synergies of balanced diets for climate, biodiversity and pollution objectives necessitates the consideration of the overall and regionally-specific environmental impacts of food production, including through the use of primary data to measure environmental impacts such as carbon footprint (OECD, 2025^[72]).

4.2.3. Ecosystems

Retain and enhance natural carbon sinks

Countries increasingly invest in the protection and restoration of natural carbon sinks through economic, (e.g. subsidies and tax incentives), regulatory (e.g. standards) and other policies as part of their climate mitigation strategies (OECD, 2024^[95]). In particular, maintaining the intactness of natural ecosystems such as forests is highly important for carbon storage and other indispensable ecosystem services, including freshwater regulation (Watson et al., 2018^[96]). Contrary to other “negative emissions” technologies that are still relatively nascent, afforestation, reforestation and soil carbon sequestration can be implemented as readily available mitigation options (Fuss et al., 2018^[97]).

These solutions are referred to under a broad umbrella term of “Nature-based Solutions (NbS)”, recently defined by the UNEA-5 resolution as “actions to protect, conserve restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” (UNEP, 2022^[98]). NbS already feature explicitly in 41% of the Nationally Determined Contributions submitted as of the end of 2021 (Nature-based Solutions Initiative, 2022^[99]).

There are a variety of NbS that have been widely adopted. Planting trees can enhance natural carbon sinks,¹³ as they remove carbon from the atmosphere and store them during tree growth (Smith et al., 2022^[100]). In addition, planted trees can eventually become substitute materials for emissions-intensive concrete. Canada’s Green Construction through Wood program, for instance, encourages the use of wood-based products in infrastructure projects as a low-carbon building material (Government of Canada, 2025^[101]). Reforestation generally contributes positively towards restoring biodiversity as it involves reducing pressures from land use and restoring ecosystems to a less disturbed state (Smith et al., 2018^[102]). However, there are important context-specific considerations without which ecosystem restoration may result in trade-offs that need to be carefully weighed. In particular, a narrow focus on carbon storage, particularly through the planting of a limited variety of fast-growing and climate-resilient

tree species, can undermine native forest cover and threaten species that are dependent on them (Girardin et al., 2021^[103]).

Although “reforestation” (planting trees to restore forests in cleared land) and “afforestation” (planting trees in non-forested areas) can both contribute to carbon storage, their impact on biodiversity can differ considerably (Dooley, Harrould-Kolieb and Talberg, 2021^[67]). Planting trees in areas that do not support natural forests introduces alien species, although it is possible to reforest areas that had been cleared with endemic species. In particular, the use of exotic monoculture plantations is associated with negative impacts on biodiversity (Di Sacco et al., 2021^[104]). Afforestation via monocultures in biomes such as (previously unforested) grassland, savanna and non-forested wetland can therefore run counter to biodiversity goals. Studies also suggest that the use of non-native species can result in trade-offs for water availability (Chausson et al., 2020^[105]), which can be particularly problematic in dry regions, as trees can reduce groundwater and river flow (Di Sacco et al., 2021^[104]). Relatedly, trade-offs can arise from responses to policies for enhancing carbon sink capacity of forests. An analysis of past policies for incentivising tree planting (e.g. subsidies) suggests that, while tree cover increased as a result of these policies, they reduced overall carbon storage and biodiversity because the expansion of plantations of exotic and commercially valuable trees was favoured at the cost of natural regeneration (Heilmayr, Echeverría and Lambin, 2020^[106]). Safeguards and a locally-adapted approach that prioritises regeneration of natural ecosystems are therefore needed for these policies to deliver synergies.

Wetlands are also integral to NbS for climate mitigation. Their conservation and restoration can also provide habitats for a wide range of species. Known for their ecological function as “the kidney of the world” (Mitsch and Gosselink, 2007^[107]), wetlands deliver important benefits of water purification. Often referred to as “blue carbon” stocks,¹⁴ there has been a particular emphasis on rooted vegetation in coastal areas (i.e. seagrass meadows, tidal marshes and mangroves) that store carbon in their soils and sediments.¹⁵ Together with the protection of other key ecosystems, such as macroalgae and seafloor, coastal wetlands can play a substantial role in climate mitigation while providing habitats for species (see also Section 4.3.3).

Improve capacity and effectiveness of climate adaptation

As demonstrated by the widespread adoption of national adaptation strategies and plans, there is growing awareness that climate mitigation needs to be accompanied by efforts to enhance resilience of people, ecosystems and economies through effective climate adaptation (OECD, 2024^[108]). For certain types of adaptation action, the prevailing approach has been to develop and adopt engineered solutions, such as grey infrastructure (with man-made materials). For example, adaptation to extreme weather events has historically placed an emphasis on infrastructure assets and retrofitting, although there is a growing recognition of the importance of integrating other ecological and social considerations to strengthen climate resilience.

Studies identify that some of these engineered solutions may lead to “maladaptation”, defined as climate adaptation that causes an unintended harm, despite their crucial role in protecting lives and livelihoods from the impacts of climate change (Seddon et al., 2020^[109]). Environmental impacts of grey infrastructure for climate adaptation have often been overlooked (Enríquez-de-Salamanca et al., 2017^[110]). For instance, various shoreline hardening structures (e.g. seawall and submerged breakwater) have been installed to prevent coastal erosion and provide flood protection, but these structures are also found to support lower marine biodiversity (Gittman et al., 2016^[111]). Similarly, building dams for the purpose of water storage and the reduction of the impacts of earthquakes or tidal waves can also adversely affect a range of species through habitat fragmentation (Wu et al., 2019^[112]).

In this context, carefully implemented NbS can complement engineered solutions, offering synergies between climate adaptation and biodiversity conservation (OECD, 2021^[113]). In coastal areas vulnerable to flooding and sea level rise (OECD, 2023^[114]), restoration of coastal habitats (e.g. coral reefs and mangroves) can alleviate these impacts (Salem and Mercer, 2012^[115]). For instance, one estimate

suggests that these ecosystems can reduce wave heights by an average of 35-71%, and provide defense at a cost 2 to 5 times lower compared to grey infrastructure such as breakwater (Narayan et al., 2016^[116]). These ecosystems can also help control the erosion of riverbanks, stabilise sediments and protect from landslides (Dudley et al., 2015^[117]).

As urban areas are particularly vulnerable to the heat island effect, many jurisdictions are turning to the development of green and blue infrastructure (broadly defined in this context as natural and semi-natural land and water-related spaces) as a means of strengthening their climate adaptation capacity. As features of the urban environment such as the availability of trees and water spaces moderates the microclimate, green and blue infrastructure provide a number of regulating roles (Jay et al., 2021^[118]). For instance, blue infrastructure provides evaporative cooling benefits, while green infrastructure regulates temperature through transpiration from leaves, evaporation from soil moisture and shading, thereby reducing daytime air temperature (Ziter et al., 2019^[119]).

Urban green space, such as city parks and green roofs, can also provide refuge for biodiversity, as well as mitigate air pollution, particularly by lowering concentrations of particulate matter (PM) (Diener and Mudu, 2021^[120]). A modelling study of over 200 cities around the world finds that urban greening can serve as a cost-effective solution for both climate mitigation and air pollution control (McDonald, 2016^[121]). There is, however, a modest risk that these benefits may be partially offset, as the impact of planted vegetation on BVOC emissions which can form aerosols, remains uncertain (Sanaei et al., 2023^[122]) and may vary by types of tree species used (Gu, Guenther and Faiola, 2021^[123]).¹⁶ Tree canopy cover can also intercept rainfalls and reduce flooding from stormwater runoff from impervious surfaces in urban areas. However, they may entail some unintended consequences for other environmental objectives unless carefully managed; for instance, urban green space may contribute to litter-derived nutrients (e.g. from leaves and twigs), which can add to nutrient loading of stormwater and eutrophication in receiving water bodies (Taguchi et al., 2020^[124]).

Another concern that has garnered policy and public attention in recent years is the increased frequency and severity of wildfires under climate change. While wildfires are a natural component of various ecosystems (and fire-adapted ecosystems recover naturally), an increase in the frequency, size and severity of wildfires has been observed in many countries (OECD, 2023^[125]). Ecosystem protection, restoration and adaptive management can therefore constitute part of wildfire prevention (OECD, 2023^[125]). For instance, using vegetation thinning (selectively removing parts of vegetation to lower forest density to prevent the spread of fire) can make forests more resilient to wildfires. However, some practices can also lead to trade-offs. For instance, “salvage logging” in the aftermath of wildfire can reduce richness of taxonomic groups or abundance of insects, fungi and bacterial species that rely on dead and decaying wood (Thorn et al., 2018^[126]; Campbell and Ager, 2013^[127]) and may in turn adversely affect water and soil quality (Leverkus et al., 2020^[128]).

Importantly, there is a temporal dimension to synergies and trade-offs of climate policy, which has important implications for policy planning. For instance, health-related synergies of climate policy, such as reduced air pollution, tend to arise in shorter timeframes than climate impacts (Deng et al., 2017^[129]; Vandyck et al., 2020^[130]). Conversely, NbS such as tree planting that can deliver climate and biodiversity synergies need to be planned for longevity, as they require maintenance and take decades to fully realise their climate objectives (Holl and Brancalion, 2020^[131]). For instance, Diochon, Kellman and Beltrami (2009^[132]) find that postharvest soil carbon storage capacity is half that of intact forests, even after 30 years of growth. Similarly, biodiversity measured in terms of species richness in reforested areas increases with forest age, and it is estimated that species richness in reforested areas only reaches the level comparable to the adjacent intact forests after over a century (Wang et al., 2022^[133]). Investments into NbS, in turn, need to account for the risk of being undermined by climate change to ensure viability and longevity of the solutions.

4.2.4. Summary of synergies and trade-offs: Climate policy objectives

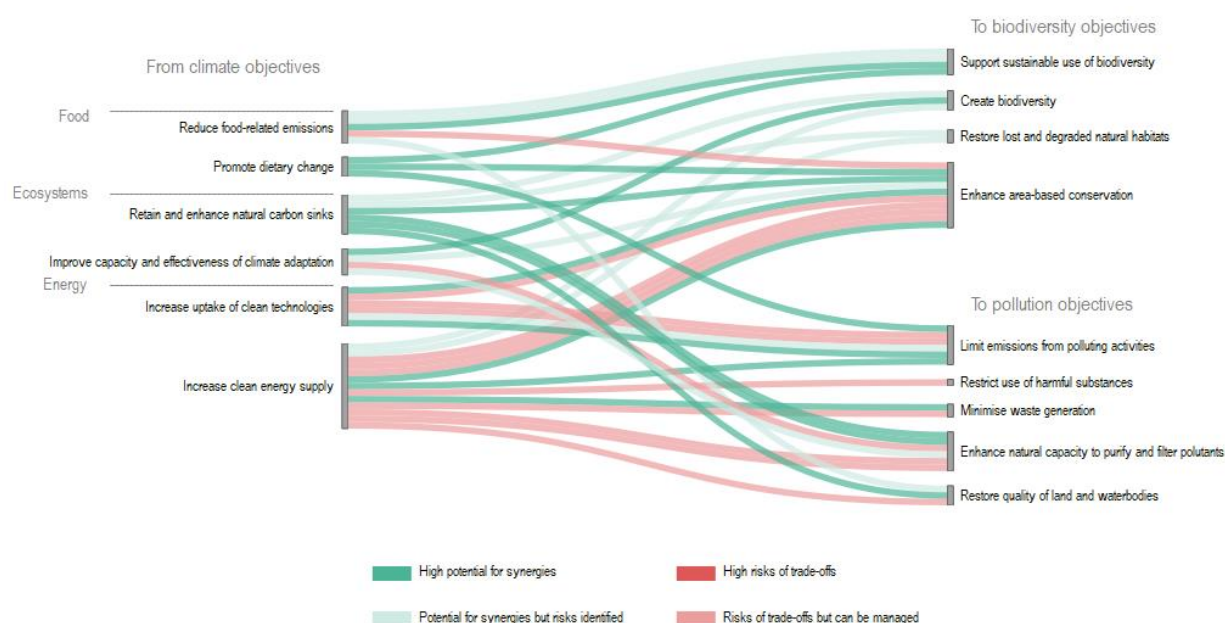
The synergies and trade-offs between key climate policy objectives with those aimed at curbing biodiversity loss and controlling pollution discussed in the preceding sections are summarised in Figure 4.3. The interlinkages with high potential for synergies are indicated in dark green, while lighter green represents synergies with some associated risks. The interlinkages with high risks of trade-offs are presented in dark red, with lighter red indicating trade-offs that can be managed and mitigated in certain contexts. While specific interlinkages remain highly context-dependent, this summary offers insights into broad patterns of synergies and trade-offs to help identify key interactions that need to be considered in developing an integrated policy approach to address climate change, biodiversity loss and pollution together.

This analysis suggests that climate policy objectives to reduce food-related GHG emissions are generally synergistic with biodiversity conservation, particularly when the interventions can alleviate pressures on land use and land use change. Although there is large variation in how environmental processes respond to interventions, policies that promote agricultural practices that improve soil carbon content, for instance, can also yield pollution control synergies by regulating water flow and reducing soil erosion. Incentivising the adoption of locally tailored and appropriate sustainable farming practices can help deliver synergies. Promoting shifts towards sustainably produced food and plant-based diets can also play a complementary role for biodiversity conservation and pollution control.

Similarly, preserving natural ecosystems that play an outsized role in storing carbon, such as forests and wetlands, also helps maintain the quality of habitats for wildlife and improve the natural capacity to filter pollutants. NbS offer important means for climate change mitigation and adaptation, although risks for trade-offs must be carefully managed. For instance, the oft-cited example of afforestation via fast-growing monocultures and the associated risks for trade-offs for biodiversity and water retention, serve as a cautionary reminder to incorporate a consideration of trade-offs. In addition, NbS often require a long period of time before their synergies with biodiversity and pollution control can be realised. In this context, it remains important that efforts to pursue these synergies through NbS complement, rather than distract from, rapid and drastic emissions reductions through other climate mitigation policies (Seddon et al., 2020^[109]). In parallel, climate adaptation can help strengthen the viability of NbS over time by protecting natural carbon sinks from heightening climate risks, such as increased frequency and severity of droughts, which compromise the ability of vegetation in ecosystems to capture and store carbon (OECD, 2025^[134]).

To the extent it contributes to a shift away from fossil fuels as the primary source of energy, increasing the viability and availability of clean energy is fundamental to addressing climate change. Given the far-reaching lifecycle impacts of fossil fuels from extraction (e.g. habitat destruction) and combustion (e.g. air and water pollution), it also delivers substantial synergies for biodiversity conservation and pollution control. However, the energy transition is illustrative of the complex trade-offs arising from extensive spatial requirements of infrastructure and pollution associated with upstream material requirements and the limited recyclability of renewables technologies. Managing these trade-offs requires more explicit consideration of biodiversity and pollution control objectives throughout the entire lifecycle (see also Chapter 6). These risks of trade-offs also highlight the importance of complementing uptake with strategies for improving energy efficiency and reducing energy demand, thereby alleviating pressures on biodiversity via land- and sea-use.

Figure 4.3. Synergies and trade-offs of climate policy objectives



Source: Authors' own elaboration.

4.3. Biodiversity policy objectives

4.3.1. Protecting biodiversity

Enhance area-based conservation

Protecting biodiversity, specialised and narrowly distributed species in particular, requires large areas of intact environments (Balmford, 2021^[135]). Research also suggests that intact ecosystems also provide greater ecosystem services compared to their managed or restored equivalents. For instance, a recent study on tropical forests finds that primary forests store 35% more carbon than forests that are commercially used (e.g. logging) on average (Mackey et al., 2020^[136]). Protecting existing biodiversity and ecosystem intactness can deliver important synergies for climate change mitigation and adaptation by increasing the capacity of carbon sinks and attenuating the impact of extreme weather events. Protecting biodiversity also delivers synergies for tackling pollution, providing natural relief and regulating air, water and soil quality (Pörtner et al., 2021^[32]). Protected areas help avoid the degradation of natural carbon sinks and are reported to contribute to significant GHG mitigation (Lee and Ignaciuk, 2025^[137]).

Protected areas have been used as a cornerstone of biodiversity conservation policy globally, although their characteristics vary widely (see also Section 6.3, which provides a deep dive on management and expansion of protected areas). They have expanded around the world, and together with other effective area-based conservation measures (OECMs),¹⁷ currently cover around 17.6% of land and 9.8% of the ocean (Protected Planet, 2025^[138]). The Kunming-Montreal Global Biodiversity Framework (KMGBF) sets out an ambitious target of expanding the global protection and conservation to at least 30% of terrestrial and inland water areas and 30% of marine and coastal areas by 2030.

Protected areas also contribute to climate change mitigation by storing and preventing carbon losses. Where effective, terrestrial protected areas simultaneously contribute to mitigating climate change by preventing deforestation and degradation, thereby preserving carbon stocks (Wolf et al., 2021^[139]). A study estimates that forested protected areas store 26% of the all of the aboveground carbon globally, with

designated protected areas contributing disproportionately more (on average 28% per unit area) than unprotected areas (Duncanson et al., 2023^[140]). In addition, protected areas and OECMs are estimated to store 21% of the belowground biomass, 15% of the soil organic carbon and 7% of the marine sediment carbon (Secretariat of the Convention on Biological Diversity, 2022^[141]). The type of carbon stored in protected areas also matters. Importantly, over half of “irrecoverable carbon”¹⁸ (which, if lost, constitutes a permanent debt to the remaining carbon budget) is stored within protected areas and the areas managed by Indigenous Peoples, as well as local communities (Noon et al., 2022^[142]).

Marine and coastal protected areas can play an important role in climate mitigation and adaptation, as well as pollution control. Marine protected areas enhance blue carbon ecosystems, such as seagrass meadows, and prevent carbon losses (Marcos et al., 2021^[143]). Relatedly, sediments in the seabed in protected areas are found to sequester substantially more carbon compared to trawled areas (Jacquemont et al., 2022^[144]). Marine protected areas limit human disturbances within natural ecosystems and also contribute to the recovery of substrate and habitat heterogeneity and regulate biogeochemical flows (e.g. nutrient cycling) (Marcos et al., 2021^[143]).

There is a growing recognition of the need to optimise the designation of protected areas across multiple objectives including carbon storage and water quality (Jung et al., 2021^[145]). Many biodiversity-rich areas are areas with high carbon storage potential. A recent study suggests that only 12% of areas that are both suitable for proactive biodiversity conservation and carbon storage¹⁹ are currently protected, underscoring the remaining potential for optimising the designation of protected areas to deliver climate synergies (Soto-Navarro et al., 2020^[146]). Relatedly, assessments of conservation of specific species (e.g. tigers) also suggest that conservation efforts deliver carbon storage benefits, highlighting the alignment between the two objectives (Lamba et al., 2023^[147]).

However, such spatial congruence should not be taken for granted. For instance, coral reefs host a wealth of marine species²⁰ and provide relief against extreme weather events, even if they are not net carbon sinks (Arneth et al., 2023^[148]). Similarly, prioritising areas for biodiversity conservation and carbon storage may come at the cost of food production and fisheries (Sala et al., 2021^[149]). While marine protected areas can enhance fisheries catch and terrestrial protected areas can provide habitats for pollinators (Gutiérrez-Arellano and Mulligan, 2020^[150]), expanding the coverage of terrestrial areas in particular leaves less land available for agricultural production (Arneth et al., 2023^[148]). These trade-offs underscore the importance of considering the siting and effectiveness of protected areas, as well as complementary policies that alleviate pressures such as those targeted at reducing food loss and waste (Arneth et al., 2023^[148]).

While protected areas are important for local biodiversity conservation (Wiens and Bachelet, 2010^[151]), realising synergies between climate mitigation and pollution control through biodiversity policy also requires consideration at multiple spatial scales as the impacts of protecting specific areas extend beyond the immediate sites. More synergistic outcomes may be progressively possible at a larger scale of “scape” (Pörtner et al., 2023^[1]). Protected areas enhance natural capacity for filtering water-borne pollutants and for providing clean freshwater. They deliver 20% of the global total continental runoff and contribute to freshwater provision for nearly two-thirds of the global population (Harrison et al., 2016^[152]). With about 70% of river reaches (by length) estimated to lack protected areas in their upstream catchments (Abell et al., 2016^[153]), remediation of water quality is an additional consideration for optimising protected areas for simultaneously tackling biodiversity loss and pollution together.

More broadly, it is also important to mitigate the risk of dichotomisation of protected and unprotected areas. Without adequate consideration of this risk, land or sea-use restrictions in protected areas can have unintended negative spillovers on neighbouring areas, for instance, through direct displacement of activities to unprotected areas for forestry (Murray, McCarl and Lee, 2004^[154]) and fishing activities (Sen, 2010^[155]). Such displacement can indirectly lead to adverse impacts through the intensification of the land use within unprotected areas (Bastos Lima, Persson and Meyfroidt, 2019^[156]).

Control the introduction and spread of invasive alien species

Invasive alien species (IAS) are estimated to play a role in 60% of global animal and plant extinctions (IPBES, 2023^[157]). IAS have extensive impacts on the environment, including causing “regime shifts” (i.e. oft-irreversible changes in states of ecosystem structure and functions) (Pyšek et al., 2020^[158]). As highlighted in Target 6 of the KMGBF, preventing the introduction and establishment of IAS is critical for protecting biodiversity (CBD, 2023^[159]). As IAS can alter belowground carbon pools (e.g. root biomass, soil organic carbon and soil inorganic carbon) and CO₂ and CH₄ emissions (Raheem et al., 2024^[160]) and reduce the resilience of ecosystems, effective IAS control strategies that coalesce around prevention and management can indirectly enhance the contribution of soil ecosystems towards climate mitigation and strengthen resilience against extreme weather events (IPBES, 2023^[157]).

However, there can be unintended trade-offs from some of the measures to control IAS. The treatment of ballast water (water pumped into the lower part of ships to stabilise them; identified as one of the key dispersal pathways through which marine species are translocated), now mandatory under the International Convention on the Control and Management of Ships’ Ballast Water and Sediments, provides an illustrative example. Although it restricts dispersal pathways of IAS, retrofitting ships can be associated with a small increase in CO₂ emissions from fuel consumption (Ejder et al., 2024^[161]). This underscores the need for considering the substitute shipping fuels and fuel efficiency together with the measures to tackle IAS introduction through ballast water. Furthermore, chemical management of established IAS can also have adverse implications as pesticides and herbicides widely deployed for the purpose of eliminating established IAS can also affect non-target species and infiltrate in soil and water, posing risks for pollution (IPBES, 2023^[157]).

4.3.2. Managing biodiversity

Support sustainable use of biodiversity (including for biomass production)

Many indispensable anthropogenic activities rely on biodiversity and the ecosystem services it offers. While it is critical to avoid land use change to the extent possible, not all land and sea can be spared entirely from anthropogenic pressures, underscoring the importance of better use of managed land in a way that can also contribute to biodiversity conservation (Kremen and Merenlender, 2018^[162]). From subsidies that ensure cross-compliance with multiple environmental objectives to Payments for Ecosystem Services (PES),²¹ there are a wide range of policy approaches that are adopted to incentivise and reward changes towards more sustainable land and resource use practices.

Agriculture is the prime example. Various dimensions of biodiversity sustain agriculture and underpins “provisioning services” of ecosystems, which sustain lives and livelihoods through providing a range of food, feed, fibre as well as other materials including fuel (Millennium Ecosystem Assessment, 2005^[163]). Biodiversity also provides “regulating services”, such as pollination and pest control, as well as water regulation and soil erosion control. However, modern farming is characterised by growing limited varieties of plants and animals, which leads to more homogeneous and simplified land (Nicholson and Williams, 2021^[164]). Landscape diversification in agriculture can help mitigate biodiversity loss, with research finding that more complex agricultural landscapes host richer biodiversity taxa and functional groups than simplified landscapes (Estrada-Carmona et al., 2022^[165]). For instance, landscape diversification through embedding vegetation strips can enhance pollinator biodiversity (Buhk et al., 2018^[166]).

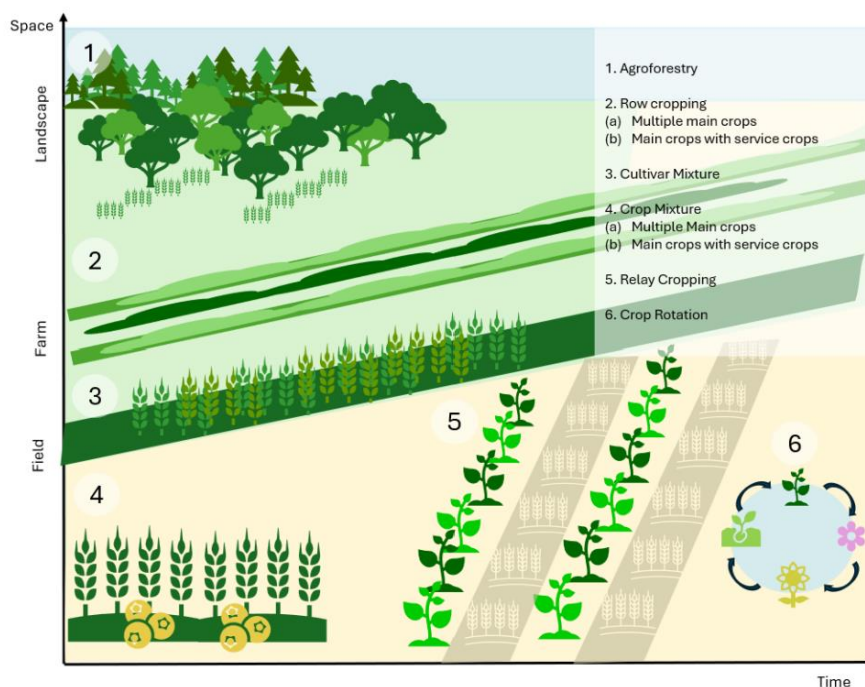
Practices for promoting agricultural diversification can foster synergies for pollution control by reducing the need for fertilisers and pesticides. There are no one-size-fits-all solutions for agricultural diversification. These practices can be adopted at various spatial and temporal scales (Figure 4.4). Adopting long-standing practices of agroforestry as part of a landscape mosaic²² have gained renewed attention, and about 40% of the global agricultural land have at least 10% tree cover (Zomer et al., 2016^[167]). Although the impact varies considerably by sites, agroforestry practices are associated with lower pesticides,

herbicides and other pollutant losses (on average by 49%) and reduced run-off (on average by 58%) and soil erosion, as well as more efficient use of water and nutrients (Zhu et al., 2020^[168]). These areas also provide habitats for species, which in turn improves agricultural productivity by retaining nutrients in soil and purifying water (Torralba et al., 2016^[169]). Relative to conventional agricultural practice, studies have shown that agroforestry results in reduced impacts on biodiversity (Jose, 2009^[170]), as well as increased carbon storage in above and belowground biomass (OECD, 2020^[171]).

Agricultural diversification can also be achieved at the level of individual fields through biodiversity-friendly practices, such as intercropping and crop rotation, which can also enhance nutrient uptake (Cappelli et al., 2022^[172]). Furthermore, these practices can improve other ecosystem functions (e.g. pollination, weed control), as pests spread more slowly on spatially and temporally diverse crop systems, thereby reducing the need for pesticides, irrigation and fertilisers (Letourneau et al., 2011^[173]). In turn, reduction and efficient use of pesticides and fertilisers can further help prevent air, soil and water pollution (Smith et al., 2020^[73]). These contribute to improved soil health, nutrient cycling, water replenishment and erosion control, which are fundamental to agricultural productivity (Khangura et al., 2023^[174]).

Diversified agriculture can also contribute towards climate mitigation and adaptation. Practices that enhance plant biodiversity can also support the mitigation potential of soil, as they contribute to soil microbial diversity (Cappelli et al., 2022^[172]) which is suggested play a role in carbon cycling due to its importance for soil carbon respiration and plant tissue decomposition (De Graaff et al., 2015^[175]). Greater biodiversity can also reduce the risks of plant pathogens – which are heightened with climate change (Singh et al., 2023^[176]) – through dilution effects, thereby supporting adaptation of agriculture to climate change (Keesing, Holt and Ostfeld, 2006^[177]). Local and community-level efforts for protecting genetic diversity through conservation measures can indirectly support climate adaptation. For example, seed banks and botanical gardens²³ can help maintain and develop resilient varieties of crops to ensure food security (Dempewolf et al., 2014^[178]).

Figure 4.4. Practices for diversifying agricultural production at different scales



Source: Adopted from Cappelli et al. (2022^[172]).

Despite these synergies and the potential for supporting long-term growth in agricultural productivity, these practices can also entail complex trade-offs for yields, which may occur at various temporal and spatial scales. For instance, at the farm-level, shade provided through agroforestry can simultaneously enhance resilience against extreme heat and increase the risk of reduced crop yields (OECD, 2020^[171]). While some practices are relatively low-cost and scalable (e.g. crop rotations) (OECD/FAO, 2025^[80]), it is also important to note that the impacts of agricultural diversification are highly context-dependent and can also result in increased burden for farmers, which may lead to lower income or yields for smallholders (Bravo-Peña and Yoder, 2024^[179]). There is a need for ensuring that efforts for facilitating sustainable agricultural practices do not undermine the purported benefits for biodiversity conservation and climate mitigation by causing further conversion of agricultural land elsewhere (Balmford et al., 2025^[180]).

Ensuring the sustainable use of biodiversity extends beyond agricultural production on land. For instance, removing incentives that can be harmful to biodiversity (for instance, for overfishing and improving fishery practices (e.g. minimising bycatch) is critical for the sustainable use of biodiversity, including fish stock, with potential synergies for climate change mitigation. Maintaining healthy fish stocks and marine ecosystems by limiting disruptions to their habitats can help maintain the ocean's capacity for carbon absorption and storage (Sumaila and Tai, 2020^[181]). Protecting marine ecosystems from pressures from industrial trawling and dredging fishery can also help prevent release of organic carbon sequestered in marine seabed sediments (Epstein et al., 2022^[182]). Furthermore, improving fisheries management constitutes a cost-effective means to reduce GHG emissions associated with fisheries itself (OECD, 2022^[183]).

Reducing the impact of aquaculture is also important as fish farms interact with local ecosystems, resulting in risks for competition and genetic contamination of wild fish stocks (Asche et al., 2022^[184]). Aquaculture is associated with significant GHG emissions and water consumption, particularly in developing countries (Jiang et al., 2022^[185]). Improving aquacultural practice and integrating NbS, such as the use of algae, is suggested to simultaneously reduce negative impacts on biodiversity and address water and soil degradation from effluents and medications such as antibiotics (Vijayaram et al., 2024^[186]).

Reduce food loss and waste

Globally, around one-third of all food produced is lost or wasted every year (FAO, 2023^[187]).²⁴ In addition to raising concerns over sustainably meeting nutritional needs of the growing population (Alexander et al., 2017^[188]), unconsumed food constitutes one quarter of global water, cropland and fertiliser use (Kummu et al., 2012^[189]). Along with dietary change, promoting conscious food consumption to reduce food loss and waste has important synergies for climate mitigation, from avoided agricultural emissions as well as CH₄ emissions from landfilled food waste (Poore and Nemecek, 2018^[84]; Hoy et al., 2023^[190]). A recent estimate suggests that halving food loss and waste can lead to a 4% reduction in agricultural GHG emissions by 2030 (OECD/FAO, 2024^[191]).

Reducing food waste can also improve air, water and soil quality, primarily through indirectly reducing nitrogen applications in agriculture. Associated reduction in ammonia emissions is suggested to have substantial impact through reducing air pollution (ammonia reacts with acid forms of SO₂ and NO_x and form PM_{2.5}) as well as reducing nitrogen deposition that can negatively affect biodiversity.²⁵ For instance, an estimate suggests that eliminating food waste can reduce ammonia emissions by 16%, lower PM_{2.5} concentrations by up to 5 µg/m³, and mitigate nitrogen deposition above the damage threshold²⁶ in biodiversity hotspots²⁷ by (up to) 19% (Guo et al., 2023^[192]). Furthermore, cutting CH₄ emissions results in lower ground-level ozone.

Certain materials, such as plastics, play a vital role in reducing food waste through preventing food contamination, reducing post-harvest losses and enabling shelf-life extension (Khangura et al., 2023^[174]), although these positive contributions need to be carefully balanced against the potential health and environmental risks of alternative material choices.

Furthermore, attention is warranted to behavioural responses, as policies that target food loss and waste reduction may result in rebound effects. For instance, lower prices from efficiency improvements may lead to increase consumption (Hegwood et al., 2023^[193]). Furthermore, notwithstanding the important synergies for climate mitigation and reduced pressures on land, stringent targets for reducing food waste can also suppress food demand and therefore reduce agricultural income, underscoring the importance of policy consideration, including through measures to alleviate these concerns to improve the viability and acceptability of environmental measures, to ensure the balance between environmental and economic objectives (Nenert et al., 2025^[194]).

4.3.3. Restoring biodiversity

Restore lost and degraded natural habitats

With 75% of land surface already significantly altered and 66% of the ocean area experiencing cumulative impacts through human activities (IPBES, 2019^[195]), many of the natural habitats sustaining rich biodiversity have been lost, degraded or abandoned. As highlighted in Target 2 of the KMGBF, restoration of degraded terrestrial, inland water, coastal and marine ecosystems are a key lever for stemming the tide of biodiversity loss, which can also deliver important synergies for climate change mitigation and pollution control. In particular, as discussed in Section 4.2.3, well-designed NbS can help deliver on climate and biodiversity objectives simultaneously. While research investigating the contribution of biodiversity towards carbon storage has typically focused on taxonomic diversity to date, there is a growing body of evidence on how functional traits and composition of species contribute towards achieving climate objectives (Rahman et al., 2021^[196]).²⁸

In parallel with protected areas, prioritising restoration in areas that are important both for biodiversity and carbon storage can maximise synergies. A recent analysis identifying areas of value for both biodiversity conservation and climate mitigation suggests that an integrated approach can triple the number of species spared from extinction while doubling the capacity for carbon sequestration (Strassburg et al., 2019^[197]). However, achieving restoration that benefits both biodiversity and climate change is not always straightforward (Pettorelli et al., 2021^[198]). Biodiversity and climate priorities in restoration do not always overlap spatially, particularly in regions that are rich in endemic species with limited ranges because a neighbouring area with higher carbon storage capacity can contain very different species assemblages (Reside, VanDerWal and Moran, 2017^[199]). The climate mitigation impact of forestation also varies by biomes and embedding biodiversity consideration, such as the reliance of rare species on non-forested drylands, may further limit the areas that are suitable for forestation (Rohatyn et al., 2022^[200]).

There are also some cases in which prioritising biodiversity conservation may diminish climate mitigation synergies. At the global level, wetlands are of the highest relative importance to biodiversity together with forests (Strassburg et al., 2020^[201]). However, restoring certain types of wetlands can result in substantial CH₄ and N₂O emissions, because the same sedimentary conditions that slow aerobic microbial decomposition and enable carbon storage may also lead to the production and emission of these GHGs (Rosentreter et al., 2021^[202]). While restoring degraded inland wetlands is positive for climate mitigation overall, its benefits are expected to materialise at a relatively slow pace,²⁹ over decadal to century-long time-scales, highlighting the desirability of conservation over restoration (Pörtner et al., 2021^[32]; Taillardat et al., 2020^[203]).

Create biodiversity

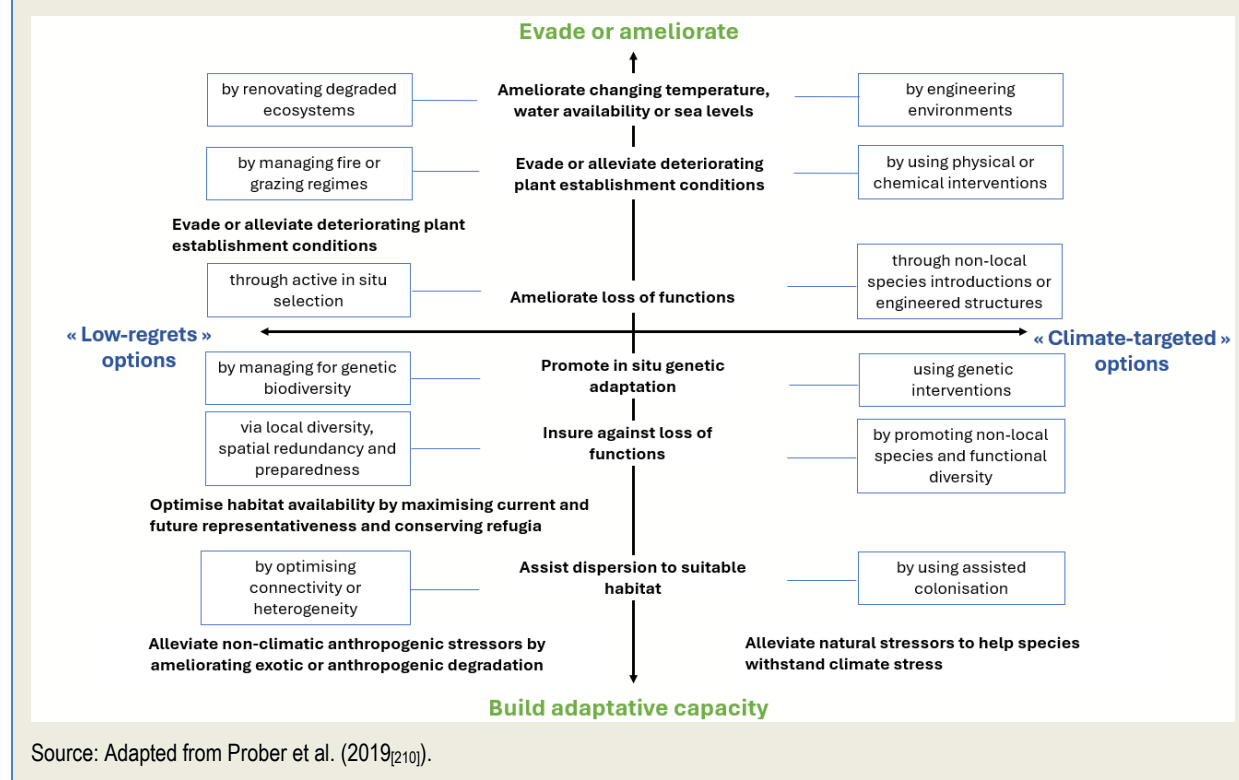
“Creating” biodiversity as part of NbS offers additional ways to stem the tide of biodiversity loss, while buffering against the impact of climate change and pollution. Re-introducing species can enhance climate adaptation capacity and coastal protection, with a wide array of examples ranging from the direct use of oyster or seagrass beds for attenuating flooding impact to incorporating them in man-made systems (e.g. dikes) (Borsje et al., 2011^[204]). This approach is also an important consideration for adapting the biodiversity conservation strategy to the changing environment (Box 4.1).

While the evidence is relatively limited, it has also been suggested that trophic rewilding, reintroducing certain species for enabling top-down trophic interactions and their cascades, can also contribute towards climate change mitigation (Perino et al., 2019^[205]). There is emerging research suggesting that rewilding can complement conventional plant-focused carbon sink strategies, given the impacts of animals on vegetation biomass through roaming across landscapes (Schmitz et al., 2018^[206]). The population decline in megafauna (large animals) that play a critical role as “ecosystem engineers” has cascading impacts across species. For instance, as frugivores (e.g. elephants) become less abundant, seed dispersal of fruited and high-biomass trees becomes more limited, leading to their replacement by shorter trees with lower biomass and lower capacity for carbon storage (Watson et al., 2018^[96]). Selectively re-introducing these frugivores and restoring their habitats can therefore offer climate synergies (Cromsigt et al., 2018^[207]; Berzaghi et al., 2019^[208]). Similarly, megafauna help maintain soil carbon storage in grassy biomes such as grasslands and savannahs; an important consideration for the regions in which afforestation is infeasible or unsuitable due to potential impacts on native species (Rohatyn et al., 2021^[209]).

Box 4.1. Measures to facilitate persistence and adaptation of biodiversity in a changing climate

There is increasing recognition that biodiversity conservation practices themselves need to adapt to the changing climate (see also Chapter 6). A wide array of climate change adaptation measures of nature conservation has been developed and can be categorised using the matrix typology proposed by (Prober et al., 2019^[210]) (see Figure 4.5). The **vertical axis** represents the ecological mechanisms, ranging from measures that evade or ameliorate changing environments to measures that build adaptive capacity to promote nature’s inherent resilience. The **horizontal axis** represents the level of interventions, ranging from “low-regrets” measures which are likely to be beneficial regardless of the rate or extent of climate change to “climate-targeted” measures which may entail higher risks of unexpected negative spillovers, i.e. impact of assisted migration of exotic species on endemic species. The most interventionist approaches are genetic engineering and engineering environments (such as engineering topography to create moisture concentrations). The least interventionist approach is the restoration and preservation of the wildness of an ecosystem without any human intervention. The typology helps consider trade-offs between implementing climate-targeted approaches that are more interventionist and maintaining (or recreating) natural and wild areas. A meta-analysis of 473 reviewed studies covering worldwide nature conservation options for terrestrial areas shows that most current efforts consisted in “low-regrets” approaches that aimed to build adaptive capacities (i.e. lower left quadrant).

Figure 4.5. Typology of measures to facilitate the persistence and adaptation of biodiversity in a changing climate



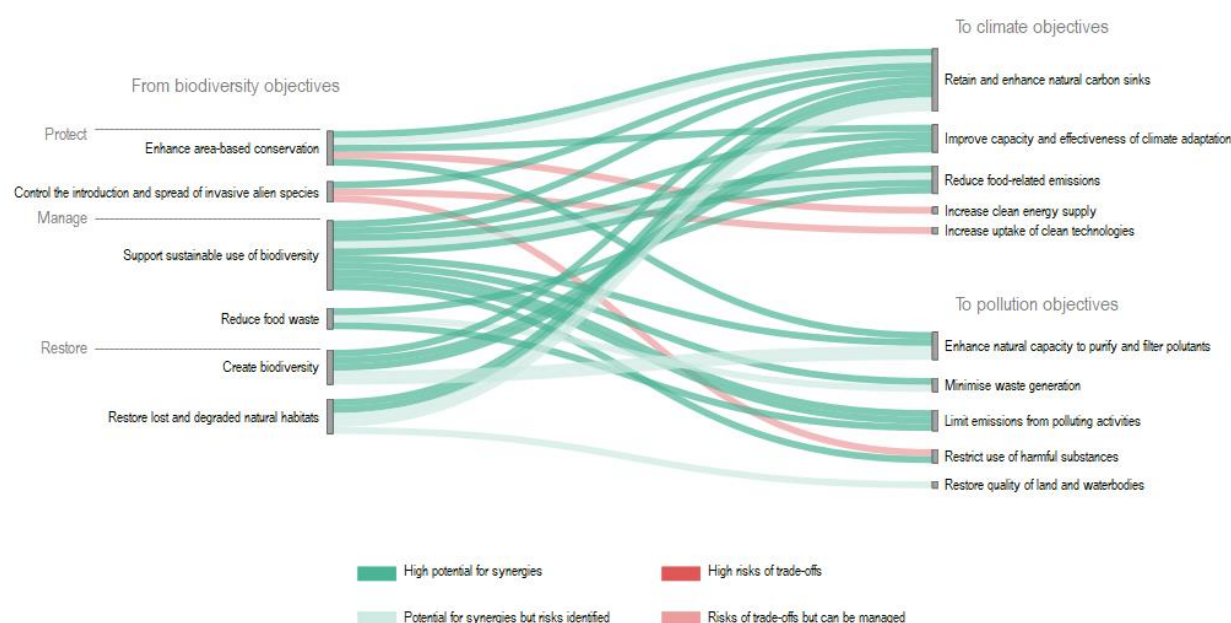
4.3.4. Summary of synergies and trade-offs: Biodiversity objectives

The synergies and trade-offs between biodiversity policy objectives with those aimed at addressing climate change and managing pollution discussed in the previous sections are summarised in Figure 4.6. Notably, there are significant complementarities between the objectives to protect, sustainably use, manage and restore biodiversity and GHG emissions reduction and pollution control, underscoring the importance of biodiversity and the indispensable ecosystems services it underpins.

Biodiversity conservation through protected areas can create synergies by improving carbon storage, offering climate adaptation solutions and providing natural relief against pollution. Many biodiversity-rich areas also have high carbon storage potential, although such spatial congruence is not universal, and optimisation is required to balance competing demands on land- and sea-use. It is also important to consider the goal of biodiversity conservation at multiple spatial scales, as dichotomisation of protected versus unprotected areas can lead to intensification of activities at the margin, which can in turn diminish the synergies or even increase overall GHG emissions and amplify the risks of pollution.

As not all land and seas can be spared from anthropogenic pressures, particular attention is warranted to ensure that the use of biodiversity is sustainable, such as through improved practices in agriculture, fishery and aquaculture that are attuned to the local context and balance environmental, social and economic objectives. In parallel, reducing food loss and waste can not only contribute to biodiversity objectives, but also helps avoid GHG emissions from production and landfilled food and packaging waste, as well as nitrogen applications in agriculture. While restoring lost biodiversity have the potential to foster synergies for climate and pollution objectives, strengthening these synergies requires the consideration of the interactions between various dimensions of biodiversity (e.g. functional traits of species and community composition) and environmental processes.

Figure 4.6. Synergies and trade-offs of biodiversity policy objectives



Source: Authors' own elaboration.

4.4. Pollution policy objectives

4.4.1. Preventing pollution at source

Limit emissions from polluting activities

Quantitative constraints and emission standards are commonly deployed around the world to control air, water and soil pollution at source. Insofar as major pollutants originate from the same sources as GHG emissions, and given that pollution is one of the primary drivers of biodiversity loss (IPBES, 2019^[195]), preventing pollution at source has the potential to bring considerable synergies for climate change mitigation and biodiversity conservation.

Emission standards and air quality standards facilitate the shift in production and consumption to address stationary and mobile sources of air pollution. These regulatory approaches are also often complemented by market-based measures such as tradeable permits and taxes (Lanzi et al, 2022^[211]). Limiting air pollution across sectors can also contribute towards reducing co-emitted GHG emissions (e.g. (Fouré, Forthcoming^[212])) and short-lived climate pollutants, such as black carbon (see also Chapter 6.4, which provides a deep dive into policies for air pollution control). For the industrial sector, uptake of clean technologies and reduction in energy intensity can reduce both air pollution and GHG emissions, although some solutions such as end-of-pipe technologies may only address air pollutants (Qian et al., 2021^[213]). For road transport, emission standards and complementary measures, such as low emission zones,³⁰ can help reduce emissions of particulate matter and NO_x from diffuse mobile sources (i.e. vehicles) while simultaneously reducing GHG emissions (Xu and Qin, 2023^[214]).

Air quality improvements can also contribute towards biodiversity conservation. In particular, lowering ground-level concentrations of ozone can alleviate pressures on terrestrial ecosystems, as ground-level ozone is associated with adverse impacts on plants and their subsequent interactions with insects and microbial species (Agathokleous et al., 2020^[215]). While less documented, it is suggested that effective

regulations of ozone precursors have also averted the decline in bird species populations (Liang et al., 2020^[216]). In addition, there are some less direct synergies associated with air pollution mitigation. For instance, deposition of air pollutants and dust on the surfaces of solar PVs can lower their performance (e.g. PM reduces visibility and reduces available solar radiation reaching the PV surfaces) and compromise solar energy conversion into electricity (e.g. black carbon absorbs heat) (Yassaa, 2016^[217]; Song, Liu and Yang, 2021^[218]).³¹ Reducing air pollution can therefore contribute towards increased clean energy supply by improving the efficiency of solar energy conversion.

However, addressing air pollution can also give rise to a complex trade-off, due to the “lost” cooling impact of scattering aerosols (e.g. pollutants such as SO₂ form sulfate aerosols), implying that climate policy needs to be amplified to meet the temperature target (Im et al., 2022^[219]). Between 1850-1900 and 2010-2019, it is estimated that aerosols of various sizes have contributed to lowering the temperature by 0.0°C to 0.8°C compared to what it would otherwise have been (IPCC, 2021^[220]), although there remains considerable uncertainty over the direct and indirect impacts of aerosols on climate (Li et al., 2022^[221]).

Compared to air pollution, improving ground and surface water quality has been challenging, partly due to their diffuse and intractable sources and the sheer range of pollutants that end up in aqueous media (OECD, 2017^[57]). Globally, it is estimated with variation that up to 80% of wastewater enters the natural environment without effective treatment (Jones et al., 2021^[222]; UNESCO, 2017^[223]). Effective monitoring and regulation of contaminants of emerging environmental and health concerns, such as endocrine disruptors, should address the lifecycle of chemicals and proactively identify the risk of endpoints (OECD, 2023^[224]). These measures can also help reduce adverse impacts on aquatic biodiversity.

Limiting nutrients applied as fertilisers can confer biodiversity conservation synergies. Across environmental media, managing nitrogen pollution from agriculture can help address biodiversity loss, given the cascading impact of nitrogen that leads to lower air quality, soil acidification and eutrophic water bodies (OECD, 2018^[225]). Policies that enhance nutrient use efficiency and reduce applications by improving the precision of application in terms of location and timing can address N₂O emissions and contribute to mitigating GHG emissions from agriculture without significant changes in yield (Adegbeye et al., 2020^[226]; Pan et al., 2022^[227]) (see also Section 6.5 in Chapter 6, which provides a deep dive on nutrient management). Excess phosphorous in freshwaters also leads to eutrophication, which in turn lead to higher CH₄ emissions and contributes to climate change (Nijman et al., 2022^[228]).

Restrict the use of harmful substances

The importance of sound management of chemicals and waste is increasingly recognised, as exemplified by the recently adopted Global Framework on Chemicals (ICCM5, 2023^[229]). Substances known to be hazardous above a certain threshold can be restricted in terms of the use in products and production processes, which can in turn induce development and deployment of alternatives. Newly developed alternatives have the potential to contribute to climate mitigation objectives, particularly if they replace feedstock and emissions-intensive production processes. For instance, a synthesis of LCA studies for bio-based products suggests that, for the chemical industry as a whole, replacing primary petrochemicals with bio-alternatives may offer the dual benefit of reducing pollution and addressing climate change. GHG emissions are on average 45% lower compared to fossil-based counterparts, although variability and exceptions do exist (Zuiderveen et al., 2023^[230]).

However, unanticipated responses to policies may diminish potential synergies or even result in burden shifting. For example, alternatives developed in response to policies may result in “regrettable substitution” (i.e. the use of chemicals that are no less harmful than the ones they are replace) (Zimmerman and Anastas, 2015^[231]). Policy efforts to address atmospheric ozone depletion, following the phaseout under the Montreal Protocol on Substances that Deplete the Ozone Layer are particularly illustrative of the complexity of managing burden shifting risks. While the substitutes to ozone-depleting substances (ODS) provided better protection of the ozone layer and therefore protected species from harmful UV radiation,

many of the initial replacements (e.g. Hydrofluorocarbons (HFCs)) of ODS had high global warming potential (GWP), contributing to climate change (UNEP, 2023^[232]). Subsequently, HFCs are now being phased down under the Kigali Amendment to the Montreal protocol. The next generation of refrigerants and coolants have lower GWP, but many of them break down to trifluoroacetic acid (TFA) – a persistent substance – although TFA is currently judged not to pose a risk to human health or to the environment under the Montreal Protocol (UNEP, 2023^[232]).

While limiting the use of pesticides can help conserve biodiversity, there are also similar concerns that bans on certain pesticides can incentivise producers to turn to new chemicals, which could ultimately prove more toxic to non-target species or harm a different group of species (Feckler et al., 2023^[233]; Möhring et al., 2020^[234]). Without careful consideration, reduced pesticide usage may also result in higher tillage intensity to maintain the crop yields, resulting in overall less ecotoxicological, but more energy-intensive crop production (Böcker, Möhring and Finger, 2019^[235]).

Similarly, producers and consumers may turn to bio-based materials as substitutes, resulting in increased demand for land and biomass and subsequent trade-offs for nutrient pollution and risks for eutrophication (Zuiderveen et al., 2023^[230]). Concerns over the land-use impacts of the increased uptake of bio-based plastics, for instance, illustrate the importance of considering the wider environmental implications (OECD, 2022^[236]). While bio-based materials tend to be considered “green” by definition, relatively little is understood about their behaviours in the environment, their thermal stability under climate change, and their recyclability (Green et al., 2023^[237]). Without adequate consideration of lifecycle impacts, these materials can result in burden shifting between different end points, such as health risks and environmental challenges, solving one challenge while unintendedly creating another.

Reducing the risk of regrettable substitution requires a better understanding of hazard and exposure, but also the consideration of the functionality they serve (Maertens, Golden and Hartung, 2021^[238]). Disparate approaches, lack of data and expertise, as well as the ambiguity around what constitutes “safer”, can make it difficult to select safer chemicals alternatives. In this context, the OECD Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives discusses the minimum assessment criteria and recommended assessment practices for advancing a consistent understanding of the minimum requirements (OECD, 2021^[239]).

4.4.2. Reducing leakage of pollutants into the environment

Minimise waste generation

The environmental toll of extraction, processing and use of materials underscores the need for recovery of materials and waste minimisation to alleviate pollution (UNEP, 2024^[240]). From material sourcing, design and production to consumption and end-of-life, there is a suite of policies across the lifecycle of materials and products to improve resource efficiency and productivity (Svatikova, Brown and Börkey, 2025^[241]; OECD, 2022^[242]). Promoting reuse of products (e.g. through repair), components (e.g. remanufacturing), and materials (e.g. via recycling) can lower the pressures from primary production and help minimise waste.³²

Secondary materials tend to be considerably less polluting on a number of environmental parameters, although it is important to note that there are some caveats (e.g. hazardous chemicals in plastics can become concentrated in recycled plastics (Singh and Walker, 2024^[243]). For instance, the per kg environmental impacts of secondary copper (e.g. acidification, eutrophication, freshwater toxicity) are lower by a factor of 4 to 60 than primary copper (OECD, 2019^[244]). Diverting waste from landfills can limit associated air pollution from suspension and water and soil pollution from contaminated leachates from heavy metals and VOCs (Vaverková, 2019^[245]). As decomposition of landfilled waste is a significant source of potent and short-lived GHG (CH₄) emissions, minimising waste can also contribute towards climate goals (Hoy et al., 2023^[190]).

A key aspect of minimising waste is to recover value from materials and products for secondary and alternative use, which can deliver multiple synergies. In the agricultural sector, processing manure and crop residues and repurposing them as fertilisers can provide an alternative to chemical-based fertilisers, although due attention is warranted to avoid inadvertently exposing soil to toxic substances (e.g. heavy metals and antibiotics from manure from industrial livestock) (Köninger et al., 2021^[246]). A recent analysis suggests that the amount of nitrogen available in animal manure could meet a large share of crop nutrient requirements in countries where manure is diverted for non-agricultural uses such as energy for household cooking (Jones and Deuss, 2024^[247]). The use of recycled agricultural waste can directly reduce N₂O and CH₄ emissions from waste decomposition, as well as indirectly through reducing energy-intensive fertiliser production (Sharma et al., 2019^[248]). The impact can be considerable, since production and use of nitrogen in agriculture is estimated to be responsible for over 2% of global emissions (Menegat, Ledo and Tirado, 2022^[249]).

While facilitating secondary and alternative use is important, it is also worth noting that recycling itself can still be a polluting or energy-intensive process in some cases. For recycling to become more viable, there is a need to accelerate the transition to a cleaner energy system and incentivise more sustainable product design through the consideration of the full lifecycle of products. For instance, recycling critical raw materials from renewable technologies still remains highly specialised and complex, and as a result can be energy-intensive and associated with complex waste streams (IEA, 2024^[250]).

A number of life cycle assessments of recycling e-waste also suggest that transport and energy consumption can offset some of the reduced emissions from lower primary production and result in ecotoxic impact through degraded air, water and soil quality (Lee, Choi and Kim, 2024^[251]). Meanwhile, most e-waste is recycled informally, exposing workers to heavy metals and persistent organic pollutants while causing contamination of aquatic and terrestrial environment (Parvez et al., 2021^[252]). Recycling of plastics offers another example demonstrating the need to consider the wider environmental and health impacts of recycling policies beyond waste prevention, with some evidence finding that recycled plastics may contain environmentally harmful contaminants (Carmona et al., 2023^[253]; Singh and Walker, 2024^[243]). Relatively novel technologies, such as chemical recycling of plastics, can also be highly energy-intensive, and their by-products may result in soil acidification and air pollution (OECD, 2022^[236]). These risks also underscore the growing importance of integrating “safe-and-sustainable-by-design” within approaches to developing chemicals, which aims to identify and minimise the risks for human health and environment early on, considering various environmental aspects from a lifecycle perspective (OECD, 2025^[254]).

There is also a need to consider the unintended consequences of policies to minimise waste that may partially offset the purported synergies for biodiversity conservation and climate change mitigation. Some of these unintended consequences stem from direct cost-avoiding behaviours. For instance, levies such as landfill tax can provide incentives for illegal dumping, also referred to as fly-tipping (Purdy et al., 2022^[255]). Others can be more indirect and arise from misalignment in availability and prices of less polluting secondary products and resultant “rebound effects”.³³ For instance, for secondary materials and products to contribute to lower environmental pressures, they must displace primary production and new sales (Cooper and Gutowski, 2017^[256]; Zink and Geyer, 2017^[257]). Available evidence suggests that the increase uptake of secondary products does not always translate into a proportionate decrease in the primary production and sale of new products (Zink and Geyer, 2017^[257]).

When options for reduction, recycling and recovery are exhausted, otherwise energy-intensive and polluting waste disposal methods can be less environmentally harmful through deploying “waste-to-energy” technologies of varying sophistication and infrastructure needs (Makarichi, Jutidamrongphan and Techato, 2018^[258]). For instance, incineration can be accompanied with heat recovery, while biogas can be produced from anaerobic digestion of sewage sludge (Abanades et al., 2022^[259]; Khan et al., 2022^[260]).

Enhance natural capacity to filter pollutants

Some policy approaches and solutions to reduce leakage of pollutants rely on healthy ecosystems and their ecological functions. In particular, constructed wetlands have rapidly expanded globally as a mechanism to help remove pollutants, including diffuse pollution from heterogeneous sources, such as excess nutrients from agriculture and chemical residues from wastewater (Feckler et al., 2023^[233]). They have been deployed in over 50 countries, as low-cost and less energy-intensive complements to wastewater treatment plants (Wu et al., 2023^[261]).

Constructed wetlands offer several important synergies for climate adaptation and biodiversity conservation. For instance, they can provide an effective means for management and treatment of urban stormwater runoff, speed and volume of which has increased due to impervious surfaces in urban areas as well as altered precipitation patterns (Hale et al., 2019^[262]; Bettez and Groffman, 2012^[263]). As natural wetlands that harbour rich assemblages of biodiversity are disappearing at an accelerated speed, constructed wetlands can potentially offer refuges for wildlife including for migrating and nesting birds. In turn, rich biodiversity can support their water purification capacity (Zhang et al., 2020^[264]).

However, there is mixed evidence on the overall impact of constructed wetlands on biodiversity, highlighting the importance of considering the multifaceted nature of biodiversity beyond the conventional focus on taxonomic diversity and species abundance. While species abundance may be high, there is some evidence that constructed wetlands could be used as an incidental and sub-optimal habitat and can create an “ecological trap” for wildlife, leading to their poorer fitness quality measured by growth, survival and reproduction (Hale et al., 2019^[262]). Moreover, there may be modest trade-offs between pollution control and biodiversity conservation objectives in practice. For instance, desirable features of constructed wetlands for biodiversity conservation, such as shallow depth and large surface area that provide habitats for terrestrial and aquatic species (Hansson et al., 2005^[265]) may reduce their efficiency in removing pollutants. Conversely, prioritising the objective of wastewater treatment and runoff prevention can result in simplified species composition and the use of alien species, thereby increasing the risk of invasion (Zhang et al., 2020^[264]).

Moreover, there is a risk of unforeseen pollution swapping that can result in reduced synergies (Kanter et al., 2020^[266]). Incomplete denitrification (soil microbes converting nitrate into nitrogen under low oxygen level) in constructed wetlands and riparian buffer zones³⁴ can result in N₂O emissions and create waterlogged soils that increase emissions of potent GHG, such as CH₄ (Stevens and Quinton, 2009^[267]). These potential trade-offs suggest that multiple objectives of constructed wetlands must be integrated from the initial design phase (Sharley et al., 2017^[268]).

4.4.3. Remediating pollution

Restore quality of polluted land and water bodies

Restoring the quality of the environment from the consequences of pollution is important for human and planetary health. There is a heightened need for remediation in light of the competing needs for land. For instance, limiting additional land take implies that brownfield sites around the world, estimated to number around 5 million, need to be remediated and redeveloped for their alternative use, including residential space (Hou et al., 2023^[269]).³⁵ However, although cleaning up polluted sites generally delivers environmental benefits, conventional approaches may run counter to climate and biodiversity objectives. For instance, thermal desorption of contaminated soil is highly energy-intensive, and chemical treatment of contaminants in soil and groundwater can create toxic by-products that can adversely affect terrestrial biodiversity (Hou et al., 2023^[269]). Similarly, remediating contaminated and eutrophic water bodies requires careful considerations of its broader environmental impact. Physical techniques, such as dredging, involve the removal of the bottom sediments of water bodies, potentially causing disruptions to aquatic ecosystems (Pereira and Mulligan, 2023^[270]; Akinawo, 2023^[271]).

In light of these risks, various methods of “bioremediation” of polluted soil and water offer an increasingly viable alternative to physical and chemical treatments, including phytoremediation, which uses plants and their capacity to absorb and degrade pollutants for the clean-up of contaminated sites (Hou et al., 2023^[269]). Biosorption using agricultural and food waste and bioaccumulation by microbes can help remove heavy metals from water and soil (Pande et al., 2022^[272]; Zhang et al., 2023^[273]). While some of these bioremediation techniques can be time-consuming as plants need sufficient time to grow before they can effectively remove contaminants (Wang et al., 2024^[274]), there are emerging practices that seek to meet multiple environmental goals simultaneously. For instance, growing crops for biofuels on these lands can avoid creating competition for land with food production while meeting the remediation objectives (Espada et al., 2022^[275]).

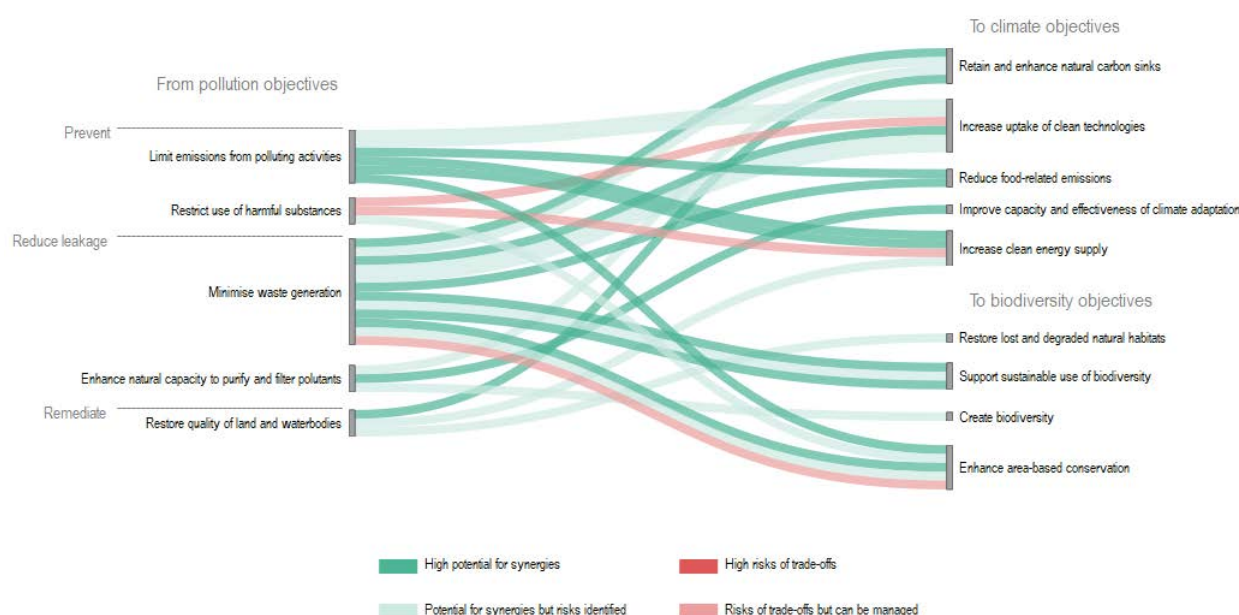
4.4.4. Summary of synergies and trade-offs: Pollution policy objectives

The synergies and trade-offs between pollution policy objectives with those aimed at addressing climate change and biodiversity loss discussed in the previous sections are summarised in Figure 4.7. Policy approaches that seek to address pollution at source bring important synergies for climate change through reducing co-emitted GHGs. However, the loss of the “cooling” effects of air pollution implies the need for more ambitious climate action. It is also important to consider the risks of trade-offs that may arise over time in response to policies. For instance, despite the positive environmental outcomes of restricting and limiting certain pollutants over the years, bans on harmful substances may lead to the development and the uptake of alternatives which can carry uncertainties on a range of factors, including their safety and environmental fate. Concerns have been raised for a range of chemicals, including pesticides and alternatives to ODS.

Promoting the reuse of products, components and materials, as well as diverting waste from landfills, can also contribute towards emissions reduction. Minimising waste holds important relevance for pursuing synergies with climate and biodiversity objectives, as it obviates the need for primary production and typically results in lower environmental pressures. Nonetheless, it is also important to consider the environmental impacts of these approaches; for instance, recycling of some CRMs still remains an energy-intensive and complex process.

As discussed in Sections 4.2 and 4.3, there are inherent interlinkages among the quality of natural carbon sinks, habitats for wildlife and capacity to filter pollutants, although replicating natural ecosystems for the purpose of managing pollution may entail trade-offs in terms of their design. Finally, meeting the heightened need for remediating contaminated land and water bodies requires the careful consideration of its broader environmental impacts, as some techniques can be highly energy-intensive and result in toxic by-products.

Figure 4.7. Synergies and trade-offs of pollution control policy objectives



Source: Authors' own elaboration.

4.5. Key insights

Climate change, biodiversity loss and pollution are mutually driven and share common causes. It may therefore seem intuitive that addressing one issue would automatically contribute towards resolving others. However, this analysis suggests that policy approaches that seek to tackle each issue in an isolated manner can often be at odds with the interlinkages of the planetary processes underpinning these challenges. Trade-offs between policy objectives can diminish, though they may not entirely negate, the benefits of policies implemented to address an issue. Conversely, identifying and accounting for synergies appropriately can alter the calculus of policy costs and benefits, potentially increasing the viability of ambitious action that may have otherwise been considered cost ineffective.

Many existing policies have the potential to deliver synergies, which can be enhanced through enabling policies. An important step is identifying and considering the possibility of synergies and trade-offs that can materialise differently across contexts and measuring them to determine their relative importance to inform decision-making. Given that various dimensions of biodiversity underpin irreplaceable ecosystem services, it is perhaps not surprising that actions to protect, manage and restore biodiversity can bring synergies within local sites. However, trade-offs can arise from spillover impacts, unless appropriate incentives as well as safeguards are in place. For instance, restrictions of land use change may lead to intensified land use for agriculture or increased fertiliser use, posing a risk of increasing GHG emissions and nutrient runoff.

Considerable synergies can be gained from policy actions that address the common drivers of the interconnected challenge, such as reducing fossil fuel use as primary sources of energy. NbS such as wetlands restoration can be also highly synergistic, as they can simultaneously contribute towards climate mitigation and adaptation and pollutant filtration, while providing habitats for species. While NbS offer important advantages in terms of efficiency of resources, durability and benefits across environmental domains, they operate on a longer time frame. There is also a need for action to avoid short-term impacts of climate change, biodiversity loss and pollution. The contributions of NbS can also be compromised by extreme weather events. Maintaining and increasing the viability of these solutions therefore require complementary policies that deliver more immediate and visible benefits.

Consideration should also be given to the risks of trade-offs that materialise later (i.e. a temporal scope), or that cause impacts upstream or downstream of the actions targeted by policy (i.e. a spatial or geographical scope) through measurement and assessment. Notably, increases in clean energy supply and uptake of renewables technologies are necessary for addressing biodiversity loss and pollution, yet their deployment is not entirely without environmental cost. These technologies may generate pollution associated with large material requirements upstream (e.g. for the production of wind turbines), as well as biodiversity impacts through habitat fragmentation, degradation and losses. These considerations necessitate assessments of risks of trade-offs at various stages of renewables infrastructure development and deployment, so that the challenge is addressed together with, rather than at the cost of, other dimensions of the triple planetary crisis.

Importantly, synergies and trade-offs are unlikely to remain static over time. For instance, ecotoxic properties of pollutants might be heightened, and protected areas may not provide home to wildlife at higher temperatures. This underscores the need for adaptive and proactive management to ensure effectiveness and adequacy of policy mixes.

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Notes

¹ The category of “create” is considered under the cluster of policies to “restore” biodiversity.

² The mitigation hierarchy has been used explicitly and implicitly as an underlying principle for biodiversity policy around the world, applied at various scales including for Environmental Impact Assessment processes (Milner-Gulland et al., 2021^[290]).

³ In accordance with the definition provided by (IEA, n.d.^[276]), clean energy is used here as “an umbrella term that groups energy sources, infrastructure, applications and related assets that are compatible with a net zero emissions energy system.” The discussion in the chapter focusses primarily on “renewable energy”, defined as “modern bioenergy, geothermal, hydropower, solar photovoltaics, concentrated solar power, wind, marine (tide and wave) energy and renewable waste” (IEA, n.d.^[276]).

⁴ Protected areas are defined as “a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values” (IUCN, 2008^[277]).

⁵ Key biodiversity areas are sites that contribute significantly to the global persistence of biodiversity. These areas are identified based on rigorous scientific criteria, including the presence of threatened species, geographically restricted species, ecological integrity, biological processes, and irreplaceability. KBAs are not legally designated but serve as a tool for conservation planning and prioritisation (IUCN, 2016^[295]).

⁶ For instance, an estimate suggests about 43 litres of water is required for every kg of hydrogen throughout the lifecycle, while an average water footprint estimate for extracting and refining of oil is 133 litres of water (Woods, Bustamante and Aguey-Zinsou, 2022^[52]) (see also Chapter 6).

⁷ They refer to emissions capture from large point sources, such as gas processing plants and subsequent long-term storage and use or recycling.

⁸ It is likely to remain secure for over 99% of the time over 100 years and is likely to exceed 99% over 1 000 years, while the majority of CO₂ will gradually be immobilised through various trapping mechanisms, allowing it to be safely stored for up to millions of years (IPCC, 2005^[68]).

⁹ CDR can be understood as one of the two broad categories of geoengineering (other being Solar Radiation Management, SRM) referring to the deliberate, large-scale manipulation of Earth’s climate system to counteract anthropogenic climate change (Smith et al., 2024^[60]; Edenhofer et al., n.d.^[291]). SRM can refer to reflecting a portion of incoming solar radiation back into space to reduce temperatures such as Stratospheric Aerosol Injection (SAI) (UNEP, 2023^[294]). See also Section 6.5 in Chapter 6.

¹⁰ Biological CDR, including through restoration of forests and wetlands, are discussed in the section on Ecosystems.

¹¹ Using food crops directly for bioenergy purposes has much larger consequences and directly competes with food production.

¹² The impact depends by type of animals as well as practices of production. For instance, non-ruminant animals (e.g. poultry) use nutrients more efficiently compared to ruminants (Adegbeye et al., 2020^[226]).

¹³ Carbon sinks refer to “process, activity and mechanism which remove a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere” (Minx et al., 2018^[278]).

¹⁴ Blue carbon is defined as “all biologically driven carbon fluxes and storage in marine systems that are amenable to management” (IPCC, 2019^[279]).

¹⁵ The Ramsar Convention categorises wetlands into three types (1) coastal/marine, (2) inland and (3) human-made (Ramsar Convention Secretariat, 2016^[280]).

¹⁶ For instance, broad-leaved and coniferous tree species are found to be a source of BVOCs such as isoprene. Isoprene constitutes about half of total BVOC emissions (Mahilang, Deb and Pervez, 2021^[281]).

¹⁷ Other effective area-based conservation measures (OECMs) are geographically defined areas distinct from protected areas that are governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socio-economic, and other locally relevant values (Convention on Biological Diversity, 2018^[296]).

¹⁸ The authors define the concept of irrecoverable carbon based on three criteria relevant for conservation efforts. They assess ecosystem carbon stocks according to: (1) how they can be influenced by direct and local human action (‘manageability’), (2) the magnitude of carbon lost upon disturbance (‘vulnerability’) and (3) the recoverability of carbon stocks following loss (‘recoverability’).”

¹⁹ This is higher (21%) for reactive (high threat, high irreplaceability) biodiversity conservation, although the percentage of the overlap in areas suitable for carbon storage and conservation (5%) are smaller than for proactive conservation (38%) (Soto-Navarro et al., 2020^[146]).

²⁰ It is estimated that they support around a quarter of marine species despite covering only 0.2% of the seafloor (Souter et al., 2020^[282]).

²¹ Payments for ecosystem services (PES) are defined as “(1) voluntary transactions (2) between service users (3) and service providers (4) that are conditional on agreed rules of natural resource management (5) for generating offsite services (Wunder, 2015^[283]). There are over 550 PES programmes around the world constituting USD 36-42 billion in annual transactions (Salzman et al., 2018^[284]).

²² Agroforestry in this context is used as a generic term that includes a variety of practices and can be defined as “land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/ or animals” (FAO, 2024, p. 17^[292]).

²³ Biodiversity conservation actions are typically categorised into in-situ (on-site) and ex-situ (off-site) conservation (Mestanza-Ramón et al., 2020^[285]). Seed banks for crops are an example of ex-situ conservation.

²⁴ Post-harvest losses from structural and infrastructure deficiencies are common in developing countries, while losses at retail/consumer stage is the primary driver of food waste in developed countries (Smith et al., 2020^[73]).

²⁵ Deposition refers to the process by which nutrients (or pollutants more generally) are transferred from the atmosphere to the land or water surface. This can be through wet deposition (via rain, snow, fog) or dry deposition (dust, particles, gases settling).

²⁶ Known as “critical loads”, the damage threshold is used in policy to mitigate adverse impact of nitrogen deposition on terrestrial biodiversity.

²⁷ Biodiversity hotspots, like the Western Amazon, are large-scale regions that are (1) unique and rich in biodiversity (minimum 1,500 species of vascular plants endemic to the region), (2) endangered (at least 70% of its vegetation lost). There are 36 hotspots constituting 2.3% of the Earth surface yet host 44% of the plants and 35% of land vertebrates (Guo et al., 2023^[192]).

²⁸ Impacts of various dimensions of biodiversity on capacity for carbon storage has been explained in terms of (i) niche complementary hypothesis (capacity to store carbon is influenced by variance in the traits of species that compose the community) and (ii) selection (key species determine the ecosystem-wide capacity for carbon storage) (Mensah et al., 2016^[286]).

²⁹ Coastal wetlands deliver more rapid mitigation benefits compared to inland wetlands, suggesting that restoration can also be viable (Taillardat et al., 2020^[203]).

³⁰ Often implemented in cities, low emission zones charge or ban vehicles that exceed certain emission standards (Chamberlain et al., 2023^[287]).

³¹ For instance, the estimates suggest that atmospheric aerosols can reduce the capacity by between 2 and 68% (Song, Liu and Yang, 2021^[218]).

³² Wastes are materials that are not prime products (i.e. products to be placed on markets) and have no further use and are discarded (OECD, 2019^[293]). They can refer to a range of materials such as plastics waste and e-waste.

³³ Rebound effects can be understood as impact that diverge from the intended benefits due to the responses within the system, both in terms of production and consumption (Castro et al., 2022^[288]).

³⁴ Riparian buffer zones are vegetation strips along waterways to limit pollutants enter them by reducing the impact of soil erosion by slowing the overland flow (Stevens and Quinton, 2009^[267]).

³⁵ For instance, the European Union’s soil strategy aims to achieve “no net land take by 2050” (European Commission, 2021^[289]).

5

Attention to policy interlinkages between climate change, biodiversity loss and pollution at the national level

This chapter explores the extent to which countries consider the interlinkages between the components of the triple planetary crisis by reviewing the Biennial Transparency Reports (BTRs) under the Enhanced Transparency Framework of the Paris Agreement and the latest National Biodiversity Strategies and Action Plans (NBSAPs) aligned with the Kunming-Montreal Global Biodiversity Framework from a representative set of ten countries around the world. These documents reflect “whole of government” perspectives and are aligned to multilateral environmental agreements, facilitating cross-country comparison. While similar national documents do not exist for pollution, some interlinkages with pollution are explored in both BTRs and NBSAPs and with reference to a subset of relevant national documents. The chapter first introduces the methodological approach and scope of the analysis. It then presents the findings from the analysis, identifying the varying focus and notable examples.

5.1. Introduction

Tackling the triple planetary crisis of climate change, biodiversity loss, and pollution necessitates consideration of policy interlinkages to maximise synergies and manage trade-offs, as detailed in the conceptual overview provided in the previous chapter (Chapter 4). There are important interlinkages between the planetary processes underpinning the triple planetary crisis, as well as between the policies developed and implemented at multiple levels of government.

National policies, institutional arrangements and capacities are integral to tackling environmental challenges (OECD, 2021^[1]; Fiorino, 2011^[2]). Policymaking at the national level plays a critical role in unifying the actions taken at multiple levels; it is a key unit of analysis for assessing the progress towards global environmental goals, while setting the direction for local and regional implementation. The consideration of the interlinkages at the national level can therefore facilitate an integrated policy approach. However, the knowledge on whether and how countries acknowledge these interlinkages in policymaking is currently limited.

To identify the broad trends across countries and potential policy gaps, a national policy stocktake is conducted for a representative set of ten countries around the world varying in geographical location, biodiversity richness, size and income. Two documents have been selected for the analysis: (i) the first Biennial Transparency Reports (BTRs) by the Parties to the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) and (ii) the latest National Biodiversity Strategies and Action Plans (NBSAPs) aligned with the Kunming-Montreal Global Biodiversity Framework (KMGBF) adopted by the Parties to the UN Convention on Biological Diversity (CBD).

While there are other documents detailing a range of national sectoral strategies (e.g. energy, agriculture) and multi-year plans, BTRs and NBSAPs are developed in the context of reporting to multilateral environmental agreements. Their standardised and largely contemporaneous submissions facilitate cross-country comparison. These documents also reflect the official and “whole of government” perspectives based on cross-ministerial co-ordination. While similar national documents do not exist for pollution, the chapter examines interlinkages with pollution as covered in BTRs and NBSAPs, as well as with reference to standardised documents where relevant and available.

At the same time, it is important to note that an analysis of national documents only presents a broad picture. BTRs and NBSAPs are not intended as documents detailing and attributing implemented and planned policies to outcomes. They also do not reflect how the interlinkages between climate change, biodiversity loss and pollution manifest themselves during the implementation stage and how these synergies and trade-offs are dealt with across sectors and projects. These synergies and trade-offs at the policy design and implementation stage are examined through “deep-dives” in the next chapter (Chapter 6).

5.2. Methodological approach and scope of the policy stocktake

5.2.1. Methodology

This chapter analyses the extent to which countries pay attention to the interlinkages between climate change, biodiversity loss and pollution and their policy responses. The analysis builds on the methodological approach for content analysis developed in Gagnon-Lebrun and Agrawala (2007^[3]), which assessed progress on adaptation in developed countries through examining the National Communications under the UNFCCC. Content analysis is a tool that has been used to systematically assess written material in the context of both academic research and policy evaluation (Seymour-Ure and Berelson, 1972^[4]). The analysis of the two sets¹ of national documents was carried out in two steps. The first step involved the development of thematic categories to map the consideration of the pairwise (e.g. between climate change

and biodiversity loss) interlinkages of: (i) the biophysical impacts and (ii) policy responses and projects. The second step involved categorising the level of detail of the consideration of these interlinkages on a five-point qualitative scale: (i) absent, (ii) generic, (iii) moderate, (iv) substantive, and (v) extensive and in-depth.

5.2.2. Scope

Selection of documents

BTRs submitted by the Parties to the Paris Agreement are examined to explore the extent to which they pay attention to the interlinkages with biodiversity loss and pollution. The BTRs encompass a country's National Inventory Report (NIR) of anthropogenic emissions by sources and removals by sinks of greenhouse gases (GHGs), progress towards its climate goals (especially its Nationally Determined Contribution, NDCs), policies and measures, climate change impacts and adaptation, levels of financial, technology development and transfer and capacity-building support, capacity-building needs and areas of improvement (UNFCCC, 2019^[5]). Parties were required to submit the first BTRs by the end of 2024 (UNFCCC, 2019^[6]).² The common modalities, procedures and guidelines for the Enhanced Transparency Framework allow for a cross-country comparison of the BTRs.

For countries from which the BTRs were not yet available,³ National Communications (NCs) documents were analysed. While the comparability of the NCs is more limited, they still detail a country's inventory of anthropogenic greenhouse gas emissions⁴ and its planned or implemented actions (UNFCCC, 2009^[7]). They are submitted periodically by all Parties to the UNFCCC and follow an established structure (UNFCCC, 2025^[8]). Nevertheless, it is important to note that the NCs can vary in the year and the round of submission across countries. Moreover, both the breadth and the depth with which countries deal with different topics in their NC submissions may diverge from their previous submissions.

NBSAPs are analysed to examine the extent to which they consider the interlinkages with climate change and pollution. NBSAPs outline approaches and policies to protect biodiversity and ecosystem services as key instruments for the implementation of the CBD at the national level (CBD, 2022^[9]). In 2022, 196 Parties to the CBD adopted the KMGBF, which is built around the 4 goals for 2050 and 23 targets for 2030, including two targets which explicitly establish the links between biodiversity loss, pollution (target 7) and climate change (target 8). Subsequently, the Parties have been requested to revise the NBSAPs aligned with the KMGBF. As of October 2025, 55 Parties have submitted their revised NBSAPs (CBD, 2025^[10]). While the length and depth of the content can vary, the overarching framework makes the documents relatively comparable across countries.

No similarly standardised national documents describe the strategies for addressing pollution as such. This reflects, in part, the multifaceted nature of pollution, varying in pollutants and media (e.g. air, soil and water). Furthermore, policies targeting pollution are developed in the complex landscape of multilateral frameworks targeted at specific sets of pollutants (e.g. the Minamata Convention on Mercury), hazardous chemicals and wastes (e.g. the Basel, Rotterdam and Stockholm Conventions) as well as types of pollution (e.g. the UNECE Convention on Long-Range Transboundary Air Pollution). While some of these Conventions also have established reporting frameworks such as National Implementation Plans and National Reports, they are distinct in focus areas, scope and timeliness. The interlinkages that pertain to pollution are therefore assessed indirectly in the analysis through the review of BTRs and NBSAPs, complemented by a review of a subset of national documents and other relevant information provided under multilateral frameworks.

It is important to note that national documents also do not cover the full range of existing policies, instruments and projects within a country, as they contain relatively high-level descriptions of approaches and strategies. Furthermore, national documents can refer to planned policies and may not necessarily reflect implemented policies or projects. Notwithstanding these limitations, the analysis can help elucidate the extent to which countries already consider the interlinkages and help identify the gaps that can be addressed to develop an integrated policy approach.

Selection of countries

Only those countries with both a BTR (or an NC) and a KMGBF-aligned NBSAP were selected for the stocktake analysis, limiting the sample to 55 countries (as of October 2025). From this set of countries, the current analysis examines twenty national documents in total from ten countries: Argentina, Australia, Canada, China, France, India, Indonesia, Japan, Peru, and Uganda. While limited in number, this subset of countries nevertheless encompasses considerable variation in terms of geographical location, biodiversity richness, size and level of income (see Table 5.1). Australia, China, India, Indonesia and Peru are megadiverse, which means that they are home to at least 5 000 of the world's endemic plants and have marine ecosystems within their borders (Mittermeier and Goettsch Mittermeier, 1997^[11]). The selected countries also vary in their level of development as defined by the World Bank country and lending groups classification (World Bank Group, 2025^[12]): four are high-income countries (Australia, Canada, France and Japan), four are upper-middle-income countries (Argentina, China, Indonesia and Peru), one is lower-middle-income (India), and one is a low-income country (Uganda). A point to note is that the submission year of these documents can still vary slightly, and they may therefore not reflect the latest policies (see Table 5.2).

Table 5.1. Characteristics of the countries examined

Country	Continent	Biodiversity richness	Income group
Argentina	South America		Upper-middle income
Australia	Australia	Megadiverse	High income
Canada	North America		High income
China	Asia	Megadiverse	Upper-middle income
France	Europe		High income
India	Asia	Megadiverse	Lower-middle income
Indonesia	Asia	Megadiverse	Upper middle income
Japan	Asia		High income
Peru	South America	Megadiverse	Upper-middle income
Uganda	Africa		Low income

Source: Authors' own elaboration using Conservation International's classification for the biodiversity richness column (WEF, 2024^[13]) and World Bank Group (2025^[12]) classification for the income group column.

Table 5.2. Submission year of the latest national documents by country

Submission Years / Country	2022	2023	2024	2025
Argentina			BTR1, NBSAP	
Australia			BTR1, NBSAP	
Canada			BTR1, NBSAP	
China			BTR1, NBSAP	
France		NBSAP	BTR1	
India		NC3	NBSAP	
Indonesia			BTR1, NBSAP	
Japan		NBSAP	BTR1	
Peru			NBSAP	BTR1
Uganda	NC3		NBSAP	

Notes: 1. BTR refers to the Biennial Transparency Report under the Enhanced Transparency Framework of the Paris Agreement, and the number following it refers to the round of national submission. 2. NBSAP refers to the *National Biodiversity Strategy and Action Plan* document aligned to the Kunming-Montreal Global Biodiversity Framework. 3. NC refers to the *National Communication to the United Nations Framework Convention on Climate Change* document, and the number following it refers to the round of national submission.

Source: Authors' own elaboration based on the UNFCCC (2025^[14]; 2025^[15]) and the CBD (CBD, 2025^[16]).

5.3. Findings of the content analysis of national documents

This section first explores whether BTRs and NBSAPs contain a high-level of acknowledgement of pairwise interlinkages between climate change, biodiversity loss and pollution as well as the prevalence of framing of the three-way interlinkages in these national documents. This section then turns to an assessment of the level of detail with which the pairwise interlinkages are considered and introduces notable examples from ten countries.

5.3.1. High-level acknowledgement of pairwise and three-way interlinkages

A review of the BTRs and NBSAPs reveals that all ten countries acknowledge the pairwise interlinkages between climate change, biodiversity loss, and pollution in some fashion (see Table 5.3), referring to interactions between these environmental challenges and their impacts, as well as relevant policy responses, implementation challenges, institutional arrangements and resource needs.

Four of the ten countries also refer to the “triple planetary crisis” or its three components altogether in at least one of the two national documents. This ranges from a high-level mention in Indonesia’s NBSAP (MoNDP, Indonesia, 2024, p. 2^[17]) to India’s identification of “slow percolation, poor understanding and realisation of biodiversity concepts, conservation priorities, and impact of interconnected triple crisis at the grassroot level” as a key issue for which they identify a “communication, education and public awareness” strategy as a potential remedy (MoEFCC, India, 2024^[18]). Canada’s NBSAP contains a dedicated section explaining the interlinkages of the triple planetary crisis. Its national target 14 (mainstreaming of biodiversity values) states that the federal government may explore ways to address the triple planetary crisis “in an integrated manner, while seeking to maximise co-benefits in novel ways” (ECCC, 2024, p. 87^[19]). France mentions in its BTR that it is pursuing its climate, biodiversity and pollution reduction objectives (Government of France, 2024^[20]).

Canada and France further elaborate on their recently implemented policies, which aim to address the triple planetary crisis in an integrated manner. As of April 2024, Canada’s new *Climate, Nature and Economy Lens* requires federal public servants to weave considerations of climate change, biodiversity loss and pollution in government decision-making (see Box 5.1 for further details). France discusses its

national ecological planning approach, formally instituted in July 2022 with the creation of the General Secretariat for Ecological Planning. Through this approach, France aims to mobilise all stakeholders including households, businesses, and local authorities to advance a broad set of environmental objectives including addressing climate change, biodiversity loss and pollution (Government of France, 2024^[20]).

Table 5.3. Acknowledgement of pairwise interlinkages and the triple planetary crisis

Crises linkages / Countries	Biennial Transparency Reports (BTRs) or National Communications (NCs)			National Biodiversity Strategy and Action Plans (NBSAPs)		
	Climate Change and Biodiversity	Climate Change and Pollution	Triple Planetary Crisis	Biodiversity and Climate Change	Biodiversity and Pollution	Triple Planetary Crisis
Argentina	●	●	○	●	●	○
Australia	●	●	○	●	●	○
Canada	●	●	○	●	●	●
China	●	●	○	●	●	○
France	●	●	●	●	●	○
India ¹	●	●	○	●	●	●
Indonesia	●	●	○	●	●	●
Japan	●	●	○	●	●	○
Peru	●	●	○	●	●	○
Uganda ¹	●	●	○	●	●	○

Legend	● Acknowledged in the document	○ Absent in the document

Note: In the absence of a BTR, the analysis was completed using the country's latest NC document.

Source: Authors' own elaboration based on the review of national documents.

Box 5.1. The Climate, Nature and Economy Lens in Canada facilitates consideration of the interlinkages of the triple planetary crisis in policy proposals

The Cabinet Directive on Strategic Environmental and Economic Assessment, focused on the consideration of the potential environmental and economic impacts of key government decisions, has introduced a standardised *Climate, Nature and Economy Lens* (CNEL) template on April 1, 2024 (Government of Canada, 2024^[21]). The CNEL template must be completed by federal public servants when submitting proposal assessments to the Cabinet, the Prime Minister and the Minister of Finance (ECCC, 2024, p. 168^[22]). The CNEL, highlighted in Canada's BTR and NBSAP, requires evaluations of a proposal's effects (positive or negative) on climate change (e.g. capture and sequestration of GHG), nature and biodiversity (e.g. migratory birds) and pollution (e.g. soil). Mandatory preliminary screening and a set of exceptions helps ensure that the application of the CNEL assessment is necessary and proportionate. A CNEL assessment is also not required for proposals already subject to federal environmental or impact assessment legislation (e.g. the *Impact Assessment Act* or the *Canadian Environmental Assessment Act*) as well as routine procedures that are considered to pose minimal risk to the environment.

For instance, the integrative tool requires federal public servants to indicate whether the policy proposal has an "improving effect" or "deteriorating effect" on the following categories: GHG emissions, effects on species at risk, general effects on wildlife, noise, air, water, soil, among others. The template encompasses direct and indirect GHG emissions (Scope 1, 2 and 3 emissions) (OECD, 2024, p. 34^[23]) (see Figure 5.1). Whether an impact is positive, negative or undetermined, a justification of up to 200

words is requested: “Provide a narrative response below that outlines how this proposal will not have an important impact on nature and/or biodiversity” (Government of Canada, 2024, pp. 3;14-15^[24]).

Figure 5.1. CNEL template extract: Assessing policy impacts on climate change and biodiversity

Environmental topics	Improving effect	Deteriorating effect
Climate Change		
Emission of greenhouse gases The production of gases that trap heat in the atmosphere.	☐	☐
Capture and sequestration of greenhouse gases The capture and/or removal of greenhouse gases.	☐	☐
Reducing potency of GHG emissions (e.g. combustion of methane to carbon dioxide) Decreasing the concentration of greenhouse gas emissions.	☐	☐
Albedo Effect The ability of a surface to reflect sunlight. Darker surfaces reflect less sunlight and contribute to temperature rise. For example, an open lake or snow-free landscape will capture and retain more heat than its snow/ice-covered counterpart.	☐	☐
Nature and Biodiversity		
Effects on species at risk Effects on any extirpated, endangered or threatened species or a species of special concern.	☐	☐

Source: Government of Canada (2024^[24]).

5.3.2. BTRs detail climate change-biodiversity interlinkages and policy synergies, with only a few discussing how to manage potential trade-offs

All ten countries discuss country-specific climate change impacts on biodiversity (Table 5.4). BTRs discuss heterogeneous climate change impacts on ecosystems, flora and fauna, and microorganisms. Australia notes that 18 out of 19 ecosystems assessed across the country are under pressure from climate change. Climate risks to biodiversity encompass “risks to aquatic and terrestrial ecosystem condition and function or landscape function and collapse, including through species loss and extinction” (DCCEEW, Australia, 2024^[25]). Australia also discusses how climate change is impacting the frequency, severity and duration of weather conditions (fire season starting earlier in spring and lasting longer into autumn) conducive to bushfires that impact ecosystems (e.g. loss of pasture), as exemplified by the Black Summer bushfires over 2019-2020⁵ that burned more than 24 million hectares (DCCEEW, Australia, 2024, p. 232^[25]).

Uganda discusses the impacts of climate change on water, which is a cross-cutting resource sustained through ecosystem services (MoWE, Uganda, 2022^[26]). In particular, Uganda details that increasing temperatures reduce oxygen concentration in water bodies, leading to less availability of aquatic plants that serve as food for fish, which in turn contributes to fish mortality. China similarly reports that the significant increase in the frequency and intensity of marine heatwaves is severely impacting “marine organisms, ecosystems and aquaculture” in its coastal waters, citing mass mortality of cultured sea cucumbers in the Yellow and Bohai seas in 2018 as an example (China, 2024^[27]).

Table 5.4. Climate change and biodiversity interlinkages in BTRs (and NCs)

	Discussion of the impacts of climate change on biodiversity (loss)	Discussion of the impacts of biodiversity (loss) on climate change	Discussion of synergistic policies or projects	Discussion of trade-offs in policies or projects
Argentina	●	◎	◎	●
Australia	●	●	●	○
Canada	●	●	●	○
China	●	●	●	○
France	●	◎	●	●
India ¹	●	◎	●	○
Indonesia	●	◎	●	○
Japan	◎	●	●	●
Peru	●	●	●	○
Uganda ¹	●	●	●	○

Legend

● Extensive and in-depth	Country-specific impacts ² are discussed extensively and in-depth . Implemented government actions ³ consider climate change and biodiversity linkages, focusing on maximising synergies or managing trade-offs extensively and in-depth .
◎ Substantive	Country-specific impacts cover more than one dimension of biodiversity ⁴ , with at least one impact discussed substantively . Implemented government actions consider linkages, with at least one policy action substantively focusing on maximising synergies or managing trade-offs.
◎ Moderate	Country-specific impacts cover more than one dimension of biodiversity, but are not discussed substantively . Implemented or planned government actions consider linkages, with some consideration of policy action aimed at maximising synergies or managing trade-offs.
○ Generic	Impacts are discussed in generic terms based on global or regional assessments, or with very few details. The document contains a generic acknowledgement of the need to consider synergies maximisation or trade-off management in policy action in the context of linkages.
● Absent	No information found in the assessed national document.

1. In the absence of a BTR, the analysis was completed using the country's latest NC document.
 2. Impacts refer to the biophysical impacts of climate change on biodiversity (loss) and vice versa.
 3. Government actions refer to policies and projects.
 4. Dimensions of biodiversity include species, ecosystems and biota.
- Source: Authors' own elaboration based on the review of national documents.

Similarly, the impacts of biodiversity loss on climate change are well-acknowledged, albeit to a lesser extent than climate change impacts on biodiversity. Six out of the ten countries provide country-specific examples, which demonstrate the vital contributions of biodiversity to climate mitigation and adaptation, as well as the observed impacts of biodiversity loss. These examples commonly pertain to the carbon removal capacity of ecosystems. For example, Australia highlights the role of its rich blue carbon ecosystems – mangroves, saltmarshes and seagrasses – which are estimated to hold approximately 12% of global blue carbon stock. These ecosystems also help shield coastal areas from climate change impacts such as flooding, sea level rise, and intense storm surges (DCCEEW, Australia, 2024^[25]). Meanwhile, Japan highlights the declining trend of the amount of carbon removals due to the maturity of its planted forests making up 40% of the country's forests, half of which are over 50 years old⁶ (Japan, 2024, p. 28^[28]). Peru, where the Amazon biome represents about 60% of the country's surface area, identifies deforestation – induced by the land-use change and conversion of intact ecosystems for agriculture, grasslands and mining – as the primary driver of GHG emissions (MoE, Peru, 2024, p. 34^[29]). Canada notes that over the century, the thawing of permafrost in its boreal and arctic regions will release large stocks of sequestered methane (CH₄), a potent GHG (ECCC, 2024^[22]).

The interlinkages between climate change and biodiversity loss are also well-acknowledged in policy responses detailed in BTRs in nine countries (Table 5.4). Policies discussed include management and expansion of protected areas, tax incentives and grants for tree planting, as well as carbon credits and offsets schemes. Most countries provide examples of policy response considering synergies between climate change mitigation and biodiversity conservation (see Table 5.5 for illustrative examples).

In its BTR, Indonesia highlights the importance of restoring and preserving peatlands in order to protect these natural carbon sinks and their biodiversity (MoE, Indonesia, 2024^[30]). The participation in peatland restoration is mandatory for all companies with a Business Permit for the Utilisation of Timber Products and Oil Palm Plantations. Meanwhile, restoration of non-concession areas is carried out under the Peatland Steward Village Program (extending over 200 villages) through which communities, together with the field facilitator, co-develop a work plan at the site level. From 2016 to 2021, the restoration of peatlands in seven priority provinces has led to the revegetation of 1 892 hectares of land (MoEF, Indonesia, 2022, p. 58^[31]).

In response to the increased frequency of heavy precipitations, Japan promotes “Ecosystem-based Disaster Risk Reduction” to simultaneously pursue resilience against natural disasters and biodiversity conservation. To foster a shared understanding of the important areas for climate and biodiversity objectives and inform policy planning and cross-sectoral engagement, Japan is developing a mapping tool⁷ for identifying areas with the potential to deliver multiple benefits by overlaying various data including topographic wetness and diversity of natural landscape (Ministry of the Environment, Japan, 2023^[32]). In addition, Japan’s water basin management project for all 109 rivers classified as significant incorporates the ecosystem-based approaches through promoting green infrastructure. The design of water reservoirs and river channels are calibrated to serve the purpose of enhancing resilience against natural disasters, while at the same time contributing to the formation of ecosystem connectivity to provide foraging and breeding grounds for vulnerable species (Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2019^[33]; MILT, n.a^[34]).

Canada highlights its Sustainable Canadian Agricultural Partnership (Sustainable-CAP), which is a five-year (2023-2028) partnership that integrates the three dimensions of the triple planetary crisis. In addition to the goal of cutting GHG emissions by 3 to 5 million tonnes of carbon dioxide equivalent (MtCO_{2e}) in the sector (which resulted in emissions of 55 MtCO_{2e} in 2020) (ECCC, 2025^[35]), the programme also aims to facilitate the sector’s adaptation to climate change, as well as the efforts to protect and restore critical wildlife habitats and soil, water and air quality. As part of the Sustainable-CAP, the Resilient Agricultural Landscape Program offers targeted funding to increase the uptake of beneficial management practices and technologies that can simultaneously deliver several environmental benefits in addition to GHG emissions reduction, in accordance with varying local priorities across different provinces and territories.

Table 5.5. Examples of implemented policies and projects cited at the climate change-biodiversity interlinkages in BTRs

Environmental policy type	Implemented policies and projects
Economic instruments	• Blue- and forest-based carbon credits, including for private landholders • Greenhouse gas offset credit system for improved forest management on private land • Tax incentives and grants for tree planting • Aligning new voluntary biodiversity market with existing carbon credit markets • Grants to promote sustainable agricultural practices
Regulatory instruments	• Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards climate change mitigation
Information policies	• Information campaigns on food waste reduction to achieve emissions reduction and improved soil health
Government provision of goods and services	• Research and development for data and monitoring infrastructure to inform climate change mitigation, adaptation and biodiversity conservation • Wildfire management to reduce the severity and frequency of bushfires • Appropriate design of reforestation (and afforestation) projects to enhance carbon sequestration while delivering for biodiversity synergies • Ecosystem restoration (e.g. mangroves) and coastal adaptation projects to improve resilience against climate change • Greening of urban and port infrastructure to enhance carbon sinks • Monitoring of environmental quality and ecosystem mapping • Engagement with stakeholders, including recognition of traditional and Indigenous knowledge in the management of land and sea to support climate adaptation and improve resilience while protecting biodiversity

Source: Authors' own elaboration based on the review of national documents.

Management of trade-offs in policies is much less extensively discussed, with three out of ten countries providing examples of such consideration in policies and at the project level. For instance, Japan discusses the need to optimise environmental impact assessments to alleviate adverse biodiversity impacts of wind power facilities (Japan, 2024^[28]). Similarly, France highlights the need to balance biodiversity conservation with the expansion of ground solar photovoltaics (PV) as outlined in their second Multi-year Energy Plan (PPE 3). Calls for tenders prioritise the installation of ground solar PV on converted or degraded lands over farms and biodiversity-rich lands (see Chapter 6 for more details) (Government of France, 2024^[20]). This is also in line with its legally binding target to achieve “no net land take” by halving the conversion of natural, agricultural and forest areas over 2021-2031 relative to the previous decade and eliminating it by 2050. Meanwhile, Argentina discusses its insurance mechanism for facilitating investments into reforestation while preserving native forest ecosystems (see Box 5.2).

Box 5.2. Argentina's Green Insurance channels funds to offset transport emissions and sustain native forest ecosystems

In its BTR, Argentina addresses the trade-offs between climate change mitigation measures and biodiversity protection by highlighting the Environmental Sustainability and Insurance Programme (PROSAS) (SSA, Argentina, 2024^[36]). Implemented in 2009, the programme encourages investments in reforestation and enrichment of the native forests as a tool for climate mitigation, while ensuring effective biodiversity conservation (SSA, Argentina, 2024^[36]). The Programme, also referred to as the “Green Insurance”, is based on a voluntary agreement between 12 insurance companies and the Argentinian Government. It allocates 1% of the premiums from motor-insurance policies to tree planting (90%) and to environmental education (10%) (SIF, 2020^[37]).

In 2019, the Argentinian National Insurance Superintendecy (*Superintendencia de Seguros de la Nación* (SSN)) stated that the Green Insurance had contributed to financing for the planting of more than 21 million trees (SIF, 2020^[37]). As a result, the forested area more than doubled from 1990 to 2022, reaching 1.26 million hectares in 2022 (SSA, Argentina, 2024^[36]). This represents an offset of 10% of the annual CO₂ emissions from motor vehicles (SIF, 2020^[37]). The law on investments in cultivated forests (MoJ, Argentina, 1999^[38]), which provides the policy framework for the insurance programme, includes safeguards for protecting native forests, stipulating that the reforestation strategy should not alter the original land use in native forest ecosystems and should ensure the preservation of biodiversity (SSN, 2018^[39]). For instance, zoning by forest basins for the location of enterprises must respect the territorial planning of native forests and environmental, economic and social criteria (MoJ, Argentina, 1999^[38]).

5.3.3. BTRs discuss climate change-pollution interlinkages, synergies and trade-offs in less detail

Climate change impacts on pollution are discussed by most countries, though largely in generic terms (Table 5.6). A notable, detailed acknowledgement is made in China's BTR, highlighting that rising sea levels along its coast have exacerbated coastal erosion and led to sea and saltwater intrusion in estuarine areas. For example, saltwater intrusion in the Pearl River Estuary has seriously affected the quality of drinking water (China, 2024^[40]). Uganda, a land-locked country, also highlights in its NC that climate change will result in significant impacts on the availability and quality of water resources, mainly due to prolonged droughts, floods and run-off (MoWE, Uganda, 2022^[26]).

All of the ten countries mention the impacts of pollution on climate change, albeit with different levels of detail and with varied focus on the types of pollution. Peru cites GHGs emitted from the untreated wastewater discharge into water bodies (MoE, Peru, 2024^[29]). Uganda discusses the rise in GHG emissions due to the increased volume of waste, especially in urban areas, due to population growth, urbanisation and industrial development. In particular, solid waste disposal contributes to significant amounts of CO₂, CH₄ and nitrous oxide (N₂O) emissions (MoWE, Uganda, 2022^[26]).

Table 5.6. Climate change and pollution interlinkages in BTRs (and NCs)

	Discussion of the impacts of climate change on pollution	Discussion of the impacts of pollution on climate change	Discussion of synergistic policies or projects	Discussion of trade-offs in policies or projects
Argentina	○	○	○	○
Australia	○	○	●	○
Canada	○	◎	●	○
China	●	●	●	○
France	○	○	●	◎
India ¹	○	◎	●	○
Indonesia	○	◎	●	○
Japan	○	○	●	◎
Peru	○	●	◎	○
Uganda ¹	◎	●	●	○

Legend	
● Extensive and in-depth	Country-specific impacts ² are discussed extensively and in-depth . Implemented government actions ³ consider climate change and pollution linkages, focusing on maximising synergies or managing trade-offs extensively and in-depth .
○ Substantive	Country-specific impacts cover more than one dimension of pollution ⁴ , with at least one impact discussed substantively . Implemented government actions consider linkages, with at least one policy action substantively focusing on maximising synergies or managing trade-offs.
◎ Moderate	Country-specific impacts cover more than one dimension of pollution, but are not discussed substantively . Implemented or planned government actions consider linkages, with some consideration of policy action aimed at maximising synergies or managing trade-offs.
○ Generic	Impacts are discussed in generic terms based on global or regional assessments, or with very few details. The document contains a generic acknowledgement of the need to consider synergies maximisation or trade-off management in policy action in the context of linkages.
○ Absent	No information found in the assessed national document.

1. In the absence of a BTR, the analysis was completed using the country's latest NC document.

2. Impacts refer to the biophysical impacts of climate change on pollution and vice versa.

3. Government actions refer to policies and projects.

4. Dimensions of pollution include subsets of media (e.g. air) as well as types (e.g. nutrient).

Source: Authors' own elaboration based on the review of national documents.

All ten countries examined⁸ touch upon synergistic policies advancing climate action and pollution management in their country. Examples include economic, regulatory and information instruments touching upon waste management, road transportation, ecosystem restoration, and sustainable agriculture (see Table 5.7 for illustrative policies). Some countries call for an economy-wide plan to synergistically tackle pollution and GHG emissions. For example, China highlights its “Synergistic Implementation Plan for Pollution Reduction and Carbon Reduction”, which informs the integrated approach involving different levels of governments and five economic sectors to 2030 (China, 2024_[40]). One of the approach taken is to integrate the country's land-use and spatial planning systems with the “Three Zones and One Line” environmental zoning systems, identifying polluted and at-risk areas to inform and adjust the land use (Wang et al., 2020_[41]). Another example is pilots of innovation models such as “waste-free cities”. Shenzhen is one of the first of the 11 pilot cities, and green buildings accounted for almost all of the new construction in the city in 2023 (Shenzhen Daily, 2023_[42]). Most countries acknowledge the synergy between climate mitigation and reduction in co-emitted air pollutants in their BTRs (and NCs). Several countries also discuss transport sector policies aimed at transitioning fuel- and gas-based public transport systems to lower- and zero-emission ones. For example, Queensland, Australia, has recently implemented the Zero Emissions Bus Program, where all new buses in South East Queensland will be replaced with battery electric buses between 2025 and 2030. China also promotes the adoption of inland river vessels powered by liquified natural gas (LNG) and batteries, and the use of shore power for vessels docking in key economic regions such as the Yangtze River Economic Belt (China, 2024_[40]).

Countries also highlight sustainable agriculture policies that synergistically address climate change as well as nutrient pollution and hazardous chemicals. For example, France is addressing nitrous oxide (N₂O) emissions from nitrogen fertiliser use (with the latter also being a significant contributor to atmospheric ozone depletion) through policies aimed at a 15% reduction in N₂O emissions by 2030 relative to the level of 2015 (Government of France, 2024^[20]). Uganda implements a project that reuses waste sludge, rich in nutrient and organic matter for producing fertilisers, which can reduce GHG emissions while promoting more environmentally safe waste disposal methods. Indonesia's Integrated Planting Calendar Information System (KATAM) programme provides information on planting timings, crop varieties and optimal quantity of fertilisers and pesticides calculated based on the rainfall forecast (MoEF, Indonesia, 2018^[43]). The information provided can help foster resilience of the agricultural sector to climate change, while facilitating the management of chemical and nutrient pollution. In addition, Indonesia and China rely, respectively, on an integrated watershed management strategy and an eco-compensation mechanism to improve synergies among the three components of the triple planetary crisis (see Box 5.3).

Box 5.3. Watershed management: a key strategy to improve synergies among the three components of the triple planetary crisis

The interconnectedness of climate change, biodiversity loss and pollution is salient in watershed areas. Climate change significantly impacts watershed ecosystems and water resources, and also exacerbates soil erosion and water pollution (Qiu et al., 2019^[44]). For example, in Indonesia, upstream watersheds are prone to floods and landslides during the rainy season and droughts in the dry season, which make them particularly vulnerable to climate change (MoEF, Indonesia, 2022^[31]). Diffuse pollution from the upstream catchment can also potentially trigger regional conflicts of interest between upstream and downstream areas (Sheng, Cheng and Wu, 2023^[45]). Activities conducted in upstream areas, such as the use of pesticides in agriculture or discharges from industrial plants, can introduce pollutants into water that flows towards downstream areas (Chakraborti, 2020^[46]).

Indonesia's BTR discusses watershed management as an integrated key strategy for enhancing synergies between climate change mitigation, ecosystem development and the protection of terrestrial water resources (MoE, Indonesia, 2024^[30]). Integrated watershed management encompasses the holistic approach of management of water, soil and community well-being, simultaneously addressing environmental protection, natural resource use, and human needs. As part of the "FOLU Net Sink 2030" strategy, Indonesia rehabilitates the land with tree seedlings of fruits and nuts sourced from 57 permanent nurseries around the country and through soil and water conservation structures (e.g. gully plug) development. The country prioritises the rehabilitation of areas that are particularly vulnerable to climate change (MoEF, Indonesia, 2022^[31]).

In its NBSAP and BTR, China identifies improving the watershed eco-compensation (WEC) system as a priority action to enhance ecological protection (China, 2022^[47]; China, 2024^[27]). Based on the "beneficiary pays" principle, the system is a combination of Payments for Ecosystem Services (PES) and Ecological Compensation (EC). WEC mechanisms function as incentive-compatible mechanisms between downstream beneficiary areas and upstream provider areas through the transfer of fiscal payments and other methods such as the provision of goods, services or infrastructure (China, 2018^[48]; Sheng, Cheng and Wu, 2023^[45]). Between 1999 and 2016, more than 50 WEC projects were implemented in multiple provinces in China to reduce polluting activities (Jiang, Eaton and Kostka, 2021^[49]).

Policies and projects tackling climate and pollution objectives sparsely touch upon the trade-offs in the BTRs, although there are some mentions of the risks and the need to manage them. For instance, France mentions its plan for light pollution reduction in its renewables expansion policy to support biodiversity (Government of France, 2024^[20]). For example, red aviation lighting (to signal the presence of wind turbine farms to nearby aircraft) attracts migratory bats, which heightens the species' collision risk (Voigt et al., 2018^[50]). One of the proposed ways France aims to avoid this trade-off generated by its wind farm expansion policy is through adaptive lighting that is activated based on presence of aircraft near farms (Government of France, 2024^[20]).

Table 5.7. Examples of implemented policies and projects cited at the climate change-pollution interlinkages in BTRs

Environmental policies	Implemented policies and projects
Economic instruments	• Carbon credit schemes that deliver synergies for soil health • Strengthening and expanding the scope of Extended Producer Responsibility (EPR) systems to reduce waste • Taxes on waste to limit their incineration and disposal in landfills • Subsidies for land restoration • Demand-side measures including a discount for new or used bicycles
Regulatory instruments	• Air quality standards to reduce pollution from wood heaters • Legal frameworks for shared economy (e.g. carpooling) • Designation of low-emission zones to reduce air pollution • Law mandating the phaseout of coal power generation • Restrictions on certain single-use plastics
Information policies	• Information campaign: promotion of the 3 Rs (Reduce, Reuse, Recycle), of clean cooking technologies to reduce the consumption of fuel thereby reducing GHG
Government provision of goods and services	• Research and development to inform restoration of ecosystems threatened by climate change and to introduce synergistic nature-based solutions (e.g. introducing natural pest predators to reduce the use of agrochemicals while preserving forest carbon sinks) • Monitoring of air and water quality • Urban greening to enhance carbon sinks and improve air quality • Establishing sustainable drainage systems to reduce water pollution and limit the impacts of floods • Water management programmes in agriculture to reduce nitrous oxide emissions from agricultural runoff while conserving wetland habitats to enhance carbon sequestration • Improve wastewater treatment through reusing sludge to reduce GHG and produce fertilisers • Investments into infrastructure (e.g. air quality monitoring facilities) and technologies (e.g. low-emission agriculture) • National and international climate finance provision for (low-emission) public transport to alleviate air pollution and climate change

Source: Authors' own elaboration based on the review of national documents.

5.3.4. NBSAPs discuss biodiversity-climate change interlinkages and synergies, but only a few illustrate how trade-offs are managed

All ten countries examined acknowledge interlinkages between climate change and biodiversity loss in their NBSAPs, albeit to a varying degree (Table 5.8). The country-specific examples provided in NBSAPs vary in their scales, ranging from responses of endemic species to climate change and altered interactions between species to ecosystem-wide impacts arising from the climatic conditions. For instance, Japan mentions the northward expansion of its warm-climate bamboo species (*moso* bamboo and giant timber bamboo) and the southern species of butterflies (MoE, Japan, 2023^[51]). Uganda discusses the climate-change-driven spread of invasive species such as sicklebush, which causes extensive alterations of ecosystems, including in protected areas (NEMA, Uganda, 2024^[52]). Indonesia mentions the risk to the species in the Arafura Sea due to their sensitivity to rising sea surface temperature and acidity (MoNDP, Indonesia, 2024^[17]).

Countries similarly discuss the impacts of the adaptive behaviours of species to climate change, including the migration of species in search of suitable climatic conditions (MoNDP, Indonesia, 2024^[17]) and altered interactions between different species (Commonwealth of Australia, 2024^[53]). India mentions additional conservation management of 53 tiger reserves across the country (NTCA, India, 2022^[54]), which also contribute to enhanced carbon storage as these ecosystems are protected from pressures such as deforestation (Lamba et al., 2023^[55]).

Other examples highlight the ecosystem-wide implications of climate change. Peru highlights the risk of climate-induced losses of Yungas montane forests⁹ and Puna grasslands,¹⁰ threatening a range of habitats and their microclimatic conditions upon which a rich assemblage of endemic species rely. Endemic

species in alpine areas are often considered particularly vulnerable to climate change due to various factors, including the limited possibility for them to migrate further upward (Anthelme et al., 2014^[56]). Australia also attributes “mass deaths of flora and fauna” to the impacts of climate change, including more frequent wildfires and coral bleaching (Commonwealth of Australia, 2024^[53]).

Conversely, the impacts of biodiversity loss on climate change are less commonly discussed in the NBSAPs. The examples provided focus on the decline in regulating ecosystem services (e.g. climate regulation and CO₂ fixation) (SSA, Argentina, 2024^[36]) and the diminishing role of biodiversity in climate change mitigation and adaptation (ECCC, 2024^[19]). Various countries also note the mutually reinforcing nature of biodiversity loss and climate change. For instance, Uganda mentions that its extensive wetlands have been severely degraded, diminishing their role both as an important habitat for species and a carbon sink (NEMA, Uganda, 2024^[52]).

Table 5.8. Biodiversity and climate change interlinkages in NBSAPs

	Discussion of the impacts of climate change on biodiversity (loss)	Discussion of the impacts of biodiversity (loss) on climate change	Discussion of synergistic policies or projects	Discussion of trade-offs in policies or projects
Argentina	○	○	⊙	○
Australia	⊙	○	⊙	⊙
Canada	○	○	●	●
China	○	○	○	○
France	○	○	●	●
India	○	⊙	⊙	○
Indonesia	○	○	⊙	○
Japan	●	●	●	●
Peru	●	●	⊙	○
Uganda	●	⊙	●	⊙

Legend

● Extensive and in-depth	Country-specific impacts ¹ are discussed extensively and in-depth . Implemented government actions ² consider biodiversity and climate change linkages, focusing on maximising synergies or managing trade-offs extensively and in-depth .
○ Substantive	Country-specific impacts cover more than one dimension of biodiversity ³ , with at least one impact discussed substantively . Implemented government actions consider linkages, with at least one policy action substantively focusing on maximising synergies or managing trade-offs.
⊙ Moderate	Country-specific impacts cover more than one dimension of biodiversity but are not discussed substantively . Implemented or planned government actions consider linkages, with some consideration of policy action aimed at maximising synergies or managing trade-offs.
○ Generic	Impacts are discussed in generic terms based on global or regional assessments, or with very few details. The document contains a generic acknowledgement of the need to consider synergies maximisation or trade-off management in policy action in the context of linkages.
● Absent	No information found in the assessed national document.

1. Impacts refer to the biophysical impacts of biodiversity (loss) on climate change and vice versa.

2. Government actions refer to policies and projects.

3. Dimensions of biodiversity include species, ecosystems and biota.

Source: Authors' own elaboration based on the review of national documents.

The NBSAPs from ten countries acknowledge the interlinkages between biodiversity and climate change in policies and projects, highlighting ways to foster synergies (Table 5.8 and Table 5.9). For instance, Uganda's biodiversity policy is shifting away from the focus on the conservation of specific species to the recognition of the interconnected ecosystems. It aims to take a holistic view “of the broader ecological context in which species live, including habitats, landscapes, ecosystem services, and the impacts of human activities on these systems” (NEMA, Uganda, 2024, p. 193^[52]) (see Box 5.4).

Box 5.4. Uganda's strategy embraces ecosystem interconnectedness to tackle biodiversity loss and climate change

Uganda is home to rich assemblages of species, ranked among the top ten countries in the world in terms of the number of species recorded (CBD, n.d.^[57]). In recent years, deforestation has threatened biodiversity; once covering almost a quarter of the land, forest cover has diminished to less than 10% by 2015 (NEMA, Uganda, 2023^[58]). The impact of climate change on key agricultural exports such as coffee is also a rising concern (NEMA, Uganda, 2023^[58]).

In recent years, Uganda has set out an ambitious plan to enhance biodiversity. The focus of biodiversity conservation in Uganda has progressively moved away from targeting species and broadened to the interconnected ecosystems. Uganda has implemented several ecosystem-based conservation plans, including in the Kidepo Critical Landscape (a vast savanna woodland in northeastern Uganda) and the Mount Elgon Landscape (a national park hosting a range of endemic species). In Uganda, the establishment of monoculture is recognised as a threat to biodiversity and ecosystem health (Government of Uganda, 2016^[59]). For instance, the monoculture tea plantations in Mulehe wetland, or the monoculture paddy rice cultivation, have negatively affected the diversity of flora in the country (Government of Uganda, 2016^[59]). The regulations of the Kidepo landscape ensure that areas surrounding streams and rivers are protected from monoculture plantations and enriched with suitable native species to protect the existing natural vegetation (NEMA, Uganda, 2018, pp. 81-82^[60]).

The Mount Elgon National Park mitigates the impacts of climate change on its rich ecosystem by restoring degraded areas through tree planting and riverbank management. The implementation of softwood plantations also responds to the economic demand for poles, timber and fuel wood. The plantations are operated “on a rotational harvesting period of 20 years with intermittent harvesting of thinnings at agreed intervals.” (UWA, Uganda, 2022, p. 21^[61]). Long rotation length allows harvested areas a period of rest, thus enhancing the ecosystem’s ability to regenerate. It also reduces soil erosion and increases species diversity (Başkent and Kašpar, 2023^[62]).

In 2024, Uganda became the first country in Africa to submit national targets in accordance with the KMGBF (CBD, 2024^[63]). Notably, recognising the interlinkages between biodiversity and the vital ecosystem services they provide in adapting to and mitigating climate change, Uganda’s NBSAP highlights the importance of pursuing synergies with other environmental objectives and the need for mechanisms for monitoring and evaluation. For example, biological monitoring and field surveys have been conducted to track pests and diseases of Arabica coffee in the Mount Elgon area (Kucel et al., 2024^[64]). Planting shade trees, such as banana crops, reduces the temperature in coffee gardens and solar radiation, thus, providing fodder and shelter for animals that are natural predators of coffee pests and protecting the coffee plants from microclimate variability (Kagezi et al., 2018^[65]; Harelimana, Rukazambuga and Hance, 2022^[66]).

Canada’s NBSAP calls for harnessing nature-based solutions (NbS) to reduce the effects of climate change while supporting biodiversity. Canada has set up the Natural Climate Solutions Fund as a horizontal initiative to promote NbS to mitigate and adapt to climate change, improve air and water quality and provide habitats for wildlife, including through progressing towards its goal of planting two billion trees across the country in both rural and urban areas under the 2 Billion Trees Program. To ensure planting also contributes to biodiversity conservation and pollution prevention and control, shrubs are planted together with trees as the mixture provides numerous benefits for forests, including preventing the (re)establishment of invasive species, enhancing wildlife corridors and preventing soil erosion (Government of Canada, 2023^[67]). The emphasis on nature-based solutions is also echoed in the Canada’s approach to international climate finance, which allocates a minimum of 20% of the funding (which has doubled to CAD 5.3 billion for 2021-2026) to nature-based climate solutions and projects that deliver synergies for biodiversity.

Similarly, France implements rewilding projects in cities by expanding urban tree canopy cover and de-sealing soils under built structures (e.g. roads) to simultaneously improve soil health and capacity for carbon sequestration. The programme also aids with climate adaptation by providing cooling benefits for local residents against the backdrop of increasingly intense heatwaves (Government of France, 2023^[68]). Relatedly, Japan's NBSAP highlights the importance of local action and engagement with local economic activities (including agriculture, fishery and forestry) for the expansion of conservation areas, formation of ecological connectivity and appropriate management of alien species. The NBSAP is translated into local strategies, ensuring that local action is tailored to specific needs while adding up to national objectives (see Box 5.5).

Box 5.5. Sub-national governments in Japan translates NBSAP into locally tailored and synergistic strategies

The NBSAP in Japan emphasises that the local action is integral to effective biodiversity conservation, noting important local synergies as well as some risks of trade-offs. For instance, Japan highlights that while ecological connectivity is important, it needs to be carefully managed at a local scale as enhancing connectivity also runs the risk of accelerating the spread of highly pathogenic avian influenza (HPAI), which can bring adverse impacts on rare species as well as livestock production (Japan, 2023^[69]).

Japan facilitates the consideration of synergistic action by promoting the development of locally tailored strategies and providing tools and mechanisms for informing local action and engagement. Under the technical guidance and support of the national government, the NBSAP is translated into a local biodiversity strategies and action plans (i.e. "L" BSAP) across all 47 prefectures, as well as 178 cities and towns within prefectures in Japan. Recognising that establishing and enhancing ecosystem connectivity for biodiversity conservation requires co-ordination at the units (e.g. watershed) that may not necessarily coincide with administrative units, it also encourages co-ordination, and where relevant, the development of a joint-strategy for biodiversity conservation across administrative areas (Ministry of the Environment/Japan, 2023^[70]). The Ministry of Environment has also developed a pilot mapping tool to visualise the protected areas to disseminate information about notable examples, highlight the ecosystem services and track and inform local spatial planning (Ministry of the Environment/Japan, 2025^[71]).

As part of the strategy to meet "30by30 target" under the KMGBF, Japan has also officially certified 328 sites managed by corporations and local stakeholders as the Nationally Certified Sustainably Managed Natural Sites since 2023 (Japan, 2023^[69]; MoE, Japan, 2025^[72]). One of the certified sites delivering synergies is a marine area in Yamakawa (Kagoshima), where local fishing communities and conservation organisations restore withering seaweed beds caused by warmer sea temperature and altered feeding behaviours of fish and marine invertebrates (e.g. sea urchins) due to climate change. Beyond hosting and protecting a wide range of species including sea turtle hatchlings, the restoration of seaweed beds delivers a number of synergies. Seaweed beds play a number of roles including carbon storage (blue carbon) as well as removal of excess nitrogen and phosphorous. To better integrate various related measures, the government provides current and prospective managers of the certified sites with information on relevant local and regional initiatives including Decarbonization Leading Areas and the Circular and Ecological Economy¹ (Japan, 2023^[69]).

1. The national government implements a number of initiatives to support local governments implement locally specific strategies while providing an overarching framework and technical capacity. Among these, Decarbonization Leading Areas (90 proposals were selected as of September 2025) and Circular and Ecological Economy (implemented by 167 subnational governments as of March 2025) seek to pursue synergies by tackling local socio-economic challenges and environmental challenges together (OECD, 2025^[73]).

There are examples of funding mechanisms for projects that are anticipated to deliver synergies between climate change mitigation, adaptation and biodiversity conservation. For example, Australia's NBSAP highlights the Nature Repair Market Scheme – the world's first legislated national voluntary biodiversity market established in 2023 – and its alignment with the carbon markets under the Australian Carbon Credit Unit (ACCU) Scheme, which outlines the scope for various vegetation management including tidal restoration of blue carbon ecosystems. The project proponents can therefore design a project and earn both a biodiversity certificate and the ACCU credit by designing a synergistic project that aims to revegetate land and replant local native vegetation and enhance ecological connectivity (DCCEEW, Australia, 2025^[74]).

However, discussions of policies or projects managing trade-offs are limited, although some countries mention their institutional arrangements that facilitate such consideration. For instance, France has implemented Green Budgeting since 2020 to assess the potential impact of public expenditure on the environment, including biodiversity conservation, climate change mitigation and adaptation and pollution reduction to inform budgetary allocation (see Box 5.6).

Box 5.6. France's Green budgeting and its tagging tool integrate six environmental objectives in budget allocation

Green budgeting refers to the use of budgetary policy tools to better understand and advance climate and environmental objectives. As of 2022, 22 OECD countries have integrated green budgeting practices, with the most common approaches being environmental impact assessments (18 countries) and green budgeting tagging (13 countries) (OECD, 2024^[75]). The NBSAP mentions that France promotes the “widespread adoption” of the green budgeting approach, which encompasses the three components of the triple planetary crisis (Government of France, 2023^[68]). Since 2020, France has produced a Green Budget report annually, as an annex to its Finance Bill. The report lists and assesses all planned public expenditures for the coming year based on their positive or negative impact on the environment. In line with the EU green taxonomy, it tags budget appropriations, tax expenditures and taxes allocated to public bodies according to their impact on six environmental objectives: climate change mitigation, climate change adaptation, water resources management, circular economy, pollution abatement and biodiversity protection (Government of France, 2023^[76]).

Each expenditure receives an overall tag once the action or sub-action has been rated across six environmental objectives. The action is tagged “favourable” if at least one dimension is rated favourable, and the others are neutral; “unfavourable” if at least one dimension is rated unfavourable, and the others are neutral; “mixed” if at least one dimension is rated favourable and at least one other is unfavourable; “neutral” when all dimensions are neutral. For example, the construction of new railway lines funded by taxes is rated as “mixed” because it has a positive impact on climate change and pollution, but it generates waste and leads to the artificialisation of land, which is rated as “unfavourable” in terms of waste management and biodiversity (Government of France, 2023, p. 76^[76]) (see Figure 5.2). In the 2024 Finance Bill, out of a total state budget of EUR 569.7 billion, favourable expenditures account for EUR 39.7 billion, mixed expenditures for EUR 3.1 billion, and unfavourable expenditures for EUR 13.1 billion. The majority (76%) of the expenditures is “neutral” and 16% is untagged. The “untagged” category may be due to a lack of data or to the heterogeneity of an expenditure's effects (Government of France, 2023, p. 36^[76]).

Figure 5.2. Extract from France's Green Budget: Three possible tags applied to mobility projects

Earmarked taxes	Outturn 2022	2023 Initial Budget Act	2024 Budget Bill	Climate (Mitigation)	Climate (Adaptation)	Water	Waste	Pollution	Biodiversity	Classification
Mobility	€2,578.1 m	€3,146.3 m	€3,951.6 m							
<i>Programme 203 : Transport infrastructure and services</i>										
French Agency for Transport Infrastructure funding - road building	€309.7 m	€409.9 m	€519.7 m	●	●	●	●	●	●	Unfavourable
French Agency for Transport Infrastructure funding - rail maintenance and rolling stock	€275.9 m	€365.2 m	€317.6 m	●	●	●	●	●	●	Favourable
French Agency for Transport Infrastructure Funding - new rail lines	€551.6 m	€729.9 m	€1,078.1 m	●	●	●	●	●	●	Mixed

Source: Government of France (2023, p. 76^[76]).

Table 5.9. Examples of implemented policies and projects cited at the climate change-biodiversity interlinkages in NBSAPs

Environmental policies	Implemented policies and projects
Economic instruments	- Carbon credits to finance maintenance and management of protected areas (including REDD+ projects) - Subsidies for tree planting to increase carbon sequestration while delivering synergies for biodiversity
Regulatory instruments	Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards climate change mitigation
Information policies	Certification of natural sites (aimed at reducing GHG emissions and enhance carbon sequestration) to finance protected areas
Government provision of goods and services	- Facilitating knowledge-sharing and research on mitigating the adverse impacts of renewables expansion on biodiversity - Recognition of traditional and Indigenous knowledge in the management of forest to support climate change adaptation and mitigation while facilitating the continuity and survival of species - National ecosystem services assessment - Monitoring of environmental quality (air, water and soil) and ocean and forest resources - Implementing appropriate wildfire management appropriate attuned to the evolving vulnerability of species under climate change - Ecosystems restoration including blue carbon (e.g. wetlands, seaweed beds, tidal flats and coral reefs) and terrestrial ecosystems - Urban greening to promote carbon sinks and preserve green spaces

Source: Authors' own elaboration based on the review of national documents.

5.3.5. NBSAPs discuss biodiversity-pollution interlinkages in a dissimilar way, and illustrate synergies in more detail than trade-offs

All of the ten countries discuss the impacts of pollution on biodiversity, although the discussion varies in terms of the level of detail (Table 5.10). Most NBSAPs provide detailed examples of pollution affecting freshwater and marine ecosystems. Peru highlights the issues of contamination of river basins associated with gold mining (mercury) waste, as well as water used during oil extraction (MoE, Peru, 2024^[77]). Peru

also details the cumulative nature of acids and heavy metals due to mining activities affecting the Amazon basin. In 2021, 6 902 sites were identified to have been contaminated by mining activities and associated waste (INEI, 2022^[78]). In a more generic consideration, Indonesia explains that at the national level, its aquatic systems are the most affected by pollution, with sources mainly originating from land, such as plastic waste, excess nutrients and pesticides (MoNDP, Indonesia, 2024^[17]). Land is at the nexus of tackling climate change and biodiversity loss (see Box 5.7), and countries' NBSAPs also mention soil pollution and soil health degradation, albeit with fewer details than water pollution.

Conversely, biodiversity loss impacts on pollution are discussed in less detail. Key impacts of biodiversity loss on pollution discussed in the NBSAPs include the role of biodiversity in soil formation, nutrient recycling (see Box 6.10 in Chapter 6), water filtration, and air pollution control. For instance, Canada and Uganda both mention how the loss of wetlands leads to lower water quality (ECCC, 2024^[19]; NEMA, Uganda, 2024^[52]), while Australia notes that urban green spaces can attenuate harm from air pollution (Commonwealth of Australia, 2024^[53]). Meanwhile, India notes the importance of more than 300 types of agriculturally important insects (MoEFCC, India, 2024^[79]), which provide regulating and supporting ecosystem services to agriculture and biodiversity conservation, such as pollination, natural pest control, waste disposal and nutrient recycling (Redhead et al., 2020^[80]; Noriega et al., 2018^[81]).

Table 5.10. Biodiversity loss and pollution interlinkages in NBSAPs

	Discussion of the impacts of pollution on biodiversity (loss)	Discussion of the impacts of biodiversity (loss) on pollution	Discussion of synergistic policies or projects	Discussion of trade-offs in policies or projects
Argentina	○	○	⊙	○
Australia	⊙	○	⊙	⊙
Canada	○	○	●	○
China	○	○	⊙	○
France	○	○	⊙	○
India	○	⊙	⊙	○
Indonesia	○	○	⊙	○
Japan	●	○	●	⊙
Peru	●	⊙	⊙	○
Uganda	●	⊙	●	⊙

Legend

● Extensive and in-depth	Country-specific impacts ¹ are discussed extensively and in-depth . Implemented government actions ² consider climate change and pollution interlinkages, focusing on maximising synergies or managing trade-offs extensively and in-depth .
○ Substantive	Country-specific impacts cover more than one dimension of pollution ³ , with at least one impact discussed substantively . Implemented government actions consider interlinkages, with at least one policy action substantively focusing on maximising synergies or managing trade-offs.
⊙ Moderate	Country-specific impacts cover more than one dimension of pollution but are not discussed substantively . Implemented or planned government actions consider interlinkages, with some consideration of policy action aimed at maximising synergies or managing trade-offs.
○ Generic	Impacts are discussed in generic terms based on global or regional assessments, or with very few details. The document contains a generic acknowledgement of the need to consider synergies maximisation or trade-off management in policy action in the context of interlinkages.
● Absent	No information found in the assessed national document.

1. Impacts refer to the biophysical impacts of biodiversity (loss) on pollution and vice versa.

2. Government actions refer to policies and projects.

3. Dimensions of pollution include subsets of media (e.g. air) as well as types (e.g. nutrient).

Source: Authors' own elaboration based on the review of national documents.

Box 5.7. Land at the nexus of tackling climate change, biodiversity loss and pollution

Defined as “a terrestrial bio-productive system that comprises soil, vegetation and other biotas and the ecological and hydrological processes” in the United Nations Convention to Combat Desertification (UNCCD, 1994^[82]), land is a critical nexus at which climate change and other pressing environmental challenges converge (Rackelmann et al., 2024^[83]).

Climate change and land degradation are mutually reinforcing. Increased temperature and altered precipitation patterns can accelerate the processes of desertification and land degradation (e.g. soil erosion and vegetation loss) (IPCC, 2019^[84]), as well as diminish soil moisture and accelerate soil erosion. Climate-induced disturbances such as droughts and pest outbreaks can also cause the loss of soil organic carbon, the largest carbon sink on land that is also integral to soil productivity and ecological processes, including nutrient cycling (Chotte et al., 2019^[85]). Furthermore, climate change affects direct (e.g. sea level rise) and indirect drivers (e.g. irrigation) of soil salinisation, which lowers the soil quality (Eswar, Karuppusamy and Chellamuthu, 2021^[86]). In turn, poor soil quality can amplify the impacts of extreme weather events.

The feedback dynamic affects and is affected by anthropogenic activities, and further drives climate change and biodiversity loss. The expansion of crop and pastureland is already among the main drivers of land conversion (UNCCD, 2024^[87]). Climate change impacts on land degradation (e.g. increased temperatures diminish soil moisture and accelerate soil erosion), in turn, can reduce the quality and availability of agricultural land, grazing areas and water resources and lead to abandonment of cropland and pastureland and subsequent land conversion elsewhere at the expense of intact ecosystems (Yang et al., 2024^[88]).

While only a handful of countries currently have dedicated soil-related legal instruments (FAO, 2025^[89]), some countries are developing national and regional strategies to protect soil in recognition of its contribution to climate mitigation, adaptation, and biodiversity. For instance, Australia's NBSAP highlights the importance of soil quality and its BTR mentions the National Soil Action Plan 2023-2028 under the National Soil Strategy 2021-2040, which recognises the interlinkages between soil health and climate resilience and biodiversity, calling for an integrated and aligned approach to value, manage and improve soil health (DAFF, Australia, 2023^[90]). Four priority actions under the Plan include the development of a common measurement, monitoring and reporting with which to better understand soil health, as well as an integrated policy approach and strategies for ensuring the value of soil is recognised across policy portfolios, emphasising the engagement with stakeholders at local, regional and national levels.

All ten countries consider some synergistic policy action to address biodiversity loss and pollution in their NBSAPs, including circular economy policies (see Table 5.11). For instance, one way France is tackling both issues is through its circular economy law, which includes a phase-out plan to close all former municipal landfill sites along the coast to eliminate the risk of (plastic) waste leakage to the marine environment (Government of France, 2023^[68]). Similarly, Japan and Australia mention a range of policy measures to halt and reverse biodiversity loss, focusing on the circular economy transition to address pollution and alleviate pressures on biodiversity (see Box 5.8 for more information).

Other examples of synergistic policy considerations include the use of economic instruments and information policies to contribute towards dual objectives. For example, India implements a scheme for promoting soil health through alternative farming practices and fertiliser use through allocating grants. The scheme incentivises sustainable agricultural practices by reducing government subsidy for chemical fertilisers and reallocating half of the saved fertiliser subsidy to States and Union Territories consuming less chemical fertiliser compared to the previous three-year average (MoEFCC, India, 2024^[18]). Argentina aims to improve its research and the development of a tool for identifying important areas for biodiversity, considering a range of environmental factors including nutrient cycles and soil formation to support the planning and implementation of land restoration policy of regional and local governments (SSA, Argentina, 2024^[36]).

Box 5.8. Circular economy as a cross-cutting solution to tackle biodiversity loss and climate change in Japan and Australia

The principle of circular economy features prominently in Japan's BTR and NBSAP, which call for the transition to a more circular economy both as a mean to tackling climate change and stemming biodiversity loss, as well as an objective in itself. The BTR in Japan emphasises the synergies between climate change mitigation and circular economy built around the "3Rs+Renewable" (reduce, reuse and recycle and promoting biomass and use of recycled materials) (Japan, 2024^[28]), with the Circular Economy Roadmap developed in 2022 highlighting that circular economy has the potential to contribute towards emission reductions for 36% of sources of GHG emissions (Ministry of the Environment/Japan, 2023^[91]). Japan's NBSAP similarly highlights the role of circular economy in alleviating pressures on biodiversity. Japan aims to double the treatment volume of recycled metal materials (which has already doubled between 2001 and 2020) by 2030 to reduce energy use and adverse biodiversity impacts associated with extraction and processing of metals, while enhancing access to the materials. Japan also promotes repurposing of dredged sediment and other by-products from port development to restore and enhance natural (e.g. tidal flats and seaweed beds) and engineered blue infrastructure (e.g. algae farm) to tackle nutrient pollution and prevent adverse impacts on water quality (e.g. turbidity) (Japan, 2023^[69]).

Improving circularity of resources use is also an important consideration for tackling biodiversity loss in Australia. Along with climate change, marine and coastal pollution constitute the main drivers of biodiversity loss in Australia, which is now suggested to have 19 degraded ecosystems across the continent that signal their (near) collapse. In its latest NBSAP, Australia states its aim to reduce the impacts of pollution on biodiversity by propelling the circular economy strategy and lowering material footprint and waste generation by 2030 (Commonwealth of Australia, 2024^[53]). Australia's Circular Economy Framework highlights restoring biodiversity as one of its circular economy transition objectives. It also describes some of the types of indicators that can help track a more circular economy such as biodiversity loss, alongside other indicators such as water use; GHG emissions; water, soil and air quality; and nutrient capture and reuse (DCCEEW, Australia, 2024^[92]). The NBSAP also emphasises addressing plastic pollution to alleviate pressure on freshwater and marine ecosystems and robust environmental management of chemicals to manage the risks on water resources, wildlife and human health (DCCEEW, Australia, 2024^[93]).

Table 5.11. Examples of implemented policies and projects cited at the biodiversity-pollution interlinkages in NBSAPs

Environmental policies	Implemented policies and projects
Economic instruments	• User charges for wetlands to incentivise appropriate level of resource use
Regulatory instruments	• Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards pollution control and management • Water quality standards to conserve aquatic ecosystems • Impact assessment of agrochemicals (including pesticides) and registration to assess, prevent and manage the potential risks to terrestrial and aquatic species • Management of invasive alien species (e.g. sanitary and phytosanitary measures at border) • Closure of landfills along coastal areas to avoid waste leakage into the sea
Information policies	• Labelling and environmental certification on food produced from sustainable agricultural practices,
Government provision of goods and services	• Advancing scientific research for pollution prevention to protect migratory birds (e.g. Canada) • Air and water quality monitoring to identify, for instance, effects of atmospheric pollution on ecosystems (e.g. Japan) • Monitoring of pollutant emission and residues (e.g. pesticides) as well as volume of waste • Initial environmental risk assessment of chemical substances • Remediation of degraded and contaminated land • Construction and operation of drainage facilities • Conservation and restoration of blue carbon ecosystems to improve water quality

Source: Authors' own elaboration based on the review of national documents.

However, much less attention is paid to manage the risks of trade-offs between policy actions targeted at biodiversity conservation and pollution control and management. Given the importance of regulating ecosystem services for air, water and soil quality, this may partially reflect the fact that enhancing biodiversity often deliver synergies automatically for pollution objectives. Nonetheless, the lack of substantive discussions on trade-offs in NBSAPs appears to constitute a missed opportunity for considering the risks associated with policies to tackle pollution, such as unintended burden shifting (see also Chapter 4).

5.3.6. National documents on pollution are disparate and diverse, but some interlinkages with climate change and biodiversity loss are acknowledged

While the need for an integrated approach to tackle pollution is recognised (e.g. the Recommendation on Integrated Pollution Prevention and Control (OECD, 1991^[94])), there are no national documents that detail countries' plans for addressing all the different dimensions of pollution¹¹ and can be considered as equivalents to the BTRs and NBSAPs. Instead, the national pollution control and management policy landscape is shaped by a set of disparate policies and plans developed in response to different priorities and multilateral environmental agreements targeting different environmental sinks (e.g. air) and pollutants (e.g. hazardous chemicals) across different stages of their lifecycle (Allan et al., 2025^[95]).

Air pollution is a widely recognised as a key environmental challenge that affects human health and ecosystems (WHO, 2021^[96]). Air pollution comprises the complex interactions between a range of substances, which vary in their sources and characteristics. For instance, emissions sources can be both stationary (e.g. industrial facilities) and non-stationary (e.g. vehicles). Air pollutants can be emitted directly or formed from precursors (e.g. CH₄ and NO_x for ground-level ozone). Pollutants emitted into air also affect other environmental sinks. For instance, as a result of deposition through precipitation, air quality in turn can also affect water quality through acidification and eutrophication (Edo et al., 2024^[97]).

While many countries implement air quality control measures building on the Air quality guidelines developed by the World Health Organization (WHO, 2021^[96]), there is no single global framework for addressing air pollution (UNEP, 2021^[98]). Efforts to tackle air pollution have been progressively strengthened and expanded in scope in terms of the acknowledgement of the interlinkages with other environmental challenges, notably through the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention), along with its eight Protocols and their subsequent amendments.¹² The “multi-pollutant and multi-source” Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) has been amended to include black carbon – both a component of particulate matter with a diameter smaller than 2.5 micrometres (PM 2.5) and a short-lived climate pollutant (UNECE, 2012^[99]). The most recent revision process launched in 2023 considers the interlinkages between air pollution and climate change explicitly and proposes a number of broader consideration including the inclusion of CH₄ under the reduction commitments, integrated approach for air quality, climate change and energy policies, as well as risk-based targets to alleviate the adverse impacts on health and ecosystems (UNECE, 2024^[100]).

Information sharing on strategies and policies is encouraged by the Air Convention, but national reporting on policies is far less systematic than the emission inventory reports. However, the Convention has been instrumental in the development and amendments of legislations and there are standardised national documents on air pollution in some regions. For instance, the emissions limits (including from specific sources such as combustion plants) set out in the Gothenburg Protocol have been transposed in the National Emission Reduction Commitments Directive in the European Union (EEA, 2024^[101]). Countries develop and communicate the plans for achieving emission reduction under the common template of the National Air Pollution Control Programme (NAPCP) (European Commission, 2018^[102]). The template explicitly recognises the interlinkages between air pollution and climate change and ensures that relevant sectoral policies are considered in relation to climate change as well as energy priorities (see Section 6.4 of Chapter 6 for more discussions on policies to address air pollution).

Growing evidence also highlights the interlinkages between hazardous chemicals and wastes and climate and biodiversity. The Basel, Rotterdam and Stockholm Conventions are multilateral environmental agreements administered by the joint secretariat to protect human health and the environment from hazardous chemicals and wastes. While none of the articles of the Basel, Rotterdam and Stockholm Conventions mention climate change or biodiversity explicitly, there has been a greater recognition of these interlinkages in recent years. The joint secretariat (together with the secretariat of the Minamata Convention on Mercury) conducted exploratory studies, highlighting the interrelated nature of managing chemicals, wastes and climate change (2021^[103]) and biodiversity loss (2021^[104]).

The key findings of these exploratory research strengthen the rationale for integrating climate change and biodiversity loss in efforts to tackle issues relating to hazardous chemicals and wastes. Climate change influences *primary* emissions of hazardous chemicals with adverse impacts on biodiversity. For instance, higher incidence of pest outbreaks may necessitate increased pesticide usage, which can have adverse effects on species, including birds and pollinators. Climate change can also increase *secondary* emissions, as they are released from reservoirs, including soil and glaciers. For instance, the melting of permafrost – a significant reservoir of mercury – is suggested to be increasing the export of mercury to downstream environments (Chételat et al., 2022^[105]). Furthermore, climatic variables such as temperature, wind speed and precipitation patterns affect the transport and environmental fate of hazardous chemicals. Since many chemicals can bioaccumulate and travel over long distances, species and environments far removed from the original sources can also be exposed.

Beyond these biophysical interlinkages, the need for more consolidated environmental monitoring efforts is also increasingly highlighted as a solution to these challenges. For instance, the recent global monitoring report on the Stockholm Convention highlights the potential for enhancing co-ordination with other multilateral environmental agreements, including the CBD and the UNFCCC, for monitoring and modelling efforts (UNEP, 2023^[106]).

Examining the national implementation plans (NIPs) submitted by select Parties to the Stockholm Convention for which the BTR and NBSAP documents are analysed, these interlinkages are sparsely discussed in NIPs. Discussions focus on (i) acknowledgement of the bioaccumulative nature and long-range transport through air, water and migratory species (as specified in the text of the Convention) and, relatedly, (ii) the results of monitoring of the concentrations of POPs in species across different types of ecosystems.

However, there are some limited examples in which climate and biodiversity considerations are discussed in greater detail. For instance, Canada's latest NIP notes the impact of climate change on the release and environmental fate of POPs (ECCC, 2024^[107]) as highlighted in the assessment conducted by the Arctic Monitoring and Assessment Programme (2020^[108]). It also discusses Canada's assessment and regulatory schemes for both new and existing substances, including pesticides and industrial chemicals. The New Substances Notification regime under the Canadian Environment Protection Act mandates assessments of new substances to determine if they enter the environment in a quantity, concentration or conditions that "have or may have an immediate or long-term harmful effect on the environment or its biological diversity" among other conditions. Screening assessments of existing substances also determine whether such substances are harmful to human health and/or the environment. The NIP of Canada also acknowledges the particular vulnerability of Canada's Arctic due to the tendency for POPs to settle in colder climates and the disproportionate exposure of Indigenous Peoples in the region due to their diets traditionally rich in marine mammals. In response, Canada implements several programmes, including the Northern Contaminants Program (NCP), which was established to reduce and eliminate the contaminants contained in harvested foods wherever possible. The NCP also facilitates engagement, capacity building and awareness activities to ensure informed decision-making.

In Peru, where agriculture (mainly consisting of smallholders) constitutes an important part of the economy, excessive use and improper handling of pesticides remain a key challenge. The five most commonly detected pesticides in the country are considered to be highly hazardous (this includes chlorpyrifos¹³, which has been added to the list of pesticides to be eliminated under the Convention in 2025) (MoE, Peru, 2024^[77]). The NIP discusses its goal to eliminate or reduce the use of pesticides listed under the Convention by promoting alternatives, including less hazardous chemicals and agro-ecological practices for natural pest control (MoE, Peru, 2022^[109]). For instance, sweeping methods and soil sanitation are mentioned as an alternative to chlordecone, a pesticide commonly used in tropical climates. In this context, the National Agrarian Health Service of Peru (SENASA) offers information and training through Good Agricultural Practices Guides for 20 types of commonly grown crops in the country. The NBSAP of Peru similarly highlights the importance of facilitating the take-up of these agro-ecological practices to alleviate the issue for human health and degradation of microorganisms in the soil.

5.4. Key takeaways

This chapter analysed twenty national documents of ten diverse countries to examine the extent to which countries pay attention to interlinkages between the dimensions of the triple planetary crisis. The analysis suggests that all ten countries examined recognise the pairwise interlinkages between climate change, biodiversity loss, and pollution in both their BTRs and NBSAPs. However, the framing of the “triple planetary crisis” is less commonly used, with only four countries explicitly discussing it in their BTR (France) and NBSAPs (Canada, India and Indonesia).

Examining the level of detail with which the interlinkages are considered, the analysis finds that they are unevenly considered across countries. There are relatively extensive and detailed discussions on the interlinkages between climate change and biodiversity in terms of their biophysical impacts, particularly in the BTRs. However, in both BTRs and NBSAPs, the impacts of climate change on biodiversity feature more prominently than the implications of biodiversity loss on climate change. Most of the ten countries examined also consider ways to foster synergies between climate mitigation and adaptation and biodiversity conservation in both BTRs and NBSAPs. In addition to integrating the consideration of other environmental objectives in the design of economic, regulatory and information instruments, a range of nature-based solutions feature prominently in these documents, recognising the role of nature in regulating the climate and enhancing resilience against the impacts of climate change. A few countries also highlight the importance of circular economy and resource efficiency in alleviating environmental pressures arising from the common interlocking drivers of climate change, biodiversity loss and pollution. Relatedly, countries also discuss various institutional mechanisms and tools that facilitate broadening of a “lens” in decision-making and budgetary allocation, such as the “Climate, Nature and Economy Lens” in Canada and “Green Budgeting” in France.

While the analysis demonstrates a number of examples of integrated policy solutions, it also identifies two potential areas of oversight. Notably, although some of the synergies in policies are discussed in terms of the sector-specific approaches as specified in the common reporting format of BTRs, such as in energy, agriculture, transport and waste(water) management, considerations of how climate change and biodiversity loss might affect the severity and the extent of pollution are largely lacking from both BTRs and NBSAPs. Furthermore, discussions on trade-off management in policies are almost entirely absent or are discussed in generic terms, particularly for pollution. Given the growing salience of the potential trade-offs, such as between the need for renewables expansion to tackle climate change and the risks it carries for biodiversity, the lack of consideration appears to constitute a missed opportunity for anticipating and managing trade-offs.

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Notes

¹ For countries from which the first BTRs were not yet available, National Communications (NCs) documents were analysed as complementary materials.

² Small Islands Developing States (SIDS) and Least Developed Countries (LDCs) can submit the information at their discretion.

³ Within the scope of this analysis, India and Uganda.

⁴ The emissions inventory encompasses “sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, to the extent its (the Party) capacities permit, using comparable methodologies to be promoted and agreed upon by the Conference of the Parties” (UNFCCC, 2009^[7]).

⁵ The unprecedented scale of the fire prompted large-scale studies on its impact on biodiversity, finding an overall decline in species abundance in the areas while identifying both positive and negative impacts that are mediated by land tenure, drought and recent fire history (Driscoll et al., 2024^[110]).

⁶ Planted trees are considered to peak in their capacity to absorb carbon around 4-5 age classes (i.e. between 16 to 25 years), after which they decline.

⁷ The tool is called “Ecosystem Conservation/Restoration Potential Map” and overlays statistical analyses with geospatial information using Geographic Information System (GIS). The Map helps stakeholders understand the current and anticipate future status, evaluate the potential for disaster risk reduction and biodiversity conservation and land-related regulations.

⁸ Argentina’s BTR does not cover this point, but its latest NC from 2015 does, in a “moderate” way.

⁹ The Peruvian Yunga are a mosaic of montane forests which offer a highly varying microclimate.

¹⁰ The South American Puna spreads along the Andean mountain range across Argentina, Bolivia, Chile and Peru, located between 30 000 and 4 000 m above sea level.

¹¹ One possible exception at a regional level is the “Zero Pollution Action Plan” of the European Union, which sets out a vision to reduce air, water and soil pollutions to levels “no longer considered harmful to health and natural ecosystems [...]” and integrates pollution prevention in relevant EU policies to maximise synergies and identifying trade-offs (European Union, 2021^[112]).

¹² These legally binding Protocols set targets for emission reductions and define the specific measures to be undertaken.

¹³ Chlorpyrifos has also been banned for agricultural use as of August 2024 (National Agrarian Health Service of Peru, 2023^[111]).

6

Deep dives on the management of synergies and trade-offs in the triple planetary crisis

This chapter explores how synergies and trade-offs between responses to climate change, biodiversity loss and pollution manifest themselves at the design and implementation stages at various geographical scales and how they can be managed. These are explored through four deep-dives on: (i) renewable energy expansion, (ii) management and expansion of protected areas, (iii) air pollution control, and (iv) nutrient management.

6.1. Introduction

The interlinkages between climate change, biodiversity loss and pollution play out at multiple scales. Preceding chapters have provided a conceptual overview of synergies and trade-offs between policy objectives to tackle these challenges (Chapter 4) and explored how these considerations are currently reflected in national documents (Chapter 5). Yet, some of the key trade-offs and synergies between different policy objectives are fundamentally local, even if they ultimately affect national or even global outcomes. Thus, policy effects have to be assessed at the relevant levels, to allow for all major synergies and trade-offs to be appropriately accounted for and measured.

To grasp these interactions at different geographical scales, this chapter provides deep-dives into the existing tools and policies that can help harness synergies and manage trade-offs during design, implementation, and operation by exploring policy responses in four key areas (Figure 6.1): (i) renewable energy expansion, (ii) management and expansion of protected areas, (iii) air pollution control and (iv) nutrient management. Each of these cases examined has a primary objective (climate change mitigation, biodiversity conservation and pollution control¹ for the latter two, respectively), but with significant interactions with the other objectives. By adjusting existing modalities and policy design, the primary policy objective can be aligned with the other objectives to reduce trade-offs and reap synergies.

Figure 6.1. Selected deep dives of key policy responses to the triple planetary crisis



Source: Authors' own elaboration.

These four topics have been selected because their implementation is inherently local in nature, yet they span key policy responses across the three objectives, with significant interaction effects on the other objectives.² Nonetheless, they differ crucially in how they are interlinked. Each can serve as a clear example of the different types of interlinkages, providing additional insight into the various core trade-offs and synergies. Together, the policy responses in the four areas highlight that a core response to one objective may risk trade-offs with other objectives, but may also spur synergies, depending on how they are implemented.

First, the large-scale deployment of wind and solar photovoltaic (PV) energy generation is key to climate change mitigation. However, despite their clear climate advantages the deployment of these technologies can negatively affect biodiversity and exacerbate pollution during (i) the extraction and processing of materials and manufacturing, (ii) the installation and operation stage, and (iii) the decommissioning and waste disposal stage. Anticipating these locally specific impacts as well as the upstream and downstream impacts can help alleviate the risks that the renewable energy expansion – critical for reducing climate-induced pressures on biodiversity and reducing pollution associated with fossil fuels – is stalled due to unintended adverse environmental impacts or due to lengthy permitting procedures to evaluate and mitigate such impacts.

Second, protected areas are a cornerstone of biodiversity conservation policy and are, via their positive spillovers on climate change mitigation, adaptation and pollution control, a key tool to address the interconnected environmental challenges together. At risk of declining, degrading or becoming less effective, and more vulnerable to climate change and pollution, integrating these linkages in the selection, design and management of protected areas is essential to preserve their conservation goals.

Third, air pollution control policies have been widely implemented and are fundamental to improve air quality at the local, national and global scales. Air pollutants have extensive impacts on terrestrial and aquatic biodiversity. Conversely, the loss of the pollutant filtration function due to ecosystem degradation leads to increased air pollution. Moreover, air pollutants can have warming (or cooling) effects through their impact on cloud properties, precipitation, and radiative forcing, while climate change affects both natural and anthropogenic sources of air pollutants and can lead to either lower or higher air pollution depending on climatic variables. Thus, policies aiming at preventing or reducing air pollution must consider the feedback loops of climate change and biodiversity in their design and implementation.

Fourth, releases of excess nutrients – not least nitrogen and phosphorus – to the environment can contribute to climate change, pollution in air, water, and soil, as well as affect ecosystems and drive biodiversity loss. Regulating excess nutrients requires an integrated approach across sinks as well as sources, considering the full nitrogen and phosphorus cycles. This includes considering the different nitrogen compounds, such as nitrate (NO_3^-) leaching in the soil and nitrous oxide (N_2O) emissions in the air. Furthermore, as phosphorus is a non-renewable resource, it links directly to resource management.

Often, the ex-ante ambitions of policies when designed are not fully achieved upon implementation, for a variety of challenges and barriers. This “implementation gap” implies that while synergies between the various dimensions can be well-covered in policy design, they may be muted in reality. Specific attention is therefore paid to the available tools for effective implementation of synergistic approaches, including through measurement of impacts. The chapter concludes with key takeaways that can be distilled from the detailed analyses of the four deep-dives.

6.2. Integrating biodiversity and pollution in renewable energy expansion

The accelerated deployment of renewable energy, in particular wind and solar power, constitutes one of the core responses to climate change. In light of the United Nations Framework Convention on Climate Change (UNFCCC) COP28 pledge for tripling the capacity of renewable energy by 2030, many governments have announced their targets to expand the share of renewable energy by 50% or more between 2023 and 2030 (IEA, 2024^[1]). To meet these targets, countries are adopting a suite of market-based (e.g. feed-in tariffs) and non-market-based (e.g. renewable portfolio standards) policies. Under current policies, solar and wind power is projected to represent 37% of global electricity in 2050 (up from 9% in 2020; see Chapter 2).

Renewables expansion is integral to reducing greenhouse gas (GHG) emissions, which in turn can help alleviate climate-induced pressures on biodiversity. To the extent that it replaces fossil fuels, it is also critical for addressing pollution. Nonetheless, wind and solar power can incur new environmental pressures upstream (e.g. high material requirements) and downstream (e.g. limited recyclability of components), while posing threats to biodiversity through their spatial requirements and operation.

6.2.1. Synergies and trade-offs of renewable energy expansion, biodiversity conservation and pollution control

Synergies between renewable energy expansion, biodiversity conservation and pollution control

To the extent that renewables can reduce the reliance on fossil fuels as the primary source of energy, expanding renewables is key to avoiding the adverse environmental impacts associated with the lifecycle of fossil fuels (see Box 6.1 for more details). The transition away from fossil fuels can significantly reduce GHG emissions and address anthropogenic climate change. Renewables expansion also contributes to biodiversity conservation indirectly (by mitigating climate change, the fastest growing driver of biodiversity loss; see also Chapter 3) and directly (by reducing pressures on biodiversity from fossil fuel extraction) (OECD, 2024^[2]). This is an important consideration, particularly given that the terrestrial and marine environments in which oil and gas infrastructure are currently located in areas which have higher species richness and range rarity compared to where no exploitation was taking place (Harfoot et al., 2018^[3]).

Renewables expansion can alleviate pressures from the fossil fuels extraction, which can degrade, fragment and destruct natural habitats. From clearing of forests for mining to disruptions of deep-sea ecosystems through seismic survey and oil and gas drilling, the biodiversity impacts of fossil fuels span across various types of ecosystems. Coal mining is associated with an especially high biodiversity loss compared to other energy sources (Holland et al., 2019^[4]) because it can substantially alter the land surface and subsurface by disrupting deep soil and lithologic structures, resulting in a near-complete loss of terrestrial and wetland habitats for mammals and amphibians in the area (McManamay, Vernon and Jager, 2021^[5]; Wickham et al., 2013^[6]).

Wind and solar energy expansion can also indirectly reduce the distinct risks associated with transport of fossil fuels. For instance, historical oil spills have resulted in mortality of species, with enduring ecological impacts due to the persistence of toxic compounds of oil and impacts of restoration actions on marine and terrestrial wildlife (Barron et al., 2020^[7]). Through tidal currents and wind, oil spills also affect coastal shorelines that provide erosion protection and typically serve as habitats for rich assemblage of species (Asif et al., 2022^[8]).

Shifting from fossil fuels to renewables can also help reduce various forms of pollution, such as air pollution. From the extraction and refining processes to combustion, fossil fuels are responsible for nitrogen oxides (NO_x), sulphur oxides (SO_x), volatile organic compounds (VOCs) and particulate matter (PM). Oil, gas and coal are also associated with high methane (CH₄) emissions, both a potent GHG and a precursor to tropospheric ozone, also known as ground-level ozone (O₃). Of the total 130 million tonnes (Mt) of CH₄ emissions³ associated with the energy sector (more than a third of total emissions associated with anthropogenic activities), oil operations (50 Mt), coal (40Mt) and natural gas supply chain (30 Mt) contribute most significantly to CH₄ emissions of the sector (IEA, 2024^[9]).

Renewable energy expansion can also deliver synergies by reducing the adverse impacts of fossil fuels on water pollution. For example, coal mining incurs the risk of land subsidence and potentially alters the topography as well as groundwater quality (Rouhani, Skousen and Tack, 2023^[10]). Acid mine drainage from surface runoffs, seepage from stockpiles, dumps and open pits contaminate water as well as soil (Simate and Ndlovu, 2014^[11]). Fly ash and sludge from coal can contain heavy metals including mercury, arsenic and lead (Munawar, 2018^[12]), while flowback water from hydraulic fracturing for oil and gas can be highly saline unless treated appropriately (Caldwell et al., 2022^[13]).

Box 6.1. Comparison of environmental impacts of fossil fuels, wind and solar energy

Fossil fuels can cause adverse impacts on biodiversity and result in pollution across different environmental media throughout their lifecycle from extraction, processing and refining, transport and storage, combustion and waste management (Table 6.1). Like-for-like comparisons of the environmental impact of different types of fossil fuels and wind and solar energy are challenging. While the total environmental impacts may not be directly comparable due to different material and process requirements across energy systems, methodologies such as lifecycle assessments (LCAs) and material flow analyses can provide quantitative estimates of (a subset of) environmental impacts in comparable units.

Various studies attest to the lower environmental impacts of renewables on several metrics. A study analysing the impact of doubling the renewable electricity generation between 2005 and 2018 in the EU suggests that impact potentials of renewables are lower for eutrophication, PM formation as well as acidification (European Environment Agency, 2021^[14]). The requirements of the surface and ground water withdrawal and consumption for solar and wind power are also significantly lower than those of fossil fuels (Jin et al., 2019^[15]). For instance, lifecycle water consumption of oil per megawatt hour are estimated to be about 10 times larger than solar PV and 75 times larger than wind (Jin et al., 2019^[15]). Importantly, adverse human health impacts are also considerably lower for renewables (UNECE, 2022^[16]).

However, these studies also suggest that renewables carry some environmental risks that need to be carefully managed. These include higher freshwater ecotoxicity and land occupation impacts (European Environment Agency, 2021^[14]). Although there is a large variation in the estimates of the land-use impacts, existing studies highlight that spatial requirements can be significantly higher for wind and solar power than for fossil fuels per unit of electricity produced. For instance, a study comparing the land-use intensity (measured by hectares per terawatt-hour of electricity) of a large sample of energy facilities in operation concludes that land-use intensity is higher for concentrated solar power and ground-mounted PV than for coal, despite the large variability (Lovering et al., 2022^[17]). The potential land-use impacts underscore the importance of leveraging various spatial planning and land-sharing measures (see Section 6.2.2).

Table 6.1. Select impacts of fossil fuels on pollution and biodiversity throughout the stages

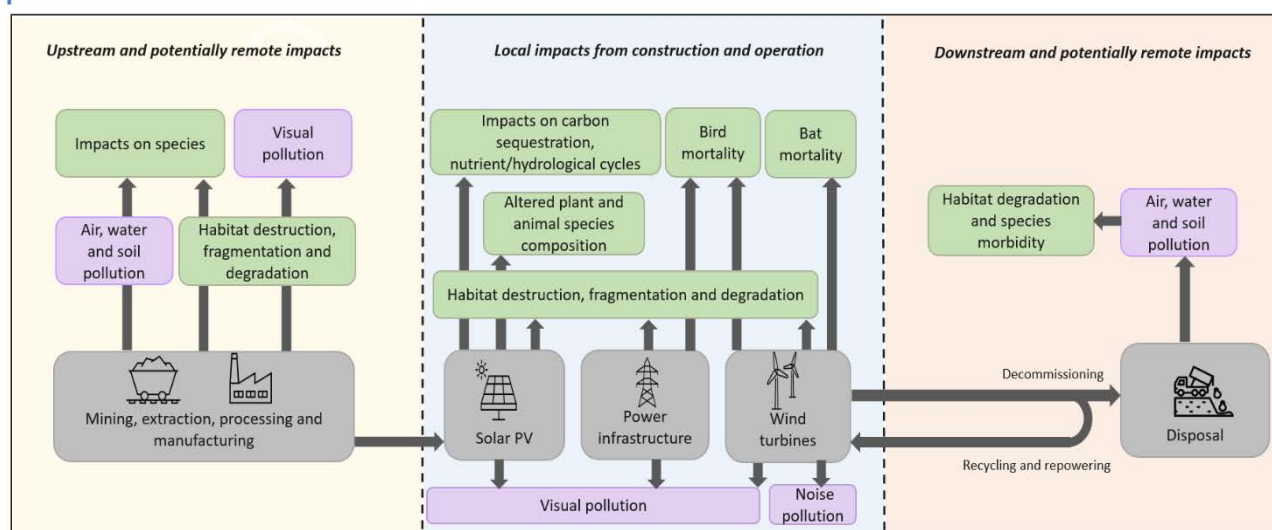
Stage	Coal	Petroleum	Natural Gas
Extraction and processing/refining	Acid mine drainage from surface runoffs, seepage from stockpiles, dumps and open pits can contaminate water and affect soil and harm aquatic and terrestrial species (Simate and Ndlovu, 2014^[11]). Different risks associated with mining methods used: • Surface mining (e.g. mountain top removal) can result in surface and groundwater contamination and decline in species abundance in nearby freshwater ecosystems (Giam, Olden and Simberloff, 2018^[18]); • Underground mining can trigger land subsidence and affect groundwater quality (Rouhani, Skousen and Tack, 2023^[10]).	Drilling for oil extraction causes emissions of VOCs (e.g. benzene) and other air pollutants including PM, sulphur dioxide (SO₂) and NO_x (Johnston, Lim and Roh, 2019^[19]). Refining processes also result in air pollution; mainly from VOCs but also NO_x, SO₂, PM, O₃, CO, as well as hydrogen sulfide, hydrogen cyanide and lead (Tavella et al., 2025^[20]). Higher salinity and level of chloride affecting the quality of surface water (Johnston, Lim and Roh, 2019^[19]). Hydraulic fracturing can lead to habitat degradation, fragmentation and destruction, may amplify other risks including introduction of invasive species (e.g. (Olive, 2018^[21])).	Deep sea oil and gas extraction can affect the assemblages of the deep-sea species (that are generally sensitive to anthropogenic disruptions) (Cordes et al., 2016^[22]). Risk of CH₄ leakage (Fu, Liu and Sun, 2021^[23]). High water withdrawal for hydraulic fracturing risks aquifer depletion (Caldwell et al., 2022^[13]). Clearing of land for well pad and other infrastructures causes habitat loss, fragmentation and an increase in "habitat edges" (Caldwell et al., 2022^[13]).
Transport and Storage	Coal stockpiles contributes to PM_{2.5} emissions from wind erosion, oxidation and other light dust during transport (Jha and Muller, 2018^[24]).	Spillage and leaks into soil during storage and transport release PAHs on soils (Johnston, Lim and Roh, 2019^[19]). Risk of spills during transport causing lasting harm to marine and terrestrial wildlife (Barron et al., 2020^[7]).	Natural gas pipelines can disturb soil and lead to habitat fragmentation (Fu, Liu and Sun, 2021^[23]). Liquefaction into LNG for the purpose of transport over long distance results in CO₂, SO₂ and NO_x emissions (Yuan et al., 2020^[25]).
Combustion	Combustion results in oxides of carbon, sulphur and nitrogen: CO₂, CO, SO₂, SO₃, NO_x (Munawer, 2018^[12]). Coal fly ash leads to the formation of PM; fly ash deposition inhibits plant transpiration and photosynthesis (Gupta et al., 2002^[26]).	Refined transport fuels (e.g. shipping, road) result in high level of CO₂, PM, NO_x, CO, NMVOC, black carbon (BC) emissions (Aminzadegan et al., 2022^[27]).	Results in air pollutant emissions including NO_x and PM, although the levels are significantly lower than coal and oil (Fu, Liu and Sun, 2021^[23]).
Waste management	Trace amounts of heavy metals such as mercury, arsenic, lead and cadmium accumulate in large quantities within post-combustion wastes (fly ash and slag) and affect air, water and soil quality (Munawer, 2018^[12]).	Risk of release of saline wastewater into the environment (Johnston, Lim and Roh, 2019^[19]).	Flowback water has high salinity, contains chemicals and can be ecotoxic unless treated appropriately (Caldwell et al., 2022^[13]).

Source: Authors' own elaboration based on the cited references.

Trade-offs between renewable energy expansion and biodiversity conservation

While the benefits of renewables expansion discussed in the previous section are paramount, the deployment of renewables is not entirely without environmental cost. Without adequate consideration, it risks posing threats to biodiversity and causing pollution at different stages (upstream, construction and operation and decommissioning) and across different geographical scales (Kiesecker et al., 2019^[28]) (key impacts are summarised in Figure 6.2). There is also a cross-border dimension to the impacts of renewables expansion if the part of the supply chain for renewable energy equipment – such as mining, extraction, processing, and manufacturing – is not located in the same country or region where the renewable energy is used.⁴

Figure 6.2. Risks for adverse local and remote impacts throughout the lifecycle of wind and solar power



Note: The most significant impacts are reported here. Environmental impacts not included in the figure include light pollution, shadowing from turbines and the potential introduction of invasive alien species due to movement of people, construction material and equipment.

Source: Authors' own elaboration.

Although the trade-offs between renewable energy expansion and biodiversity are highly site-specific and vary significantly depending on the local climate and management (IUCN, 2022^[29]; Carvalho et al., 2024^[30]), there is a wide range of risks for adverse impacts on biodiversity (OECD, 2024^[2]).⁵ Collision with wind turbines can result in mortality of certain avian species (Thaxter et al., 2017^[31]). Soaring birds (e.g. raptors and other large-winged species) can be particularly vulnerable to collision due to their flight altitude in the rotors' swept zone, reduced flight manoeuvrability for avoidance due to their size, as well as their reliance on thermal updrafts and orographic uplift (and hence the preference for windy slope regions such as mountain ridges) (Santos et al., 2022^[32]).

While bird mortality due to wind turbines is considered small in magnitude relative to other anthropogenic causes (Loss, Will and Marra, 2015^[33]), even a small number of fatalities can affect the population dynamics of long-lived species with low reproductivity. For example, increased fatalities of raptors due to wind turbines have been documented around the world (Estellés-Domingo and López-López, 2024^[34]). However, there are also some concerns that the impacts of smaller passerine birds may be underestimated due to difficulties in identifying fatalities through methods commonly deployed such as carcass surveys (Nilsson et al., 2023^[35]). Beyond direct impacts on fatalities through collision, bird species are also affected indirectly through displacement and habitat alterations and degradation (Shaffer and Buhl, 2016^[36]; Reusch et al., 2022^[37]). For instance, key foraging and breeding habitats for white-tailed eagles often overlap with

optimal locations for setting up wind turbines. Nebel et al. (2024^[38]) suggest that installing them within 5 km of white-tailed eagle nests in Finnish coastlines has resulted in 7.6% lower survival rates.

Wind turbines are identified as the leading cause of multiple mortality events for bats (O'Shea et al., 2016^[39]). High incidences of bat fatalities have been recorded across continents, and available estimates suggest that incidents of migratory bat fatalities by wind turbines could lead to their drastically smaller population size (Frick et al., 2017^[40]). Beyond direct habitat loss on the turbine sites and mortality impacts, recent evidence also shows that bats are avoiding large areas around wind turbines because of the generated wake turbulences and noise, restricting their habitats further (Frick et al., 2017^[40]). For example, Barré et al. (2018^[41]) estimated that the activity of some types of bat ensembles declined by over half on European farmland up to 1 km in distance from wind turbines. The direct and indirect impacts of wind energy on bats pose a serious challenge to local and global bat diversity (Voigt et al., 2024^[42]) and to biodiversity more broadly, given the ecological importance of bats and the key roles they play in pest control, pollination, and seed dispersal across many ecosystems (Jones et al., 2009^[43]).

Offshore wind farms are also associated with varying impacts on biodiversity. While the impacts of construction are predominantly negative, operational impacts can depend on the site and species, and there remains much uncertainty (Watson et al., 2024^[44]). Studies have documented some positive impacts in terms of species abundance as the submerged infrastructure can create artificial reefs for certain benthic and soft-sediment fish species, and can help prevent bottom trawling in the vicinity (Buyse et al., 2022^[45]; Degraer et al., 2020^[46]). However, existing studies also highlight the risk of colonisation of windfarm infrastructure by invasive alien species (Watson et al., 2024^[44]). While offshore wind farms have often been set up as fixed structures in shallow waters, expansion further offshore through floating technologies are also gathering pace (Bennun et al., 2021^[47]). As offshore floating structures are anchored on the deep sea floor, they may also have uncertain impacts on deep sea ecosystems on which there is limited knowledge (Danovaro et al., 2024^[48]).

Land-based solar PV also affects biodiversity through changes in habitats, although their effects are not as well understood as for wind power. Installing solar PV farms on crop lands or wooded areas alters or destructs natural habitats and provokes changes in hydrology, water availability and quality (Hernandez et al., 2015^[49]). Fences around solar PV farms create physical barriers, further contributing to habitat fragmentation (McInturff et al., 2020^[50]). Solar PV farms installed on natural land also generate shading that alters the composition of plant and animal species as well as the provision of ecosystem services such as carbon sequestration in the soil and pollination (Walston et al., 2018^[51]; Grodsky and Hernandez, 2020^[52]; Graham et al., 2021^[53]). In addition to the impacts on habitats, solar PV farms can also alter the behaviour of animal species by drawing birds and bats to the large concentration of insects that mistake panels for water surfaces due to their reflective effects on light (Horváth et al., 2009^[54]). Finally, bird and bat mortality from collision with solar PV infrastructure and exposure to concentrated sunlight has been documented, although it is likely lower than mortality from fossil fuel facilities, wind turbines and power lines (Walston et al., 2016^[55]).

Importantly, both wind and solar power require electricity transmission, distribution and energy storage infrastructure to meet the needs of urban areas, typically distant from renewable energy sources. The impacts of transmission and distribution lines on biodiversity loss are well documented, particularly for birds (OECD, 2024^[2]). Power lines are estimated to kill a large number of birds every year by collision and electrocution (Loss, Will and Marra, 2015^[33]), with vulnerability factors including their body weight, size of wings, flight behaviour, and flight routes (Bernardino et al., 2018^[56]). Electrocution of birds can also ignite wildfires (Guil et al., 2018^[57]). Vegetation is cleared in the safe zone below transmission lines (i.e. "right of way"), and can become colonised by invasive plant species (Biasotto and Kindel, 2018^[58]). However, knowledge gaps remain, particularly for impacts on non-avian species (e.g. amphibians), as well as for disruption of habitats and ecosystems from distribution lines and underground cables (OECD, 2024^[2]).

Trade-offs between renewable energy expansion and pollution control

Among the most significant pollution challenges associated with solar PV and wind turbines is waste management of decommissioned equipment at their end of life. Cumulative solar PV panel waste could increase from 250 kt in 2016 to 8 Mt in 2030 and 78 Mt in 2050 under a scenario of early attrition (IRENA and IEA-PVPS, 2016^[59]). Crystalline polysilicon panels that account for 98% of the global market share consist around 70% of glass (IEA, 2022^[60]), which is a relatively low value material that makes solar panel recycling relatively expensive, increasing the risk of unsustainable disposal.

Disposal of end-of-life panels in landfills can be problematic since they can contain materials such as lead and cadmium that pose risk both to human health and the environment (Li et al., 2020^[61]; Kwak et al., 2020^[62]). Disposal in landfills also constitutes a missed opportunity to recover materials such as aluminium, copper, silver and zinc, further driving demand for primary materials and the environmental damages associated with mining and processing. Mismanagement of end-of-life panels is already a prominent issue in some developing countries, where a growing number of small standalone solar devices with relatively short lifetimes are being improperly disposed of due to a lack of appropriate collection and recycling infrastructure (ACE, 2021^[63]). The mismanagement of solar panel waste in countries without adequate waste management systems can also be amplified by illegal trade in discarded solar panels, which remains difficult to quantify (Nyffenegger et al., 2024^[64]; Huisman et al., 2015^[65]).

Recycling of end-of-life solar panels is technically complex due to the heterogeneity in size and composition (IEA, 2022^[60]). Solar panels have typically been designed for their durability rather than recyclability, with sandwich-like structure that makes sorting and separation of materials challenging (IEA-PVPS, 2021^[66]). Economic viability can be compromised due to high recycling costs and limited recovery of homogeneous and high-purity content of materials.

Similarly, the development of wind power is projected to generate 43 Mt of cumulative wind turbine blade waste by 2050 (Liu and Barlow, 2017^[67]). Wind turbines are made of three main parts: the tower (primarily made of steel), rotor (a hub and three blades made of composite materials), and nacelle (contains gearbox, generators, controller and brakes). Most components of a wind turbine such as the foundation, tower, gear box and generator are already recyclable. However, due to their heavy weight and heterogeneity, wind turbine blades are not currently widely reused or recycled (Khalid et al., 2023^[68]). Furthermore, developments in blade designs have resulted in lightweighting with the use of composites such as fibre-reinforced plastics that cannot be easily recycled (Shen, Guo and Feng, 2023^[69]).

Landfilling turbine blades has land use implications as it requires space to store large composite components that are non-biodegradable. Blades that are not landfilled or recycled are thermally recycled or incinerated. The pyrolysis or thermal recycling of blades separates the resin from the fiberglass or carbon fibres producing gas, oil and char. However, this process is highly energy intensive and can contaminate the recycled fibres with char (ACP, 2023^[70]). With the average life of 25-30 years, limited recyclability of these technologies poses an imminent challenge, as their rapid deployment in the last two decades can result in a large quantity of decommissioned solar panels and wind turbines that end up in landfills (Lichtenegger et al., 2020^[71]).

In addition to end-of-life management, wind power and solar PV generate pollution during their construction and operational phase, including visual and noise pollution that has significant effects on public perception of renewable energy. The visual and aesthetic impacts of wind energy facilities on landscapes are one of the main challenges faced by wind energy development at the local level (Krekel and Zerrahn, 2017^[72]), although its importance for acceptability relative to other factors is highly context specific (Rygg, 2012^[73]).

Closely related to the impacts on biodiversity, heightened demand for minerals used in renewable energy technologies can result in increased pressures for water- and land-intensive mining and processing activities, pollution consequences of which extend across various ecosystems. Wind turbines are associated with substantial material requirements and intensity, both in terms of bulk (e.g. steel and

cement) and critical materials. Onshore and offshore wind infrastructure use large amounts of concrete and steel (Farina and Ancil, 2022^[74]); production of which is currently associated with high CO₂ emissions. Furthermore, manufacturing of rare earth metals or alloys for generators entails many steps including mining and refining that emit toxic chemicals into the soil, water and air such as PM and hydrogen fluoride (Zapp et al., 2022^[75]). The extraction and processing of copper used in both solar PV and wind turbines generate slags, dusts and aerosols that are contaminated with metals and metalloids, including toxic elements such as arsenic, cadmium and lead (Izydorczyk et al., 2021^[76]).

Manufacturing of solar PV also involves the use of different hazardous materials to extract and purify the raw materials such as silicon or copper and to manufacture the modules. These include ammonia (NH₃), arsenic, and cadmium, some of which are associated with cancer and other chronic diseases (Aman et al., 2015^[77]). Some of the materials used for improving the efficiency of solar panels can also carry the risk of release of pollutants. For instance, fluoropolymer containing per- and polyfluoroalkyl substances (PFAS) is used for coating in solar panels for front sheets (to increase the amount of light reaching the panel) and as back sheets (to protect the modules from moisture and degradation) (OECD, 2022^[78]).

6.2.2. Integrating biodiversity and pollution control in siting of renewable energy infrastructure

Procedures informing and deciding the siting of wind and solar infrastructure, including by considering their current and alternative use of the siting areas, are critical for avoiding the risks of biodiversity loss and pollution. Countries can actively identify appropriate sites for renewable energy infrastructure based on specific site characteristics such as the proximity to existing power infrastructure or steer them away from certain areas that are important for biodiversity. Environmental Impact Assessments (EIAs) as part of the licensing and permitting procedures can also help elucidate the broader environmental impacts of a project, although there is a need to reconcile comprehensive consideration of the environmental risks with the speed and predictability of permitting process so as to avoid well-intended safeguards from becoming an impediment to the accelerated deployment of renewable energy.

Spatial planning

Aided by tools such as Strategic Environmental Assessment (SEA), a range of “analytical and participatory approaches that aim to integrate environmental considerations into policies, plans and programmes and evaluate the interlinkages with economic and social considerations” (OECD, 2006^[79]), spatial planning can help identify appropriate sites for renewables projects and streamline the permitting processes for the renewable infrastructure. Spatial planning can also inform land-sharing strategies to reduce the spatial footprint of the renewable energy infrastructure. While the site-specific impacts limit the generalisability of the findings, some existing studies suggest that land-sharing can deliver synergies for biodiversity conservation and pollution control while managing the risks of trade-offs. These mechanisms include installing solar PV on degraded land to prevent habitat loss and soil degradation in natural ecosystems (Gómez-Catasús et al., 2024^[80]). For instance, France mandates that solar panels installation prioritises areas with limited biodiversity concerns such as parking, buildings, abandoned roads or railways (France, 2024^[81]). Projects involving the clearing of over 25 hectares in natural, agricultural and forest areas have been systematically rejected by regional authorities, and as of 2024, it is no longer possible to apply for a permit if the clearing exceeds this threshold.

Combining solar PV setup and conventional agriculture (“agrivoltaics”) is another land-sharing mechanism that has the potential to offer synergies in terms of pollution control and management. For instance, agrivoltaics in drylands is suggested to enhance water use efficiency (by decreasing the evaporation from soil) and enhance agricultural productivity (by reducing heat and light stress on food production) while the crops or other infrastructure underneath can provide cooling effects for the panels to improve their efficiency of electricity generation (Barron-Gafford et al., 2019^[82]). Harnessing these potential synergies, a

project (“Ecolume”) in the semi-arid regions of Brazil aims to promote water reuse through rainwater collected on solar panel surfaces with an aquaponic system located beneath photovoltaic panels (Lacerda et al., 2020^[83]). In addition to energy generation, it also contributed to the cultivation of 17 types of vegetables for local consumption as well as seedlings that were utilised for local reforestation (Vidotto et al., 2024^[84]).

Agrivoltaics can also provide a means for income diversification for farmers (Mamun et al., 2022^[85]). For instance, against the backdrop of aging labour force of the agricultural sector, Korea provides support for small-scale agrivoltaics projects to prevent farmers from abandoning their land and to provide an additional source of income (Schindele et al., 2020^[86]). Some countries in Europe are also taking steps towards the development of technical specifications (Germany), guidelines (Italy) and a definition of agrivoltaics (France) (Chatzipanagi, Taylor and Jaeger-Waldau, 2023^[87]).

However, practical policy and technical challenges for widespread deployment of agrivoltaics still remain. In particular, the dual use of land for electricity generation and agriculture brings uncertainty over the land characterisation, which may have implications for other policy domains including agricultural support (Chatzipanagi, Taylor and Jaeger-Waldau, 2023^[87]). Furthermore, optimising both agricultural and power generation can be challenging, especially as the impact of solar PV on crop growth (e.g. due to shading) is highly site- and crop-specific (Asa’a, 2024^[88]) and synergies cannot always be assumed (Mamun et al., 2022^[85]).

Co-locating different types of renewable infrastructure with other economic activities can also help realise synergies and manage the risks of trade-offs (OECD, 2024^[2]). Well-recognised synergies include the co-location of different types of renewables for resource complementarity of the infrastructure and existing grid connection. A recent study on the European Atlantic also suggests that co-locating offshore wind and solar farms, for instance, may also confer additional benefits by contributing to lower power output variability, particularly in the areas where there is a negative relation between the seasonality of solar irradiance and wind resources (Martinez and Iglesias, 2024^[89]). Spatial planning and early engagement with stakeholders can also help assess the viability of co-locating renewable infrastructure with other economic activities. For instance, offshore wind farms can also provide synergies for aquaculture to improve resource use and operational efficiency (Manolache and Andrei, 2024^[90]) – the research on the optimal co-location sites is expanding to aid marine spatial planning (e.g. (Stockbridge, Brown and Kuempel, 2025^[91])).

Environmental permitting and use of environmental assessment as integrative mechanisms

There is an important balance to be struck between accelerating renewables expansion and ensuring the risks for adverse impacts are managed during licensing and permitting processes, including EIAs. The processes, scope and timeline of an EIA can vary significantly across countries (see Annex 6.A for more details and examples of requirements for renewable energy projects). Existing regulations can require additional steps for permitting. In the European Union, the EU Habitats Directive prohibits the destruction or disturbance of the certain animal species and their habitats, although derogations can be made under certain circumstances by authorities in member countries.

Similarly, in Ontario, Canada, under the province’s Environmental Protection Act, a renewable energy generation facility cannot be installed in a provincial park or a conservation reserve, unless permitted by the Provincial Parks and Conservation Reserves Act. There are prohibitions on transmission and distribution lines, transformer and distribution stations and other activities within the distance 50 to 120 meters from natural habitats and cultural and heritage sites. To obtain derogation from these restrictions, applicants must submit an environment impact study that meets specific requirements and guidelines including: (i) assessment of environmental impacts, (ii) identification of mitigation measures, (iii) description of monitoring, (iv) explanation as to why installing at an alternative location is infeasible, as well as written

confirmation from the Ministry of Natural Resources and Forestry that the study has been prepared in accordance with the Natural Heritage Assessment Guide.

Governments can implement various measures to help streamline and expedite the process, while maintaining the rigour of the assessment and ensuring compliance with (and where necessary review of) existing regulations. Improving predictability of the timelines can allow for greater cost- and time certainty for project proponents (McMaster et al., 2021^[92]). In this context, some jurisdictions streamline the process by centralising the permitting process within one authority. For instance, in Scotland, offshore wind development licenses are issued by one central authority, the Marine Directorate Licensing Operations Team, which oversees all steps of the permitting process including Habitats Regulations Appraisals (Vasconcelos et al., 2022^[93]).

Countries can also provide detailed guidance to support developers of wind and solar projects conduct an EIA to prevent practitioner discretion, which can arise from the lack of clear definitions and facilitate a shared understanding of what constitutes a significant environmental impact (Gasparatos, Ahmed and Voigt, 2021^[94]). For instance, Australia has developed guidance on key environmental factors to consider for offshore windfarms, such as displacement of marine fauna and invasive marine species (Department of Climate Change, Energy, the Environment and Water, 2023^[95]).⁶ Similarly, the European Commission provides guidance on wind energy developments, detailing relevant legal provisions for biodiversity conservation as well as highlighting good practices (European Commission, 2020^[96]). More generally, the International Union for Conservation of Nature (IUCN) and the Biodiversity Consultancy have developed guidelines for project developers to mitigate biodiversity impacts associated with solar and wind energy development across lifecycle (Bennun et al., 2021^[47]).

Enhancing availability and access to relevant information can also help alleviate burdens on project proponents. In France, for instance, the Renewable Energy and Biodiversity Observatory was established in 2024. In collaboration with research institutes, energy industry and NGOs, the Observatory synthesises and disseminates findings from existing studies and data to inform stakeholders, to reconcile the objectives of Energy Sovereignty and Carbon Neutrality 2050 with Zero Net Loss of Biodiversity and Zero Net Artificialisation.

As spatial planning facilitates the identification of the areas in which renewable energy projects can be set up with relatively limited environmental impacts, it can also help streamline the permitting process. For instance, the recently amended Renewable Energy Directive in the EU, which requires designating renewables acceleration areas stipulates that the permit granting procedure for renewable energy projects in the designated areas shall not exceed 12 months for renewable energy sites on land and 2 years for offshore wind projects.⁷

While renewables result in significantly less pollution during operation compared to fossil fuels, there are risks of pollution associated with production and end-of-life management (see Section 6.2.1). Consideration of these risks is mandated in the regulations governing the EIA in some countries. For instance, the Infrastructure Planning Regulations 2017 in the United Kingdom requires that the Environmental Statements submitted by project proponents provide information on pollutants emissions as well as the management plan for the disposal and recovery of waste, among others (United Kingdom, 2017^[97]).

Opportunities for improving EIA processes

Establishing and assessing the baseline (initial state), such as via the landscape, species diversity and abundance, is fundamental to a robust quantification of impacts associated with renewable energy projects. Given the different impacts of solar and wind power at various geographical scales, it is also important to clearly define geographical perimeters. In France, for instance, considerations of (i) potential siting zone, (ii) biological study area (200 m around siting zone), (iii) close study area (6 km radius) and

(iv) the remote study area (18 km radius) are facilitated by the guideline that collates various steps and data sources to understand the initial states of these areas (MTE, 2020^[98]).

Examining alternative scenarios, including alternative siting zone, technology and the sourcing of the equipment, can also help project proponents examine the impacts more holistically, although these efforts need to be carefully balanced with the objective of accelerating renewable energy expansion. It is important to consider the temporal dimension of biodiversity, as new risks can arise from climate-induced range shifts of species even if initial siting has considered and avoided the most vulnerable areas; an important consideration given that the renewables infrastructure is typically installed for decades (Ashraf et al., 2024^[99]). In some jurisdictions, it is mandatory to consider a “no project” scenario. For example, the EU amended its EIA Directive in 2014 to require including “a description of the reasonable alternatives studied by the developer” and indicating the main reasons for the chosen option, rather than just “an outline of the main alternatives” as stipulated in the previous version of the Directive of 2011. In Austria, the “zero-alternative” is often discussed, comparing the planned situation with a baseline scenario and representing the development of the state of the environment without the project (Jiricka-Pürner, Bösch and Pröbstl-Haider, 2018^[100]).

Considering the cumulative impacts of renewable projects, i.e. both contemporaneous and future impacts is also conducive to management of trade-offs. Such considerations can be mandated by legislations or informed by non-binding guidelines. The European Union mandates the assessment of cumulative impacts through the Environmental Impact Assessment Directive, the Strategic Environmental Assessment Directive, and the Marine Strategy Framework Directive (Willstead et al., 2018^[101]).

Protocols for impact monitoring can also detailed in EIA. These protocols can mandate specific impacts to be monitored (e.g. bat and bird populations and fatalities) as well as the frequency and set the different thresholds that trigger response actions. In some jurisdictions, regular monitoring is mandatory. For example, in France, Article 12 of the Decree of 26 August 2011 (as amended by the Decree of 10 December 2021) specifies that the wind power facility operator must set up environmental monitoring within the 12 months of installation (unless exempt in special circumstances) and conducted every decade at minimum to estimate the mortality of birds and bat species due to the presence of the wind turbines. The first criminal case against wind farm operators (Box 6.2) is illustrative of the potential cost of the failure to account for the implications of renewable energy projects on biodiversity.

Box 6.2. First criminal judgement against wind farm operators in France

In December 2024, the French Council of State cancelled a prefectorial order that had rejected a request for a “protected species” exemption, on the grounds that environmental permits issued for the wind farms were considered final. In the Prefect’s view, it precluded any subsequent derogation request. In April 2025, the Montpellier Correctional Court (France) ordered a one-year shutdown of the Bernagues wind farm in Hérault, holding its operators responsible for the death of a golden eagle, a protected bird.

The operating company of seven turbines was fined EUR 200 000 while its manager faced a EUR 40 000 fine. This decision was issued just after a similar order that mandated a four-month suspension of the 31 turbines at the Aumelas wind farm, located in a Natura 2000 site (also in Hérault), during the nesting period of the lesser kestrel (*Falco naumanni*). The ten operating companies were found responsible for the illegal killing of 160 birds from 20 protected species, in addition to bats from 7 protected species. Each of the ten companies involved was fined EUR 500 000 (with EUR 250 000 suspended) and the former CEO of one of the operating companies was sentenced to six months of prison with a suspended term and fined EUR 100 000 (of which EUR 30 000 was suspended). The judicial decisions by the Court of Montpellier mark a first in France in penalising wind energy operators for wildlife destruction.

Source: FNE-OCMED (2025^[102]).

Incorporating the impacts of renewables throughout the lifecycle can also help broaden the consideration. The information regarding the type and the estimated quantity of waste generation during construction and operations are typically provided as part of EIA. However, with some exceptions (e.g. the United Kingdom), the impact of decommissioned renewables equipment at their end-of-life tends to be inadequately considered in EIA, possibly owing to the fact that waste management is prescribed by national and municipal laws rather than being specific to a site or a project.⁸

Procedural improvements and institutional arrangement such as public consultations at an early stage and independent review can further enhance the integration of a broader set of objectives. While these procedures can be time-consuming, anticipating the environmental risks at an early stage of project planning can reduce the risk of delays and cancellations of projects. In England, public consultations are mandatory at a pre-application stage for onshore wind projects involving more than two turbines or the hub height of any turbine exceeding 15 m (Rankl, 2024^[103]). Some countries also provide specific resources to improve public consultations and bring broader environmental impacts into consideration. In Germany, the KNE (dedicated to biodiversity and renewable energy, founded by the Ministry of the Environment, Climate Action, Nature Conservation and Nuclear Safety, provides a team of mediators to help resolve conflicts relating to nature protection in the context of renewable energy developments (OFB, 2023^[104]).

In France, the French Environmental Authority and regional agencies are responsible respectively for reviewing authorisation applications of large- and small-scale renewable energy project and for providing an independent opinion. The review is intended to help improve the design of the project, as well as informing the public and enabling their participation in the decision-making. While the opinion is not intended to determine the appropriateness of the project, the competent authority takes the opinion into the consideration for the decision on authorisation. These environmental authorities also help highlight the common issues such as the inadequate consideration given to the connection of wind farms and solar PVs to electricity grid (IGEDD, 2023^[105]). India's EIA Process & Procedures legislation similarly mandates that the Ministry of Environment, Forest and Climate Change form an appraisal committee to review the project (Ministry of Environment, Forest and Climate Change, 2024^[106]). Additional consultations with experts and can also be held when necessary and the appraisal committee is granted 90 days to review the EIAs (Ministry of Environment, Forest and Climate Change, 2024^[106]).

6.2.3. Additional safeguards to minimise the impacts on biodiversity and pollution

While licensing and permitting processes are important regulatory tools, they can be complemented by other policies that provide additional safeguards. In line with the “mitigation hierarchy”, there is a need to minimise the risks to the extent that their avoidance is not feasible. Similarly, upstream and downstream management of wind and solar power equipment constitutes an important lever for minimising the impact on air, water and soil quality.

Safeguards for minimising the impact on biodiversity

Safeguards can range from physical (e.g. diverters on power lines) and operational controls (e.g. shutdown of wind turbines) as well as various “curtailment” strategies for wind turbines, such as preventing their blades from turning at low wind speeds, although only a small portion of wind turbines currently operate with curtailment (Voigt et al., 2024^[42]). Creating and conserving microhabitats for preserving pollinator biodiversity can help reduce the risks associated with utility-scale PV farms such as the use of herbicides to reduce panel shading and fire risks (Vaverková et al., 2022^[107]; Blaydes et al., 2021^[108]). The need for these safeguards can be specified to provide legal certainty for developers, clarify the expectations of administrative authorities at an early stage and simplify the appraisal process.

Better management of upstream and downstream risks of renewables technologies

There can be extensive upstream impacts of renewable technologies due to the quantity and the type of materials required to produce them (see Section 6.2.1). In this context, improving traceability of inputs to these technologies can help identify and address the upstream impacts. For example, the European Union recently introduced the Critical Raw Materials Act, which aims to promote sustainability in raw material sourcing by requiring mineral supply chain mapping until the point of extraction while empowering the European Commission to establish rules for the environmental impact of material extraction (European Union, 2024^[109]). To improve traceability of domestic mining supply chains, Colombia has also developed Minerals Traceability Platform, which requires and verifies information regarding all stages of the domestic mining and transaction processes (Republic of Colombia, 2024^[110]).

Relatedly, policies that mandate biodiversity protection for mining activities can also help alleviate the risk of pollution. For instance, the Administrative Order 2022-04 by the Ministry of Environment and Natural Resources in the Philippines requires mining companies to conduct biodiversity assessments before exploration in accordance with national regulations, guidelines and technical orders that identify the appropriate monitoring entity along with specific criteria to include in their reports. Further, the administrative order stipulates that the mining company maintain at least 85% survival rate along with similar diversity of species after rehabilitation (Republic of The Philippines, 2022^[111]).

To support better management of components of solar and wind technologies with limited reusability and recyclability, downstream provisions can be applied. For instance, several countries around the world prohibit disposal, landfilling and incineration of wind turbine blades and facilitates recycling of end-of-life solar panels. In Germany, a large proportion of the decommissioned wind turbine blades is directed towards energy recovery in cement co-processing, contributing to the recovery of materials and energy generation (CGEDD and CGE, 2019^[112]), although there are some concerns that this constitutes downcycling and is associated with PM_{2.5} emissions (Engie, 2021^[113]; ACP, 2023^[70]).

Decommissioning policies can also entail financial guarantees to cover the cost and to ensure appropriate dismantling and restoration of the site. For example, in Scotland, offshore renewable energy installations decommissioning policies may require a financial assurance for decommissioning, and compliance with reporting and records requirements over the lifetime of the project. Under the Energy Act 2004, financial security can be provided prior construction in the form of an upfront cash security paid into an escrow account, or through performance bonds (Scottish Government, 2022^[114]).

6.3. Integrating climate change and pollution in protected area management policies

Protected areas serve as a cornerstone of biodiversity conservation policy and are, via their positive spillovers on climate change mitigation, adaptation and pollution reduction, a key tool to address the triple planetary crisis. Without protected areas, global loss of biodiversity would be even higher (Laurance et al., 2012^[115]; Gill et al., 2017^[116]; Geldmann et al., 2018^[117]; UNEP-WCMC, IUCN and NGS, 2018^[118]). Protected areas are also key policy instruments to manage land- and sea- use systems at local, national and international levels. The importance of protected areas as a core response to biodiversity loss is reflected in the ambitious target under the Kunming-Montreal Global Biodiversity Framework (KMGBF) to expand the global protection and conservation to at least 30% of terrestrial and inland water areas and 30% of marine and coastal areas by 2030.

The IUCN defines a protected area as “a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values” (Dudley, 2008^[119]). The IUCN has developed six categories to classify protected areas based on their management objectives (see Annex 6.B) which

regulate human activities with varying levels of stringency. The types of protected areas employed are influenced by national land contexts, particularly in relation to land tenure and unmanaged areas (OECD, 2020^[120]).⁹ In countries with secure land tenure and relatively little unmanaged land, land-use restrictions tend to be controlled through protected area designations that overlap with or are entirely within private land. In countries with large areas of unmanaged land, protected areas can play a key role in preventing the conversion of forests and other ecosystems (Nolte et al., 2013^[121]; Pfaff, Santiago-Ávila and Joppa, 2016^[122]; Gaveau et al., 2012^[123]).

Protected areas are often instated with biodiversity conservation as the primary objective. They can also include benefits for climate change mitigation and adaptation and pollution control, not least through providing a diverse set of ecosystem services. Protected areas mitigate climate change mainly through carbon absorption, sequestration and avoided carbon release. They also constitute nature-based solutions to climate change adaptation by mitigating the risks and impacts of extreme events and natural disasters. Moreover, protected ecosystems can filter water and air-borne pollutants. Last, protected areas are also key policy instruments of sustainable land-use to align biodiversity, climate, and food policies (OECD, 2020^[120]).

6.3.1. Synergies and trade-offs between protected areas, climate change and pollution

Synergies between protected areas, climate change and pollution

Protected areas, through their biodiversity conservation objectives and effects on ecosystem services, can provide multiple synergies related to climate change and pollution reduction. The most salient synergies to climate change mitigation are carbon absorption, sequestration and avoided carbon release. In 2020, protected areas accounted for 11% of the global forested area and stored 26% (61.4 Giga tonnes (Gt) carbon (C)) of the estimated above ground carbon (Duncanson et al., 2023^[124]). Of this total of 61.4 Gt, around 9.65 Gt of additional stored carbon can be attributed to protected area status. These higher carbon stocks are mainly from (i) avoided emissions from deforestation and (ii) a combination of enhanced growth and or avoided degradation in protected forests compared to unprotected ones. In addition, protected areas and other effective area-based conservation measures are estimated to store 21% of the belowground biomass, 15% of the soil organic carbon and 7% of the marine sediment carbon (Secretariat of the Convention on Biological Diversity, 2020^[125]). Protected areas also store about 23% of the irrecoverable carbon in Earth systems, and about half is concentrated in just 3.3% of world's land area (Noon et al., 2021^[126]). For example, at the national level, Parks Canada has estimated that the average carbon stock contained in 31 national parks¹⁰ between 1990-2020 was almost 1.5 Gt C, and that the average carbon density for forested ecosystems within national parks was a little more than 250 t of C per hectare (Sharma, 2023^[127]).

Protected areas play a critical role in climate change adaptation by mitigating the risks and impacts of extreme events and natural disasters, such as wildfire. Protected areas can create thermal buffers (Xu et al., 2022^[128]), mitigate the effects of floodings and storms (e.g. service provided by mangroves and coral reefs ecosystems (Salem and Mercer, 2012^[129])), stabilise shoreline or control the erosion of riverbanks, stabilise sediments and protect from landslides (Dudley et al., 2015^[130]).

Protected areas have in the past not been fully integrated in Nationally Determined Contributions (NDCs) under the Paris Agreement. In the 168 latest NDCs submitted by Parties (as of 9 September 2024), only 50% of Parties reported measures related to conserving, protecting, and restoring nature and ecosystems – including protected areas – within their conditional mitigation commitments (UNFCCC, 2024^[131]). Thus, the third round of NDCs due in 2025 represents a decisive opportunity to integrate nature-based solutions including protected areas, to reduce global emissions and strengthen the resilience of ecosystems (Nature4Climate Coalition, 2024^[132]).

Protected areas contribute to water quality improvements by filtering, sequestering, or storing waterborne pollutants. Their role in providing clean freshwater is particularly significant as they deliver 20% of the global total continental runoff and supply freshwater to nearly two-thirds of the global population living downstream (Harrison et al., 2016^[133]). Moreover, protected areas offer water provisions less exposed to threats compared to unprotected areas. Over a quarter of water supplied by protected areas faces low threat levels, compared to only 10% of water provisions outside protected areas. In contrast, less than 10% of water provisions from protected areas are exposed to high threat levels, compared to a quarter outside of protected areas (Harrison et al., 2016^[133]). However, challenges remain in ensuring comprehensive protection as about 70% of global river reaches (by length) have no protected areas in their upstream catchments, and only 11% (by length) achieve full integrated protection (Abell et al., 2016^[134]).

By reducing ecosystem loss and degradation, especially in forest ecosystems, protected areas provide significant air purification services by absorbing pollutants – including PM_{2.5} generated by wildfires (Prist et al., 2023^[135]). In the Brazilian Amazon, a quasi-experimental evaluation found that doubling upwind protected areas decreases PM_{2.5} by 10% and respiratory hospitalisations by 7% in the months of most active biomass burning (Sheehan et al., 2023^[136]).

Trade-offs between protected areas, climate change and pollution

While protected areas provide significant benefits for biodiversity conservation, their use can entail trade-offs with climate change mitigation and pollution reduction objectives. Two types of trade-offs can arise: (i) pressures from climate change on biodiversity and the management of protected areas, and (ii) conflicts between climate change, pollution and biodiversity objectives in protected areas.

Renewable energy production such as bioenergy avoids the use of fossil fuels but can create competing land and forest uses and exert pressures on protected areas. Burning biomass also leads to air pollution. Bioenergy based on woody biomass – especially in combination with carbon capture, utilisation and storage – can potentially contribute to climate change mitigation but needs to reconcile biodiversity conservation with sustainable exploitation of forests and other ecosystems. The BioEUParks project in the European Union accompanied five European Parks in Austria, Hungary, Slovenia, Italy and Greece to develop models of small-scale supply chain for solid biomass harvested from sustainably managed forests (BioEUParks, 2016^[137]). Among the project's main recommendation is the call for a legal framework to use waste material from conservation actions, such as alien species removal, for energy production so as not to be considered as regular waste material.

Renewable energy projects, such as wind and solar power farms, contribute to reducing global pressures on biodiversity through climate change mitigation. However, when these projects are located within or near protected areas, they may exert direct pressures on local biodiversity and ecosystems, including impacts on bird and bat populations or pollution, as outlined in the previous section. The location of renewable energy projects may then affect the efficiency of protected areas to reach their biodiversity conservation goals. At the global level, in 2018, out of the 12 658 large-scale renewable energy facilities, 2 206 were operating inside important conservation areas, including 169 in protected areas and 122 inside strictly managed protected areas (IUCN categories I-IV) where no development activity should occur (Rehbein et al., 2020^[138]). Furthermore, 252 renewable energy facilities were under development within protected areas, including 100 in strictly managed ones.

Renewable energy projects such as hydropower facilities can exert pressure on biodiversity in or near protected areas by changing the connectivity and river flows inside or upstream of protected areas. Dams affect sediment and thermal regimes and alter the water quality and the ecological functions downstream. Globally, between 1900 and 2016, at least 1 249 large dams were located within protected areas with two-thirds built before their designation (Thieme et al., 2020^[139]). The primary uses of these dams located inside protected areas were hydroelectricity (22%), irrigation (22%); water supply (15%) and flood control (7%).

Efforts to maximise carbon storage can conflict with objectives to conserve endemic species, and adaptation to changing climate. In forested areas – including protected forest areas – planting fast-growing exotic tree species to enhance carbon sequestration and resilience to climate change may alter local ecosystems and displace native species. The expansion of tree plantations between 2000-2012 affected 4% of protected areas across the humid tropics, most frequently in southeast Asia, West Africa and Brazil (Fagan et al., 2022^[140]).

The increasing frequency and severity of wildfires, exacerbated by climate change, necessitate wildfire prevention measures that may conflict with biodiversity conservation. Healthy forests are generally less susceptible to wildfire ignition and spread. Ecosystem protection, restoration and their adaptive management can therefore constitute part of wildfire prevention (OECD, 2023^[141]). Nevertheless, fuel-reduction treatments, such as clearcutting corridors and removing dead biomass to create tree discontinuities, can reduce carbon storage and harm species dependent on deadwood such as insects, fungi and bacteria (Campbell and Ager, 2013^[142]). Fuel breaks or prescribed fires can also create invasive plant risk by letting the invasion of exotic species along wildland corridors (Keeley, 2006^[143]). For example, the British Columbia Parks requires different fuel management across designation types within and across protected areas, from Intensive Recreation zones where management can be more intensive to Wilderness Conservation zones where land management is avoided (British Columbia Wildfire Service, 2024^[144]). In the aftermath of wildfire, “salvage logging” can also reduce species richness and negatively impact soil and water quality (Thorn et al., 2018^[145]; Leverkus et al., 2020^[146]).

Protected areas often overlap with high-risk zones for natural disasters. Infrastructure to mitigate disaster risks, such as tide walls, coastal levees, or sand-control dams, can exert direct pressures on biodiversity. For example, large coastal levees were constructed in Sanriku Fukko National Park (Tohoku, Japan) after the 2011 Great East Japan Earthquake, creating tensions between disaster risk reduction and ecosystem preservation (Tanaka and Takashina, 2023^[147]).

6.3.2. Dealing with risks to the synergistic effect of protected areas from negative climate change and pollution impacts

Protected areas face significant risks from climate change and pollution, which threaten their ability to deliver biodiversity and ecosystem services benefits. As climate conditions – including temperature and hydrological systems – have evolved since many protected areas were designated, these areas must adapt to remain effective. Climate change directly alters natural habitats, leading to shifts in species distribution and range. Fauna and flora may move poleward, upslope, or to deeper waters in search of suitable conditions, while vulnerable species face heightened risks of extinction. Climate change can modify the timing of biological events, such as flowering or breeding, disrupting established interactions between species. Protected areas may also experience an influx of new exotic species, some of which could become invasive and disrupt existing ecosystems. Changing climate conditions may alter the patterns of disease vectors (organisms that transmit infectious diseases), further threatening biodiversity.

As discussed in Chapter 3, while climate change is a main driver of biodiversity loss, pollution also contributes significantly to biodiversity loss and threatens the functioning of protected areas. Protected areas are vulnerable to pollutants from agricultural fertilisers, pesticides, heavy metals, animal waste, and sewage, which can originate upstream, in contiguous zones, or within the areas themselves (Jaureguiberry et al., 2022^[148]). These pollutants threaten air, soil, and water quality, directly endangering the flora and fauna of protected ecosystems (Gross et al., 2017^[149]). The adverse effects of pollution add another layer of complexity to the management of protected areas. Approaches to pollution control and mitigation vary across protected areas, reflecting differences in local contexts and capacities.

Accounting for climate change in designating new protected areas and expanding their network

Biodiversity conservation strategies need to consider the current and upcoming risks related to climate change in the design and expansion of protected areas. The scientific literature provides five categories of recommendations (Ranius et al., 2022^[150]): (i) ensure sufficient connectivity to enable species to shift distributions or recolonise patches in habitat networks; (ii) protect areas that remain relatively preserved from the effects of climate change over time (climate refugia) and that provide high habitat heterogeneity to capture variability in micro-climatic conditions; (iii) protect a few large rather than many small areas; (iv) protect areas predicted to become important for biodiversity and with the most suitable environmental conditions as predicted by projected climate change; (v) complement permanently protected areas with temporary protection as a response to species' distributions and shifting habitat suitability.

In prioritising areas to protect, governments may consider the overlap between hotspots for carbon and areas with both high biodiversity and intactness. At the global scale in 2015, protected areas represented only 12% of the 38% overlap between carbon and biodiversity hotspots (Soto-Navarro et al., 2020^[151]). Prioritisation can also target specific ecosystems. For example, peatlands, which cover only 3% of global land but store around 600 gigatons of carbon in their soil, store more carbon than all world's forest biomass (Xu et al., 2018^[152]; Kopansky, 2022^[153]; Pan et al., 2024^[154]). Despite their importance, only 17% of peatlands worldwide were within protected areas in 2023 – significantly less than other high-value ecosystems such as mangroves (42%), saltmarshes (50%), and tropical forests (38%) (Spalding, 2021^[155]; UNEP-WCMC, 2025^[156]; WRI, 2024^[157]). Moreover, within protected peatlands, just over half benefited from strict protection (Austin et al., 2025^[158]). The assessment of protected areas' ecosystem services or the expected consequences of land use changes on species can help the mapping and prioritisation of other areas of importance to protect as well as areas to strictly protect (Watson et al., 2023^[159]; Chen et al., 2025^[160]).

Protected areas that are well-designed and managed more effectively retain cold-adapted species than unprotected sites (Gillingham et al., 2024^[161]). Protected areas designation can also have a positive effect on species' persistence at trailing-edge warm range margins, although with a decreased magnitude at higher latitudes and altitudes (Gillingham et al., 2015^[162]). Marine protected areas contribute significantly to ecosystem resilience. For example, coral reefs within Australia's Great Barrier Reef marine protected areas have demonstrated greater resilience to climate stressors, such as bleaching, diseases, outbreaks of *Acanthaster planci*, and storms (Mellin et al., 2016^[163]). Similarly, the Maria Island Marine Reserve in Australia showed enhanced resistance of fish communities to climate warming, with greater stability in species richness and diversity over both annual and decadal timescales (1992–2012). Benefits also included the recovery of large-bodied temperate species and resistance to colonisation by subtropical species (Bates et al., 2013^[164]). However, smaller and more isolated protected areas may be more vulnerable to climate change impacts. These areas are often more exposed to range-expanding species and may lack the capacity to support species persistence under shifting climatic conditions (Loarie et al., 2009^[165]; Gillingham et al., 2015^[162]).

A broad range of adaptation measures has been developed to enhance the persistence of species and ecosystem functions in the face of climate change. However, selecting appropriate measures requires a tailored and local approach that considers the specificities of each species, habitat, and ecosystem within a protected area. Managers must balance climate-targeted, interventionist approaches to enhance carbon storage with the preservation or restoration of natural and wild areas. This trade-off is particularly relevant when deciding between active management interventions and allowing ecosystems to adapt naturally, emphasising the need for careful, context-specific decision-making.

Environmental assessment as integrative tools

Environmental assessment instruments are vital to identify the main direct and indirect environmental impacts of economic activities inside or adjacent to protected areas. For example, in the United Kingdom, in 2013, the Marine Management Organisation determined that the proposed deepening of the channel to Falmouth Harbour would not guarantee the protection of the Fal and Helford Special Area of Conservation, which is home to a sensitive maerl bed. The conducted EIA identified potential impacts such as sediment quality degradation and water contamination from tributyltin and loss of maerl and benthic communities (Hoppit et al., 2022^[166]; Marine Management Organisation, 2010^[167]).

Strategic Environmental Assessments (SEAs) can be conducted at the ecosystem level going beyond the boundaries of a protected area. For example, Parks Canada, responsible for the management of national parks, national historic sites, and national marine conservation areas across the country, has developed a layered system of planning and impact assessment framework which involves assessing environmental changes, including those caused by climate change, human activities, invasive species, and habitat removal. It applies to specific species or habitats and considers a broader zone than a protected area, typically at the subnational scale (habitats and considers a broader zone than a protected area, typically at the subnational scale (Parks Canada, 2021^[168]). For instance, the assessment of cumulative effects of building and development projects was conducted on the major components of the Jasper National Park in Alberta: glaciers, wetlands, terrestrial birds, carnivores, and mountain goats. Strategic mitigations were conceived to protect each of these species or habitats: from the description of the current status to a vulnerability and risks assessment, and the outline of the corresponding strategic and project-level mitigation measures (Jasper National Park, 2022^[169]).

SEAs can also be conducted by focusing on a cross-cutting component such as water quality. In Australia, the Queensland government conducted a Strategic Environmental Assessment of the Great Barrier Reef coastal zone - spanning over 2 300 kilometres – and analysed direct, indirect, and cumulative impacts on Matters of National Environmental Significance (MNES) (State of Queensland, 2014^[170]). Dovetailing this, in 2015, the Australian and Queensland governments launched the Reef 2050 Long-Term Sustainability Plan, a collaborative framework to guide management of the Great Barrier Reef in the short, medium, and long term. Part of this plan, the Reef 2050 Water Quality Improvement Plan (2017-22) guides how industry, government and the community can co-ordinate and work together to improve the quality of water flowing to the Great Barrier Reef (Australian and Queensland governments, 2018^[171]). The plan sets targets for improving water quality and land management practices upstream, such as reducing loads of pesticides, sediments, and nutrients (OECD, 2019^[172]).

Complementary measures to environmental assessment

The implementation of additional regulatory measures such as *permitting procedures*, play a critical role in preventing or mitigating pollution that may threaten protected areas. In the European Union, permitting procedures under the Habitats Directive¹¹ are required for any new plan or project, including renewables, likely to have a significant impact on a Natura 2000 site.¹²

National programmes including *pollution reduction targets* can play a key role in the integration of protected areas policies. For instance, the Nitrogen Reduction and Nature Improvement Programme adopted in 2021 in the Netherlands aimed at reducing nitrogen deposition on at least 50% of the surface area of the nitrogen-sensitive nature areas within the Natura 2000 network to less than the critical deposition load by 2030.

Economic instruments, such as *Payments for ecosystem services* (PES) (see Box 6.3), can be leveraged to expand protected areas, enhance biodiversity conservation, and support climate change adaptation. PES can address the impacts of natural disasters and extreme events. For example, in France's National Park of Forests (Parc National de Forêts), some local farmers receive payments for flood risk reduction. In exchange, agricultural land is left uncultivated to function as prairie reservoirs, which are intentionally inundated during flooding events to mitigate downstream impacts. The valuation of ecosystem services and the final agreement of payment schemes are dependent on the natural and institutional characteristics of each site, and require building strong capacities among protected areas' administrators (Gaglioppa, 2016^[173]).

Box 6.3. Payments for Ecosystem Services

PES can be described as voluntary transactions between users and service providers that are conditional on agreed rules of natural resources management for generating offsite ecosystem services (Wunder, 2015^[174]). For example, Costa Rica has been a global leader in PES with its Payment for Environmental Services Program established in 1997. The programme pays landowners for reforestation, forest conservation, and agroforestry practices (OECD, 2023^[175]), which helps maintain biodiversity corridors and supports protected areas' connectivity. Between 1997 and 2021, the programme covered 1.3 million hectares, with over 560 000 hectares added between 2011 and 2021, 90% of which were under forest conservation contracts. For example, under the reforestation scheme, landowners agree to reforest abandoned cleared lands and maintain the trees for 15 years. The programme resulted in two-thirds of the new area to be located within biological corridor and 28% is in national wildlife refuges that include private land. Overall, between 1997 and 2021, the programme has paid more than USD 600 million to small and medium producers (OECD, 2023^[175]).

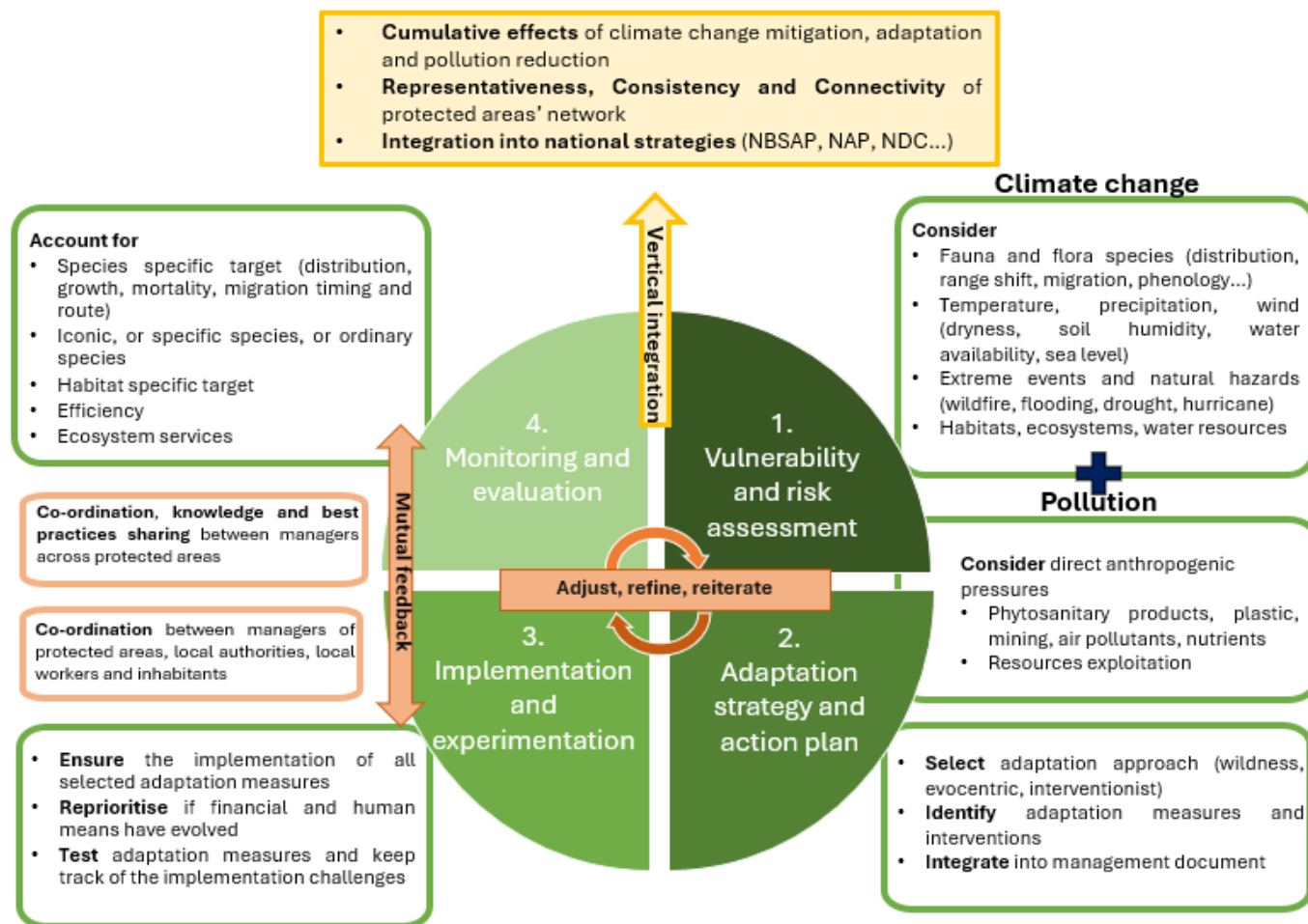
When habitat protection alone is insufficient, additional *classification policies* can be implemented to reduce threats affecting biodiversity, such as climate change or pollution. For instance, certain species may be granted priority status. Norway's 2009 Nature Diversity Act allows authorities to prohibit damage or extraction of such species, reinforcing conservation efforts.

Voluntary mechanisms can strengthen biodiversity conservation by reducing sources of pollution within protected areas. These approaches involve commitments between governmental authorities and private stakeholders or among private entities themselves (OECD, 2024^[176]). For example, in France's Cévennes national park, the 2013 Chart involved 40 localities that adopted stricter environmental commitments than required by law (Parc national des Cévennes, 2018^[177]). The "zero chemical pesticides" action consisted in conducting diagnoses of the common weeding practices, providing advice and training to local stakeholders and designing action plans to use alternative weeding means such as mechanical weeding, sowing ground cover plants, eco-grazing). At the national level, the use of phytosanitary products by public authorities for the maintenance of green spaces, forests and walks accessible to the public has been banned only after (in 2017). The national park management raised awareness of higher environmental value and engaged local inhabitants and stakeholders to reduce pollution. Voluntary protection schemes can also increase the robustness of protected areas, and reduce the threats induced by human activities.

Monitoring and evaluation of protected areas to ensure synergistic outcomes

The integration of climate change and pollution considerations into protected area planning involves several iterative steps (Figure 6.3): (i) a vulnerability and risk assessment to understand the effects of climate change and pollution on the protected area; (ii) the design of an action plan that includes targeted adaptation measures; (iii) the implementation and experimentation to operationalise the plan and test the measures; (iv) monitoring and evaluation to assess the outcomes and refining the adaptation plan based on observed results. These steps should be repeated periodically, after several years of implementation and monitoring, to adjust and update the adaptation strategy. The effects and effectiveness of adaptation measures, along with other desired or unintended outcomes, often take years or even decades to become fully apparent. Robust monitoring frameworks are essential to track these outcomes over time. Monitoring should involve the collection of data on key indicators, which must be systematically integrated at subnational and national levels. This vertical integration ensures the coherent tracking of individual protected areas and the overall network, enabling the identification of synergies, gaps, and areas for improvement. In France, the National Strategy for Protected Areas (2020–2030) explicitly emphasises the need for protected areas to incorporate climate change considerations into their management plans (Measure 7, Actions 9 and 10) (Ministère de la Transition écologique; Ministère de la mer, January 2021^[178]). The Natur'Adapt project (2018–2023), co-ordinated by *Réserves Naturelles de France*—the association responsible for France's nature reserves—has been a key initiative in translating this strategy into action and integrated climate change adaptation considerations in the French national strategy for protected areas. Methodological tools have been developed and experimented in pilot sites and now need to be scaled-up and applied across all protected areas at the national level, in accordance with the Third National Adaptation Plan to Climate Change.

Figure 6.3. Key aspects in the integration of climate change and pollution in protected areas management



Source: Authors' own elaboration based on Gross et al. (2017^[149]) and Coudurier, Petit and Tissot (2023^[179]).

6.3.3. Tools and indicators to assess environmental effectiveness of protected areas

Assessing the effectiveness of protected areas at project, national, and global levels presents numerous challenges, and is essential to enhance synergies with climate change mitigation, adaptation and pollution reduction policies. These challenges include the site-specific design and management of protected areas, the connectivity and ecological representativeness of the protected area network, and the appropriateness of the management processes employed (UNEP-WCMC and IUCN, 2024^[180]; Rodrigues and Cazalis, 2020^[181]).

Protected areas' effective management as well as representativeness, consistency, and connectivity need to be taken into account to tackle the triple planetary crisis efficiently. There is currently no systematic and mandatory standardised assessment methodology to evaluate the effectiveness of protected areas, but several tools exist, at the project level, subnational, national and at a larger scale. Impact evaluation studies remain relatively scarce, and hint toward more studies to be conducted. Existing tools and indicators have the potential to enhance synergies between climate change mitigation, adaptation and pollution reduction by providing regular and comparable data and indicators across protected areas, accounting for their ecosystem services and monitoring their evolution.

An important advancement of the KMGBF compared to the Strategic Plan for Biodiversity 2011–2020 is the inclusion of a robust monitoring framework to track and assess the effectiveness of biodiversity conservation efforts, including the progress on protected areas and other effective area-based conservation measures.¹³ The framework includes indicators on protected areas' extent, fragmentation, intactness, species richness, management effectiveness and their connectivity. The monitoring framework aims at evaluating the contributions of biodiversity conservation to multiple global challenges, among which climate change and pollution.

At the supranational level, the eight member countries¹⁴ of the Amazon Cooperation Treaty Organization implemented a guiding framework for the development and implementation of strategic actions for regional co-operation on biodiversity in the Amazon Region. The Regional Program on Biological Diversity for the Amazon Basin/Region was launched in 2021 to achieve the objectives of the Convention on Biological Diversity (CBD). In 2023, the Amazon Cooperation Treaty Organization assessed that nearly 23% of the Amazonian basin was protected (OTCA, ANA, ABC, COBRAPE, 2023^[182]).

The effectiveness of protected areas at the site level lacks a systematic and mandatory standardised assessment methodology, although many assessments are based on the IUCN World Commission on Protected Areas (WCPA) framework for Protected Areas Management Effectiveness (PAME) (see Box 6.4). Among these tools, the Management Effectiveness Tracking Tool (METT), a questionnaire-based approach, is the most widely used globally (UNEP-WCMC, 2017^[183]). The latest version of METT the tool laid greater emphasis on threat assessment, including severity and management responses (Stolton, 2016^[184]). Assessments of protected areas are compiled in the Global Database on Protected Area Management Effectiveness, which includes records from 177 countries using 75 different methodologies. While this diversity reflects varied management contexts, it also complicates the vertical integration of data and highlights the need for harmonisation at the international level. However, the coverage of effectiveness assessments remains limited. Only 6.8% of protected areas listed in the World Database on Protected Areas have been assessed. These assessments encompass 28 969 evaluations for 20 603 protected areas, covering 4.8% of the world's terrestrial protected areas, and 1.3% of the world's marine protected areas (UNEP-WCMC and IUCN, 2024^[180]). Therefore, more effort is needed to conduct assessment and to report at a supranational or global scale.

Each protected area has its specific species, habitats, and ecosystems to protect, and the effectiveness of conservation can be assessed through observation, tracking and recording biodiversity indicators. The dynamics of so-called keystone species and threatened species (i.e. those belonging to the IUCN Red List of Threatened Species) can be tracked, but also more ordinary species. For example, in France, the charter of national parks spans 15 years and includes a monitoring and evaluation framework. These charters are assessed midway and at the end of their duration to ensure alignment with conservation objectives and to adapt management plans as needed. At the national level, the LIFE Biodiv'France project (2024-2032) supports skills development among managers of protected areas, such as management planning and management effectiveness evaluation (OFB, 2024^[185]). This structured approach illustrates how to integrate assessment into long-term protected area governance while addressing local and national conservation priorities.

Box 6.4. Protected areas' environmental effectiveness assessment tools

Existing tools to assess protected areas at the site level

The IUCN WCPA framework for Protected Areas Management Effectiveness (PAME) covers three main topics: (i) design matters referring to the individual sites and the protected areas networks, (ii) capability and suitability of management strategies, and (iii) achievement of protected areas objectives and biodiversity conservation values (Hockings, 2006^[186]), (Pulido-Chadid, Virtanen and Geldmann, 2023^[187]). A Management Effectiveness Tracking Tool (METT) has been developed to operationalise the PAME framework. Initially created by the World Bank/WWF Alliance for Forest Conservation and Sustainable Use in 2002, this open-source tool has been modified and extended by users to fit specific site and ecosystem contexts. The most recent version, METT-4 (2024), has been published by Protected Planet, the authoritative source of data on protected areas and effective area-based conservation measures.

Protected areas' impacts on climate change and pollution can be assessed using ecosystem services assessments, though no standardised implementation exists. The IUCN proposes a participatory method where managers, stakeholders, and local communities engage in consensus-building workshops. These workshops assess the benefits provided by a protected area and classify the types of benefits (Ivanic et al., 2020^[188]).

Existing Tools to report Protected Areas ecosystem services at the national level

Reporting on ecosystem services provided by protected areas can be achieved through Natural Capital Accounting. This method measures changes in the stock and condition of natural capital (ecosystems) across various scales. It integrates the flow and value of ecosystem services into standardised accounting and reporting systems. Natural capital accounting can comply with the international standards of the System of Environmental-Economic Accounts Ecosystem Accounting (SEEA EA).

The SEEA EA is an internationally agreed-upon statistical framework developed under the United Nations Statistical Commission. It provides a consistent methodology for measuring ecosystems and the services they supply, aligned with the System of National Accounts (United Nations et al., 2021^[189]). The SEEA EA offers information on ecosystem extent, condition, species ecosystem services and associated economic activities from different data sources and of different data types to be unified through the same framework. This allows trends in ecosystem assets and species, trends in ecosystem services and benefits and land or sea use activities to be compared with one another. This provides crucial information for decision-makers who need planning sustainable development and protected areas management (King, 2022^[190]).

Existing tools can be more systematically relied on to improve the integration of the triple planetary crisis in protected areas policies. First, the *METT* explicitly includes questions related to climate change, pollution and ecosystem services. The *METT-4* tool asks through a multiple-choice question whether the protected area is consciously managed to adapt to climate change and whether the protected area is consciously managed to prevent carbon loss and to encourage further carbon capture. It also specifies pollution threats to the protected area to be recorded such as industrial, mining and military effluents and discharges, agricultural and forestry effluents air-borne pollutants. Moreover, a specific question is dedicated to qualitatively assess whether land and sea use planning outside of the protected area recognise the protected area and contribute to the achievement of its management objectives. Finally, the *METT* tools also covers whether the management of the protected area considers ecosystem service provision. This investigates both whether existing or potential ecosystems services are even known about and, if so, whether some or all of them are being managed.

Second, conducting ecosystem services assessments and reporting results across vertical (local to national) and horizontal (across – networks of – protected areas) levels is essential to integrate the synergies of protected areas. These assessments require strengthened monitoring and reporting capacities at project, network, and national levels. Key synergies of protected areas include regulating services such as climate mitigation with carbon absorption, sequestration or avoided carbon release, climate adaptation that is strengthening resilience and adaptive capacity to climate-related hazards and natural disasters and pollution reduction with the provision of clean freshwater and the purification and pollutants removal of water. The EU LIFE Programme mandates the use of the Mapping and Assessing Ecosystems and their Services framework, based on the Common International Classification of Ecosystem Services, to ensure comparability and facilitate reporting through the LIFE KPI Webtool (European Climate, Infrastructure and Environment Executive Agency, 2021^[191]).

Third, *Natural Capital Accounting* can improve the integration and mainstreaming of protected areas at higher levels, while achieving several major goals: (i) help illustrate and make more visible the manifold benefits provided by protected areas provide; (ii) contribute to promoting their establishment and maintenance (United Nations Department of Economic and Social Affairs, 2020^[192]); (iii) boost the return on investment in protected areas to meet government objectives for the environment, economic growth and social wellbeing (Varcoe, 2015^[193]); (iv) support the decision-making process related to protected areas.

Fourth, the adoption of the *SEEA EA* can facilitate the mainstreaming of protected areas into economic planning and monitoring processes. This framework ensures consistency and can be integrated directly with national accounting workflows. Adopting *SEEA EA* also translates into providing a coherent set of statistics on the environment-economy nexus that can easily be integrated into policy analysis. Although, not widely implemented yet for protected areas (King et al., 2023^[194]), *SEEA EA* has the potential to provide regular and consistent information on the state, evolution and benefits from protected areas such as ecosystem services, climate change mitigation, climate change adaptation, pollution reduction and contributions to economic activity and human well-being.

6.4. Integrating climate change and biodiversity in air pollution control policies

Air pollution has significant effects on human health, with impacts of outdoor air pollution (OECD, 2016^[195]) and ozone-related mortality rates (see Chapter 3) projected to increase significantly. These health impacts are by themselves part of the interlinkages between the different pillars of the triple planetary crisis. Other direct links are the effects of air pollutant emissions on radiative forcing – and thus climate change – and the pollutant filtering services provided by ecosystems – which are threatened by biodiversity loss. Air pollution policies can affect these linkages but also interact more indirectly with policy objectives for climate mitigation and biodiversity conservation in other ways.

6.4.1. Synergies and trade-offs of air pollution control for biodiversity conservation and climate change mitigation

Synergies and trade-offs between air pollution control and climate change mitigation

Many air pollutants and GHGs share common sources, not least energy production and use (Climate Watch, 2022^[196]). As outlined in Chapters 1 and 3 with regards to air pollutants, ozone (O₃) is not emitted directly, but results from reactions of heat and solar radiation with precursor gases (NO_x and VOCs including CH₄). Air quality is therefore affected by emissions of several pollutants and a by-product of the combustion of fossil fuels and biofuel, agriculture, manufacturing and extracting industries, energy production and use, forest fires and other processes that also generate GHGs (Bhattu et al., 2024^[197]; Adams et al., 2015^[198]; Mukherjee and Agrawal, 2017^[199]). Analysis using the modelling toolbox developed for this Outlook suggests that population exposure to global PM_{2.5}, which include BC, organic carbon and other particles with a diameter lower than 2.5 µm, are expected to decrease from around 23 µg/m³ in 2020 to around 19 µg/m³ in 2050. Equivalent regional estimations are discussed in more depth in Chapter 3.

Many air pollutants do not have a direct effect on climate but there are several important interactions (Lanzi and Dellink, 2019^[200]), most of which are synergies where reductions in air pollutions benefit climate mitigation:

- N₂O is a GHG and its contribution to overall GHG emissions has been estimated at 2.6 Gt of CO₂, which is about 4.5% of all GHG emissions (Gao and Cabrera Serrenho, 2023^[201]).
- Fluorinated gases (F gases) are also GHGs; they were introduced as a substitute for atmospheric ozone-depleting substances called chlorofluorocarbons (CFCs). Their share of all GHGs in CO₂ equivalent (CO₂e) is about 2% (IPCC, 2023^[202]). They grew significantly when first introduced to replace CFCs. Emissions of F gases are now declining in high-income countries but not in all emerging and developing economies.
- BC aerosols¹⁵, CH₄, O₃ and hydrofluorocarbons (HFCs) are also short-lived climate pollutants (SLCPs) that simultaneously contribute to climate change and compromise air quality. BC accelerates the melting of snow and ice and prevents clouds from forming. Estimating emissions of BC is subject to considerable uncertainties for example as BC emitted per fuel consumed by a given activity varies greatly under different condition of combustion and across countries, especially between developing and developed countries (Wang et al., 2014^[203]). Wang et al (2014^[203]) estimate a global increase of around 72% from 1960 to 2007 (Wang et al., 2014^[203]), less than the increase in all GHGs over the same period (see also Chapter 3). Reductions in SLCPs undertaken to reduce environmental and health effects will also contribute to mitigating climate change.
- Several aerosols have a cooling effect on climate. Sulphate (SO₄²⁻) aerosols (a by-product of SO₂-emitting fossil fuel combustion as well as industrial processes) act to reduce the warming effect of GHG emissions by scattering sunlight and reflecting part of the sunlight away from Earth. Although about two-thirds of such emissions come from developing countries their impact on temperature is about the same as the lower share from developed countries, on account of the latter emissions being located at higher northern latitudes and being more evenly distributed zonally (Lin et al., 2022^[204]). Nitrate aerosols (e.g. NH₄NO₃), formed from NH₃ and NO_x emitted from fossil fuel combustion, biomass burning, and agriculture, similarly also contribute to cooling, although this is more limited than for SO₄²⁻ aerosols (IPCC, 2021^[205]). OC aerosols also have a cooling effect, although less than SO₄²⁻ aerosols and NH₄NO₃ (IPCC, 2021^[205]). Overall, between 1750 to 2019, aerosols' cooling effect is estimated to around -0.5 °C – although there is uncertainty about the magnitude, with a range of -0.2 °C to -0.9°C (IPCC, 2023^[206]).

Given the trade-off between sulphur emissions reductions and climate mitigation efforts, the use of sulphur aerosols in the higher atmosphere as part of solar radiation management, called stratospheric aerosol injection, is a possible measure to limit warming. Stratospheric aerosol injection is a geoengineering method that refers to injecting different types of aerosols, typically SO_4^{2-} , into the stratosphere to reflect sunlight, which should cause rapid global cooling. However, this method is controversial as the possible effects of large-scale deployment are not fully known yet. Some research suggests that it might cause, among others, changes in regional precipitation, acid rain, stratospheric warming and increases in stratospheric water vapour (UNEP, 2023^[207]; CBD, 2016^[208]). Sudden and sustained termination of stratospheric aerosol injection would also produce rapid temperature increases, known as termination shock (UNEP, 2023^[207]; CBD, 2016^[208]).

Synergies and trade-offs between air pollution control and biodiversity conservation

Air pollutants are associated with various adverse environmental impacts by acting as direct physiological stressors to plant species. For instance, the impact of O_3 on plant physiology and interactions with pollinators is well-documented. High concentration of O_3 can compromise plant growth, damages agricultural crops and forests, as well as intervene with the scents of flowering plants, altering the foraging behaviours of pollinators (Rollin et al., 2022^[209]). Global relative yield losses are estimated to range between 7% and 12% for wheat, between 6% and 16% for soybean, between 3% and 4% for rice, and between 3% and 5% for maize (Van Dingenen et al., 2009^[210]). Global losses from O_3 on agriculture are estimated at USD 34 billion in 2010 and under business as usual are expected to be USD 36 billion in 2030 and USD 45 billion in 2050, with the People's Republic of China (hereafter 'China') facing 23% of global damages and India 12% in the base year (Sampedro et al., 2020^[211]).

Deposition of air pollutants, and especially SO_x and NO_x , through rainfall (commonly known as acid rain) can lead to acidification of soils and water bodies. The deposition of air pollutants can be in a different place from where the emission took place, as the pollutants are carried by wind over significant distances. The pollutants in the air react with water, oxygen and other chemicals to form sulfuric and nitric acids which fall to the ground, increasing the acidity of the soil and negatively affecting ecosystems, forests in particular.

Nitrogen deposition on land and in water bodies is mainly caused by the air pollutant NH_3 from agricultural activities (see Annex 6.D) and NO_x air pollutants from combustion processes. Excessive amounts of nitrogen introduced to an ecosystem lead to several negative impacts (United Nations Environment Programme/Food and Agriculture Organization of the United Nations, 2024^[212]). In water bodies, it contributes to eutrophication, characterised by algal blooms and less available oxygen. In sensitive terrestrial ecosystems such as grasslands, if critical loads for nitrogen deposition are exceeded, sensitive species can be lost. In tandem, species that benefit from high nitrogen levels can flourish, which can change the structure and functioning of an ecosystem.

Although the impact of air pollution on animal species is less well-researched than on plant species, studies find a range of potential negative impacts. Air pollution can have lethal and sub-lethal effects on species through affecting respiratory organs (Sanderfoot and Holloway, 2017^[213]). It can also negatively affect reproductive capacity (Carré et al., 2017^[214]). These physical impacts on different species can cascade through the trophic chain, resulting in reduced abundance and altered community composition, threatening biodiversity and the critical ecosystem services it sustains.

Conversely, reducing air pollution through dedicated policies such as the assisted natural regeneration of forests (World Resources Institute, 2022^[215]) can contribute towards biodiversity conservation and restoration. However, as outlined in the earlier sections, there are some potential trade-offs with biodiversity conservation when e.g. renewable energy policies are used as an instrument to reduce air pollution. Regulating air pollutant emissions, for example through mandated use of filters, does not have such trade-off effects.

Air pollution intensifies during wildfire events, resulting in the release of PM_{2.5}, nitrogen dioxide (NO₂), O₃, and the heavy metal lead. Implementing wildfire prevention measures can mitigate the risk of air contamination by these harmful pollutants. However, fuel-reduction treatments to create tree discontinuities may adversely affect local biodiversity by removing shrubs, trees, and species reliant on deadwood¹⁶ (Campbell and Ager, 2013^[142]).¹⁷

6.4.2. Tools for synergistic air pollution control policies

Countries can conduct cost-benefit analysis of mitigation pathways for air pollutants to identify opportunities for synergistic policy. Including both data and input from authorities responsible for climate and biodiversity mitigation in cost-benefit analysis is key in identifying potential synergies. For example, in 2013, Mexico's National Institute of Ecology and Climate Change conducted a cost-benefit analysis that integrated emission data from Mexico's Special Programme on Climate Change and particulate data from the Climate and Clean Air Coalition to identify BC as a key priority for mitigation efforts (Molina Center for Strategic Studies in Energy and the Environment, 2013^[216]). As a result, Mexico included BC for the first time in its 2015 Intended Nationally Determined Contribution under the Paris Agreement (Climate and Clean Air Coalition, 2019^[217]). Building on this momentum, Mexico launched its 2019 Integrated SLCP Strategy to Improve Air Quality and Reduce the Impact of Climate Change, which will reduce BC emissions by around 53% by 2030 if nine identified mitigation measures in eight key BC source sectors are fully implemented (Climate and Clean Air Coalition, 2019^[217]), exceeding Mexico's NDC target.

Air quality Habitat Regulations Assessment (HRA) can help evaluate the impact of air pollutants on conservation areas and promote synergistic outcomes. For example, an HRA conducted on a proposed development plan in Greater Manchester, England, concluded that the development plan would generate air pollutants likely to negatively affect nearby conservation areas (Ricardo Energy and Environment, 2021^[218]). In response, the developers submitted a revised plan 2023 that included mitigation measures such as a green belt, a boundary between the development and protected areas consisting primarily of hedgerows (Greater Manchester Combined Authority, 2023^[219]). A subsequent HRA determined that the updated plan would exert no adverse air quality effects on the nearby conservation areas (The Green Manchester Ecology Unit, 2023^[220]).

Countries can additionally conduct source apportionment¹⁸ studies for air pollutants to support the development of synergistic air quality management plans. In 2024, for example, Bangladesh's Department of Energy and Ministry of Environment, Forest and Climate Change conducted a source appointment study using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model to identify sources of emissions contributing to both air pollution and GHG emissions (Bangladesh Ministry of Environment, Forest and Climate Change, 2024^[221]). Bangladesh synthesised these findings into their National Air Quality Plan 2024-2030, which outlines specific actions and responsible agencies for reducing air pollutants with GHG potential. One highlighted measure involves the increase of the environmental protection tax for highly polluting companies that fail to comply with emissions standards (Bangladesh Ministry of Environment, Forest and Climate Change, 2024^[221]) – see also Annex 6.C for further information on pollution taxes.

To enhance the cross-border integration of synergies and trade-offs between air quality, climate change, and biodiversity, systematically using comprehensive environmental assessments and cost-effectiveness analysis is essential. For instance, adopting Natural Capital Accounting (NCA) would be highly beneficial. NCA aims to assess natural capital values, including e.g. the value of clean air by capturing the costs associated with air pollution, including healthcare expenses, productivity losses, and the degradation of ecosystems and the environment. Implementing annual NCA would systematically incorporate air quality into standardised accounting and reporting frameworks. Since 2019, for example, the United Kingdom's Natural Capital team has published annual NCA reports that assess the economic value of various ecosystem services, including the regulation of air pollution, GHG, noise and urban heat. According to the

2024 NCA, the estimated annual stock value of the air pollution regulation service alone is GBP 133 billion (Natural Capital team, 2024^[222]). Furthermore, NCA can facilitate international co-operation at the airshed level by enabling the exchange of comparable information, in alignment with the international standards set by the SEEA EA. The examples also show that vertical integration can help facilitate the effective implementation of different policies for air pollution.

Policies can promote horizontal and vertical integration to effectively manage air pollutants, with key tools outlined below. In many cases, improvements in air quality in an urban area require reductions in emissions outside that area. Research increasingly suggests the benefits of implementation of measures at the airshed level (Khan et al., 2024^[223]; World Bank, 2025^[224]; World Bank, 2023^[225]), which requires adequate demarcation of the airshed area¹⁹ that can span different geographical scales (local, regional, national, international). Considering airsheds can help identify measures that are more cost effective than if considering only a narrow area within city lines, both by encouraging horizontal integration through sector-specific interventions in high-polluting sectors and through vertical integration by leveraging regional co-operation in joint air pollution strategies (World Bank, 2023^[225]). In many cases, airsheds cross national boundaries, which in turn requires some form of international co-ordination and sharing of the burdens of reducing emissions in an acceptable way.²⁰

Common tools of international co-ordination efforts include: (i) an overarching regulatory framework that sets emissions and air quality targets for participating jurisdictions, (ii) a well-funded central institution that ensures accountability and transparency, (iii) decentralised planning of abatement policies within the parameters set centrally, and (iv) economic incentives to reduce emissions, for example, through taxes and subsidies or by making access to funds conditional on abatement performance (World Bank, 2023^[225]). An example regulatory framework for promoting vertical and horizontal integration is outlined in Box 6.5, for the case of the National Air Pollution Control Programme in the European Union.

Box 6.5. A common framework plan for promoting vertical and horizontal integration: An example of the National Air Pollution Control Programme in the European Union

There is no global framework for addressing air pollution, although there are key instruments, notably the regional Convention on Long-Range Transboundary Air pollution (1979). Their subsequent amendments have progressively imposed stricter and expansive requirements (e.g. BC and PM_{2.5} under the Gothenburg Protocol). In the EU, the National Air Pollution Control Programme provides the common format for discussing national plans for air pollution control, which contains an explicit reference to climate change. The reporting template ensures that “relevant climate change energy policy priorities” for key sectors including industry, transport and agriculture are considered in developing policies to control air pollution. The template also makes explicit references to the need for vertical integration (from international to local levels) for managing air pollution.

For instance, the Air Pollution Control Programme 2023-2030 in Spain highlights the importance of coherence and co-ordination between policies to tackle air pollution through 61 individual measures (across 12 packages) with other environmental policies such as climate change and energy transition plan, setting out the structure for informing local implementation on a range of sectors (e.g. transport policy of establishing low-emission zones in municipalities with over 50 000 inhabitants) through national-level planning. Reduction of burning pruning waste is also discussed in relation to synergies for alleviating the adverse impacts on soil biodiversity and improving soil carbon content as well as crop resilience against climate change.

In France, alignment to national objectives such as the national low carbon strategy and the national plan for reducing emissions of air pollutants including SO₂, NO_x, NMVOCs, NH₃, and PM_{2.5} (MoET, 2022^[226]) are ensured at the regional, local and municipal levels. At the local level, Climate Air Energy

Territorial Plan helps operationalise policy measures to propel energy transition in sub-regional territories (MoET France, 2023^[227]). Public inter-municipal co-operation bodies with over 20 000 inhabitants must establish a Climate Air Energy Territorial Plan, while smaller bodies may do so on a voluntary basis. As with the regional planning tools, these plans entail actions towards multiple objectives including air pollution control and climate mitigation. As of December 2023, 60% of the 750 bodies with over 20 000 inhabitants had adopted their Climate Air Energy Territorial Plan, and 97% had at least initiated the process (ADEME, 2024^[228]). These regional and territorial plans also need to be aligned with Atmosphere Protection Plans at the local level. These plans are established under the authority of Prefects within urban areas of more than 250 000 inhabitants, and in areas where regulatory limits are exceeded or at risk of being exceeded. The plans set the objectives and measures to bring pollutant concentration below the regulatory thresholds. Together, these regional, local and municipal plans form the foundation for France's approach to integrating climate, energy, and air quality targets. The vertical integration with national, regional and local frameworks ensures the implementation of strategic objectives while accommodating local specificities.

6.4.3. Integrating synergies of different types of air pollution policies with climate change mitigation

The synergies between air pollution and climate change identified in Section 6.4.1 act through a range of policies, including caps on emissions, taxes and sectoral control policies.

Caps on emissions of air pollutants

Caps on emissions of air pollutants can facilitate climate change mitigation when the effects of the pollutants that contribute to radiative forcing dominate. For example, Prinn et al. (2007^[229]) considered the effects of caps set at 2005 levels on common air pollutants such as carbon monoxide, NO_x and VOCs, and on CH₄ – which is both an air pollutant and a major GHG – and SO₄²⁻ aerosols. First, as these air pollutants contribute to O₃ creation, the caps can lower O₃ concentrations causing less warming; second, they lower hydroxyl free radicals (OH·) that are considered the “detergents of the atmosphere” because they react with pollutants such as CH₄ – hence a reduction of OH· increases warming; third, as OH· are essential for converting SO₂ into SO₄²⁻ aerosols, they also lower SO₄²⁻ aerosols yielding more warming; and fourth, through O₃ reduction caps allow more carbon uptake by ecosystems as O₃ is toxic to plants (Franz and Zaehle, 2021^[230]), leading to less warming. Overall, these effects roughly offset each other suggesting that an across-the-board air pollution strategy would have a relatively small net effect on the global mean surface temperature and sea level rise. The analysis does not, however, take account of overall demand for fossil fuels and on the choice of fuel, nor any caps on BC or organic carbon aerosols on climate. These effects, if included, could lead to more substantial synergies between capping air pollutant emissions and climate change mitigation.

In general, countries do not set caps on air pollution emissions uniformly. For example, Germany transposed the EU Medium Combustion Plant Directive into national law through default NO_x caps for medium-sized combustion plants (Bundesamt für Justiz, 2019^[231]). Parallely, it includes provisions for its Länder (states) to apply stricter or accelerated limits regionally. The limits are determined to a significant extent by their effects on concentrations of pollutants, which in turn has impacts on human health and ecosystems. States like Baden-Württemberg or Bavaria enforce stricter NO_x limits precisely because their air quality monitoring shows excessive NO₂ concentrations, exceeding EU limits. As the net climate effect of NO_x emissions is generally considered to be warming, particularly through its role in increasing methane levels, such policies tend to reduce warming.

Ideally, any emission caps would take account of the benefits of the reductions in terms of their impacts relative to the costs and policies would be then selected to ensure the most cost-effective sources of emissions reductions were undertaken. The costs of reductions by source should take account not only of the direct costs but also any co-benefits, such as reductions in GHGs. In practice, standards are partly set based on benefits and costs using monetary estimates of these items but co-benefits such as lower GHG emissions are rarely accounted for. Consequently, the climate and other co-benefits of air pollution controls vary considerably. This can be seen by looking at policies to reduce PM. Here the co-benefits for climate can be quite large but vary by source of PM reduction. The World Bank led a study in South Asia that looked at measures at an airshed level across the sub-continent (World Bank, 2023^[225]). Implementing key measures in South Asia to bring PM_{2.5} down to WHO interim target 1 (35 µg/m³) and WHO interim target 4 (10 µg/m³) by 2030 would reduce CO₂ by 22 and 41 percent, BC by 81 and 89 percent, and CH₄ by 21 and 28 percent, respectively. In the case of CO₂, the largest contributions to CO₂ reduction come from measures on power and heating plants and agriculture. In the case of BC, the biggest ones are from residential combustion and waste and in the case of CH₄ they are from agriculture and waste (World Bank, 2023^[225]).

A key aspect of setting limits on local pollutants is to integrate the implications for climate change as well. The issue has been discussed in the literature on co-benefits as well as on that of trade-offs. In the case of co-benefits, the focus has been on seeing air pollution reduction as a co-benefit of climate policy rather than the other way round. For the latter the most important trade-off is with respect to sulphate and other aerosol emissions, the reduction of which contributes to global warming. Reductions in aerosol emissions have been significant, not only in OECD countries but also in China, where they have declined 90% over the last two decades (The Economist, 2024^[232]). In all, these are believed to have contributed to the observed global warming in recent years.

Air pollution tax policies

An analysis of the effects of air pollution tax policies on climate is included in a few selected studies. An example is (The Ex'tax Project, 2022^[233]), which used the E3ME macroeconomic model to investigate the impacts of a range of hypothetical EU-wide taxes including those on all forms of transport, a price on carbon and taxes on air pollution (NO_x, SO₂, PM_{2.5} and NH₃). Tax rates were based on the external costs although not implemented at the full external cost of each activity or pollutant.²¹ While the set of policies do reduce CO₂ emissions (by a little more than 7%) – as well as positive employment and GDP effects – it is not possible to separate out the effects of air pollution charges from those of carbon prices.

While studies such as these show considerable benefits from environmental taxes, implementing them at the proposed rates faces considerable opposition at the local levels as well as difficulties in reaching agreement at the regional level (Levi, 2021^[234]; Kallbekken and Sælen, 2011^[235]).

Controls on emissions from transport

A number of large cities around the world have a congestion or vehicle user charge to drive in city centres that have significant environmental impacts (Chamberlain et al., 2023^[236]). These can take form of area-based charges (e.g. London) and facility-based charges (e.g. tolled roads in Melbourne) (Veitch and Rhodes, 2024^[237]). The rate of the charge can vary by the type of vehicle, with more polluting vehicles paying a higher charge and less polluting ones paying a lower charge or none at all. Significant reductions in air pollutants as well as carbon emissions were found in Milan (CO₂ -35% and PM₁₀ -18%), London (CO₂ and PM₁₀ -12%) and Stockholm (PM₁₀ -18%) (EPOMM, 2015^[238]).

Alternatively, some controls are set for Low Emissions Zones (LEZs), where polluting vehicles are either banned or only allowed to enter on payment of a higher charge. Several cities around the world have such controls. (Beedham, 2022^[239]) evaluate the effectiveness of LEZs by using Tomtom's traffic data. It estimates effectiveness of LEZs in Paris, Berlin and London for reducing CO₂ (0.3-0.4% reduction), NO_x (7-8% reduction) and PM (27-35% reduction). They emphasise that 'most low emission zones focus on pollutants (NO_x and PM), which heavily penalises diesel vehicles, and commercial vehicles such as trucks and vans in particular'. A fully integrative policy would weigh both the air pollutant and GHG emission characteristics of vehicles.

In all the studies reviewed there was no comparison of the effectiveness of direct regulations versus using charges as a means of managing LEZs. Given the limited evidence on this topic, further research is needed to evaluate the different instruments. Instruments that provide an incentive to drivers to switch to cleaner vehicles (potentially accompanied with a subsidy to phase out polluting vehicles) can generate stronger synergies with climate change mitigation. There are also some examples of policy approaches that integrate climate objectives in addressing air pollution from road transport (see Box 6.6).

Box 6.6. Greening highways to tackle air pollution and climate change in India

Road transport is one of the largest contributors to air pollution in India, accounting for 27% of the country's total outdoor air pollution (IEA, 2023^[240]) and is responsible for 13% of the country's CO₂ emissions (IEA, 2021^[241]). Launched in 2015, the Green Highways Policy in India set out a comprehensive framework for planting, transplanting and maintaining trees alongside and between highways to alleviate pollution. The main objective is to reduce air pollution and dust while addressing vegetation loss due to the development of highways by planting trees and shrubs. Acting as natural sinks for air pollutants, trees also help mitigate noise pollution and prevent soil erosion along embankment slopes (MoRTH, 2015^[242]). Plantations alongside and between highways, as well as compensatory afforestation, are also carried out to offset carbon emissions resulting from tree felling and forest clearance during highway construction (CSIR-CRRI/CSIR-IIP/IORA/TERI, 2023^[243]). The compensatory afforestation mechanism implemented by the Indian Ministry of Environment and Forests (MoEF) mandates planting a minimum of 50 plants or 10 times the number of trees felled for the construction of a highway, whichever is greater (MoEF, 2019^[244]).

Over almost a decade, 46.5 million saplings have been planted along national highways under the Green Highways Policy (MoRTH, 2024^[245]). These plantations and compensatory afforestation are estimated to sequester approximately 584 000 t of CO₂ over a period of 20 years, while forest clearance and tree felling have emitted 653 000 tonnes. Furthermore, by allowing smoother traffic flow and more efficient fuel use, the improved highways are projected to avoid 25 Mt of CO₂ emissions over the same period (CSIR-CRRI/CSIR-IIP/IORA/TERI, 2023^[243]).

Controls on emissions from domestic heating

The burning of solid fuels, and especially coal, for heating is a major source of air pollution in temperate climates. In Europe more than half of the particulate emissions come from the burning of solid fuels for heating (European Parliament, 2023^[246]). Globally, data for contributions of all household air pollution (including cooking and heating) to particulate emissions is estimated at around 20% but with a high level of uncertainty (Chowdhury et al., 2023^[247]). Encouraging fuel switching (away from coal and other solid fuels) and use of more efficient heating technologies (such as certified fireplaces or pellet stoves) can reduce the emissions from residential wood and coal heating devices. Filters and a switch to electric cooking stoves may further reduce health effects from indoor air pollution. Educational campaigns may also be useful tools to reduce emissions from residential solid fuel heaters (WHO, 2015^[248]).

These interventions have demonstrable health benefits and also reduce GHGs such as CO₂, although the amount of such reduction varies across the measures taken. A study in Ireland found that banning the marketing, sale and distribution of coal (specifically bituminous coal) improved air quality, carbon emissions and health, and reduced deaths from respiratory and cardiovascular causes (Clancy et al., 2002^[249]). Connecting households using stoves to district heating systems that operate on clean fuels is also a very effective way of reducing air pollution as well as GHGs, as Werner (2017^[250]) shows for Sweden.

Emissions controls from domestic heating can simultaneously contribute to GHG emissions reduction. The “Clean Air Programme” in Poland, for example, provides subsidies for replacing inefficient heating boilers and facilitating modernisation of buildings. With its dual environmental objectives to reduce PM emissions and GHG emissions, it has been progressively strengthened since its launch in 2018. For instance, the Programme has withdrawn co-financing support for coal-fired boilers in 2022 to improve consistency of the Programme with climate objectives.

The promotion of efficient stoves using pellets from processed biomass is seen as an effective way of reducing both air pollution and CO₂ emissions. The European Commission proposals for updating the 2014 directive on air pollution control of domestic stoves imply that implementing eco-design standards involving such stoves, combined with energy labelling, are expected to reduce CO₂, along with a fall in PM emissions, organic gaseous compound emissions and CO emissions. To achieve the adoption of these more efficient stoves countries are using a number of instruments, including partial grants for the new equipment, lower rates of value added tax, restrictions on the use of old stoves in some locations on particularly high pollution days and even a mandatory replacement of appliances (WHO, 2015^[248]).

These measures can have considerable co-benefits for climate as examples given above indicate. Further evidence for this is provided by a World Bank study which found that replacing current wood stoves and residential boilers used for heating with pellet stoves and boilers and replacing chunk coal fuel with coal briquettes (mostly in eastern Europe and China) could provide significant climate benefits. It would also save about 230 000 lives annually across the world, with the majority of these health benefits occurring in OECD member states (Parson et al., 2013^[251]).

Furthermore, action in this area is of particular importance to climate change in the Arctic (OECD, 2021^[252]). This is because widespread dissemination of pellet stoves and coal briquettes have a disproportional benefit to mitigating warming from BC deposition in the Arctic (UNEP and WMO, 2011^[253]). The World Bank found that replacement of wood logs with pellets in European stoves could lead to a 15% less warming in the Arctic (about 0.1 °C). For Arctic nations the modelling strongly indicates that the most effective BC reduction measures would target regional heating stoves for both climate and health benefits (Parson et al., 2013^[251]).

The difficulties that governments have found in implementing programmes on wood stoves are significant. They arise in part from the costs involved to replace old equipment where subsidies are used as an instrument. Where regulations mandating replacement are used, they face a considerable backlash. Legislation had to be cancelled in Sweden on account of protests (Sahlberg et al., 2022^[254]) in 2019 and more recently in Scotland (Johnson, 2024^[255]). Finding the right combination of support to households and regulatory instruments remains a challenge.

Issues that arise include costs of alternatives for poor households, knowledge about alternative methods and conviction that they are effective and their compatibility with end-users (Boudewijns et al., 2022^[256]). These challenges imply that economic support and information, in addition to adequate price signals, are key to achieving the adoption of clean fuel technology among mostly poor, rural households.

Controls on emissions from agriculture

Measures for reducing air pollution from agriculture include the following:

- *Reduction of emissions from burning of agricultural wastes.* Policies that eliminate, or at least reduce, the burning of fields can be a cost-effective measure for the region. Compliance with regulations prohibiting burning has been a problem. Surveys show that farmers' reasons for burning crop residues are mainly the high cost of incorporating, collecting, transporting, and processing crop residues in South Asia. Labour shortages, the marketability of the crop residue and the short time interval between harvest and next cropping seasons also influence farmers decision (Lin and Begho, 2022^[257]). Recent evidence from India shows that cash transfers as payments for ecosystem services can reduce agricultural burning by up to 80 percent (Jack et al., 2022^[258]), although Indonesia's attempt to control agricultural burning through cash transfers has had mixed results (Falcon et al., 2022^[259]). Other examples of payments for sustainable agriculture, have shown promising results in Latin America (Balseca et al., 2022^[260])
- *Efficient use of fertiliser and management of livestock emissions.* Agriculture also contributes to air pollution through the emissions of NH₃ stemming from fertiliser use and manure management. Through chemical reactions NH₃ is a major contributor to PM_{2.5}. Adopting more efficient fertiliser management is important but challenging; see also Section 6.5. While reducing subsidies for fertiliser would be cost effective it faces strong opposition in countries where subsidies are used. Measures to better manage livestock emissions are available and involve combining controls for CH₄ and NH₃. However, implementing them at scale requires integrated management of both GHGs and local pollutants and considerable outlays (World Bank, 2023^[225]; Sapkota et al., 2019^[261]).

6.4.4. Integrating synergies of different types of air pollution policies with biodiversity

Air pollution policies that provide biodiversity benefits can involve determining threshold values for concentrations of air pollutants such that damage to ecosystems is limited, so-called critical loads or critical levels described for example in Annex 1 of the 2012 Gothenburg Protocol revision (UNECE, 2012^[262]). For example, critical levels (as defined in article 1 of the Gothenburg Protocol) of NH₃ are determined to protect plants in accordance with the Convention's Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends (UNECE, 2012^[262]). Critical levels can then be translated into limits on emissions from sources that contribute to the concentrations. Threshold values are determined as levels above which damage to ecosystems is expected to be significant; the literature, however, does not demonstrate that costs of meeting threshold values relative to damages sustained have played a part in arriving at the values.²² The SEEA EA being set up by the UN under which spatially detailed accounts of ecosystem services are being drawn up will be a major factor in helping determine threshold values at the ecosystem level based on values of services and costs of abatement (United Nations et al., 2021^[263]; United Nations, 2022^[264]).

The impacts of air pollution on ecosystems and biodiversity are tracked through the effects of emissions of SO_x and NO_x on forests (acid rain) and through the effects of for example O₃ on other ecosystems.

Acid rain

Measures to reduce transboundary SO_x and NO_x pollution, key drivers of acid rain, have had a significant spill-over effect on ecosystems and biodiversity. Given the large-scale effects on ecosystems and its transboundary nature, co-ordinated policy actions under the UNECE Convention on Long-range Transboundary Air Pollution (the Air Convention) on SO_x and NO_x emissions were undertaken in Europe and North America. These included for example the implementation of protocols that set national emission targets and identify specific measures for cutting emissions across a wide range of sectors (UNECE, 2015^[265]). Air pollution emissions were substantially reduced through these actions (for the most important acidifying compound, SO₂, emissions in Europe have decreased by 80% or more since the peaks around 1980–1990). Acid rain has thus been mitigated and ecosystem impacts including on European forests decreased (Grennfelt et al., 2019^[266]).

In the US, similar actions took place. Congress passed several amendments to the Clean Air Act in 1990 that cut emissions of SO₂ through a cap-and-trade scheme. The goal was a 50 percent reduction in such emissions from 1980 levels. That goal was achieved in 2008: SO₂ emissions fell from 17.3 million tons in 1980 to 7.6 million tons in 2008. The effect has been remarkable. The Smithsonian notes that the rain falling in the Northeast today is about half as acidic as it was in the early 1980s. Consequently, surface waters have become less acidic and fragile ecosystems are beginning to recover (Willyard, 2010^[267]).

Another region where acid rain is an issue is East Asia. In the two decades to 2000, countries in the region reduced emissions of SO_x and NO_x, thus lowering damages on terrestrial and aquatic ecosystems. Since 1975 China has decreased its emissions of SO₂ by more than 75%. Acid rain remains, however, significant (Xuan et al., 2021^[268]). Thus, potential solutions can address the problem from multiple scales and perspectives, including collecting reliable and relevant data, showing the synergies and trade-offs between emissions that cause acid rain and climate change, and recognising the need to take account of transboundary movement in agreeing on cost effective emissions reductions. The last makes use of dispersion models that are now well developed (Shah et al., 2000^[269]). Lanzi et al (2022^[270]) highlighted that integrated policy approaches across China, Japan and Korea can have very significant beneficial effects in comparison with domestic policies only.

Managing ground-level ozone concentrations

Policymakers have utilised a range of different mechanisms to address ground-level O₃. These include emissions controls for O₃ precursors, standards and guidelines which define air quality targets, alarm thresholds to advise sensitive sectors of the population to move indoors and O₃ alarm plans to restrict emissions associated with land transport and industry during O₃ peak episodes. A major part of regulations on O₃ emissions and concentrations are set for health reasons (Box 6.7) but there are some that consider impacts on biodiversity, especially in areas where O₃ is having a significant effect on ecosystems.

Box 6.7. Ground-level ozone management policies

There is no global framework in place for the direct management of O₃. The WHO has issued guidelines to policymakers for the most common air pollutants, including O₃. These are intended to provide guidance for the development of policy measures aimed at reducing the impacts of air pollutants on human health (WHO, 2006^[271]). Agreements are in place for some regions that set limits for O₃ precursors – NO_x and non-methane volatile organic compounds (NMVOCs). National limits for European countries are further based on scientific assessments of the thresholds of effects on natural ecosystems and human health, and the relative cost effectiveness of abatement options. The Protocol also defines critical levels, which together with integrated assessment modelling, are used to inform the negotiations on national obligations. For the European Union National targets for emissions are set in the National

Emissions Ceilings (NEC) Directive. Also relevant for O₃ control is the Integrated Pollution, Prevention and Control (IPPC) Directive. The Directive imposes a requirement for stationary sources of pollutants from new and existing industrial and agricultural sources with high polluting potential to be permitted only where certain environmental conditions are met. This includes sources associated with the energy industries, production and processing of metals, mineral industry, chemical industry, waste management and livestock farming (Fowler et al., 2008^[272]).

Where regional agreements are in place to limit precursors, they have been quite effective. A review of the Gothenburg Protocol showed that the emissions of the O₃ precursors NO_x and NMVOCs have declined substantially as a result of emissions controls. In spite of this, however, as noted above there has not been a strong decline in O₃ concentrations across North America and Europe. This partly reflects an increase in hemispheric background concentrations of precursors and indicates a need for further controls – e.g. on emissions from shipping and aviation, which are currently under consideration (Fowler et al., 2008^[272]). In addition, episodic high O₃ events caused by temperature variations prevent many areas from attaining O₃ air quality standards. This is despite the large reductions in NO_x emissions. A recent study finds that a time variant price for NO_x emissions instead of a uniform price set by tradable allowances within a cap can be most cost effective in attaining O₃ concentration standards (Holt and Linn, 2024^[273]). For such a differentiated pricing policy, however the regulator must commit in advance to trading rules that depend on the forecast marginal effects of the regulated pollutant. The cost savings of a differentiated price depend on forecast accuracy and emissions abatement costs; if forecasts are sufficiently inaccurate, a uniform price could be less costly.

1. For the UNECE region the key agreement in place is the 1999 Gothenburg Protocol for, amongst others, VOC and NO_x emissions. The Gothenburg Protocol was amended in 2012 to introduce national emission reduction commitments for 2020 and beyond, with a further revision process in progress (UNECE, 2023^[274]).

Specific actions to address O₃ concentrations' impacts on ecosystems include selecting cultivars less sensitive to O₃ and strong limits on emissions of CH₄. Avnery et al (2013^[275]) compare two O₃ mitigation strategies applied worldwide: a gradual reduction in emissions of CH₄, an important O₃ precursor, and choosing crop varieties less sensitive to O₃. The first increases global production of soybean, maize and wheat in 2030 by 2-8% of 2000 level, while the second could increase by around 12%. Benefits are dominated by improvements for wheat in South Asia, where O₃-induced crop losses would otherwise be severe. Both measures have net benefits (i.e. costs of implementing them are less than the benefits). Combining the two strategies generates benefits that are less than fully additive, given the nature of O₃ effects on crops.

Reduce burning of crop residues

As noted above, the burning of crop residues is a major source of air pollutants with health impacts as well as negative impacts on the ecosystem. It is reported to degrade the soil, increase the risk of erosion, and increase the soil temperature, consequently decimating soil microorganisms. This subsequently impacts the monetary cost involved in recovering soil fertility and the potential for further pollution through the increased use of fertiliser (Lin and Begho, 2022^[257]). Actions to reduce such emissions are seen as a key part of a strategy to reduction PM_{2.5} in South Asia (World Bank, 2023^[225]), with significant synergies for ecosystems and biodiversity conservation for the reasons given.

6.5. Integrating climate change and biodiversity in nutrient management policies

Nitrogen and phosphorus touch on all aspects of the triple planetary crisis (Annex 6.D). Given their centrality, maintaining a balanced nutrient cycle – which involves the movement of nutrients through soils, plants, animals, and the environment – is essential for water purification (Chapter 1) and long-term agricultural productivity, sustainability and resilience. Nutrients, particularly nitrogen and phosphorus, are essential for plant growth and are applied in agriculture through both inorganic fertilisers (made from minerals or synthetic chemicals) and organic fertilisers (especially manure).²³ However, the management of these inputs varies widely across regions, often resulting in either nutrient deficiencies or surpluses²⁴, both of which pose significant challenges. In some developing regions, notably Sub-Saharan Africa, the limited use of inorganic fertilisers and the diversion of organic inputs such as manure for non-agricultural uses such as energy for household cooking (Jones and Deuss, 2024^[276]) lead to negative nutrient balances. This means that nutrient inputs are insufficient to replenish what is removed through plant uptake (Ludemann et al., 2024^[277]). An insufficient nutrient cycle undermines long-term agricultural productivity and resilience. Over time, this may reduce soil fertility and reduce crop yields.

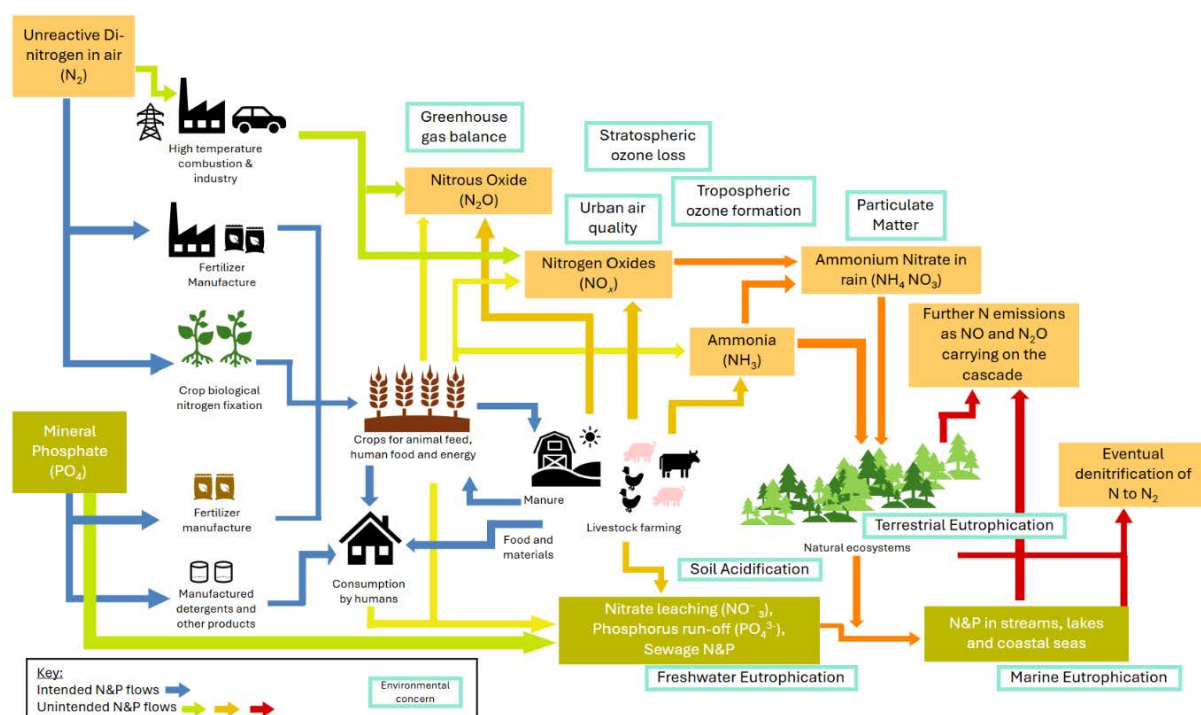
In contrast, in regions where fertiliser use is high, overapplication of nutrients can cause a range of pollution effects. Nitrogen reacts with other chemicals to form polluting compounds that have effects on the environment through air, soils, water, and ecosystems. Excess nutrients often leach into water bodies and act as fertilisers, triggering eutrophication and algal blooms (NOAA, 2024^[278]). Excess algae can reduce or deplete dissolved oxygen available to aquatic life and can produce toxins that are harmful to people, animals, and aquatic ecosystems. Nitrogen compounds can also contaminate groundwater, posing health risks such as NO_3^- poisoning, even at low levels. Infants are especially vulnerable to NO_3^- in drinking water as their bodies do not break down NO_3^- as well as adults. Phosphorus fertilisation is also threatening water quality in regions such as Europe, East Asia, and South Asia (Ros et al., 2020^[279]), although significant amounts of phosphorus are stored in the soils (and good soil management can prevent major losses to water bodies).

Striking the right balance in nutrient use is therefore essential. Integrated nutrient management that combines both organic and inorganic sources, tailored to local soil characteristics (such as pH, organic matter content, and nutrient holding capacity) and varying nutrient requirements of different crops²⁵ (Al-Shammery et al., 2024^[280]), is key to maintaining soil health, improving yields, and minimising negative environmental impacts. Strengthening farmers' access to knowledge, inputs, and technologies that support efficient nutrient use can help close yield gaps while preserving the natural resource base critical for food security (Ignaciuk et al., 2021^[281]).

6.5.1. The nitrogen cascade and phosphorus cycle touch on all pillars of the triple planetary crisis

Nitrogen easily changes chemical form and moves between air, soils, water and ecosystems, causing a cascade of damages across all pillars of the triple planetary crisis (Figure 6.4). For example, N_2O is an important GHG and, in the stratosphere, also a powerful stratospheric ozone layer depleting substance that contributes to climate change. Similarly, NO_x reduces air quality via the creation of (ground-level) ozone (O_3). NH_3 commonly originating from fertiliser and manure increases human health risks such as respiratory illnesses and cancer. Combined with NO_x , NH_3 contributes to the formation of nitrate aerosols such as ammonium nitrate (NH_4NO_3). Through the rain, these can lead to eutrophication in lakes, terrestrial and coastal areas, impacting fisheries and drinking water quality. Nitrogen can also damage ecosystems through leached NO_3^- , as well as acidification of soils and waterbodies. In the case of pollution through the soil, the application of fertiliser and manure increases the availability of soil mineral nitrogen (i.e. ammonium NH_4^+ and NO_3^-), which can result in the release of N_2O that contribute to climate change.

Figure 6.4. Simplified view of the nitrogen and phosphorus cycle



Source: Sutton (2020)^[282].

The global phosphorus cycle, which involves the movement of phosphorus between geological formations, soil, plants, and organisms, is not as well-defined as the global nitrogen cycle (Boyd, 2019^[283]). Phosphorus is predominantly found in phosphate mineral-bearing ores, known as phosphate rock²⁶. Phosphorus occurs naturally in most geological formations and soils in varying amounts and forms. Humans have enhanced the availability of phosphorus by mining phosphate rock. Rivers now transport about twice as much phosphorus as 300 years ago (Schlesinger and Bernhardt, 2020^[284]). Only about 10% of the phosphorus delivered to the oceans is potentially available to marine organisms (Schlesinger and Bernhardt, 2020^[284]). The remainder is bound to soil particles and sequestered by sediment through formation of iron, aluminum, and calcium phosphates. The phosphorus cycle has no significant gaseous component. The flow of phosphorus through the atmosphere in soil dust and seaspray is also much smaller than other transfers in the global phosphorus cycle (Schlesinger and Bernhardt, 2020^[284]). Figure 6.4 visualises the intended and unintended flows of phosphorus. Phosphorus mainly accelerates the triple planetary crisis through the mining process itself, as well as through the subsequent agricultural applications of phosphorus as a fertiliser.

6.5.2. Synergies and trade-offs of nutrient pollution policies for biodiversity conservation and climate change mitigation

Policies to mitigate nutrient pollution consist of controls in the use of inputs that generate excess nutrients as well as controls on emissions of nutrients, such as for example the EU Nitrates Directive that for example sets limits on livestock manure application per hectare. In addition, there have been some fiscal incentives and in the form of taxes on inputs such as fertilisers (Andersen and Bonnis, 2021^[285]; Andersen, 2022^[286]), taxes on mineral phosphorus in commercial animal feed (Andersen, 2017^[287]), and taxes on emissions of N₂O (OECD, 2013^[288]). These measures have synergies with climate change as they often result in a reduction on GHGs, and with biodiversity and ecosystems because the decline in nutrients causes less

damage in these areas. Finally, lower levels of nutrients and the resulting lower emissions to the air and water also have health benefits.

Vice versa, policies undertaken with a climate change goal will reduce emissions of nutrients when agricultural sources of GHGs are covered and also reduce leakage of nutrients into the environment. Climate change-induced sea-level rise and shifts in precipitation accelerate the transport of dissolved and particulate phosphorus and nitrogen from soils, further exacerbated after the application of fertilisers and manures or drought (Lucas et al., 2023^[289]). Climate change-related extreme rainfall events particularly increase phosphorus losses from agricultural lands to waterbodies (Our Phosphorus Future Network, 2022^[290]). Hence, climate mitigation is essential to limit further leakage of nutrients into the environment.

Beyond taxes that target fertilisers or nutrient feed directly, a broad tax on GHGs that covers activities that also emit nutrients, such as agriculture or livestock, will reduce nutrient pollution as it scales down the economic activities that co-emit carbon and nutrients and incentivises a shift towards less-emitting sectors. Most carbon tax programmes, however, do not cover emissions from agriculture/livestock as these are hard to estimate and monitor. Denmark constitutes an exception as it is planning the world's first carbon tax on emissions from livestock, to be introduced in 2030, as part of a vast agriculture plan called the Green Tripartite. From 2030, CH₄ emissions caused by enteric fermentation, flatulence, and mature from cattle and pigs would be taxed at a marginal rate of DKK 300 (around EUR 40) per tonne of CO₂e, a sum gradually rising to DKK 750 (around EUR 100) by 2035 (Danish Ministry of Taxation (Skatteministeriet), 2024^[291]). However, a basic deduction (tax rebate) of 60 percent applied to the average emissions per type of animal to incentivise farms that have low emissions means the effective average tax rate will be DKK 120 (around EUR 16) per tonne emitted in 2030 and DK 300 (around EUR 40) in 2035 (Danish Ministry of Taxation (Skatteministeriet), 2024^[291]).

Carbon taxes can also incentivise the use of technologies that reduce nutrient pollution. In the above Danish example of tax on emissions from livestock, calculations would be based for example on animal head count with different categories and a series of metrics that affect emissions per animal, e.g. feed composition and use of climate-friendly technologies (New Zealand Ministry of Foreign Affairs and Trade, 2024^[292]). For example, in Denmark feed changes such as the use of 3NOP (Bovaer) as a methane-reducing feed additive is encouraged. Other carbon mitigation techniques considered in the tax include biogas production (Holmes, 2024^[293]). Funds received from the new tax should also be returned to farmers to help reduce the burden over time through green technology innovation (New Zealand Ministry of Foreign Affairs and Trade, 2024^[292]).

Equally, policies implemented to address biodiversity, such as protected areas, often limit agricultural activity which also lowers nutrient levels – especially when the threats to protected areas lead to controls of nutrient emissions in neighbouring areas. However, the recent Dutch Greenpeace litigation case against nitrogen pollution in protected areas illustrate that even in the presence of national targets, location specific policies are needed and demonstrates the challenge of balancing different economic activities when implementing a nitrogen target (Box 6.8).

Box 6.8. Challenges of implementing Dutch nitrogen targets in protected areas

The agricultural sector plays an important role in the Dutch economy: On average and in relative terms, Dutch agriculture occupies more land, generates more value and is more trade-oriented than in most OECD countries (OECD, 2023^[294]). The Netherlands has built an agricultural sector that is a world leader in productivity and competitiveness.

In parallel, environmental challenges including nitrogen pollution have become increasingly urgent. Nitrogen pollution has been a problem in the Netherlands for many years, for a considerable part due to NH₃ emissions from manure and fertilisers in the emissions intensive agricultural sector as well as due to NO_x from the transport and industry sector (Government of Netherlands, 2025^[295]).

Location-specific policies have been implemented for example through a court ruling on nitrogen deposition on sensitive landscapes, including protected areas. The Nitrogen Reduction and Nature Improvement Programme of 2021 sets binding targets for the percentage of the hectares of nitrogen-sensitive habitats in Natura 2000 protected areas on which the nitrogen deposition must be brought below critical deposition values. However, the negative environmental impacts of farms that are adjacent to Natura 2000 sites that are sensitive to nitrogen deposition have meant that nitrogen deposition on sensitive landscapes remains substantially above safe thresholds in most cases, which has impaired the quality and recovery capacity of natural habitats (OECD, 2023^[294]). The government has tried to solve the nitrogen problems with an area-based approach that allocates a transition fund to reduce the impacts of adjacent farms, but further location-specific policies are needed to protect sensitive areas.

In an aim to reach the nitrogen targets, the Netherlands has considered trade-offs between different economic activities and imposed restrictions on for example the nitrogen-intensive construction sector, creating policy backlash. A 2019 court ruling put a temporary halt to all new development activity requiring permits to emit nitrogen, affecting agriculture and construction most strongly but touching many parts of the Dutch economy and placing many projects in limbo (OECD, 2023^[294]).

Announcements of measures to reduce nitrogen emissions led to large farmer protests e.g. in 2019 (Tullis, 2023^[296]) and have evolved into the Farmer-Citizen Movement party (called *BoerBurgerBeweging*, BBB). The BBB, as part of the new government, puts more emphasis on innovation and proposed to shift away from the area-based nitrogen approach.

Resolving policy backlash while sufficiently addressing the underlying nitrogen pollution problem (in the Netherlands known as the *stikstofcrisis*, the nitrogen crisis) is challenging, as a court ruling from January 2025 illustrates: the Court ordered the Dutch government to comply with the statutory nitrogen target for 2030, which means that the state must bring 50% of the area of nitrogen-sensitive nature below the critical deposition value by the end of 2030, with priority to be given to the most endangered nature types. If the Netherlands fails to achieve this goal, it must pay a penalty of EUR 10 million.

In response to the court's decision, a ministerial committee comprising four ministers was formed in 2024 to work on plans to tackle the nitrogen crisis. This committee was co-ordinated by the prime-minister's office, highlighting the cross-cutting nature of the issue, although a final plan has not been delivered yet as the government collapsed in 2025 without a clear outcome of this committee.

Beyond helping to limit nutrient emissions and leakage, climate mitigation policies also help to alleviate the impacts of nutrient pollution, given that these are exacerbated by climate change. With rising temperatures, waterbodies are more prone to eutrophication due to increased biomass growth in waters that lower dissolved oxygen concentrations, reducing the self-cleansing capacity of waterbodies and increasing the risk of eutrophication (Forber et al., 2018^[297]). This is in line with Birk et al. (2020^[298])s' findings that nutrients are not only the dominant stressors acting to degrade lakes but that parallelly the ecological effects of nutrients are exacerbated by stressors such as climate change.

A trade-off arises with respect to climate mitigation through reductions in NO_x and NH₃ emissions as a result of nutrient pollution control. NH₃ reacts with the products of NO_x to form secondary PM_{2.5}. The resulting PM_{2.5} has a cooling effect on climate as it scatters light and promotes cloud formation (see Section 6.4). Conversely, reducing NH₃ pollution will have a warming effect. However, this effect is small and relativised further by the fact that the formation NO_x creates a GHG. Although these trade-offs should not be ignored, given the comparably strong synergies the mitigation of nutrient pollution is important to tackle the triple planetary crisis.

A further potential trade-off arises in the sense that increasing fertilisation leads to higher yields and thus lower land use requirements to produce the same amount of output, which could benefit both climate change mitigation and biodiversity depending on the alternative land use. OECD scenario research (Adenäuer, Laget and Cluff, 2024^[299]) suggests that fertilisers are crucial for enhancing agricultural yield: a hypothetical elimination of fertiliser support in India prompts a rapid reduction in domestic fertiliser use and decrease in agricultural production. Globally, as the strong growth in agricultural output per unit of agricultural land is due in large part to a more intensive use of inputs, including fertilisers, reducing fertilisation could increase land use requirements for agriculture. Since 1961, global consumption of nitrogen fertilisers grew almost nine-fold, while consumption of phosphorus fertilisers nearly quadrupled (OECD, 2021^[300]).

However, increasingly yield growth is driven by total factor productivity growth, such as through efficiency gains from better farm management practices (OECD, 2021^[300]). Since the 1990s, total factor productivity growth has been the major factor driving the growth of global agricultural production (OECD, 2021^[300]). Agricultural output increased also in periods where average nitrogen surpluses declined, such as from 1990 to 2009 (OECD, 2025^[301]). The trade-off from decreased fertilisation might be particularly limited if nitrogen use efficiency (the ratio of nitrogen in crops compared to nitrogen applied as inputs through fertilisers or manure) is improved. Global nitrogen use efficiency lies only at around 50% globally, hence at better efficiency nitrogen pollution could be reduced without significant harm to yields (Lassaletta et al., 2014^[302]).

6.5.3. Integrating synergies and trade-offs when assessing policies to reduce nutrient pollution

Policies to reduce nutrient pollution have strong synergies with protecting ecosystems and biodiversity. With regards to climate change, NH₃ can have a cooling effect that is lost when emissions fall as a result of policies to reduce nutrient use and pollution. The effect, however, is small and moreover N₂O creates a GHG that contributes to climate change. Overall, therefore, there are key synergies with climate change in reducing nutrient pollution.

Integrating synergies and trade-offs with nutrient pollution policies is most effective if the selection of measures takes account of the co-benefits of the measures with respect to climate change and biodiversity. A local case study highlighting Peruvian regulations on the collection of the natural fertiliser guano is shown in Box 6.9 below.

Box 6.9. Managing trade-offs between pollution reduction and biodiversity protection in Peru by regulating the collection of guano, a natural fertiliser

The Peruvian government aims to decrease soil pollution caused by artificial fertilisers by encouraging farmers and communities to use guano, a natural fertiliser obtained from the accumulation of bird excrement, while preserving collection areas' biodiversity. Historically, the exploitation of guano, rich in nitrogen, phosphate and potassium, provided a natural source of nutrients for the agriculture before the invention of synthetic fertilisers, but its overexploitation damaged the biodiversity of the collection areas. During the 19th and 20th centuries, the overexploitation in the 22 Peruvian guano islands resulting from high demand on the international market caused the degradation of the lands and the decline of the fauna populations, starting with the guano birds themselves, whose nests were destroyed by the collection process (Doig-Alba et al., 2023^[303]). The name "guano birds" refers to the three most important seabird species involved in the production of guano in Peru: the Guanay Cormorant, the Peruvian Booby and the Peruvian Brown Pelican. At the time, the labour-intensive extraction process using picks, shovels and brooms to loosen and collect the guano deposits which in some places were several metres thick, was often accompanied by the collection of bird eggs and the poaching of adult penguins (Chauvin, 2018^[304]; Peru, 2024^[305]). The population of guano birds declined from 53 million in the late 1880s to 4.2 million in 2011 (IUCN, 2013^[306]).

While recognising the role of guano as a natural fertiliser and subsidising it, the Peruvian government has implemented measures to restore and protect biodiversity of the collection sites (Peru, 2024^[305]; Peru, 2019^[307]). To support local sustainable agriculture, guano is offered at subsidised prices to small farmers and communities when agricultural yields decline because of pest outbreaks or extreme weather conditions (Peru, 2024^[305]; Peru, 2014^[308]). In 2009, Peru designated the Guano Islands, Islets, and Capes National Reserve System as a protected natural area, part of Peru's National System of Natural Areas Protected by the State (Sistema Nacional de Áreas Naturales Protegidas por el Estado - SINANPE), whose main objective is to maintain the conservation of biodiversity and ensure the sustainable use of wild flora and fauna resources (Peru, 2009^[309]). On these islands, extraction is strictly regulated: harvesting is prohibited during the breeding season and rotational harvesting allows birds to recover and breed without interruption (Geo, 2024^[310]; Peru, 2013^[311]). The endangered Humboldt penguin population, historically negatively affected by guano collection, has increased since the creation of the reserve, with 8 025 penguins registered in 2019 (World Bank, 2020^[312]).

Comprehensive EIAs and other integrative measurement tools play a key role in highlighting the effects of nutrients – and nutrient policies – on climate change, biodiversity and pollution. The interactions of phosphorus and nitrogen (and its derivatives across air, water and soils), (highlighted in Annex 6.D), also need to be taken into account. This can be complemented by cost-effectiveness analysis of different options to meet nutrient targets, or even undertaking a full cost-benefit analysis, again taking a broad scope to include all environmental impacts. Typically, cost-effectiveness assessments in this area have only looked at the direct costs of measures that meet a given target. Information is, however, available on the benefits of nutrient reduction in terms of health endpoints and climate change (reductions in GHGs). Estimates can also be made of reductions in environmental impacts, which will vary by location within the area for which the targets are set. Such benefits can be deducted from the direct costs to give the full costs of measures, and the selection can then be based on those that have the lowest net cost. For instance, in 2021, the European Commission conducted a cost-effectiveness assessment of countries' proposed measures to meet targets set out in the Baltic Sea Action Plan 2021, including sub-basin nitrogen and phosphorus maximum allowable inputs (Baltic Marine Environment Protection Commission, 2021^[313]). The assessment incorporated the climate adaptation and habitat creation benefits of spatial measures for nutrient pollution reduction, such as artificial or restored wetlands, stormwater ponds and mussel farms,

and concluded that these measures are indeed cost-effective. The assessment further noted that targeted interventions in coastal areas are likely to yield additional biodiversity benefits (HELCOM ACTION, 2021^[314]).

Full cost-benefit or even broad cost-effectiveness analysis of nutrient management policies are exceedingly rare. Countries do, however, take account of differences in biodiversity impacts of nutrient pollution when setting controls and limits on nutrient emissions in areas, particularly those sensitive to nutrient pollution. For example, as outlined in Section 6.3, the Netherlands applies stricter nutrient emission limits and manure regulations in nutrient-sensitive areas. It aims to reduce nitrogen deposition on at least 50% of the surface area of the nitrogen-sensitive nature areas within the Natura 2000 network to less than the critical deposition load by 2030. As noted earlier, the ecosystem costs of nutrient pollution vary greatly from one location to another. Furthermore, different measures will have different implications for linked watersheds. These need to be accounted for when selecting particular measures. For instance, New Zealand's National Policy for Nutrient Management 2020 Amendment Act of 2024 provides specialised nutrient pollution targets for different water body types, including freshwater lakes and rivers, with accompanying species health targets for ecosystems that may be impacted by nutrient pollution, including fish and macroinvertebrates (New Zealand Government, 2024^[315]). Also, the health and climate benefits of the measures are not generally part of the process that sets environmental targets. Integrating these into target setting for different locations would increase synergies between the different goals.

Making the implementation of measures for nutrient pollution management more effective will also increase synergies with other triple crisis objectives. While there are major gaps in tracking the environmental and other outcomes of different policies, some key findings emerge. One is that trust in new nutrient pollution management technologies and the way they work needs to be high (Li et al., 2023^[316]). This requires their promotion to be accompanied with strong technical support. A second is that for regulations such as watershed management programmes, their adoption needs to be linked to accompanying measures such as information sharing, capacity building, technical assistance, training support for the local population and farmer-to-farmer communication networks that build trust and enhance understanding of the potential benefits of conservation practices (Piñeiro et al., 2020^[317]). Agricultural extension services, both public and private, have been shown to have a positive impact on adoption rates. Third, subsidies, where they are offered to incentivise the adoption of particular measures need to take account of possible negative environmental and social consequences (Piñeiro et al., 2020^[317]). For example, subsidies may increase the adoption of intercropping and residue mulching, but these practices may crowd out adoption of zero tillage. Finally, adoption of conservation methods depends a lot on them being profitable to the farmers in the short run (Piñeiro et al., 2020^[317]). The evidence shows that when such technologies are offered in conjunction with measures that enhance the short-term profitability of agriculture (such as new crops, biological barriers and improved agricultural production), the adoption of conservation practices increases significantly. Considerations of resource efficiency and circular economy are also important (Box 6.10).

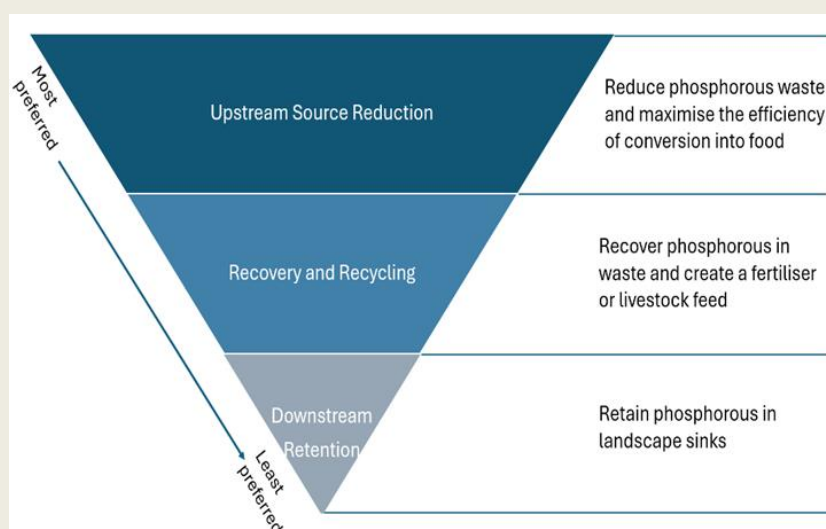
Box 6.10. Phosphorus reuse and recycling

Phosphorus used as fertiliser is normally sourced from phosphate rock, a non-renewable resource. Therefore, the use of phosphorus through fertiliser, animal feed and other products leads to depletion of the fossil phosphate stock (Smil, 2000^[318]; Van Vuuren, Bouwman and Beusen, 2010^[319]). In contrast, nitrogen and its compound derivatives can be produced on a large scale as nitrogen is the most abundant gas in the Earth's atmosphere and a renewable resource.

Reuse of phosphorus-containing waste and phosphorus recycling are increasingly supported at the policy level. In view of concerns over future phosphate rock availability, policy discourse has shifted from seeing phosphorus mainly as a pollutant in eutrophication control through downstream retention or removal of phosphorus in phosphorus landscape sinks towards increasingly considering reuse, recovery and recycling of phosphorus (Nanda and Kansal, 2021^[320]; Roy, 2017^[321]). This constitutes a move up in the phosphorus management hierarchy of Roy (2017^[321]) that positions reuse and recovery through recycling provide above strategies where downstream retention is the primary goal (Figure 6.5). Bans of direct applications of sewage sludge containing phosphorus for agricultural application due to the concerns over contaminants (e.g. heavy metals) further underscore the importance of recovery through recycling.

In Germany, an importer of phosphorus, recycling from sewage sludge will be mandatory from 2029 for all wastewater treatment plants (WWTP) larger than 50 000 person equivalents (p.e.), equal to around 500 WWTP out of around 9300 WWTP (Bundesministerium der Justiz und für Verbraucherschutz, 2017^[322]). These WWTPs will have to recover the phosphorus if the sludge contains more than 2% phosphorus per dry solid content or have to incinerate the sludge in mono-incinerators. Land application of sludge will only be allowed for WWTP below 50 000 p.e. (Bundesministerium der Justiz und für Verbraucherschutz, 2017^[322]). By the end of 2023, municipalities in Germany were already obliged to report to the competent authority their planned measures for phosphorus recycling from January 2029.

Figure 6.5. Downstream retention alone is insufficient for efficient phosphorus management



Note: Preference in the phosphorus management hierarchy is a function of potential total benefits to the environment, society, and economy (Roy, 2017^[321]). However, all three categories have a vital role to play in comprehensive phosphorus management and upstream source reduction remains crucial.

Source: Roy (2017^[321]), inspired by EPA (2017^[323]).

Phosphorus recycling and reuse are also supported at the regional level. Since 2017, phosphorus is listed in the European Union's Critical Raw Materials list (EU, 2017^[324]). The European Union 2020 Circular Economy Action Plan highlights the development of an Integrated Nutrient Management Action Plan (INMAP), with a view to stimulating the markets for recovered nutrients (European Commission, 2020^[325]). The revised Urban Waste Water Treatment Directive also encourages EU member states to “prepare for reuse, recycling and other recovery of resources, in particular phosphorus and nitrogen” (European Parliament and Council of the European Union, 2024^[326]). This directive also suggests that a minimum combined reuse and recycling rate should be set at EU level where members would be “able to choose whether to reuse or recycle, or both, urban wastewater or sludge, or both, in order to recover phosphorus” (European Parliament and Council of the European Union, 2024^[326]).

However, one challenge in phosphorus recycling and reuse is obtaining phosphorus of consistently good quality, because of for example a variation in the quality of sewage sludge (Nanda and Kansal, 2021^[320]). Concerns about energy efficiency of the recycling and reuse process have also been raised – although research progress has been made on enhancing phosphorus removal performance and its recovery potential and many technologies have been developed recently (Zheng et al., 2022^[327]). Note: Nitrogen can also be recovered for reuse and recycling but is generally harder to recover at large scale in a useful, low-energy form because nitrogen readily changes oxidation states and is often lost as N_2/N_2O gas.

Agricultural development programmes for smallholder farmers in China demonstrate the potential effectiveness of combining technical support, information sharing, and subsidies to reduce nutrient pollution. In 2009, The China Agricultural University launched The Science and Technology Backyards (STB) programme, which places researchers and graduate students directly in farming communities to co-develop agricultural best practices that increase yields while minimising environmental impacts (FAO TECA, 2022^[328]). Between 2019 and 2020, STB researchers collaborated with smallholder farmers and local government in Quzhou County to implement nitrogen pollution reduction initiatives. These included indoor technical training sessions, government subsidies for inhibitor-treated urea fertilisers and information on the expected yield benefits of deep fertiliser placement (Kang et al., 2023^[329]). Compared with traditional practices, the co-developed methods increased nitrogen use efficiency for wheat and maize by 28% and 40%, respectively, while reducing NH_3 emissions by 40% and 8% and improving profitability by 25% and 9% (Kang et al., 2023^[329]). The STB programme continues to expand, reaching 127 programmes across 29 research institutions and 45 crop varieties as of 2018 (FAO TECA, 2022^[328]).

Consultations with farmers can play a key role in developing synergistic nutrient pollution policies. In 2023, Canada held forums with farmers to discuss the voluntary national target of reducing fertiliser-related emissions to 30% of 2020 levels by 2030 (Agriculture and Agri-Food Canada, 2023^[330]). The consultations revealed that concerns over potential agricultural losses could hinder adoption, and that incentives and best-practice sharing could help support implementation (Agriculture and Agri-Food Canada, 2023^[330]). Canada's On-Farm Climate Action Fund addresses these concerns over the potential agricultural losses by providing funding to farmers to support the adoption of beneficial management practices (BMPs) that decrease GHG emissions and/or increase soil organic carbon, helping farmers tackle climate change. For example, the fund allocated CAD 50 million to the Ontario Soil and Crop Improvement Association to support the adoption of farming practices such as nitrogen management and rotational grazing, which provide climate and nutrient benefits (Agriculture and Agri-Food Canada, 2025^[331]). Although the fund was recently launched (2022), early synergies are already apparent. One farm in Ontario, for instance, used the grant to adopt a wide-drop sprayer, enabling a targeted 28% reduction in nitrogen use, allowing the farm to cut fertiliser costs while maintaining yield (Ontario Soil and Crop Improvement Association, 2025^[332]).

Given that synergies of nutrient pollution policies with climate and biodiversity benefits are strong, the question that arises is where these synergies are strongest and which policies are best suited to take advantage of them. Several findings emerge:

- Using cost-effective measures to ensure the lowest possible costs of nutrient reductions, in overall terms (i.e. taking into account synergies and trade-offs), can allow for higher targets to be set without increasing the burden on governments and society more widely. Here there is a role of market-based instruments such as a nitrogen/phosphorus tax or a tax on NH₃ emissions. These have been studied and rates proposed but they have not been implemented. It would be worth looking more closely at the proposals and introduce such a tax – something the European Commission is currently examining (European Commission, 2024^[333]). As above, the targets and tax rates should reflect the broad environmental impacts, and not only the immediate pollution benefits. Alongside market-based instruments, more detailed spatial planning could help create targeted local policies. Denmark has implemented a spatially targeted nutrient management system to reduce nitrogen runoff from agriculture into rivers, lakes, and coastal waters. Rather than applying uniform national limits, Danish authorities use detailed spatial maps that identify areas most vulnerable to nitrogen leaching and eutrophication (Hashemi et al., 2018^[334]).
- While taxes on fertilisers have had an effect in reducing nutrient application and thus nutrient emissions, they have fallen out of favour and are unlikely to be taken up. Where there is potential for making a change, however, is to reform subsidies to fertiliser use in countries where such subsidies are used. Repurposing such subsidies to other forms of support to farmers can help reduce nutrient pollution while not harming farmers' livelihoods. There are moves in this direction. The World Bank, for example has given grants to pilot initiatives to realign fertiliser support and soil health programmes in Bangladesh, Ghana, Indonesia, Mozambique, Malawi and Tanzania (World Bank, 2024^[335]).
- Carbon taxes on fossil fuels can also reduce nutrient emissions by indirectly raising the price of nutrients through the higher production costs of fertilisers. The levels of such taxes and extent of coverage varies a lot across countries. Moving carbon tax levels closer to the estimated social cost of carbon (SCC) would make a substantial contribution to reducing nutrient pollution and its attendant biodiversity and health impacts. Most national governments review the evidence on SCC and from that recommend a range of values that could be used in such an exercise. As outlined in Section 6.5.1, potential trade-offs arise on agricultural income and food prices, although these might be limited with improved nitrogen use efficiency.

Environmental assessment tools for nutrient pollution

Nutrient flow assessments can support countries in developing strategies that promote synergistic outcomes. For example, in 2021, the EU Joint Research Committee collaborated with Member States to collect data regarding nitrogen and phosphorus flows, as well as national progress towards EU nutrient waste targets. This data was used to forecast the impacts of potential nutrient pollution interventions on biodiversity, water and air quality and GHG emissions (European Commission, 2025^[336]). The European Commission will use this analysis to develop Integrated Nutrient Action Plans to help each Member Country meet the European Union's goal to reduce nitrogen and phosphorus losses to the air, water and soil by 50% by 2030 (European Commission, 2025^[336]). This objective is aligned with differentiated criteria outlined in the European Union's Biodiversity Strategy to 2030, the Farm to Fork Strategy and the Zero Pollution Action Plan (European Commission, 2025^[336]).

Countries can also conduct SEAs for policies targeting nutrient pollution to improve their practicability and effectiveness. Integrating climate and biodiversity considerations into Strategic Environmental Assessment criteria can identify additional opportunities to refine policies and advance synergistic outcomes. For example, in 2025, Ireland conducted a Strategic Environmental Assessment for its Fifth Nitrogen Action

Programme (NAP) which found that, although the policy was likely to generate synergies across the UN Sustainable Development Goals, including those pertaining to climate and biodiversity, increased guidance on thresholds would support more effective implementation (RPS, 2025^[337]). In response, Ireland committed to modelling the NAP's impacts on water quality, a step that could inform the establishment of thresholds for future NAPs (RPS, 2025^[337]).

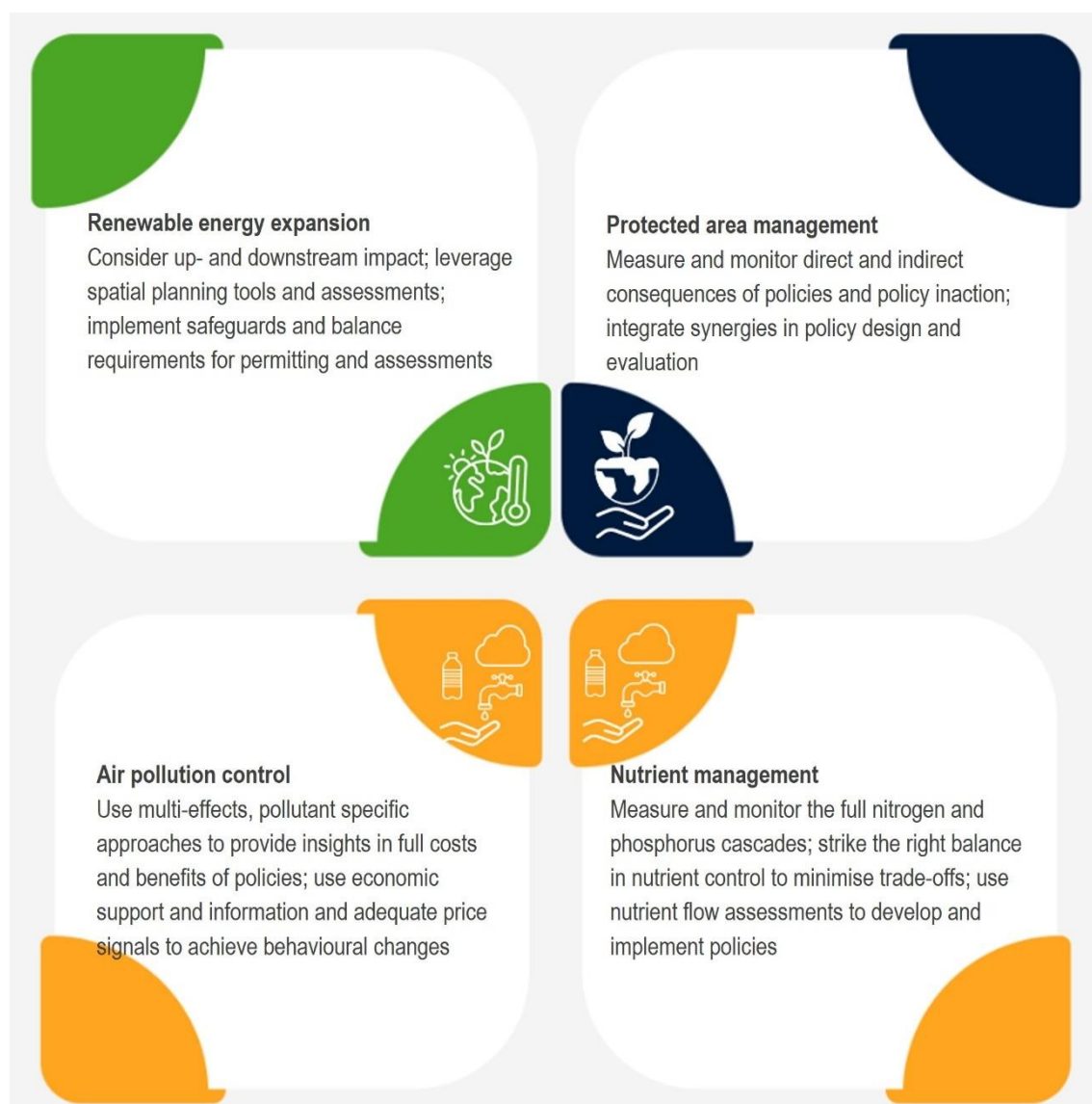
6.6. Key takeaways

This chapter highlights how some of the principles frameworks and mechanisms discussed in earlier chapters can be worked out more concretely when diving deeper into specific cases. The detailed case studies on renewable energy projects, protected area management, air pollution control policies and nutrient management clearly show how many environmental projects and proposals are inherently local, while contributing to significant global benefits when they are well designed and implemented. Each of the deep-dives presented above allows analysis of specific aspects of how the triple crisis interlinks:

- the case of renewable energy expansion emphasises the need to identify the correct counterfactual, and compare effects of projects and policies to what the alternatives may be; this includes embedding spillover effects of the policy on the other aspects of the triple crisis not directly targeted, i.e. beyond climate change mitigation;
- the case of protected areas highlights the risks that unmitigated environmental damage can do to an inherently synergistic policy – e.g. loss of pollution filtering functions due to climate change – thereby undermining not only co-benefits for the other aspects, but also the effective contribution to the core policy objective, in this case biodiversity protection;
- the case of air pollution control measures and their co-benefits for climate mitigation and biodiversity conservation demonstrates the importance of a multi-effect, pollutant-specific approach to enhance synergies;
- the case of nutrient pollution control highlights that environmental impacts are linked in various ways, from soil and water and air in the case of nitrogen and its compound derivatives, to pollution and resource management for phosphorus.

In all cases, the deep dives highlight some core aspects of integrated management of the triple crisis in both design and implementation. Some key considerations are presented in Figure 6.6.

Figure 6.6. Key policy considerations deriving from the deep dives



Source: Authors' own elaboration.

Five key policy recommendations can be formulated on the basis of the insights of these case studies – these key insights inform the roadmap for policy action developed in the next chapter.

First, **synergistic outcomes are often possible but require active consideration and integrated management to materialise**. A systematic approach can ensure that all relevant possible effects are considered; broad environmental impact assessments can help structure the assessment. This requires careful integration and alignment of policy instruments and tools for measurement and monitoring both vertically (across geographical scales – from local to regional to national and from airshed/watershed to global) and horizontally (i.e. by looking at spillover effects on other sectors, other regions and other environmental domains). Identifying the major trade-offs and synergies associated with a project or policy is essential to ensure they are taken into account.

Second, **synergistic policy design does not necessarily mean replacing existing policies with new ones, but rather leveraging existing approaches, policies and modalities better in light of their synergistic effects and trade-offs.** Using an appropriate policy instrument mix can prevent many trade-offs; this includes choosing an appropriate number of instruments to deal with different objectives, not least avoiding using one instrument to try and achieve many objectives, or having overlapping instruments that aim at the same objective. A clear hierarchy can perhaps not be established, but especially at the policy design phase, a careful consideration of the existing situation and relevant alternatives is merited. To generate biodiversity benefits, one can assign new areas to protect, but expansion of existing areas or revision of current areas to improve their connectivity are also relevant options that should be weighed. Countries can use environmental assessment tools both to help formulate and strengthen the effectiveness of policies and evaluate alternatives. Tools like environmental impact assessments and natural capital accounting can help countries determine the value of natural processes. Integrating considerations from all elements of the triple planetary crisis into these tools can help countries identify priority areas for policy consideration.

Third, **(cost-effective) policies that provide incentives to address all aspects of the triple crisis are to be prioritised.** Market-based policy instruments can provide such incentives, but may not always trigger sufficient responses or be administratively cumbersome, so an optimal toolkit contains a variety of policies. Hotspot areas where potential environmental impacts are concentrated are especially of concern and can be targeted with priority. Countries can for instance leverage spatial planning to create priority and non-priority zones to help maximise synergies while the avoiding potential downsides associated with burdensome legal requirements and limit environmental evaluations to those instances where trade-offs are potentially significant. Also important for cost-effectiveness is to weigh the cost and benefits of implementation.

Fourth, **there is a need to measure a range of indicators for climate change, pollution and biodiversity impacts, to be able to identify synergies and trade-offs.** Evaluation hinges on two key aspects (i) robust measurement of impacts and (ii) establishing the appropriate alternative. Renewable energy projects may lead to some unwanted impacts on pollution and biodiversity, but if the alternative is coal mining and coal power generation, then the relevant consideration is the difference in environmental impacts. Although it is not straightforward to measure the environmental impacts of renewable energy expansion and knowledge gaps remain (e.g. assessments of cumulative impacts), countries are adopting various approaches to reconcile the need to accelerate the expansion with more robust consideration of the risks. Examples include identifying priority areas for renewable expansion in which permitting processes are streamlined, as well as enhancing the circularity of end-of-life solar panels and wind turbine blades.

Fifth, **policies need to be aligned across different scales to ensure consistency.** Sound design and implementation will have to consider the relevant scope of the measure, both geographically (e.g. airsheds, cross-border rivers) and sectorally, to avoid undermining policy effectiveness and to exploit available synergies. Anticipating local impacts before crafting policy to proactively identify and address potential pitfalls in local implementation can be key to smooth implementation. Consultations that assess local authorities' operational and technical capacity can help countries craft practicable policies while helping countries invest in required capacity building.

Many countries have established national targets and policies that integrate elements of the triple planetary crisis. Implementation at the local level, using environmental assessments and vertical integration, can be challenging but can also create important synergies of a truly integrated policy landscape, while avoiding trade-offs where possible.

Annex 6.A. Examples of EIAs used for renewable energy projects

EIAs are mandated for major development projects above a certain threshold (e.g. spatial requirements). It is defined in dual terms as: (i) a technical tool for assessing the environmental impact of proposed projects and (ii) an institutional procedure often linked to decision-making (International Association for Impact Assessment, 2009^[338]). The use of EIA for renewables projects is already widespread across countries. At the level of the EU, the EIA Directive (Directive 2011/92/EU, as amended by the Directive 2014/52/EU) sets out the guidance for the procedures and high-level criteria for determining if projects require an EIA, including characteristics and location of projects (e.g. a proposed renewable energy project in a Natura 2000 site, which are designated protected areas for biodiversity conservation). Member states translate the guidance into more detailed criteria and thresholds such as the height of a mast and installed capacity. In Germany, for instance, wind power projects consisting of more than 20 turbines exceeding 50 metres (m) in height must go through an EIA process (Schumacher, 2019^[339]). In France, projects that include at least one wind turbine generators with a height of more than 50 m or a mast between 12 and 50 m and installed capacity exceeding 20 MW are subject to an authorisation process (DGPR et al., 2019^[340]).

In some countries, EIA requirements can be extensive in application of the mitigation hierarchy. For instance, the National Energy and Climate Plan (NECP) in Spain mandates every renewable energy project to undergo an EIA to obtain an Environmental Impact Declaration, which sets out a set of conditions and measures for implementation. These include preventative and corrective measures during construction and operation phases, as well as compensatory measures to offset residual impacts that could not be fully eliminated. Continuous monitoring throughout the projects is also mandated.

There can be a substantial variation in the scope of EIA within a country, including what triggers the EIA screening and the timelines (McMaster et al., 2021^[92]). For example, in the province of Ontario, windfarm developers must obtain a Renewable Energy Approval (REA) from the Ontario's Ministry of the Environment, Conservation and Parks for facilities with a nameplate capacity over 3 kW (Ontario, 2024^[341]).

In the UK, large-scale onshore wind power projects exceeding a production output of 50MW or above are typically subject to an EIA. Wind power installations composed of more than two turbines or exceeding a production output of 5MW are subject to an EIA screening procedure.

In Japan, an EIA is mandatory for wind power plants of capacity greater than 50 MW and for solar projects of at least 40 MW while for wind plants between 37.5-50 MW and for solar projects of 30-40 MW the government it is decided on a case-by-case basis after a thorough screening process (Ministry of the Environment/Japan, 2022^[342]). In New Zealand large-scale wind power farms that are considered to be of “National Significance” are subject to the New Zealand Environmental Protection Authority (NZEPA) evaluation that includes EIA called an “Assessment of Environmental Effects”.

Annex 6.B. Protected area categorisation

The IUCN has developed six categories to classify protected areas based on their management objectives (Dudley, 2008^[343]). These categories regulate human activities with varying levels of stringency, ranging from strict protection in Category Ia areas to sustainable use of natural resources in Category VI areas:

IUCN Category	Definition	Primary Objective
Ia	Strict Nature Reserves: Category Ia are strictly protected areas set aside to protect biodiversity and also possibly geological/geomorphological features, where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values. Such protected areas can serve as indispensable reference areas for scientific research and monitoring.	To conserve regionally, nationally or globally outstanding ecosystems, species (occurrences or aggregations) and/or geodiversity features: these attributes will have been formed mostly or entirely by non-human forces and will be degraded or destroyed when subjected to all but very light human impact.
Ib	Wilderness Areas: Category Ib protected areas are usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, which are protected and managed so as to preserve their natural condition.	To protect the long-term ecological integrity of natural areas that are undisturbed by significant human activity, free of modern infrastructure and where natural forces and processes predominate, so that current and future generations have the opportunity to experience such areas.
II	National Parks: Category II protected areas are large natural or near natural areas set aside to protect large-scale ecological processes, along with the complement of species and ecosystems characteristic of the area, which also provide a foundation for environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.	To protect natural biodiversity along with its underlying ecological structure and supporting environmental processes, and to promote education and recreation.
III	Natural Monuments or Features: Category III protected areas are set aside to protect a specific natural monument, which can be a landform, sea mount, submarine caverns, geological feature such as caves or even a living feature such as ancient groves. They are generally quite small protected areas and often have high visitor value.	To protect specific outstanding natural features and their associated biodiversity and habitats.
IV	Habitat/Species Management Areas: Category IV protected areas aim to protect particular species or habitats and management reflects this priority. Many category IV protected areas will need regular, active interventions to address the requirements of particular species or to maintain habitats, but this is not a requirement of the category.	To maintain, conserve and restore species and habitats.
V	Protected Landscapes/Seascapes: Category V protected areas are where the interaction of people and nature over time has produced an area of distinct character with significant ecological, biological, cultural and scenic value: and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values.	To protect and sustain important landscapes/seascapes and the associated nature conservation and other values created by interactions with humans through traditional management practices.
VI	Protected Areas with Sustainable Use of Natural Resources: Category VI protected areas conserve ecosystems and habitats together with associated cultural values and traditional natural resource management systems. They are generally large, with most of the area in natural condition, where a proportion is under sustainable natural resource management and where low-level non-industrial use of natural resources compatible with nature conservation is seen as one of the main aims of the area.	To protect natural ecosystems and use natural resources sustainably, when conservation and sustainable use can be mutually beneficial.

Source: Dudley (2008^[343]).

Other Effective Area-Based Conservation Measures (OECMs) are geographically defined areas distinct from protected areas that are governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socio-economic, and other locally relevant values (Convention on Biological Diversity, 2018^[344]). Unlike protected areas, OECMs may not have the primary objective of biodiversity conservation (such as sustainable resource management, cultural preservation, or human-wildlife conflict mitigation) but deliver effective conservation outcomes as a by-product of their management.

Key Biodiversity Areas are sites that contribute significantly to the global persistence of biodiversity. These areas are identified based on rigorous scientific criteria, including the presence of threatened species, geographically restricted species, ecological integrity, biological processes, and irreplaceability. KBAs are not legally designated but serve as a tool for conservation planning and prioritisation (IUCN, 2016^[345]).

Natura 2000 is an ecological network of protected areas and the key instrument to protect biodiversity in the EU, designed to ensure the long-term survival of Europe's most valuable and threatened species and habitats. Based on the Birds Directive (1979) and the Habitats Directive (1992), the network includes Special Protection Areas (for wild birds and their main habitats) and Special Areas of Conservation (for most in need habitats and species, excluding birds) and, collectively aiming to maintain or restore natural habitats and species at a favourable conservation status (European Commission - Environment, 2015^[346]).

The **IUCN Green List** is a global standard for protected and conserved areas that demonstrates effective management and equitable governance. It aims to recognise and promote areas that deliver successful conservation outcomes through fair governance, sound design, and effective management practices (IUCN and World Commission on Protected Areas (WCPA), 2017^[347]).

Annex 6.C. Policies to support renewables expansion, manage and enhance protected areas, combat air pollution and manage nutrient pollution

Policies for renewables expansion that integrate biodiversity and pollution considerations

Complementing regulatory measures that are already relatively widespread, there are also emerging examples of economic and information policy instruments countries deploy to reduce risks for biodiversity and pollution associated with renewables. Notably, some of these instruments can be designed in a manner that simultaneously supports consideration of biodiversity and pollution risks.

Taxes with a rate proportional to impacts can incentivise actions to lower risks of biodiversity loss and pollution. While many countries have taxes on solar panels or wind turbines for which the rate is proportional to installed capacity, environmental taxes that are directly proportional to environmental impacts remain rare. Belgium presents an exception, where case law on the tax on wind turbine masts calls on local authorities to determine its value on the basis of “the extent of the environmental and landscape impact caused by the mast and blades of the wind turbine” (OFB, 2023^[104]).

Conditional subsidies can incentivise renewable power and utilities companies to prevent pollution and alleviate impacts on biodiversity. *Research and Development (R&D) subsidies* can also be used to enhance the knowledge and evidence base of the impacts of renewables on biodiversity and pollution. Technological and data advances can play an important role in mitigating the environmental risks associated with renewables expansion. Subsidies can also promote research, development and demonstration of these technologies, such as AI bird-identification technology to support wind turbines’ shutdown-on-demand (OECD, 2024^[2]).

In France, the national research agency has provided support to research projects such as the ePARADISE, which aims to develop a sensor for measuring the airflow near wind turbine blades, optimising their operations and minimising acoustic emissions (IFPEN, 2022^[348]). In a similar vein, subsidies can support decision-support tools to prevent the adverse environmental impacts of renewables expansion. For instance, the UK Research and Innovation (UKRI) has awarded Plymouth Marine Laboratory with an approximately GBP 300 000 (~ USD 363 000) grant to fund the development of the Offshore Renewable Impacts on Ecosystem Services (ORIES) tool that helps stakeholders understand the impacts of planned offshore wind installations on marine biodiversity and ecosystem services.

Countries have also provided *subsidies to enhance circularity* of renewable technologies. Through its Circular Business Models for the Solar Power Industry (CIRCUSOL) programme, the European Commission has funded a range of demonstration projects to re-use, repair and refurbish end of life solar panels (CIRCUSOL, 2024^[349]).

Similar developments are widespread for improving the circularity of wind turbine blades. In Spain, among the Strategic Projects for Economic Recovery and Transformation (Proyectos Estratégicos para la Recuperación y Transformación Económica - PERTE), there was a call in 2022 for projects to support innovative facilities for wind turbine blade recycling (Ministerio para la transición ecológica y el reto

demográfico, 2021^[350]). Furthermore, there will be an additional call with a budget of EUR 100M to support facilities for recycling not only wind turbine blades but also PV panels and batteries in 2025 within the PERTE framework. In France, the Zero waste Blade ReseArch (ZEBRA) project seeks to develop a thermoplastic resin that, combined with a high-performance glass fibre, could be chemically recycled.²⁷ Funded by the European Union, the EoLO-HUBs project, with 18 European partners from 7 countries, aims to propose and demonstrate novel solutions to recycle high value materials from the wind turbine blades, developing a set of innovative composite material recycling technologies. Similarly, in the United Kingdom, the project PProGrESS – a three-year scheme, that seeks to deliver a circular model of wind turbine blades.

Green public procurement – is increasingly seen as a strategic lever for achieving environmental sustainability (OECD, 2024^[351]). Call for tender for large renewable projects is a key policy tools used by countries to subsidise the deployment of large-scale renewables, providing an opportunity for integrating biodiversity and pollution consideration in procurement and tendering.²⁸ For instance, in Spain, non-economic criteria will account for up to 30% of the overall rating in future calls for tender, allowing for the consideration of environmental impact, resilience, and local value chains.

Similarly, in the Netherlands, applications of the two wind farms in the Hollandse Kust West Wind Farm Zone were assessed based on the contribution of the project to the ecology of the North Sea, which accounted for 50% of the total points available (OECD, 2024^[2]). There are also examples of assigning a score based on the budget allocation. For instance, in France, tenders for offshore wind projects are scored based on the budget they allocate to environmental measurement and a biodiversity fund.

Environmental labelling and information schemes (ELIS), defined as “policies and initiatives that aim to provide information about one or more aspects of the environmental performance of a product or service to external users” (Gruère, 2013^[352]), can also help integrate the biodiversity and pollution impacts of renewables. Within ELIS, “ecolabels”²⁹ can help identify environmentally preferable options. There are two main types of labels for the environmental quality of projects. The first type of labels is “producer-oriented” and includes those certifying the electricity produced at source. To be labelled, producers must meet certain eco-responsibility criteria, including the preservation of biodiversity and natural ecosystems, and public participation. For example, in the Netherlands the EcoCertified Solar label certifies that soil health and biodiversity are preserved (Wageningen University, 2025^[353]). EcoCertified Solar excludes Natura 2000 and UNESCO-listed sites and labels projects that prioritise installation in cleared and degraded lands and spare natural habitats (OFB, 2023^[104]). EcoCertified Solar label further requires an environmental management plan, including the complete restoration of the site after dismantling, prevention of soil compaction as well as the monitoring and evaluation of the effectiveness of the avoidance, mitigation and compensation measures.

The second type of labels is “consumer-oriented” and certifies the electricity distributed to consumers by renewable energy suppliers by providing greater transparency for buyers (OFB, 2023^[104]). These labels can be used to enhance the effectiveness of Guarantees of Origin systems used in the jurisdictions including in the European Union and the United Kingdom. For example, the “EKOenergy” label developed in Finland is an internationally recognised label that certifies that electricity commercialised by labelled suppliers come from renewable sources that respects precise criteria such as the exclusion of production in protected areas. EKOenergy also excludes Natura 2000 sites, UNESCO-listed sites and Important Bird Areas according to BirdLife. In Switzerland, “NatureMade Star” labels both the electricity produced, and the electricity distributed to consumers, excluding as a matter of principle for instance wind farms located in Swiss regions listed in the Federal Inventory of Landscapes, Natural Sites and Monuments of National Importance. Another example is the EPEAT Registry, an ecolabel which provides information on photovoltaics to facilitate choice of solar panels that meet standards on chemical substance management, material circularity, water use and carbon footprint (Global Electronics Council, 2025^[354]).

Ecolabels can be used in conjunction to reinforce the incentives provided by economic instruments, as well as with other tools such as green power purchase agreements. However, ecolabels require a balance

between ease of implementation and ecological requirements that are key to avoid any risk of greenwashing. In this context, “EcoCertified Solar”, “EKOenergy”, and “NatureMade Star” all conduct ex post evaluation and audits of production sites to determine whether they comply with the criteria set out in the specifications, which contributes to trust in the information the labels provide.

Green power purchase agreements can help take into account biodiversity and pollution in long-term electricity purchase agreements. In some countries, long-term contracts of about 15 years have been used to finance the development of renewable energy production facilities, making it possible to take a large part of the lifecycle of a renewable energy installation into consideration. These long-term contracts can help reconcile the challenges of preserving biodiversity with developing renewable energy in the region. For example, some renewable energy producers, such as the Danish solar energy company “Better Energy”, offer long-term contracts that contain biodiversity criteria including the choice of renewable energy sites that avoid sites with high ecological risks; preservation of groundwater, soil, flora and fauna; pesticide-free vegetation management at solar PV plants and measures to maintain wild flora and fauna in a good state of conservation (OFB, 2023^[104]).

Countries can additionally leverage the auction process to incentivise developers to proactively integrate biodiversity and pollution considerations into renewable energy proposals. For instance, the European Union’s Net-Zero Industry Act of 2023 mandates that public authorities responsible for renewable energy auctions consider non-price criteria (NPC) in at least 30% of the auctioned volume or 6 gigawatts in each country (European Commission, 2024^[355]). In 2024, Denmark’s NPCs foregrounded upstream and downstream pollution by including LCA, environmental monitoring, and nature inclusive design into their auction criteria (Renewables Grid Initiative, 2024^[356]). Additionally, in 2024, the Netherlands released a permit auction with NPCs for biodiversity. The winning consortium, Noordzeke, partnered with the Dutch research institute for biodiversity to create a proposal that integrated biodiversity considerations by introducing measures to reduce marine mammal disturbance during construction and operation of the windfarm as well as integrating artificial reefs on 75% of the wind turbines (Netherlands Enterprise Agency, 2024^[357]).

Landfill taxes can discourage the disposal of end-of-life wind turbine blades and stimulate more environmentally sustainable waste management, i.e. include biodiversity and pollution considerations in renewable energy projects. The cost of landfills for composite materials is around EUR 120 per tonne in Denmark and around EUR 130 per tonne (including a tax of 95 EUR per tonne) in the United Kingdom (Beauson et al., 2022^[358]). However, in some cases, the cost of recycling composite waste is much higher than the landfill taxes for waste, suggesting that the current rate may only provide an inadequate incentive for recycling and sound waste management (Majewski et al., 2022^[359]).

Extended producer responsibility (EPR) is “an approach that makes producers responsible for their products along the entire lifecycle, including at the post-consumer stage” (OECD, 2024^[360]). Several countries including Germany and France have adopted the EU Waste regulations from Waste from Electrical and Electronic Equipment (WEEE) directives for management of end-of-life solar PV, making manufacturers responsible for the cost of collection and recycling of PVs (Ngagoum Ndalloka et al., 2024^[361]). Unlike solar panels and batteries, wind turbine blades are very large structures and cannot be collected together with municipal waste streams, which has limited the emergence of dedicated EPR schemes thus far. For instance, in the EU WEEE Directive, wind turbine blades are excluded as they are considered “Large Scale Fixed Installations” although some electric and electronic components of wind turbines, such as generators and cables are within the scope of the Directive (Majewski et al., 2022^[359]). Nonetheless, future EPR systems for wind turbine blades are conceivable, for instance, building on the existing EPR for end-of-life vehicles (Alexandre, Follenfant and Legait, 2019^[362]).

Biodiversity offsets are measurable outcomes that result from actions to compensate for residual risks to biodiversity (OECD, 2016^[363]). They can be categorised into (i) restoration offsets and (ii) averted loss offsets, which respectively refer to remediating damage and protection and maintenance of existing

biodiversity (Bennun et al., 2021^[47]). They can be used to mainstream biodiversity in renewable energy projects (OECD, 2024^[2]). For example, restoration has helped the expansion of habitats for golden eagles at the Beinn an Tuirc Wind farm in Scotland (UK) (Wind Europe, 2017^[364]).

However, offsetting is the last step in the mitigation hierarchy. Use of offsets should not be made at the expense of other instruments that are more aligned with the mitigation hierarchy. Importantly, offsets cannot be used to address the loss of irreplaceable or highly vulnerable biodiversity. Biodiversity offsets have in practice not often worked as intended and can therefore be considered with caution. The effectiveness of biodiversity offsets is difficult to ascertain; for instance, many offsets assume a certain background rate of biodiversity decline and implicitly counts aversion of this decline as gains (Maron et al., 2018^[365]). Conservation banks (also known as biobanks) aim to deliver biodiversity gains in advance, before the impacts occur but are not widely adopted (Bennun et al., 2021^[47]). Achieving equivalence of losses and gains is difficult in practice, as compensating for permanent losses, for instance, would require offsets to deliver in-perpetuity protection with ongoing funding if they are to achieve no net loss meaningfully (Maron et al., 2025^[366]). In this context, there is a need for better understanding of what can be offset in practice. Offsets are meant to deliver a quantifiable benefits to compensate for the same amount of damage; lack of efficacy and shortfalls of offsets therefore constitute not only an opportunity cost, but also a realised loss of biodiversity that might not otherwise been permitted if it was not for the introduction of offsets (Maron et al., 2025^[366]).

Policies to manage and enhance protected areas to achieve biodiversity benefits

Target 3 of the Kunming-Montreal Global Biodiversity Framework aims to ensure the effective conservation of at least 30% of terrestrial and inland water areas by 2030. Achieving this target will require the designation of new protected areas to complement the current coverage of 17.6% of terrestrial and inland waters and 8.4% of marine and coastal areas (UNEP-WCMC and IUCN, 2024^[180]).

Despite the designation, protected areas do not always effectively deter biodiversity loss caused by anthropogenic activities, and downgrading (i.e. reduction of legal restrictions on human activities), downsizing (i.e. decrease in its size) and 'degazettement' (i.e. loss of legal protection) of protected areas (PADDD) have affected both terrestrial and marine protected areas. Aska et al. (2023^[367]) examined 1 743 tailing storage facilities from mining operations, which account for 36% of global mineral commodity production, and found that 9% are located within protected areas. Half of these facilities were established after the designation of the protected area. Of these, 40% were in IUCN Category VI areas, while a concerning 10% were in Category II areas (see definitions in Annex 6.B). Within marine protected areas, 43 PADDD events have been enacted until 2020, among which in Australia, Dominican Republic, Palau, and South Africa (Albrecht et al., 2021^[368]).

Mainstreaming protected area management into national policies and decision-making frameworks is essential, alongside its incorporation into sectoral plans and strategies (UNDP, SCBD and UNEP-WCMC, 2021^[369]). The integration of protected areas entails a two-fold process (Ervin, 2010^[370]): (i) linking protected areas within a broader network of protected and managed lands and waters in order to maintain ecological processes, functions and services, such as ensuring their representativeness, consistency and connectivity; (ii) reducing habitat fragmentation and supporting the connectivity of networks of protected areas is key to ensure their effectiveness of conserving biodiversity, and their capacity to adapt to the effects of climate change.

Annex Figure 6.C.1 illustrates the concept of integration and mainstreaming of protected areas at the national level. The first level of the integration of the information on protected areas consists in measuring and collecting their extent and condition, and how much their coverage represents compared to the national terrestrial/marine area. The second level, so far rarely implemented, is to assess the ecosystem services of protected areas systematically, including at upper jurisdictional scales (local, national, supranational and

international). The third level is to consider protected areas as part of a network, and to assess how representatively and consistently biodiversity is conserved and how many ecosystem services are provided when all networks are aggregated. The fourth level of integration is to account for migration corridors of species, to ensure that the network of protected areas is well-connected. The monitoring framework of the Kunming-Montreal Global Biodiversity Framework proposes the two following global indicators to assess the ecological representativity, and the well-connectedness of terrestrial protected areas (Hilty et al., 2020^[371]): the Protected Connected land indicator (ProtConn) and the PARC-Connectedness indicator.

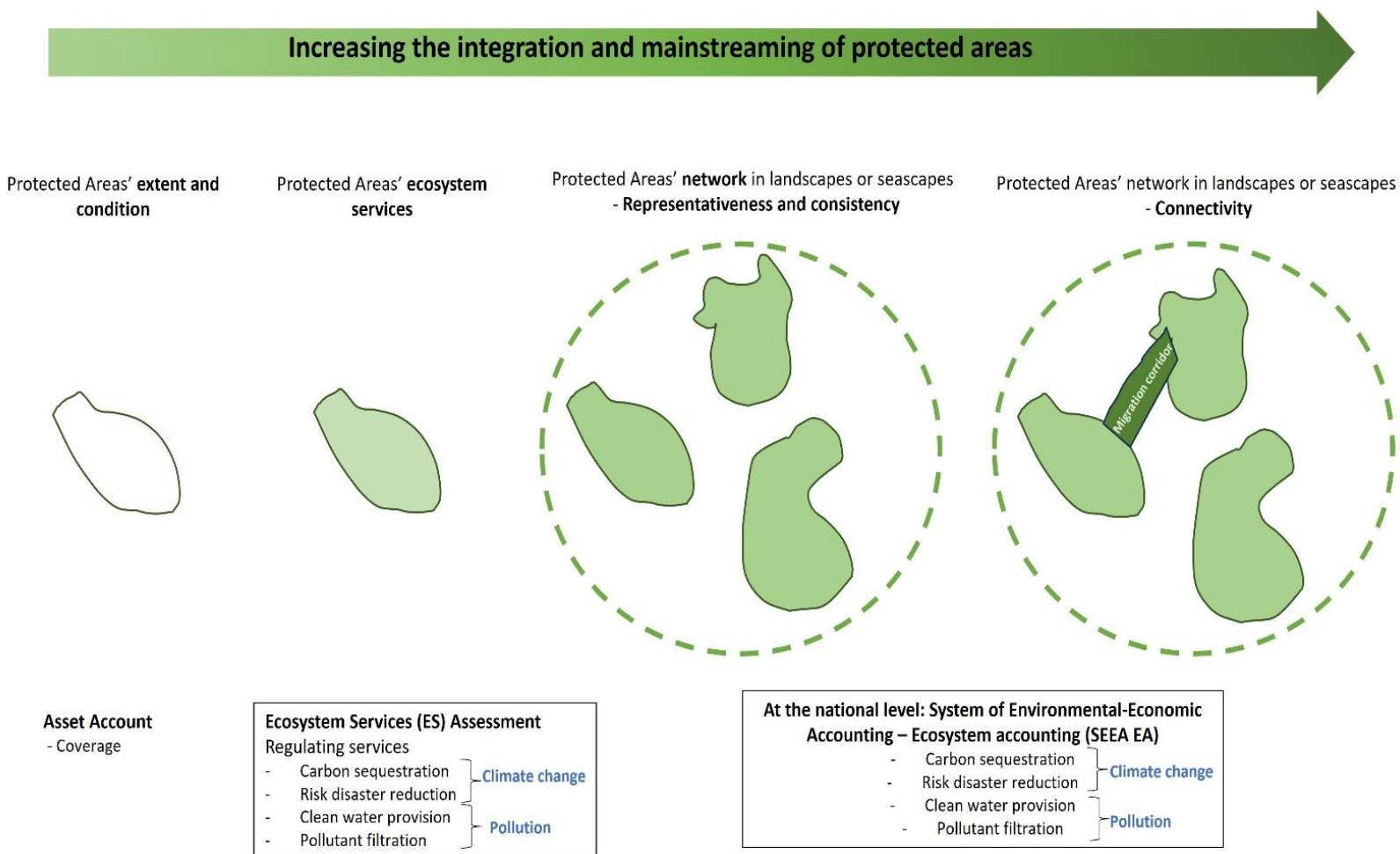
Incorporating protected areas into broader land-use plans, natural resource policies, and national strategies can maximise biodiversity benefits, enhance ecosystem services, and mitigate threats to biodiversity. Protected areas can be integrated into National Biodiversity Strategies and Action Plans (NBSAPs), National Adaptation Plans (NAPs), and Nationally Determined Contributions (NDCs). Embedding protected areas into these strategies facilitates vertical and horizontal integration, enabling the tracking of biodiversity goals alongside co-benefits for climate change and pollution. According to the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES), mainstreaming biodiversity involves incorporating biodiversity-related actions or policies into broader development processes, such as poverty reduction or climate change mitigation. (Secretariat of the Convention on Biological Diversity, 2016^[372]).

Protected areas monitoring can serve as a cross-sectoral indicator within national adaptation plans, relevant to agriculture, forestry, water management, infrastructure, and tourism (OECD, 2024^[373]). For instance, the UK has included the protection and improvement of protected sites and other areas of important wildlife habitat as an adaptation objective, linked to the target of restoring 75% of terrestrial and freshwater sites to favourable condition by 2042 (Department for Environment, Food and Rural Affairs, 2023^[374]).

Protected areas can create negative spillover effects on surrounding regions, called “leakage” or “displacement” effects. For example, restrictions on land or sea use within protected areas may displace harmful activities to unprotected areas, such as deforestation (Murray, McCarl and Lee, 2004^[375]) or fishing (Sen, 2010^[376]), and causing unintended degradation. Within a random selection of 120 protected areas established before 2001, in tropical forests of America, Africa and Asia, deforestation rates between 2001 and 2017 were higher in about half of the 10 km buffer zones of protected areas compared to inside them or in control areas (determined by propensity score matching) (Ford et al., 2020^[377]). In more than three-quarters of these documented leakage cases, reduced deforestation in protected areas was not sufficient to offset the amount of deforestation in these buffer zones to a level that would be expected without protection.

Nevertheless, assessing the causal effects – and associated spillovers - of protected areas is challenging mostly due to data availability, selection bias and heterogeneity in treatment effects. Indeed, the causal estimation of the impacts of protected areas is complex due to the (i) the need of comparable conservation metrics and indicators across protected and unprotected areas, potentially covering a wide geographic area and hence different biodiversity and ecosystems ; (ii) site selection issues may arise since the status of protected areas is not randomly distributed and is often designed in higher biodiversity zones, with lower habitat conversion pressures and lower accessibility (Brodie et al., 2023^[378]; Cooke et al., 2023^[379]; Reynaert, Souza-Rodrigues and van Benthem, 2024^[380]); (iii) the effects of protection may vary by type of ecosystem, economic restrictions, enforcement stringency, year of implementation and makes it difficult to build an average treatment effect (Vincent, 2015^[381]; Reynaert, Souza-Rodrigues and van Benthem, 2024^[380]).

Annex Figure 6.C.1. Integration of protected areas at the national level



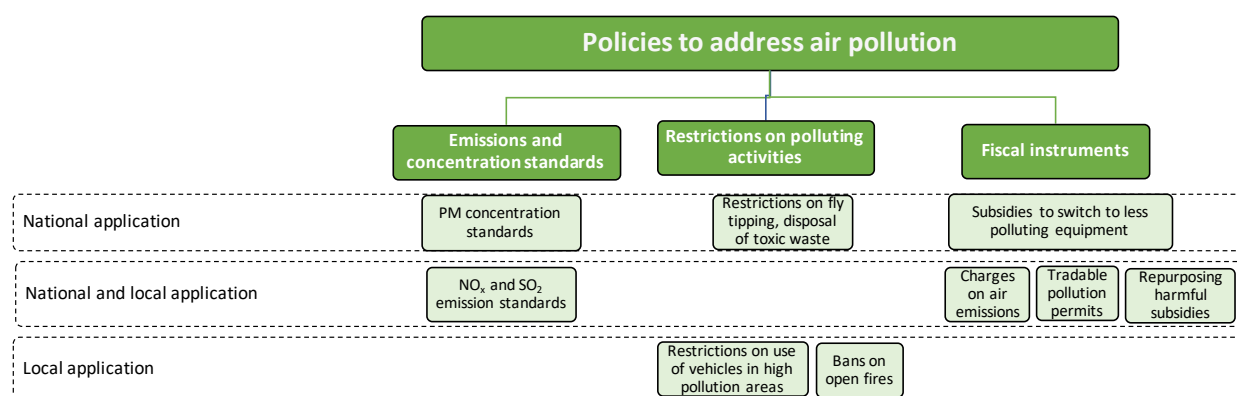
Source: Authors' own elaboration.

Policies to control air pollution

Policies to address air pollution can be classified as regulatory, legal, economic and social. They can act at the local, regional, national or international levels. Policies are implemented in packages, which include combinations of each kind, with action often taken at more than one level.

There is a very large range of policies that address emissions to air. Annex Figure 6.C.2 summarises the main pathways by which these are conducted. Primary among them are regulations that set emissions limits – e.g. to the air from vehicles, factories or power stations. Regulations also exist that set limits on concentrations of pollutants in different locations. Furthermore, governments impose restrictions on activities in different areas and at certain times, such as driving polluting vehicles in high congestion zones or burning waste when there is a fire risk. Lastly, there is a large set of fiscal instruments (taxes and subsidies) to encourage reduced emissions from several of these sources.

Annex Figure 6.C.2. Policies to deal with air pollution



Source: Authors' own elaboration.

Emissions standards for air pollution have generally been effective in lowering concentrations of key pollutants such as PM_{2.5} and NO_x, especially in developed countries. Death rates from PM_{2.5} have been declining widely (India is a notable exception). In the EU, for example, in 2021, 253 000 premature deaths in the EU were attributable to fine PM, a 41% drop since 2005 (European Environment Agency, 2023^[382]). Emissions of sulphur have also fallen but the pattern has been more mixed. From 1990 to 2015, Europe had the largest reductions in sulphur emissions in the first part of the period while the highest reduction came later in North America and East Asia. However, emissions from East Asia increased from 2000 to 2005 followed by a decrease, while in India a steady increase over the whole period has been observed (Aas et al., 2019^[383]). The decreases in PM and NO_x have been accompanied by a reduction in CO₂, which represents a lowering of the warming effect. The fall in sulphur has the opposite effect but its magnitude is uncertain.

The use of fiscal instruments such as pollution taxes, permits and subsidies has seen a considerable increase worldwide. The latest OECD PINE database identifies over 4 500 policy instruments relevant to environmental protection and natural resource management in 146 countries globally (OECD, 2024^[176]), up from 3 900 policy instruments in 2023 (OECD, 2023^[384]). Environmentally related taxes and fees are expanding in all countries. They represent over a third of the instruments in the PINE database. This now includes around 900 taxes and fees in 146 countries. Other economic instruments that address air pollution include tradable permits and offsets and voluntary approaches.

Although the number of instruments is large, information on their direct impacts is limited, and their spillover effects even more so. Studies on the direct effects have found that when taxes are high relative to abatement costs, they have reduced emissions considerably (e.g. taxes on SO₂ and NO_x in Sweden) (European Commission, 2024^[385]). More commonly, however, where tax rates are low relative to abatement costs, the impacts are much smaller. This is the case for example in a number of European countries – Italy, France and Spain, amongst others (Withana et al., 2014^[386]). The use of waste as source of energy through incineration with energy recovery has increased with a reduction of GHGs.

Subsidies to encourage a switch to less polluting production and consumption have also been introduced, although less than taxes. The PINE OECD database identifies 215 environmentally beneficial subsidies and payments across 146 countries. Subsidies have a fiscal cost, which can be distorting to the economy. They also provide an incentive to increase production, which can raise pollution levels. In general, economists find such subsidies less effective than taxes in addressing pollution problems (Stavins, 2003^[387]). An example of a subsidy is the scheme to get owners to scrap old more polluting cars for newer, less polluting ones which has been introduced (temporarily) in several countries. An ITF review of schemes finds that such schemes have a synergistic effect in reducing CO₂ and air pollutants; the costs are relatively high, however, and do not make up for the value of the scrapped cars (ITF, 2011^[388]). A car scrapping and recycling scheme was introduced in Cairo between 2013 and 2017 and has been successful in reducing CO₂ emissions there by about 350 kilotons by 2018 (World Bank, 2018^[389]) but it has not been evaluated in terms of its effects on air pollution.

Some jurisdictions set out frameworks for ensuring consistency of air pollution policies with climate and biodiversity objectives. For instance, the revised Ambient Air Quality Directive in the EU, setting higher ambition and stricter air quality standards for 2030 and the goal of zero pollution by 2050, highlights the need for consistency between air pollution policy and other policy domains, including climate and biodiversity (European Commission, 2024^[390]).

Policies to mitigate nutrient pollution

Targets for nutrient inputs and emissions

Policies to mitigate nutrient pollution are often set in terms of targets for inputs in (agricultural) production (e.g. fertiliser use) or in terms of emission levels. The United Kingdom has a target of reducing nitrogen and phosphorus pollution from agriculture into the water environment in England by at least 40% from a 2018 baseline by 2038, with an interim target of 10% by 31 January 2028 (UK Department for Environment, Food and Rural Affairs, 2023^[391]). It also aims to reduce phosphorus loadings from treated wastewater by 80% by 2038 against a 2020 baseline, with an interim target of 50% by 31 January 2028 (UK Department for Environment, Food and Rural Affairs, 2023^[391]). The European Union includes several targets by 2030: a 50% reduction in nutrient losses (known as Farm to Fork strategy) without deterioration of soil fertility, a 20% reduction in fertiliser use, as well as a 25% reduction in the total ecosystem area where air pollution threatens biodiversity relative to 2016 (key Green Deal ambitions under EU law). In addition, targets are set for individual nitrogen-based air pollutants: a 13% reduction in NO_x emissions and an 11% reduction in NH₃ emissions by 2030 (European Parliament and the Council of the European Union, 2016^[392]). Globally, there is the International Nitrogen Initiative (INI) to reduce nitrogen waste by 50% by 2030. This initiative is working with governments, businesses, and citizens to achieve this goal outlined in the Colombo Declaration on Sustainable Nitrogen Management (UNEP, 2019^[393]).

While targets for NO_x reductions have been met for most EU member states, this is not the case for NH₃.³⁰ More widely, there has been an increase in the production of NH₃ but with a small reduction in NH₃ emissions. Across the OECD region, NH₃ emissions decreased in the period 2003-15 by 3.2%. This was a slower rate than during the period 1993-2005 when the decrease was 8.6% (OECD, 2019^[394]). Since 2005, in many EU member states, NH₃ emissions have decreased only slightly or in some cases even

increased, with almost one third of EU member states having emission levels above the emission reduction commitments for 2020-2029 and requiring emission reductions to meet the commitment (EEA, 2024^[395]).

Phosphorus surpluses decreased across almost all OECD countries since the 1990s, driven by reduced phosphorus fertiliser application rates, livestock population, crop-mix changes, and policy interventions, but phosphorus pollution remains at an alarming level (OECD, 2019^[394]). Phosphorus fertiliser application rates fell for most OECD countries since the 1990s, possibly as a result of improved farm practices or usage of alternative fertilisers, but (as outlined in Chapter 2) were still substantial across all regions in 2020. Phosphorus losses from land to fresh waters have doubled in the last century and continue to increase in many regions (Our Phosphorus Future Network, 2022^[290]).

Since the 1960s, the application of mineral nitrogen fertiliser has been increasing globally across all regions. Many OECD countries have used a system of high fertiliser use and high yields, and differences in fertiliser inputs with emerging and developing economies have persisted. Thus, OECD countries tend to release large amounts of reactive nitrogen to the environment but also recovering a greater portion of added nitrogen in crops. This recovery efficiency has not changed noticeably, implying additions of nitrogen to the environment have been going up (Conant, Berdanier and Grace, 2013^[396]). Furthermore, differences in nitrogen absorption and utilisation efficiency between OECD and other countries has persisted. Improvements in efficiency especially in non-OECD countries offer scope for reducing nutrient runoff (Conant, Berdanier and Grace, 2013^[396]). As outlined in Chapter 3, nitrogen and phosphorus deliveries in agriculture are expected to increase by 2050, particularly in lower- and middle-income regions (e.g. for lower-income regions +41% for nitrogen and +40% for phosphorus).

These figures highlight the need for more effective policies targeting the agriculture sector to apply well-established agricultural practices that bring down nutrient pollution. They include practices related to applying fertilisers and manure, and balancing feed for livestock. Nutrient use efficiency is the product of nutrient uptake efficiency (how much nutrient plants can take up) and nutrient utilisation efficiency (the yield per unit of nutrient that is taken). For nitrogen, nitrogen use efficiency currently varies from around 30% to 53% (Anas et al., 2020^[397]). Nitrogen losses are up to 70% of total available nitrogen (Anas et al., 2020^[397]). While nitrogen management policies introduced in the past decades by some OECD countries have succeeded in reducing excess nitrogen use by farmers, half of global mineral nitrogen fertiliser used is still lost for crops (Andersen and Bonnis, 2021^[285]). For phosphorus, as much as 80% of the mineral is not (directly) taken up by plants (Our Phosphorus Future Network, 2022^[290]). This could be reduced by adopting policies for improved agronomic approaches as discussed below, but good soil management is also essential to ensure the phosphorus does not leak to water bodies.

Other measures to reduce nutrient pollution

Countries have introduced a wide range of measures to reduce nutrient use, covering advice to farmers on more efficient application and management, subsidies for the adoption of better practices and, in a few cases, taxes on fertilisers and emissions of nitrogen.³¹ Common measures include: more informed fertiliser application, integrated nutrient management (i.e. optimal use of indigenous nutrient components), increased use of modified fertiliser (i.e. products that improve use efficiency by reducing various losses of nutrients associated with production system and by enhancing their beneficial use in plants), improved methods of nitrogen and phosphorus application, adoption of low nitrogen feed, coverage of manure when stored and low emission animal housing (Singh et al., 2018^[398]; Giannakis et al., 2019^[399]).

Piñeiro et al. (2020^[317]) review nearly 18 000 papers on whether incentive-based programmes led to the adoption of sustainable practices (including nutrient management) and their effect on environmental, economic and productivity outcomes. The authors find a clear association between market and non-market-based incentives and environmental objectives in a subset of the papers and the review also shows an evidence base for environmental outcomes associated with cross-compliance incentives. The main cross-compliance incentives are Payments for Environmental Services (PES) and other agri-environment

payments. These are incentives offered to farmers, or landowners, in exchange for managing their land to provide some type of ecological service, including water quality, forestry, soil erosion and air pollution. For example, in 2023, the European Commission approved the Netherlands' EUR 1.47 billion in agri-environmental schemes aimed at reducing nitrogen deposition on conservation areas. This included a EUR 975 million scheme providing grants to compensate farmers for voluntarily ceasing agricultural practices, such as dairy cattle breeding, that contribute to nitrogen emissions near Natura 2000 sites. These schemes are part of the Netherlands' broader strategy to meet EU environmental objectives under the European Green Deal (European Commission, 2023^[400]).

Piñeiro et al. (2020^[317]) find less consensus and documentation in the case of regulatory measures, where more measurement and reporting are needed. It is also important to note that most of the evidence on environmental outcomes is qualitative through assessment of farmers' perceptions. Stronger identification strategies, and especially measurement and monitoring through environmental assessments, are needed to uncover the causal effect of the chain of incentives, adoption and outcomes.

In technical terms the abatement measures range from containment and capturing of manure nutrients, to employment of novel cleaner technologies and structural measures in the agricultural sector to reduce nutrient volumes. For the European Union, actions found to be most cost-effective in meeting the NH₃ targets were, in order of lowest cost first where each would fully achieve the required emission reduction: adoption of low nitrogen feed, coverage of manure when stored, improving or substituting urea fertiliser application and use of low emission animal housing (Giannakis et al., 2019^[399]). Information on adoption of such measures, however, is not available. Also, the cost-effective analysis was based only on direct costs and did not take account of climate or biodiversity co-benefits of the different actions.

Permit trading for nitrogen emissions can help reduce the cost of meeting an emissions reductions target. Hasan et al. (2022^[401]) compare the use of a market trading of permits for nitrogen emission against a uniform reduction for all emitters in Denmark (Hasan et al., 2022^[401]) and find a 56% lower cost of meeting the target of a 21.5% reduction in nitrogen emissions when using market trading of permits. A higher reduction target might be possible, with its corresponding greater GHG and other pollution reduction benefits, at the same overall cost as is experienced by the present system of uniform regulation.

Taxes on fertilisers

A tax on surplus nitrogen set in the range of the abatement costs (estimated at EUR 0.1 to 0.6 per kg of nitrogen) could generate significant environmental benefits (valued at EUR 0.3-10 per kg of nitrogen) as well as some reductions in GHGs and could be justified on these grounds. To advance the adoption of the measures, Andersen and Bonnis (2021^[285]) argue for a tax on surplus nitrogen at a rate of EUR 1-2 per kg of nitrogen as a suitable starting point. No estimate is made, however, of the likely reduction in nitrogen or the decline in GHGs that could be achieved through this tax.

A tax can also be used as a complement to direct control measures, making the latter more effective. Liu et al (2023^[402]) construct an integrated multi-scale framework for evaluating alternative nitrogen loss management policies for corn production in the US. This approach combines site- and practice-specific agro-ecosystem processes with a grid-resolving economic model to identify locations that can be prioritised to increase the economic efficiency of the policies. They find that regional measures, albeit effective in reducing local nitrogen loss, can displace corn production to the area where nitrogen fertiliser productivity is low and nutrient loss rate is high, thereby offsetting the overall effectiveness of the nutrient management strategy. This spatial spill-over effect can be suppressed by implementing such measures in tandem with nationwide tax policies. For example, a wetland restoration policy combined with split fertiliser application, along with a nitrogen loss tax could reduce nitrogen loss to the Mississippi River by 30% while only increasing corn prices by less than 2% (Liu et al., 2023^[402]). The final tax is determined by the nationally uniform 5 nitrogen fertiliser price (EUR per kg of nitrogen applied), and the product of a nationwide tax rate of USD 1 per kg of nitrogen loss and the nitrogen loss intensity (kg of nitrogen loss per kg of nitrogen application) that varies by location. The nitrogen loss tax is, however, only a proposal.

Subsidies and other regulations on fertiliser

Regulations to limit mineral fertiliser use have been introduced for example in New Zealand, which imposes a cap on the nitrogen content of mineral fertilisers used on pastoral land (New Zealand MFE, 2023^[403]). Accordingly, each hectare of grass pasture has a synthetic nitrogen fertiliser limit of 190 kg/ha/yr – anything above this requires a resource consent. On land planted with fodder crops, the limit of 190 kg/ha/yr may be exceeded to meet the needs of some types of plants, but the average across the pastoral system must not exceed 190. In the European Union, the Good Agricultural and Environmental Conditions standards require the establishment of buffer strips along watercourses to ‘protect river courses against pollution and run-off’. A ‘buffer strip’ is an area where fertilisers and plant protection products cannot be applied and must be three metres wide or more. Member States define this bottom width and may add other criteria. In Germany, farmers have not been permitted to apply urea without combining it with urease inhibitor or incorporating it into the soil within four hours (Jones and Deuss, 2024^[276]).

At the same time, several developing countries still subsidise fertilisers to increase production but with possible negative impacts on the environment, health and climate. For example, between 2020-2022 the annual average value of fertiliser subsidies provided by the government of India totalled more than USD 22 billion (Jones and Deuss, 2024^[276]). India is currently the second largest user, producer and importer of phosphorus-based fertilisers as well as the second largest user and producer, and first importer of nitrogen-based fertilisers (Adenäuer, Laget and Cluff, 2024^[299]). For urea (the main form in which nitrogen is applied by Indian farmers), the government sets a Maximum Retail Price (MRP) and pays manufacturers the necessary subsidy to achieve this (Jones and Deuss, 2024^[367]). Repurposing such subsidies to realign fertiliser support and soil health programmes can benefit the farmers livelihoods as well as climate and biodiversity (OECD, 2024^[405]; Damania et al., 2023^[406]; OECD, 2024^[407]; Valin, Henderson and Lankoski, 2023^[408]).

Bans on manure application on bare fields (after harvest) have been imposed for example in Denmark. From 2019/2020, no liquid manure can be applied to fields after harvest, except to grass or winter oilseed rape until October 1. Solid manure can be applied in autumn to fields before sowing winter crops and to bare soils from October 20 to November 15. In consequence, 92% of liquid manure was spring-applied in 2018, increasing from 55% in 1990 (Sommer and Knudsen, 2021^[409]). Sufficient manure storage capacity is a prerequisite for complying with this regulation, and since 1993, the requirement has been a minimum 9-month storage capacity (or 6 months on farms where late application of manure was acceptable) (Sommer and Knudsen, 2021^[409]).

Further regulatory restrictions encompass application techniques, as simple and cheap broadcasting spreads the manure unevenly and has given rise to concerns over NH₃ volatilisation and nutrient losses in runoff resulting from broadcasting. In Denmark, this technology has been banned since 2002 and replaced by the trail hose application technology. The requirements have since been further tightened, and from 2019/20, slurry must be applied by injection to grassland and bare soils. Alternatively, acidified slurry may be applied with trail hoses to grassland, but acidified slurry must be injected to bare soil. Adding acid may take place in animal houses, during storage or while applying the liquid manure (Sommer and Knudsen, 2021^[409]).

Taxes on nutrient feed

Beyond fertiliser-related policies, policies on nutrient management also encompass animal feed taxes, such as the animal feed mineral phosphorus tax that came into effect in Denmark in 2005. With a tax rate of DKK 4 (EUR 0.53) per kg of phosphorus, it targets commercial animal feed phosphate to encourage a switch to phytase (an enzyme that helps to enhance phosphorus uptake) to reduce the need for mineral phosphorus additives. The justification for the tax is the high loss rate of up to 90% associated with animal feed phosphorus supplied to large livestock installations, mainly pork and poultry. The tax is a measure to reduce the saturation of agricultural soil with phosphorus and to curb the leaching of phosphorus to waters (Andersen, 2016^[410]).

Mineral phosphate use in animal feed has fallen by about 2 000 t (15%) since the introduction of the tax, and phytase use has increased (OECD, 2019^[411]). The tax is thus believed to have improved overall efficiency in the use of animal feed. A new phosphorus regulation introduced in 2017 allows efficient feeding, for example using high doses of phytase, to meet requirements on phosphorus reductions. It has resulted in a stronger incentive to increase phytase and reduce mineral phosphorus use than the tax. To prevent double regulation, the tax was abolished in July 2019 (OECD, 2019^[411]).

Taxes on NO_x

Taxes on have also been added on NO_x emissions. Sweden introduced such a tax in 1992 on nitrogen oxides from large combustion sources (e.g. power plants, industrial plants, waste incinerators) that was accompanied by a refund of the revenue raised (except administration costs) according to the amount of energy generated (OECD, 2013^[288]). This ensures that facilities with low NO_x emission intensities are net beneficiaries of the scheme. Originally at SEK 40 per kg, from 1 January 2008, the tax rate was increased to SEK 50 (around EUR 5.5) per kg, partly to maintain a strong abatement incentive (OECD, 2013^[288]). Actors who continually measure and register emissions using measurement tools that meet specific requirements are permitted to calculate the charge based on their measurements, following extensive guidelines (Swedish Environmental Protection Agency, 2024^[412]). NO_x declarations are submitted via the e-service E-NO_x³².

Annex 6.D. Links among nitrogen, phosphorus and the triple planetary crisis

Nitrogen pollution accelerates the triple planetary crisis

In the case of air emissions, NH_3 from fertilisers and manure reacts with other chemicals to form particulates that are harmful to biodiversity. NH_3 is one of the main sources of nitrogen pollution. A major effect of NH_3 pollution on biodiversity is the impact of nitrogen deposition on plant species diversity and composition within affected habitats (Guthrie et al., 2018^[413]). Common, fast-growing plants well adapted to high nutrient availability can thrive in a nitrogen-rich environment and tend to out-compete species which are more sensitive, smaller or rarer – for example, sensitive lichen and mosses can be damaged by even low concentrations of NH_3 (Guthrie et al., 2018^[413]). NH_3 also impacts species composition through soil acidification (as the nitrogen compounds deposit on land through rainfall), direct toxic damage to leaves, and by altering the susceptibility of plants to frost, drought and pathogens. If changes in species composition and extinctions are large, some ecologically significant habitats may be lost (Guthrie et al., 2018^[413]). These biodiversity impacts have not, however, been quantified in relation to changes in NH_3 .

The contributions of nitrogen pollution to climate change are complex. For example, NH_3 emissions ultimately reach the ground (soil, vegetation, or water) and increase emissions of the GHG N_2O (Figure 6.4). One estimate of the synthetic nitrogen fertiliser supply chain calculates it was responsible for global emissions of 1.13 Gt of CO_2e in 2018, representing 10.6% of agricultural GHG emissions and 2.1% of global GHG emissions (Menegat, Ledo and Tirado, 2022^[414]). The actual amounts of emissions, however, vary by type of fertiliser and methods of application.

Overall, reductions in applications of nitrogen and phosphorus as mineral fertiliser are considered to provide benefits to air, soil, and water. They also have significant benefits in terms of less damages to aquatic and terrestrial ecosystems, contribute to biodiversity conservation, pollution control, climate change mitigation, and to human health for the reasons given above. To tackle the environmental and public health challenges of the various nitrogen forms, OECD (2018^[415]), in collaboration with the United Nations Economic Commission for Europe (UNECE) Task Force on Reactive Nitrogen, proposes a three-pronged policy framework consisting of (i) analysing nitrogen pathways to better manage environmental risks; (ii) addressing N_2O emissions in climate change mitigation policies; and (iii) monitoring and managing residual nitrogen by measuring the effect of the above measures on the national nitrogen budget (Annex Box 6.D.1).

Annex Box 6.D.1. OECD-TFRN three-pronged policy framework

The three-pronged approach to respond to nitrogen pollution includes:

1. Analysing nitrogen pathways to better manage environmental risks

First, there is a need to manage local pollution risks by better understanding the pathways of nitrogen between sources and impacts (the so-called “spatially targeted risk approach”), for example with regards to the resilience of ecosystems to increased nitrogen loading.

The spatially targeted risk approach framework highlights the importance of Impact-Pathway Analysis (IPA)¹ when applicable, and proposes to:

- Identify the nitrogen sources of relevance to the impact at the local level and delineate the different nitrogen emission zones that converge towards the risk area.
- Calculate the marginal abatement costs for reductions in release of the different nitrogen forms. For that, estimate the potential for new or additional emission reductions in each emission zone through cost-effective analysis.
- Compare the cost-effectiveness of emission reductions for all sources of risk in the different emission zones to ensure coherence of interventions.
- Estimate the marginal ancillary benefits of reducing nitrogen emissions in the different emission zones (i.e. the avoided damages along the pathways of nitrogen to the risk area).

The third step in IPA is yet not widespread in the implementation of nitrogen policies. For example, nitrogen sources other than agriculture – such as industry, wastewater, atmospheric sources and net nitrogen exchanges with marine waters – have not been included in assessing the cost-effectiveness of eutrophication risk management measures in Denmark.

2. Addressing N₂O emissions in climate change mitigation policies

Second, account must be taken of the observed increase in global atmospheric concentrations of N₂O that have consequences for both climate change and stratospheric ozone (the “global risk approach”).

Feasibility limitations of effective IPA might arise and highlight the need for an integrated policy approach. Nitrogen pathways do not follow the administrative boundaries and can extend beyond national borders. IPA has an important role to play in facilitating the adoption of new international provisions to manage transboundary nitrogen-related pollution.

IPA does not apply to N₂O as the risk area (be it the risk of a greenhouse effect or the risk of depletion of the ozone layer) is global. Delineating emission zones, if at all possible, would be of no use for the purposes of cost-effective analysis (or cost-benefit analysis). The more sources are compared, the more likely it is to find the one for which emission reduction is the most cost-effective. In other words, as many sources of N₂O as possible should be identified, wherever they are, so as to monitor them and compare the costs – and if possible the ancillary benefits – of reducing their emissions. This requires a global approach.

3. Monitoring and managing residual nitrogen by measuring the effect of the above measures on the national nitrogen budget

Third, there is a need to prevent “excessive” nitrogen entering the environment by developing strategies addressed to the different sources (on the basis of the most cost-effective means) to reduce them (the “precautionary approach”). Precautionary management copes with uncertainties in the nitrogen cascade in cases where conducting an IPA may not be scientifically possible yet.

The main policy responses are summarised in Annex Table 6.D.1.

Annex Table 6.D.1. A three-pronged approach to address nitrogen pollution

	Spatially targeted risk approach	Global risk approach	Precautionary approach
Nitrogen forms	All but N ₂ O	N ₂ O	All
Pathways	IPA	Global exposure	Nitrogen cascade
Focus	Media-specific (air, soil, water)	Greenhouse effect, ozone layer	"Systemic" (all-media)
Intervention points (scale)	Risk specific	Global	National (based on monitoring the country's total nitrogen load)
Policy effectiveness	High (tailored to risk)	High (tailored to risk)	Low (only targets the nitrogen load) ²
Policy priority	According to policy objectives	According to policy objectives	When IPA is not possible

Source: OECD (2018^[415]).

1. Impact-Pathway Analysis (IPA) is an evaluation of the pathways that generate an impact (including through modelling) to estimate the expected benefits of possible emissions changes (OECD, 2018^[415]).
2. It can be assumed that ecosystems respond differently to changes in nitrogen load, depending on the type of ecosystem and local conditions (OECD, 2018^[415]).

Phosphorus pollution accelerates the triple planetary crisis

The impacts of phosphorus mining on the triple planetary crisis

In terms of pollution impacts from phosphorus surface and underground mining activities, mining may transfer toxic metals and radioactive elements into the environment and contribute to air pollution. Land disturbance by phosphate mining activities increases the concentrations and loads of radioactive elements such as uranium or thorium, as well as many dissolved and toxic metals in the environment, such as arsenic, chromium, lead, mercury, nickel, vanadium and cadmium (Reta et al., 2018^[416]). The beneficiation process (which separates the phosphate minerals from other minerals by removing much of the clay, sand and other impurities) increases the amount of such hazardous elements leaking into soil, water, air and the human food chain. The major airborne emissions from phosphorus mining occur in the form of fine rock dust from drying and grinding operations of phosphate rock (Reta et al., 2018^[416]). Fluoride emissions and radon gas emissions constitute further challenges for air quality.

In terms of biodiversity impacts from surface and underground phosphorus mining activities, mines take up large amounts of habitat, with surface mining spanning particularly large areas and in many cases displacing plants and animals (Reta et al., 2018^[416]). Surface mining entails the removal of the overburden to expose bare rock surfaces, not only causing destruction of pre-existing vegetation, but also occupying large areas of land for dumping the spoil (Yang et al., 2014^[417]). Settling ponds or other waste disposal areas implies further changes to habitats and can impact the water quality of the surrounding water, hence also affecting aquatic ecosystems. In the case of dam failure, the tailings released into the environment can create widespread ecological damage, especially in aquatic environments (Islam and Murakami, 2021^[418]).

Surface and underground phosphorus mining can also affect local carbon sinks and contribute to climate change through the energy use required for mining activities. New mining sites often involve clearing vegetation, which disturbs local carbon sinks. This can lead to carbon release from soils and loss of carbon sequestration capacity. The extraction, crushing, and transportation of rock requires significant energy, which contributes to GHG emissions. Although mining contributes a relatively small fraction of total emissions in the phosphorus supply chain from phosphate rock mining to phosphorus use in crop production, with Gong et al. (2022^[419]) estimating around 8% in China for phosphorus mining versus 43%

for phosphorus fertiliser manufacturing and 48% for crop production, its impact is still significant in absolute terms given the large emissions from crop production outlined Chapter 2.

At the moment, although most phosphate rock resources occur as sedimentary marine phosphate rocks, found especially in northern Africa, China, the Middle East, and the United States (Smit et al., 2009^[420]), seabed mining is not being used. However, several companies have applied for licenses to exploit marine phosphate reserves in countries such as Namibia, New Zealand, Mexico and South Africa. Namibia had given clearance for seabed mining in 2016, but this was quickly suspended over environmental concerns, in particular potential impacts on fisheries that challenged the validity of the mining license. Potential impacts of seabed mining are explored in Annex Box 6.D.2.

Annex Box 6.D.2. Potential seabed and other marine phosphorus mining impacts

Seabed mining has been proposed as an alternative to terrestrial mining but traditional types of seabed phosphorus mining such as dredging (using suction dredges), proposed for example by NMP (NMP, 2012^[421]), could have severe and irreversible impacts on marine ecosystems and fishery resources. Mining proposals in South Africa have been found to overlap with marine protected areas and areas identified as critically endangered ecosystems (Safeguard our Seabed Coalition, 2016^[422]). Potential impacts outlined in a report on sea-bed phosphorus include the direct destruction of seabed ecosystems such as corals, the direct destruction of spawning, breeding and feeding habitats for fish species, the burial and smothering of marine organisms both in the mining block and surrounding areas (Currie, 2013^[423]). Assuming bulk mining plans would be similar to those of the NMP project in Namibia (NMP, 2012^[421]), the dredging vessel would focus on a target mining area for several years and be at sea for the majority of that time, creating a semi-permanent source of acoustic disturbance. As large volumes of dredged sediment have to be transferred ashore frequently (every 37 hours in the Namibian example), a significant increase in shipping traffic would develop between the mining site and the selected port, creating persistent disturbance along the transfer route for species sensitive to sound.

Climate impacts from dredging could also arise for example due to reduced light penetration and damage to carbon-sequestering habitats. Sediment clouds potentially reduce the photosynthesis rates of marine flora that convert CO₂ into OC while releasing oxygen, which can weaken the ocean's role as a carbon sink (Currie, 2013^[423]). If carbon-sequestering habitats degrade or die, stored carbon can be re-released as CO₂ or CH₄.

In terms of potential pollution impacts, offshore mining is particularly vulnerable to weather conditions that pose added risks of material spills and leakage into the environment (Reta et al., 2018^[416]).

As an alternative to traditional sea-bed mining, bio-based mining from marine ecosystems through removing phosphorus in waterbodies could help reduce eutrophication and therefore eutrophication-related biodiversity losses. Bio-based approaches for marine phosphorus mining through microorganisms such as phosphate accumulating organisms (PAOs) could be exploited for removal and recovery purposes from marine ecosystems (Cakmak et al., 2022^[424]). However, due to the experimental stage other environmental impacts are difficult to predict.

The impacts of agricultural applications of phosphorus on the triple planetary crisis

Phosphorus fertilisation is often used even when the soil has high levels of phosphorus as only a small fraction of it is available for uptake by cultivated plants – some authors suggest it may be less than one percent (Bünemann, 2015^[425]). The main reason for phosphorus fertilisation is that farmers aim to avoid a deficit in phosphorus uptake as that would limit plant growth and thus diminish harvest. Phosphorus fertilisation leads to a variety of impacts.

In the case of phosphorus pollution through the soil from agricultural applications of phosphorus-based fertilisers, these can disrupt biodiversity, although the overall effects of such applications are species and location specific and depend for example on the underlying phosphorus limitations of the ecosystems, as well as the timeframe examined. Almeida et al. (2019^[426]) find that the application of superphosphate, a phosphorus-based chemical fertiliser, decreased fungal biomass when combined with nitrogen. However, Korevaar and Geerts (2015^[427]) found that species-richness initially declined but started to recover after about 25 years of fertilisation. Research in Australian grasslands indicated that superphosphate application affected invertebrate populations, with some groups declining in abundance (Oliver et al., 2005^[428]).

Phosphorus applications through manure have also been linked to high microbial diversity and activity (White and Reddy, 2000^[429]; Li et al., 2021^[430]). Given that manure contains both phosphorus and nitrogen, the effects are difficult to detangle specifically to phosphorus. A global meta-analysis by Nessel et al. (2021^[431]) that synthesises data from 1 679 cases across 207 studies reveals that nitrogen and phosphorus additions decreased invertebrate abundance in both terrestrial and aquatic ecosystems, although the meta-analysis combines manure and chemical fertilisation. The study also notes that combined nitrogen and phosphorus enrichments had stronger negative impacts, particularly in tropical regions (Nessel et al., 2021^[431]).

Research on the biodiversity effects of direct phosphate rock applications is still emerging. Being natural compounds, finely ground phosphate rock can be used in organic agriculture and has been used as an alternative to soluble chemical fertilisers – although most of the phosphate rock is treated to make the phosphorus more soluble. In agricultural settings phosphate rock is often applied in combination with a microbial phosphate solubilising inoculum that improves plant phosphorus acquisition and may affect the native bacterial and fungal communities. Trabelsi et al. (2017^[432]) suggest that fertilisation with phosphate rock might foster bacteria with fast-growing rates, such as Bacteroidetes and Gammaproteobacteria, at high phosphorus levels.

In the case of phosphorus pollution in waters, primarily through agricultural runoff, sewage discharge, and industrial effluents (Jwaideh, Sutanudjaja and Dalin, 2022^[433]), phosphorus pollution is the paramount nutrient for freshwater eutrophication and the main limiting factor for algal growth in most freshwater areas (Zhou et al., 2024^[434]). When excess phosphorus enters freshwaters it hence rapidly stimulates algal blooms and eutrophication, overall leading to more than double the freshwater fish species loss than nitrogen pollution (Zhou et al., 2024^[434]). Phosphorus-driven algal blooms also affect biodiversity by reducing for example plankton diversity (Amorim and Moura, 2021^[435]). Globally, phosphorus losses from land to fresh waters have doubled in the last century and continue to increase (Our Phosphorus Future Network, 2022^[290]).

Phosphorus pollution also has significant effects on climate change, in particular through the aforementioned eutrophication. Phosphorus-driven eutrophication and the decomposition of dead algae in these oxygen-deprived environments favours the production of the GHG CH₄. Eutrophic systems tend to emit more CH₄ than oligotrophic systems, due to accumulation of organic matter on the sediment (Nijman et al., 2022^[436]). The accumulated sediment also continues emitting CH₄ even in cases where external nutrient inputs have been controlled. Empirical models demonstrate that an increase in eutrophication driven, in part, by increasing phosphorus loading could increase CH₄ emissions globally by the equivalent of up to 33 percent of annual CO₂ emissions from burning fossil fuels (Beaulieu, DelSontro and Downing, 2019^[437]). Phosphorus has also been found to affect carbon cycling in mangrove sediment, resulting in changes in soil GHG emissions and carbon stocks of mangrove ecosystems (Qiu et al., 2024^[438]). Similarly, in peatlands, Schillereff et al. (2021^[439]) suggest that long-term elevated phosphorus deposition and accumulation strongly correlate with increased organic matter decomposition and lower carbon sequestration. Continued phosphorus pollution thus places the future carbon sink of peatlands at risk.

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Notes

¹ More precisely pollution prevention and control; the shorter phrasing is used throughout in this chapter and is meant to include prevention.

² The selection has been made in consultation with governments and topical experts but necessarily remains somewhat ad-hoc. Alternative deep-dives on cross-cutting issues such as water and chemicals are beyond the scope of this report but are integrated in the analysis of the other chapters.

³ This is equivalent to around 3.7 Gt of CO₂e (IPCC, 2021^[205]).

⁴ The same is true for fossil fuels, which are also heavily internationally traded.

⁵ See Chapter 3 of (OECD, 2024^[2]) for a comprehensive and synthetic review of impacts of solar power, wind power and power lines on biodiversity.

⁶ Australia is also conducting further research about potential impacts to specific species and mitigation measures for effective and efficient regulation of both offshore and onshore windfarms.

⁷ This is in contrast with the time it currently takes. For instance, in some Member States of the EU, it can take for large renewable energy projects up to 9 years to obtain environmental permits (European Commission, 2022^[441]).

⁸ Similarly, it can be challenging to consider the full upstream environmental impacts at the level of a project-specific EIA, depending on the scope of impacts that needs to be considered; specifically, assessment of indirect effects, e.g. from the use of energy in upstream production processes, can be complicated.

⁹ Unmanaged land refers to land cover types that are suitable for exploitation but not in active use for agriculture or forestry, nor used for human settlements.

¹⁰ These 31 parks include in total 5.6 million hectares of forests.

¹¹ Articles 6(3) and 6(4) of Council Directive 92/43/EEC.

¹² See definition in Annex 6.B.

¹³ Adopted in Decision 15/5.

¹⁴ Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname and Venezuela.

¹⁵ Aerosols refer to solid particles or liquid droplets dispersed in a gas (e.g. in air).

¹⁶ Deadwood refers to non-living wood material in forests, which can increase due to factors like storms and bark-beetle outbreaks (Milad et al., 2011^[442]).

¹⁷ There are also interaction effects with the protected area management policies, as outlined in Section 6.3.

¹⁸ Source appointment refers to the practice of deriving information about pollution sources and the amount they contribute to ambient air pollution levels.

¹⁹ An airshed is a geographical area that shares a common flow of air due to topography or weather conditions and could extend across borders (World Bank, 2025^[224]).

²⁰ Such solutions require economic incentives so that the burden of the abatement costs is shared by everybody who benefits from the emissions reductions. This sharing can be accomplished by establishing regional funds or even by introducing a system of tradable emissions rights.

²¹ The imposition of these taxes is matched by a reduction in personal income taxes, employment taxes but a harmonisation of VAT at a standard rate of 22% and harmonised reduced rate of 12% for selected goods and services. In addition, income support to the lowest two quintiles is raised as are excise duties

on tobacco products. These changes are assumed to be introduced gradually over the period 2021 to 2025.

²² Estimates of damages in monetary terms are not available on a systematic basis. To get these, more information on impacts is required at a highly granular level.

²³ Especially in Latin America and Africa a large share of total nutrient inputs also comes from manure applied to soils (OECD, 2021^[300]).

²⁴ As outlined in Chapter 2, this is calculated as the difference between nutrient inputs (e.g. manure or synthetic fertiliser) and the amount of nutrients absorbed by plants.

²⁵ For example, corn has a higher nitrogen demand during its growth stages while legume crops such as soybeans can naturally fix nitrogen from the atmosphere making it less dependent on external nitrogen inputs (Adenäuer, Laget and Cluff, 2024^[299]). By contrast, legume crops have more demand for phosphorus for optimal nitrogen fixation compared to plants like cereals (Mitran et al., 2018^[440]).

²⁶ Phosphate rock includes both i) the phosphate mineral bearing rock (mostly apatite) that can be used directly as fertiliser and ii) a beneficiated concentrate of the phosphate mineral (Smit et al., 2009^[420]). In the first case, phosphate rock is finely ground and applied directly as a fertiliser. In the latter case, beneficiation of the rock removes much of the clay, sand and other impurities, raising the phosphorus concentration by separating the phosphate minerals from other minerals (Smit et al., 2009^[420]; FAO, 2004^[444]).

²⁷ However, the life-cycle carbon footprint of blades made with this new material has yet to be understood (Volard, 2023^[443]).

²⁸ This is based on compliance with technical guidelines designed to ensure compliance with the “do no harm” principle under the European Commission's Recovery and Resilience Facility Regulation (2021/C 58/01) (OFB, 2023^[104]).

²⁹ According to the ISO, environmental labelling and information schemes are classified into three main types: (i) Type I - ecolabels - multi criteria and third party verified (ISO 14024), (ii) Type II - self-declared environmental claims (ISO 14021), and (iii) Type 3 - environmental declarations (ISO 14025) (ISO, 2019^[445]).

³⁰ The EC expects the member states to use penalties that are “effective, proportionate and dissuasive” (EU Directive 2016/2284).

³¹ In addition, a few of studies have looked at the impacts of taxes that have yet to be implemented.

³² E-service available here: <https://noxdeklaration.naturvardsverket.se/>.

7 Roadmap for policy action

While there may be intrinsic policy co-benefits between some policies that tackle climate change, biodiversity loss and pollution, this Outlook underscores that measures targeting each problem in isolation will not, in and of themselves, be sufficient. There is a need for more coherent responses that fundamentally address the interconnected nature of climate change, biodiversity loss and pollution, capitalising on policy synergies and minimising unintended trade-offs in a way that also considers social and distributional concerns. This concluding chapter outlines a roadmap to support policymakers in devising such systemic responses. The roadmap is organised around the following six policy levers: (i) address key gaps in research and assessment; (ii) strengthen consideration of interlinkages in national reporting and planning; (iii) align financing and resource allocation; (iv) mitigate unintended impacts of the clean energy transition; (v) transform resource use and (vi) rethink food systems.

7.1. What this *Outlook* reveals

Climate change, biodiversity loss and pollution constitute an interconnected global challenge that poses escalating threats to environmental sustainability, human health and well-being. The analysis presented in this Outlook demonstrates that these three environmental issues are linked through complex feedback loops that can amplify (or occasionally dampen) cumulative impacts while creating opportunities for integrated policy solutions.

Global population growth remains a significant underlying driver, with projections indicating an increase from 7.8 billion in 2020 to 9.6 billion by 2050, representing 0.7% annual growth. In addition, global GDP is projected to more than double from USD 126 trillion to USD 283 trillion over the same period, growing at 2.7% annually. In both cases, there is significant heterogeneity in projected growth across regions and countries, with relatively fast growth of both population and income in large parts of Asia, Latin America and Africa. While economic growth clearly helps raise living standards, create employment and achieve a range of development objectives, the composition of the growth and the inputs used to drive it can have significant implications on its overall environmental impact. Different country circumstances, with widely varying economic profiles and socioeconomic growth projections, imply that environmental pressures also vary significantly across countries. Similarly, countries that grow fast often start from a low level and thus a fast increase in environmental pressures does not necessarily translate into high levels of these pressures.

A number of global trends emerge. Sectoral growth patterns reveal critical pressure points requiring targeted policy intervention. At the global level, under current policies, agriculture and land use, as well as chemicals production and use will continue expanding their environmental footprint, though at rates slower than overall economic growth. In addition, global fossil fuel consumption is projected to increase from 466 exajoules in 2020 to 541 exajoules by 2050, directly impacting environmental objectives and contributing to greenhouse gas (GHG) emissions, air pollution, and indirectly to biodiversity loss. Other economic activities also have significant consequences for environmental pressures, to varying degrees.

Unsustainable resource use patterns present immediate policy challenges. Primary materials use is projected to increase globally by roughly half, from 96 gigatonnes (Gt) in 2020 to 145 Gt by 2050. The growth in resource use highlights the need for faster progress in promoting resource efficiency and circularity.

These unsustainable production and consumption patterns drive climate change, biodiversity loss, and pollution. Under current policies,¹ the global mean temperature increase is projected to reach 2.1°C above pre-industrial levels by 2050. This will trigger cascading effects across ecosystems, agricultural systems and human settlements. Key biodiversity indicators are projected to decline by 2050, indicating a likely failure to meet the goals of the Kunming-Montreal Global Biodiversity Framework. For example, the terrestrial mean species abundance index is projected to further decline (from 59.7 to 56.5). This is equivalent to the conversion of pristine habitat of more than 4 million km² into an area where all the original species have been lost. Population sizes of most threatened mammal species are projected to continue declining, with only 5% of threatened mammal species expected to experience an increase in population size in the coming decades.

Pollution presents a mix of trends requiring nuanced policy approaches. While some air pollutants are projected to continue to decline — sulphur dioxide emissions are projected to decline by 64% between 2020 and 2050 — other pollutants, most notably plastic pollution, presents escalating challenges, with global leakage projected to increase by almost two-thirds over the 2020-2050 period. Agricultural pollution pressures continue rising across most regions, contributing to climate change, biodiversity loss and ecosystem degradation. Importantly, complex chemical interactions directly link various emissions. A well-known example is the nitrogen cascade: in its various forms, nitrogen directly and indirectly contributes to climate change, air pollution and water pollution, not least eutrophication.

Climate change, biodiversity loss and pollution also interact in complex ways, as detailed in Chapters 1, 2 and 3 of this Outlook. For example, climate change and pollution each contribute to around 14% of the measured biodiversity loss (IPBES, 2019^[1]). Biodiversity loss, in turn can accelerate climate change through the release of stored carbon in terrestrial and marine ecosystems and can reduce the capacity of ecosystems and societies to adapt to the impacts of climate change. Climate change can also affect pollution episodes and the transfer of pollutants through multiple channels, for example through accelerated chemical reactions leading to increased concentrations of ground-level ozone at higher temperatures and pollutant releases from the melting permafrost. Meanwhile, pollution – most notably air pollution – can compound climate change through warming effects, impacts on cloud properties and precipitation patterns. The sheer number of possible interactions defies an exhaustive analysis, with some interlinkages being more direct than others.

Given the interconnected nature of the underlying drivers, pressures and impacts of climate change, biodiversity loss and pollution, it may seem intuitive that addressing one issue would contribute towards resolving others. However, the analysis of policy responses presented in Chapters 4, 5 and 6 of this Outlook suggests that a myopic focus on one aspect may lead to inadequately managed trade-offs, such as between the expansion of renewables and potential impacts on protected areas and biodiversity, and/or missed opportunities for synergies such as between reducing air pollution and climate change mitigation.

7.2. Towards a policy roadmap for integrated action

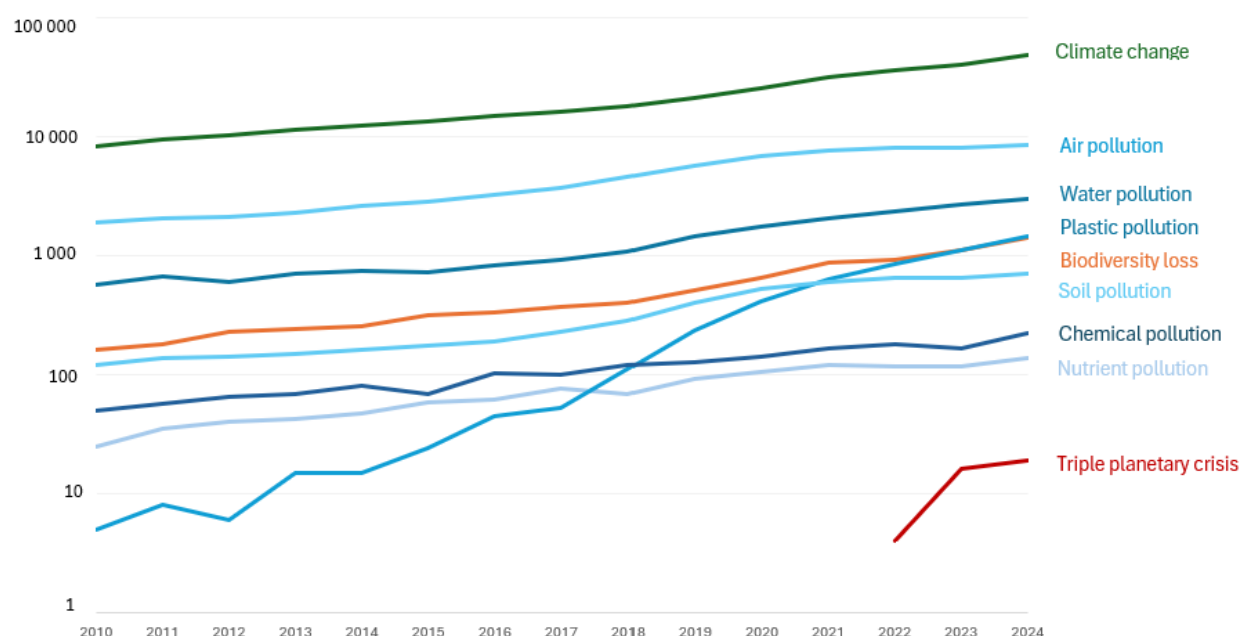
In line with global assessments of climate change (IPCC), biodiversity loss (IPBES) and various aspects of pollution, such as plastics (OECD), air pollution (WHO), chemicals (UNEP), mercury (UNEP), nitrogen (INMS) and the cross-cutting issue of resource use (IRP), this Outlook reinforces the urgency of raising the ambition of a broad suite of policies to address all of these concerns. The suite of policy responses that are needed to tackle these challenges individually are already elaborated elsewhere and are not replicated here.

While there may be intrinsic policy co-benefits, especially for policies that tackle common drivers of climate change, biodiversity loss and pollution, this Outlook also demonstrates that measures targeting one problem will not, in and of themselves, be *sufficient* to tackle the systemic challenges posed by the triple planetary crisis. Effective policy responses must also fundamentally address the interconnected nature of these environmental challenges and their drivers through integrated frameworks rather than compartmentalised approaches. These are the focus of the policy roadmap outlined below.

The roadmap outlined here has six core levers, three of which are intended to provide a foundation for more integrated policies. It also includes specific considerations for clean energy, material resources and food systems, while addressing social and distributional concerns such as job and income losses, affordability and access to food and energy. The six levers are as follows: (i) address key gaps in research and assessment; (ii) strengthen consideration of interlinkages in national reporting and planning; (iii) align financing and resource allocation; (iv) mitigate unintended impacts of the clean energy transition; (v) transform resource use; and (vi) rethink food systems.

7.2.1. Address key gaps in research and assessment

Informed and integrated policy action hinges on a strong knowledge base. However, research on the dimensions of the triple planetary crisis has historically been uneven (Figure 7.1). Publications on climate change dominate the literature, followed by air and water pollution. While research on plastic pollution has gained significant traction in recent years, other dimensions of pollution (soil, chemical and nutrient) have received more diffuse attention. Research focusing on the triple planetary crisis is nearly absent.

Figure 7.1. Number of publications per year for each environmental issue between 2010 and 2024

Note: The number of articles, review articles and conference papers containing the labels as shown in the figure (e.g. triple planetary crisis) in abstracts and/or titles between 2010 and 2024. Given the wide variation in the number of papers the results are presented on a log scale.

Source: Authors' own elaboration based on Scopus.

Likewise, attention to pairwise interlinkages, in line with their treatment in national planning documents (Section 7.2.2), varies substantially across topics. Over the last 15 years, the number of publications investigating (i) climate and biodiversity policies and (ii) climate and (air) pollution control and prevention policies have grown considerably. However, there are markedly fewer publications exploring the linkages between biodiversity and pollution control and prevention policies.

At a fundamental level, research gaps can hinder how we understand the compounding nature of inter-related issues. More broadly, the uneven research landscape amplifies the challenge of evidence-based policymaking. Research bottlenecks may have cascading implications for policymaking, with policy attention focusing on single, more salient and well-studied issues.

Leverage assessments and funding to facilitate solution-oriented research on cross-linkages

Existing and new scientific assessment processes at international and national levels can help establish a foundation of policy-relevant knowledge to foster integrated action on climate change, biodiversity loss and pollution. Countries can, for example, consider facilitating more routine investigations on interlinkages via intergovernmental science-policy panels. The inaugural joint IPBES – IPCC co-sponsored workshop on climate change-biodiversity interlinkages held in 2020 is particularly illustrative. The ensuing workshop report provided a first-of-its-kind peer-reviewed evidence synthesis on pairwise interlinkages between the two challenges. This report subsequently fed into the IPBES Nexus Assessment and IPCC Sixth Assessment reports.

The recently established Intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution likewise provides an opportunity to more systematically advance knowledge on interlinkages among pollution, climate change and biodiversity, including through targeted collaborations with the IPCC, IPBES and national focal points. The recent reports by the Secretariats of Basel, Rotterdam and Stockholm Conventions and Minamata

Convention on Mercury, on the intersections among chemicals and waste with both climate change and biodiversity, also serve as a basis for examining these interlinkages.

Public funding for research is an additional lever available to governments to help address key gaps. To mitigate biases towards funding well-researched topics, governments may wish to conduct rapid evidence syntheses prior to initiating calls for proposals. Such calls can emphasise interdisciplinary and solutions-oriented research as conditions for eligibility, to direct resources away from siloed foci. Finally, despite the integral nature of interdisciplinary research to tackle challenges like the triple planetary crisis, researchers active across different disciplines may receive less funding than their more specialised peers (Bromham, Dinnage and Hua, 2016^[2]), disincentivising research across disciplines. Collaborations between governments and research institutions – such as through targeted units or dedicated funding opportunities – can help incubate interdisciplinary work and support the next generation of researchers.

7.2.2. Strengthen consideration of interlinkages in national reporting and planning

Tackling the triple planetary crisis of climate change, biodiversity loss and pollution necessitates consideration of policy interlinkages to maximise synergies and manage trade-offs. There are important interlinkages among the planetary processes underpinning the triple planetary crisis, as well as between the policies developed and implemented at multiple levels of government. National reporting under multilateral environmental agreements, in this context on climate change and biodiversity, are particularly important as they reflect “whole of government” perspectives and policy priorities. Beyond national reporting frameworks, policymaking at the national level – including long term visions and strategies, development and sectoral plans, and regulatory frameworks – play a critical role in setting priorities, while guiding regional and local implementation. Given the resource implications of integration including time and costs for co-ordination, it is important to identify the most salient synergies and trade-offs in a given context instead of pursuing exhaustive considerations to ensure that the efforts remain targeted and manageable (OECD, 2021^[3]).

Strengthen considerations of cross-linkages in BTRs and NBSAPs

The three components of the triple planetary crisis are not equally reflected in national reporting documents. The analysis of standardised reporting frameworks for climate change [Biennial Transparency Reports (BTRs) under the Paris Agreement and previously National Communications (NCs) under the UNFCCC] and biodiversity [National Biodiversity Strategies and Action Plans (NBSAPs) aligned with the Kunming-Montreal Global Biodiversity Framework] across 10 diverse countries² shows that while countries acknowledge some policy linkages between climate change and biodiversity, these connections are often addressed generically without detailed implementation strategies (see Figure 7.2). Although no equivalent standardised document exists for pollution, BTRs and NBSAPs cover some aspects and components of pollution.

The analysis in this Outlook (see Chapter 5) finds that climate-pollution and biodiversity-pollution linkages receive less attention, and consideration of climate-biodiversity-pollution linkages taken altogether is virtually non-existent. There are relatively extensive and detailed discussions on the interlinkages between climate change and biodiversity in terms of their biophysical impacts, particularly in BTRs.

However, in both BTRs and NBSAPs, the impacts of climate change on biodiversity feature more prominently than the implications of biodiversity loss on climate change. Most countries also consider ways to foster synergies between climate mitigation and adaptation and biodiversity conservation in both BTRs and NBSAPs. Furthermore, even in cases where there is some attention to pairwise synergies, discussion of managing potential trade-offs between objectives to tackle climate change, biodiversity loss and pollution is frequently absent from policy documents.

Figure 7.2. Consideration of pairwise linkages in national reporting documents across 10 selected countries

BTRs ¹							
Climate Change and Biodiversity				Climate Change and Pollution			
The impacts of climate change on biodiversity (loss)	The impacts of biodiversity (loss) on climate change	Synergistic policies or projects	Trade-offs in policies or projects	The impacts of climate change on pollution	The impacts of pollution on climate change	Synergistic policies or projects	Trade-offs in policies or projects

NBSAPs							
Biodiversity and Climate Change				Biodiversity and Pollution			
The impacts of climate change on biodiversity (loss)	The impacts of biodiversity (loss) on climate change	Synergistic policies or projects	Trade-offs in policies or projects	The impacts of pollution on biodiversity (loss)	The impacts of biodiversity (loss) on pollution	Synergistic policies or projects	Trade-offs in policies or projects

●	Country-specific impacts ² are discussed extensively and in-depth . Implemented government actions² consider pairwise linkages, focusing on maximising synergies or managing trade-offs extensively and in-depth.
●	Country-specific impacts cover more than one dimension of climate change, biodiversity ⁴ or pollution ² , with at least one impact discussed substantially . Implemented government actions consider linkages, with at least one policy action substantially focusing on maximising synergies or managing trade-offs.
⊙	Country-specific impacts cover more than one dimension of climate change, biodiversity or pollution but are not discussed substantially . Implemented or planned government actions consider linkages, with some consideration of policy action aimed at maximising synergies or managing trade-offs.
○	Impacts are discussed in generic terms based on global or regional assessments, or with very few details. The document contains a generic acknowledgement of the need to consider synergies maximisation or trade-off management in policy action in the context of linkages.
○	No information found in the assessed national documents

Notes: 1. In the absence of a BTR, the analysis was completed using the country's latest NC document. 2. Impacts refer to the biophysical impacts of climate change on biodiversity (loss) and vice versa or to the biophysical impacts of biodiversity (loss) on pollution and vice versa. 3. Government actions refer to policies and projects. 4. Dimensions of biodiversity include species, ecosystems and biota. 5. Dimensions of pollution include subsets of media (e.g. air) as well as types (e.g. nutrients).

Source: Authors' own elaboration based on the review of national documents of ten countries: Argentina, Australia, Canada, China, France, India, Indonesia, Japan, Peru, and Uganda (see Chapter 5).

To deepen the integration of potential synergies and trade-offs in national policy documents, countries can use indicators within existing monitoring frameworks – such as those outlined in the Kunming-Montreal Global Biodiversity Framework – to better address the triple planetary crisis (WWF, 2023^[4]). Leveraging current tools to report on cross-linkages in BTRs and NBSAPs is an entry point that provides an opportunity to assess synergies and trade-offs across climate, biodiversity and pollution targets. Measuring how the implementation of NBSAPs can support progress in BTRs (and vice versa) can strengthen alignment across climate, biodiversity and pollution targets.

Harvest and scale up existing innovative integrated approaches

Despite the above limitations, BTRs and NBSAPs already offer a wealth of insights on innovative policy tools that countries have developed to address at least some synergies and trade-offs between climate change, biodiversity loss and pollution. Highlighting such examples and drawing lessons from their implementation to adapt them to other national contexts is key to scaling-up more integrated responses to the triple planetary crisis.

Table 7.1 and Table 7.2 present a range of implemented policies and instruments addressing multiple targets that were highlighted in the analysis of BTRs and NBSAPs in this Outlook. These span the gamut of economic instruments (e.g. targeted carbon credit schemes), regulatory instruments (e.g. enhanced protected areas adapting to climate change and pollution risks) and information policies (e.g. fine-tuned information campaigns aimed at reducing food waste and improving soil health). BTRs and NBSAPs also highlight how government provisions of goods and services can also tackle multiple objectives (e.g. conservation and restoration of blue carbon ecosystems to improve water quality).

Table 7.1. Examples of implemented measures tackling multiple targets in BTRs (and NCs)

Policy instrument	Climate Change and Biodiversity	Climate Change and Pollution
Economic instruments	• Blue- and forest-based carbon credits, including for private landholders (e.g. Japan, Canada) • GHG offset credit system for improved forest management on private land • Tax incentives and grants for tree planting • Aligning new voluntary biodiversity market with existing carbon credit markets • Grants to promote sustainable agricultural practices	• Carbon credit schemes that deliver synergies for soil health • Taxes on waste to limit its incineration and disposal in landfills (e.g. France) • Subsidies for land restoration • Demand-side measures including a discount for new or used bicycles
Regulatory instruments	• Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards climate change mitigation	• Air quality standards to reduce pollution from wood heaters (e.g. Australia) • Legal frameworks for shared economy (e.g. carpooling) • Designation of low-emission zones to reduce air pollution
Information policies	• Information campaigns on food waste reduction to achieve emissions reduction and improved soil health	• Information campaign: promotion of the 3 Rs (Reduce, Reuse, Recycle), of clean cooking technologies to reduce the consumption of fuel thereby reducing GHG emissions (e.g. Peru)
Government provision of goods and services	• Appropriate design of reforestation (and afforestation) projects to enhance carbon sequestration while delivering for biodiversity synergies • Ecosystem restoration (e.g. mangroves) and coastal adaptation projects to improve resilience against climate change (e.g. Argentina) • Greening of urban and port infrastructure to enhance carbon sinks • Engagement with stakeholders, including recognition of traditional and Indigenous knowledge in the management of land and sea to support climate adaptation and improve resilience while protecting biodiversity (e.g. Australia)	• Urban greening to enhance carbon sinks and improve air quality (e.g. India) • Water management programmes in agriculture to reduce nitrous oxide emissions from agricultural runoff while conserving wetland habitats to enhance carbon sequestration (e.g. Canada) • Improve wastewater treatment through reusing sludge to reduce GHG and produce fertilisers (e.g. Uganda) • National and international climate finance provision for (low-emission) public transport to alleviate air pollution and climate change (e.g. Japan)

Source: Authors' own elaboration based on the review of national documents of 10 countries: Argentina, Australia, Canada, China, France, India, Indonesia, Japan, Peru, and Uganda (see Chapter 5).

Table 7.2. Examples of implemented measures tackling multiple targets in NBSAPs

Policy instrument	Biodiversity and Climate Change	Biodiversity and Pollution
Economic instruments	- Carbon credits to finance maintenance and management of protected areas (including REDD+ projects) (e.g. Peru) - Subsidies for tree planting to increase carbon sequestration while delivering synergies for biodiversity (e.g. Canada)	Pollution charges and user charges as payment for use of resources (e.g. wetlands in Uganda)
Regulatory instruments	Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards climate change mitigation	- Enhancing the contributions of protected areas (and other effective area-based conservation measures) towards pollution control and management - Water quality standards to conserve aquatic ecosystems - Impact assessment of chemicals (including agrochemicals such as pesticides) and registration to assess, prevent and manage the potential risks to terrestrial and aquatic species - Management of invasive alien species (e.g. sanitary and phytosanitary measures at border) - Closure of landfills along coastal areas to avoid waste leakage into the sea
Information policies	Certification of natural sites (aimed at reducing GHG emissions and enhance carbon sequestration) to finance protected areas (e.g. France)	Labelling and environmental certification on food produced from sustainable agricultural practices
Government provision of goods and services	- Facilitating knowledge-sharing and research on mitigating the adverse impacts of renewables expansion on biodiversity - Recognition of traditional and Indigenous knowledge in the management of forest to support climate change adaptation and mitigation while facilitating the continuity and survival of species (e.g. Peru) - National ecosystem services assessment - Implementing appropriate wildfire management attuned to the evolving vulnerability of species under climate change (e.g. Australia) - Ecosystems restoration including blue carbon (e.g. wetlands, seaweed beds, tidal flats and coral reefs) and terrestrial ecosystems (e.g. Japan)	- Advancing scientific research for pollution prevention to protect migratory birds (e.g. Canada) - Air and water quality monitoring to identify, for instance, effects of atmospheric pollution on ecosystems (e.g., Japan) - Initial environmental risk assessment of chemical substances - Remediation of degraded and contaminated land - Construction and operation of drainage facilities

Source: Authors' own elaboration based on the review of national documents of 10 countries: Argentina, Australia, Canada, China, France, India, Indonesia, Japan, Peru, and Uganda (see Chapter 5).

Beyond these policies, many countries have developed integrative and holistic approaches to better anticipate synergies and trade-offs. For example, Canada has developed a “Climate, Nature and Economy Lens” which provides a template requiring consideration of the impacts that proposals might have on climate change, biodiversity loss and various dimensions of pollution as part of a project’s appraisal (Government of Canada, 2024^[5]). Similarly, the “Policy Compass” adopted in the Netherlands is a web-based tool to facilitate consideration of policy impacts that may arise “here and now”, “later” and “elsewhere” based on Sustainable Development Goals (Government of the Netherlands, 2025^[6]). It is also important to promote these tools and methodologies, as developing them does not automatically lead to their effective or regular use.

Many countries have also adopted local and project-level approaches to address synergies and trade-offs. For example, Uganda has implemented several ecosystem-based conservation plans that embrace ecosystem interconnectedness to tackle biodiversity loss and climate change. Moreover, Argentina carried out the Environmental Sustainability and Insurance Programme to encourage investments in reforestation and enrichment of the native forests as a tool for climate mitigation, while ensuring effective biodiversity conservation. Lastly, Indonesia has implemented integrated watershed management as a core strategy for enhancing synergies between water and terrestrial ecosystem health and community well-being, simultaneously addressing environmental protection, natural resource use, and human needs.

Develop an overarching approach to pollution

While multilateral conventions have led to standardised reporting and planning frameworks for climate change (e.g. BTRs) and biodiversity (NBSAPs), no equivalent exists for pollution. Instead, the national pollution control and management policy landscape is shaped by a set of disparate policies and plans developed in response to different priorities and multilateral environmental agreements targeting various environmental sinks (e.g. air) and pollutants (e.g. hazardous chemicals) across different lifecycle stages (Allan et al., 2025^[7]). While the principles of pollution prevention, control and management are typically laid out in broad legislative frameworks, their implementation can treat different aspects of pollution in siloes rather than as a collective unit. In a step towards more integrated approaches, the recently agreed Global Framework on Chemicals - For a Planet Free of Harm from Chemicals and Waste encourages governments to address chemicals throughout their lifecycle and includes work on waste, emissions releases and other forms of pollution. Reporting against the Global Framework on Chemicals has not yet begun, but work is ongoing to develop a set of indicators (ICCM5, 2023^[8]).

Developing national plans to tackle pollution comparable to those already available for climate change and biodiversity loss may be conducive to the identification of policy gaps, as well as opportunities for synergies and risks of trade-offs. Bringing together the ways in which different types of pollution are tackled provides the foundation for considering multiple, potentially compounding pressures species and ecosystems face. It can also improve consideration of time-delayed sources of pollution (e.g. PFAS leaching from landfills and plastics accumulating in the environment) and their impacts on biodiversity. Similarly, it can enable the consideration of relatively overlooked GHGs such as nitrous oxide (UNEP/FAO, 2024^[9]) as well as the interactions of pollutants with their climate-related properties which may have otherwise been neglected. These plans and frameworks can also serve as a focal document through which different units of environment ministries collaborate and engage in knowledge exchange.

Some jurisdictions are already pursuing comparable strategies in developing an integrated plan for pollution or outlining a comprehensive environmental plan. For example, the European Commission has adopted the EU Action Plan “Towards a Zero Pollution for Air, Water and Soil”, explicitly establishing the links with climate neutrality, ecosystem health, circular economy and resilience (European Commission, 2021^[10]). Its targets for 2030 and the vision for 2050 serve as a compass for considering pollution in all relevant new and existing policy initiatives. A cross-cutting 25 Year Environment Plan developed in the United Kingdom similarly highlights the importance of joining up policies to maximise synergies, and has been complemented by the Outcome Indicator Framework spanning across 10 broad themes including various dimensions of pollution (Department for Environment, Food & Rural Affairs, 2025^[11]).

While bringing together existing strategies and preparing a comprehensive plan may be a cumbersome and time-intensive exercise, countries can start small by prioritising key issues dictated by national circumstances and by building on existing frameworks and approaches in the interim. For instance, the “multi-pollutant, multi-effect” approach of the Gothenburg Protocol under the UNECE Air Convention – the recent revision of which expanded reduction commitments to black carbon (a short-lived climate pollutant) as a source of fine particulate matter – holds potential global relevance for simultaneously tackling air pollution and climate change. Applying a multi-pollutant, multi-effect approach can help establish policy

linkages at an early stage of planning and reinforce existing ones, thereby preventing the types of pollution that do not fit neatly into a single category, such as various forms of nitrogen, from becoming overlooked. If a pollution strategy focussing on a dimension (e.g. air or water quality) already exists, outlining the interlinkages with biodiversity and climate can be an important step. A modular or a stepwise approach can build up towards a more comprehensive plan over time. Considering liaison and co-ordination among existing agreements might offer an additional impetus, as envisioned for instance in the Inter-Convention Nitrogen Coordination Mechanism to consider the cross-domain impacts of nitrogen across multilateral environmental agreements and frameworks.

Reinforce institutional mechanisms and tools for horizontal and vertical integration

Translating ambitious policy planning into action is essential to address the triple planetary crisis. An “implementation gap” implies that while synergies and trade-offs between the various dimensions can be well-covered in policy design, they may be muted in reality. Specific attention is therefore paid to the available tools for effective implementation of synergistic approaches, including through measurement of impacts. There are key cross-cutting mechanisms that can help realise synergies and manage trade-offs in practice. These are: (i) improved mechanisms of intra-ministry and cross-ministerial co-ordination (ii) tools for environmental assessments of policies and projects and (iii) policy alignment. Together, they can help anticipate the impacts that arise at multiple scales at an early stage of planning.

To simultaneously attain multiple objectives, the integration of synergies and trade-offs is essential, both horizontally across sectors and policy domains and vertically across geographical scales, but remains challenging (see Figure 7.3). At the national level, horizontal integration can be achieved through high-level framing provided in documents such as BTRs, NCs, NBSAPs (see Chapter 5) or Nationally Determined Contributions (NDCs). Furthermore, institutional arrangements such as intra- and cross-ministerial or inter-agency committees, working groups and taskforces can enhance the integration of climate, biodiversity and pollution reduction objectives. Countries can also establish multi-year plans for sectors (e.g. food and agriculture, mining and natural resources, and energy), within which broader environmental goals can be integrated. Further, countries could consider deepening the environmental expertise of those who advise key committees to help foster integrated action. For instance, this expertise could support spatial planning committees at both national and local levels to mitigate unintended impacts of the clean energy transition through careful siting but also address other forms of unintended environmental impacts from waste management, air pollution and biodiversity.

An integrated policy approach requires better use of existing environmental metrics and their improvements to account for the interlinkages among climate change, biodiversity loss and pollution. Burgeoning research (e.g. (Bateman et al., 2024^[12])) suggests that cross-targeted policies which acknowledge linkages and spillovers in socio-environmental systems can enhance synergies in contrast to the separately targeted policies. Despite the growing recognition of the importance of nature in tackling climate change and pollution, it can be challenging to integrate in decision-making without quantitative metrics and common units. In this context, considering the contributions of natural capital as an asset that needs to be managed and maintained, the System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) can be better utilised to gain an understanding of the ecosystem extent, conditions, ecosystem services, providing an impetus for considering the interlinkages under a standardised statistical framework for natural capital accounting (United Nations, n.d.^[13]). From carbon accounts of peatlands in Indonesia to river accounts in water-scarce South Africa, SEEA EA is spatially explicit and can be applied at different scales. It can also inform the design of economic instruments (e.g. computing tax rates), as well as provide an objective baseline for private-sector natural capital accounting (Hein et al., 2020^[14]).

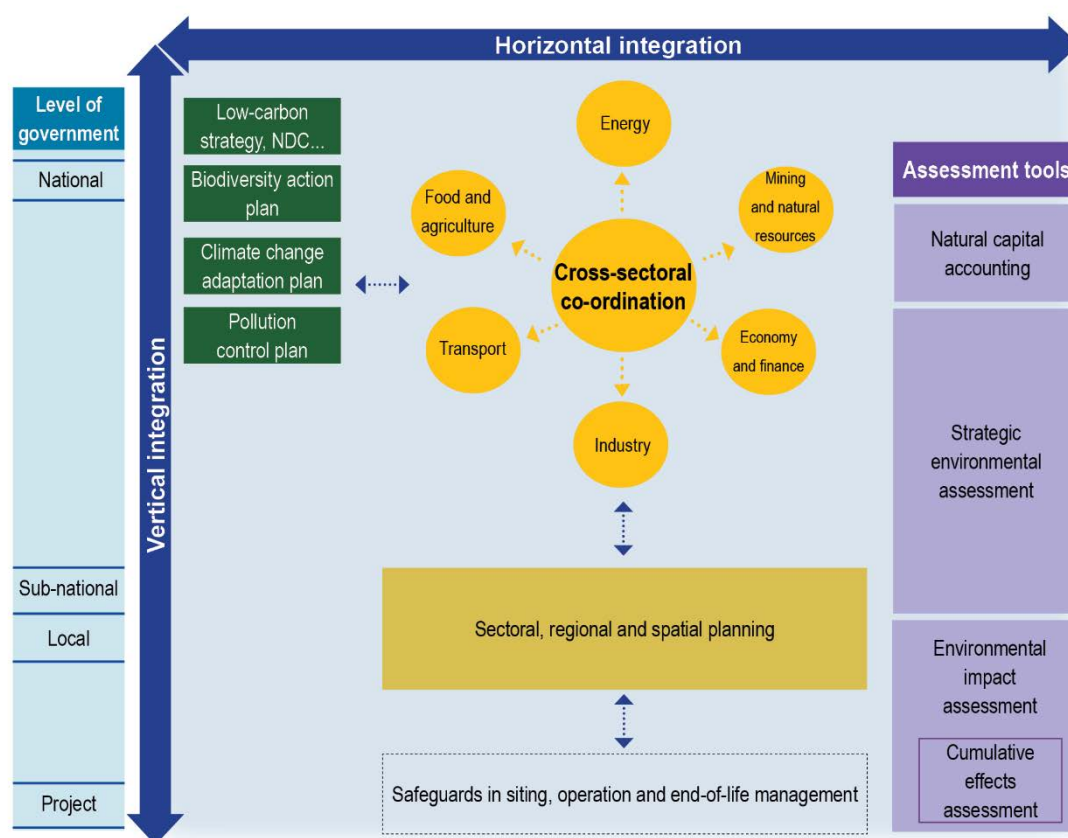
While there are several knowledge gaps, including how ecosystem accounting can help gain an understanding of ecosystem resilience and measure ecological thresholds and limits (SEEA, 2024^[15]), it can be seen as a continuous process that entails refining data and methodologies as new knowledge develops. Some countries promote its use in policy appraisal and evaluation. The United Kingdom, for instance, has developed and regularly updates “Enabling a Natural Capital Approach (ENCA)” with an assessment template and databooks on services and natural capital assets, as well as tools and case studies (Department for Environment, Food & Rural Affairs, 2025^[16]). Building on information from national accounts and tools such as environmentally extended multiregional input-output tables, several private companies have also initiated environmental impact valuation. These include Forico (which puts nature on its balance sheet), Holcim, Natura & Co and Dutch Railroads (which have integrated Environmental Profit and Loss Accounts) and Repsol and Knauf Insulation (which use environmental impact valuation for internal business tools). Furthermore, some investors are beginning to use impact accounting to engage with their portfolio companies and assess their impact performance (WBCSD, 2025^[17]).

More integrated national and sectoral planning also requires proactive consideration of the different dimensions of the triple planetary crisis at multiple spatial and temporal scales. Such integrated consideration can be aided through improved deployment of Strategic Environmental Assessment (SEA). While SEAs have been implemented in over 100 countries, there are notable gaps in their deployment and design (Dalal-Clayton and Scott-Brown, 2024^[18]). For instance, a lens considering climate change, biodiversity loss and pollution across all stages are not consistently applied in SEAs. It is also not yet a common practice to implement SEAs for the energy sector, despite potential implications of renewable expansion on biodiversity loss and pollution.

While high-level co-ordination is essential, it is often at the project level that synergies and trade-offs may manifest. Existing modalities such as environmental impact assessments (EIA) can be leveraged as integrative tools as part of permitting process to facilitate consideration of a broader set of objectives. Complementing EIA, cumulative effects assessments can elucidate the combined impacts of development projects over space and time. Although the lack of a widely accepted methodology hinders cost-effective and consistent application, cumulative effects assessments have been deployed to fill some of the gaps in EIAs, or as a part of EIA to anticipate the impact across temporal scales. Cumulative effects assessments are also a mandatory component of EIA in several countries including Bhutan, Brazil, Canada, Kenya, Panama and EU Member States (OECD, 2024^[19]). Particular attention needs to be paid to ensure that these safeguards are appropriate and proportionate to the potential trade-offs, as even well-intended safeguards can impede accelerated deployment of solutions addressing the triple planetary crisis. Risk-based checklists and preliminary screening questions can also help streamline the process by striking a balance between robust consideration and the speed of decision-making.

Ultimately, aligning existing policy frameworks with climate, biodiversity and pollution reduction objectives remains challenging. Diverse policy domains such as finance, taxation, public health, trade and innovation, or sectors such as electricity or urban mobility, may also require examination to ensure alignment between environmental and other policy objectives. For instance, transport policies aimed at reducing urban emissions need to ensure safe, affordable, accessible and sustainable transport systems for all while balancing with an efficient use of land that considers environmental costs (such as air pollution and pressures on biodiversity in urban areas). These alignments need to be tailored to national and local contexts. Low-carbon transport strategies in cities whose infrastructure is already built can encourage more efficient public transport systems, land use planning or consider reducing transport demand. Conversely, cities still in the process of developing transport infrastructure can leverage land use planning to minimise their impacts on land conversion and local biodiversity.

Figure 7.3. Integration of climate, biodiversity and pollution considerations across various levels



Source: Authors' own elaboration.

7.2.3. Align financing and public resource allocation

The interlinkages among climate change, biodiversity loss and pollution can be better addressed through financing and budgets that are designed, tracked and delivered jointly, rather than in separate silos. This is not always the case, as climate change, biodiversity loss, and pollution are tracked in different funds and ministries, underscoring the possibility to seek further alignment through existing processes.

Strengthen consideration of interlinkages in existing financing and budgeting processes

Multilateral environmental finance as well as broader development finance can play a key role in supporting countries to tackle the interconnected challenge together by explicitly embedding the consideration of interlinkages in different channels and targets³ established for each domain. The Global Environment Facility and more recently established Green Climate Fund play a key role in multilateral environmental finance for developing countries, including support for implementation of MEAs as well as broader capacity building efforts. As a point of convergence for different environmental commitments and treaties, the “Integrated Program” for multi-purpose projects from the Global Environment Facility offers an avenue for considering synergies in financing, particularly as the forthcoming next four-year cycle (GEF-9, 2026-2030) coincides with the 2030 milestone year for many global targets and commitments. Financing from other sources, including the UNEP Special Programme,⁴ as well as programmes targeted at the implementation of specific obligations under the Conventions (e.g. Specific International Programme for the Minamata Convention on Mercury) and the recently developed Global Framework on Chemicals Fund can also consider the interlinkages to prevent blind spots.

There is also substantial scope for enhancing synergies in development finance. While the share of biodiversity-related official development finance that also target climate objectives reached 89% in 2021, only 25% of climate-related official development finance also targets biodiversity objectives (OECD, 2023^[20]). More explicit targeting, complemented by improved assessments and project monitoring to ensure the anticipated synergies materialise, can contribute towards maximising its impact. This can also enhance cost-effectiveness in the long-term. The publication of common principles to track nature-positive finance by major Multilateral Development Banks is an important step in helping better mainstream nature and biodiversity conservation in these operations.

National budgeting is a fundamental lever for policy prioritisation. Its processes can be improved to better account for interlinkages that extend beyond functional categories and policy domains. The cross-cutting nature of the triple planetary crisis poses a risk of underinvestment in addressing it, because its drivers and pressures do not always neatly fall within the remit of ministries, departments and units. In this context, budgeting processes can provide an incentive for collaboration. For instance, ministries can identify opportunities to pool funds and establish or expand dedicated resources to allocate them to synergistic programmes.

Complementary tools and methodologies such as “green budgeting” can also play a role in facilitating resource allocation towards synergistic policies, while also integrating the objective of tackling the triple planetary crisis within relevant policies and programmes. Green budgeting can be used not just as a transparency tool but as a lever to prioritise investments that deliver cross-sectoral benefits could provide a clear pathway for policymakers to allocate resources more efficiently and strategically.

In France, an inter-ministerial working group assesses the environmental impact of expenditure for six objectives including climate change mitigation and adaptation, air, water and soil pollution as well as biodiversity conservation, allowing for the identification of programmes that deliver benefits across domains. Since its launch in 2020, green budgeting in France has gradually evolved from an additional budgetary document providing greater transparency on public expenditure to a tool that can inform policy planning and support budgetary decision-making. While there is no one-size-fits-all strategy for implementing green budgeting, countries can start small by considering the interlinkages articulated in national plans and strategies on climate change, biodiversity and pollution and identifying relevant policies and programmes (OECD, 2024^[21]).

Countries can also consider ways to enhance coherence between existing and new policy instruments to enhance synergies through financing and budgeting mechanisms. For example, Costa Rica's National Forestry Financing Fund administers payments for ecosystem services (carbon sequestration, water provision, biodiversity protection and natural scenic beauty) through forest conservation and sustainable management using the ring-fenced revenue generated from economic instruments, including taxes on fuels. The case for such earmarking of revenues, of course, needs careful consideration of both potential environmental and/or social benefits, as well as potential constraints on the allocation of public financing.

Another example is overlaying various offset mechanisms across domains to facilitate the consideration of synergies. For example, compliance markets in England (United Kingdom) allow land managers to sell biodiversity units (used to comply with the mandatory Biodiversity Net Gain) and nutrient credits (used for preventing the adverse impacts of housing on water quality and biodiversity) individually or in combination, incentivising land management practices that deliver synergies. Similarly, carbon and biodiversity co-crediting scheme could, for instance, help incentivise the protection of intact ecosystems (which have both greater carbon sink capacity and biodiversity) before restoration, while also reducing the overall administrative costs of implementing the scheme (Tedersoo et al., 2023^[22]). These policy designs can also be deployed in voluntary markets. For example, alignment between the two voluntary markets in Australia, the Nature Repair Market Scheme (which issues tradeable biodiversity certificates) and the Australian Carbon Credit Unit Scheme, aims to facilitate the development of synergistic projects that are eligible for both credits.

Align current patterns of public expenditure with environmental objectives

While it is important to consider ways to channel financial resources to synergistic programmes and projects, it is also critical to review public expenditure more widely (including support measures)⁵ and improve their alignment with environmental objectives. Economic activities such as agriculture, fisheries and forestry, while offering significant benefits to society, can adversely affect the environment, while their productivity and yields simultaneously hinge on planetary health.

Agriculture is a major recipient of public support worldwide, totalling USD 842 billion per year for the 54 countries covered by OECD data over 2022-24 (OECD, 2025^[23]). Reorienting agricultural support towards environmentally beneficial measures and key general services and making sustainable management and use of natural resources a core part of agricultural policy is necessary to make this sector more sustainable, productive and resilient (OECD, 2024^[24]). OECD Members acknowledged the need to “intensify efforts as appropriate to reform or reorient agricultural policy, and in particular to address those support measures that are harmful to the environment, to move towards more sustainable agriculture and food systems” in 2022 (OECD, 2022^[25]).

Certain types of agricultural subsidies linked to production outputs or the unconstrained use of variable inputs create market distortions and can encourage additional production with negative externalities and the excessive use of inputs such as water and fertilisers in some contexts (OECD, 2022^[26]; OECD, 2024^[24]). Output payments and support for the unconstrained use of variable inputs (e.g. fertilisers) currently average USD 75 billion a year (OECD, 2024^[24]). However, it is also important to note that removing subsidies coupled to production can also lead to adverse outcomes such as higher food costs and reduced farmer incomes, particularly affecting food security in developing countries (Guerrero et al., 2022^[27]). In this context, reorienting existing support from production to suitable agri-environmental practices, combined with targeted investments into productivity and abatement technologies have the potential to reduce agricultural emissions without compromising food security (Valin, Henderson and Lankoski, 2023^[28]).

Similarly, specific support that targets the fisheries sector and directly reduces the costs of fishing with support to fuel, vessel and gear subsidies can incentivise harmful practices including illegal, unreported and unregulated (IUU) fishing, which can lead to adverse social and environmental impacts including fish stock depletion, damage to ocean ecosystems and increased GHG emissions. As just under two-thirds of fisheries support present a risk of encouraging unsustainable fishing in the absence of effective management, there remains scope for redirecting resources towards investment in stock assessments, management and enforcement alongside more targeted support for sustainable fishing practices (OECD, 2025^[29]). These considerations also apply to extraction activities. Shifting away from broad support to fossil fuels towards more targeted measures can allow for more fiscal resources to be retained for the potential investments into the transition to less emission-intensive energy system (OECD, 2024^[30]).

7.2.4. Mitigate unintended impacts of the clean energy transition

Renewable energy delivers significant co-benefits beyond GHG emissions reductions. Solar and wind power substantially outperform fossil fuels across multiple environmental parameters, generating significant improvements in air quality through reduced sulphur dioxide, nitrogen oxides, particulate matter and ground-level ozone. These improvements provide immediate health co-benefits that further strengthen the case for rapid decarbonisation.⁶

Despite substantial benefits, renewable energy is not entirely without environmental cost. From hydropower infrastructure fragmenting rivers and impeding the movements of species to solar power infrastructure coinciding with the natural habitats, the spatial footprint of renewables can pose a risk for habitat loss and fragmentation. Wind farms, meanwhile, present well-documented mortality risks for birds and bats. The cumulative nature of these impacts extends their reach beyond local sites. Transboundary

species migration patterns, particularly for birds and bats, require international co-operation to address collision risks from wind infrastructure effectively.

The challenge becomes more complex when considering “energy sprawl”. Renewable energy’s diffuse nature compared to fossil fuels raises concerns about infrastructure expanding into areas that hold value for biodiversity conservation. For example, research has identified over 2 200 existing renewable facilities within protected boundaries, wilderness areas and Key Biodiversity Areas—a trend expected to accelerate (Rehbein et al., 2020^[31]).

The environmental effects of water-based renewable systems remain poorly understood compared to terrestrial applications (OECD, 2024^[19]). Hydropower presents cascading challenges beyond habitat fragmentation. Meanwhile, ocean energy harvesting technologies, while still emerging, raise concerns about marine ecosystem disruption. Materials extraction for renewable technologies also creates environmental pressures that can undermine protected area effectiveness for biodiversity conservation. Mining and processing activities for solar, wind, and battery components generate various pollution forms harmful to human and environmental health. Solar photovoltaic manufacturing involves releasing chemical compounds including cadmium, arsenic, and lead. Wind turbine blade disposal presents growing challenges due to their weight and material heterogeneity, with limited recycling options currently available. These end-of-life impacts create trade-offs with pollution control and biodiversity objectives that require proactive policy attention.

Bioenergy presents perhaps the most complex environmental trade-offs in the renewable portfolio. While many climate mitigation pathways compatible with 1.5°C warming include substantial bioenergy expansion, land-use pressures associated with dedicated energy crops create significant sustainability concerns. Bioenergy sourcing from dedicated crops can indirectly intensify agriculture through land competition and increase nitrogen pollution from fertiliser use. When bioenergy expansion comes at the cost of natural carbon sinks that are simultaneously biodiversity hotspots, it can simultaneously undermine climate and conservation objectives. The severity of these impacts varies significantly based on crop type, deployment scale and previous land use. Second-generation bioenergy derived from agricultural and forest residues generally presents fewer environmental concerns than dedicated crop production.

Beyond renewable energy, other clean technologies present their own environmental challenges. Clean hydrogen production, while offering versatile applications across industrial processes and energy storage, carries human safety and ecotoxicity risks due to hydrogen’s flammable nature and tendency to corrode containment materials. Water resource implications of hydrogen deployment warrant particular attention. Although water requirements remain substantially lower than fossil fuel alternatives, the water source significantly affects environmental footprint. Desalinating seawater produces harmful brine byproducts, though emerging technologies may enable simultaneous wastewater treatment and hydrogen production.

Negative emission technologies present both opportunities and challenges. Direct air capture using chemical sorbents can generate local water and air pollution. Enhanced weathering, while potentially improving soil fertility and reducing fertiliser needs, involves intensive mining, transport, and application processes that risk habitat destruction and water quality deterioration. Large-scale deployment of bioenergy with carbon capture and storage could create resource competition affecting food prices and exposing smallholders to global market volatility. Underground CO₂ storage may adversely affect biodiversity and exacerbate pollution through water releases that risk aquifer acidification.

These technologies vary widely in technical feasibility, scalability and certainty of environmental impact. The Convention on Biological Diversity’s Decision X/33 reflects international caution about geoengineering activities affecting biodiversity, though many national carbon neutrality targets implicitly rely on negative emission technologies.

Transport and building electrification offer clear air quality benefits through reduced direct emissions. Electric vehicles eliminate tailpipe emissions, improving local air quality conditions. Heat pumps and

electrical heating systems reduce both GHG emissions and improve indoor air quality in residential and commercial buildings.

However, electrification technologies typically require greater material inputs than their fossil fuel counterparts. Electric vehicles weigh more than conventional vehicles due to battery mass, potentially increasing non-exhaust emissions from brake, tire and road surface wear. Critical raw materials for batteries, electrolyzers, and other clean technologies create upstream environmental pressures through mining waste, drainage water and slag production.

Inappropriate disposal of electric vehicle batteries releases toxic chemicals, while recycling processes can create pollution through release of chemical components, including PFAS, cadmium or cobalt. Without parallel advances in material recovery and resource efficiency, accelerated clean technology deployment could drive unsustainable extraction from intact natural areas, including controversial deep-sea mining operations.

Core policy recommendations and actions

Procedures relating to the siting of wind and solar infrastructure are fundamental to avoiding adverse impacts on biodiversity – the first step in the “mitigation hierarchy”. Considering their current and alternative use of the siting areas can also help embed pollution control and management objectives in these procedures. As countries seek to accelerate renewables expansion, they can actively identify appropriate sites across terrestrial and marine areas for renewable energy infrastructure or steer them away from areas that are legally established as priority for biodiversity (e.g. protected areas) as well as migratory routes (e.g. of birds) (OECD, 2024^[19]). For example, the EU’s 2023 amendment to the Renewable Energy Directive (RED) requires Member States to designate Renewable Acceleration Areas (RAAs) by early 2026 on land where renewable energy development is not expected to pose significant environmental impact. This includes prioritising built and artificial surfaces and degraded land not suitable for agriculture, as well as excluding Natura 2000 sites, other national protected areas and major migratory routes of bird and marine mammal species (European Union, 2023^[32]).

Additional considerations of site characteristics, such as the proximity to existing power infrastructure, can also help reduce adverse impacts by obviating the need for extensive new infrastructure. For example, several countries including Australia, Germany, Canada and the United Kingdom have in some cases sited renewable energy sites near decommissioned coal plants to streamline electricity transmission and interconnection while promoting brownfield development (World Bank, 2021^[33]). Similarly, various land-sharing arrangements can be considered, including through combining solar photovoltaic (PV) setup and conventional agriculture (“agrivoltaics”) to reduce the spatial footprint while seeking synergies for pollution control and management and agricultural yields (Barron-Gafford et al., 2019^[34]), although optimising both energy and agricultural outcomes is not straightforward (Asa’a, 2024^[35]).

Spatial planning, aided by tools such as Strategic Environmental Assessments and decision-support planning tools, can streamline the permitting processes for renewables infrastructure while allowing for explicit integration of biodiversity and pollution considerations in siting decisions. As part of these processes, many countries require proponents of renewables projects above a certain threshold (e.g. in terms of size or capacity) to conduct an EIA. While the rigour of these processes may seem to come at the cost of the speed and the scale of renewables expansion, considering the risks at an early stage and developing plans to mitigate them also helps expedite permitting, reduce the risk of delays and cancellation of projects by improving legal and administrative certainty for the project proponents as well as authorities (OECD, 2024^[19]). In addition, licensing and permitting processes can be designed in a way that ensures their proportionality to help balance the costs against the benefits (OECD, 2025^[36]).

Beyond the siting of renewables infrastructure, additional safeguards might be needed at the operational level, as well as both upstream and downstream to minimise potential impacts of renewables on biodiversity and pollution. These include, for example, physical (e.g. bird flight diverters on power lines),

operational (e.g. shut down of turbines during migration), curtailment (e.g. blade feathering that prevents turbines from turning at low wind speeds) and abatement controls (e.g. technologies to reduce pile driving noise for offshore wind). For example, operational curtailment with a change in cut-in wind speed or blade feathering is mandated during summer months for wind farms with over 10 bat fatalities per turbine per year in Ontario, Canada. Wind turbines, however, are becoming larger and more efficient at generating energy at low wind speeds which may make curtailment less economically viable. Technological developments, however, can facilitate the implementation of “smart curtailment”, which uses real time data to reduce mortality impacts while minimising losses in energy. More research is needed in this area to understand and improve the effectiveness of safeguard measures.

The risks associated with PV farms such as land degradation and use of herbicides to reduce panel shading and fire risks can also be managed using safeguard measures, such as creating microhabitats to protect pollinator diversity. For example, well designed solar parks within intensely managed agricultural land could provide refuge for pollinators and enhance landscape connectivity. Biodiversity sensitive routing and mitigation measures are also critical for both solar and wind power generation, for example through the use of bird diverters, insulation and/or underground cabling. Specification of such safeguards early on can provide legal certainty to developers and simplify and potentially speed up the project appraisal. For example, most German Lander (federal states) have established upstream framing documents as a tool to reconcile renewables expansion with biodiversity conservation (OFB, 2023^[37]).

Due to limited reusability and recyclability, some components of solar and wind installations can result in pollution downstream. The concept of “waste hierarchy” which ranks options from most to least preferred (prevention, reuse, repurposing, recycling, recovery and disposal) can be applied to identify and manage these risks. For example, for wind turbine blades, such a hierarchy could include blade life extension, developing second hand markets for repurposed blades, and recycling, including downcycling. Several countries including Germany, Austria, the Netherlands and Finland have made an explicit reference to composite waste in their legislation that prohibits disposal, landfilling and incineration of wind turbine blades (Majewski et al., 2022^[38]). France has set progressively stringent recycling targets, with a requirement that from 2025, 55% of rotors of wind turbines must be reused or recycled (Tyurkay, Kirkelund and Lima, 2024^[39]). Similarly, countries have set regulations to encourage recycling and prohibit landfilling of solar panels. India issued a draft blueprint in 2019 to make recycling mandatory (Sharma, Mahajan and Garg, 2024^[40]), while Japan has revised a guideline on promoting recycling and other environmentally sound management of end-of-life solar PV in 2024 (Ministry of the Environment, 2024^[41]).

Social and distributional considerations

While consideration of biodiversity loss and pollution concerns are important when devising policies to facilitate clean energy transition, social considerations are equally essential to limit regressive effects. Wind farms, solar PV installations and bioenergy crops can compete with farming or Indigenous lands. Communities may also be opposed to renewables projects that alter landscapes and cultural heritage sites, or on account of new risks such as noise pollution from wind turbines and safety issues with large battery storage. The potential high installation costs of technologies like rooftop solar, electric vehicles or home battery storage could also widen inequality in terms of access in terms of income or location (e.g. between urban versus rural areas). Further, while renewables might create new jobs in manufacturing, installation and maintenance, they may not sufficiently overlap in terms of skills or location with lost fossil fuel dependent jobs.

Adequate safeguards and mitigation measures for such social and distributional effects are an integral part of the clean energy transition, in addition to the safeguards mentioned earlier to avoid trade-offs with biodiversity and pollution. For instance, lack of adequate participation in decision-making and project development – such as during an EIA – can drive public opposition to renewable energy infrastructure. Public participation prior to siting decisions can help ensure that EIA procedures are followed correctly;

that project plans follow local zoning regulations; and that companies adequately research impacts of proposed projects on the triple planetary crisis. Engaging stakeholders before there is a prescribed need can avoid unintended disruptions to project planning, siting and implementation, while assuaging the public's potential fears. Care should be taken to involve project beneficiaries, including Indigenous, disenfranchised and vulnerable communities. Beyond public participation, co-ownership and benefit sharing schemes such as royalties with the impacted communities can also help address community concerns. Meanwhile measures like subsidies and financing schemes for low-income households and ensuring grid integration for rural communities can help ensure more equitable access to renewables. Establishing safety standards and monitoring systems can help reduce local environmental impacts, while just transition policies, including reskilling programs and social protection measures can help address some of the employment effects of the clean energy transition.

7.2.5. Transform resource use

Resources are the bedrock of economies and are used in countless sectors, from construction to energy and manufacturing. Yet, current consumption patterns are unsustainable. In the past 50 years, global materials use has increased more than threefold. The materials lifecycle – from extraction to processing, use and end-of-life disposal – is linked to a range of negative impacts. The extraction and processing of materials, fuels, and food alone is responsible for over 60% of global GHG emissions, more than 90% of land use-related biodiversity loss, and 40% of particulate matter health-related impacts (UNEP, 2024^[42]).

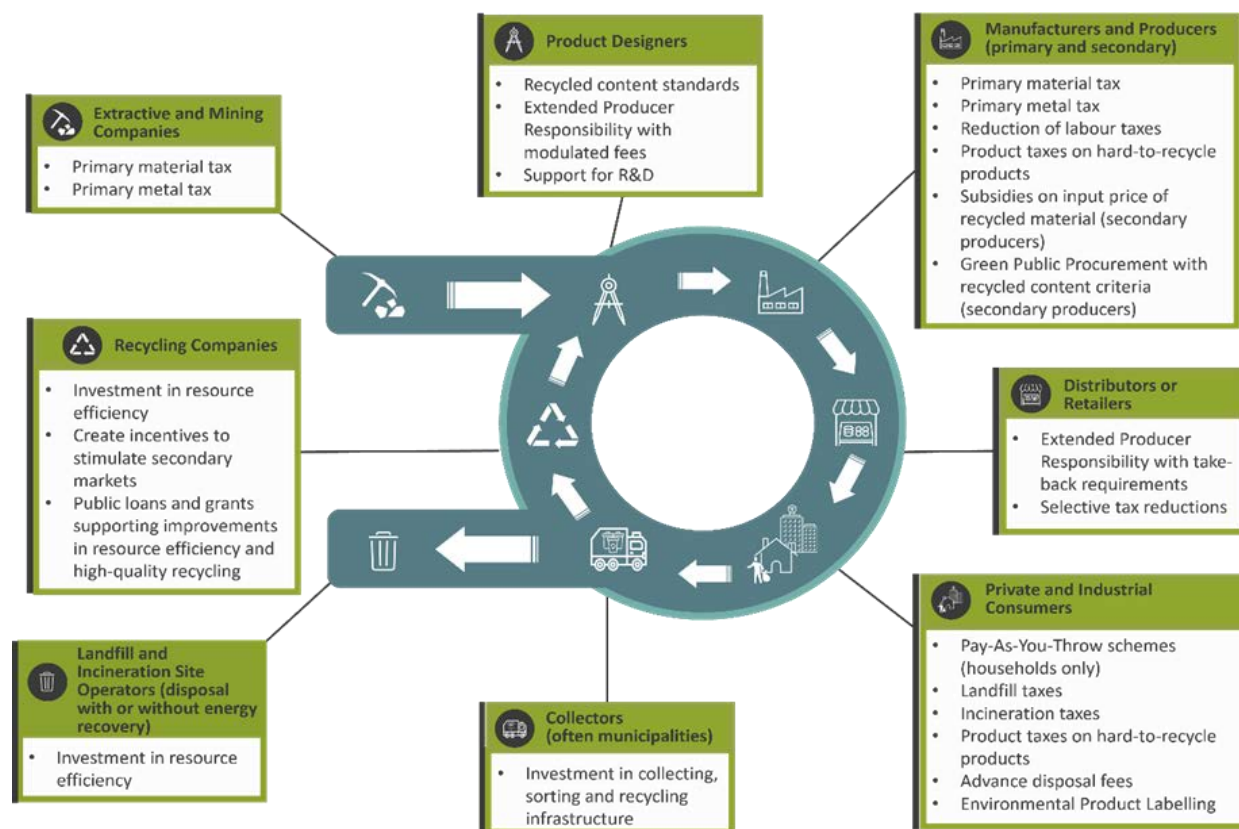
Furthermore, demand for primary material resources shows no signs of slowing down. In the coming decades, a growing population and higher incomes will increase global demand for goods and services, which will require more material resources. Gains in efficiency will only partially offset these pressures. Despite a projected relative decoupling between economic activity and materials use between 2020 and 2050, the latter is on track to increase by roughly half (from 96 Gt in 2020 to 145 Gt in 2050, Chapter 2), with cascading environmental consequences for land degradation, greenhouse gas emissions and pollutants.

The opportunity for a more resource-efficient and circular economy

Circularity can optimise energy usage, reduce waste and emissions and limit land degradation associated with biodiversity loss. In this context, accelerating the transition to a more circular economy is critical to addressing the triple planetary crisis, improving the security of resource supply and creating jobs. Such a transition involves several interlinked components, namely 1) closing resource loops to substitute virgin materials and new products with secondary raw materials and second-hand, repaired or remanufactured products; 2) slowing resource loops that seek to slow down consumption and demand for primary raw (virgin) materials by extending the life of existing goods usually thanks to more durable product design; and finally 3) narrowing resource loops to decrease the total amount of resources used per unit of output and to more efficiently use natural resources, materials, and products.

Implicit in this transition are two interlinked components: more environmentally sustainable inputs and more sustainable resource use practices among firms and households. For instance, the increased use of secondary materials (which typically have lower environmental impacts compared to their primary equivalents) hinges on changes in practices, including an uptake of recycling within industries and households. Governments can leverage a range of instruments to meet circular economy goals (Figure 7.4) such as virgin material taxes, pay-as-you-throw household waste charges and Extended Producer Responsibility schemes.

Figure 7.4. Illustrative policy instruments for a resource-efficient and circular economy, organised by their incidence on the economic agent



Source: (Livingstone et al., 2022^[43]).

Policy efforts to support a circular economy transition abound

Resource efficiency and circular economy initiatives have grown in prominence in policy agendas in recent years. 75 countries have adopted a national circular economy roadmap, strategy, or call to action, 71 of which have been introduced since 2016 (Barrie et al., 2024^[44]). While many initiatives are concentrated in European countries, roadmaps are increasingly being published throughout Latin America, Africa and Asia. These have been complemented by regional strategies and communities of practice, such as the European Union's Circular Economy Action Plan, the African Circular Economy Roadmap, the ASEAN Framework for a Circular Economy and the Global Alliance for Circular Economy and Resource Efficiency (Barrie et al., 2024^[44]). In the same vein, dialogues on resource efficiency exist within the G7 and G20. More recently, circular economy goals have been discussed in the context of ongoing international negotiations to secure a global plastics treaty.

Despite public aspiration and national policy action, progress on key circular economy metrics has been uneven and slow. As noted by the IRP, despite remaining relatively constant since 2000, the material footprint per capita of high-income countries (24 tonnes in 2020) is six times greater than that in low-income countries (4 tonnes). While upper middle-income countries continue to use fewer materials per capita (19 tonnes), this value has more than doubled since 2000 (UNEP, 2024^[42]).

Similarly, per capita domestic material consumption in OECD Member countries has decreased by roughly half since 2000, though remains higher relative to other world regions. On the heels of efficiency gains, material productivity has improved across OECD Member countries, from USD 2 per kg in 2000 to USD 2.9 per kg in 2023. However, waste generation continues to grow in most OECD Member countries. Only a few – Hungary, Japan, the Netherlands and Spain – have relatively decoupled waste generation from population and economic growth. Since 2015 alone, per capita waste generation rates have increased by over 7%. Further, despite increasing recycling and composting rates, landfilling – 40% in 2023 – remains the primary disposal method for municipal waste in many OECD Member countries (OECD, 2025^[45]).

In turn, global efforts to achieve an absolute decoupling of materials use and environmental degradation from GDP growth currently fall short, as global resource use has failed to decrease in absolute terms.

Core policy recommendations and actions

While some progress has been made in terms of a relative decoupling of materials use and GDP, policy action has traditionally focused on end-of-life recycling and waste management, leaving considerable scope for policies upstream to curb production and demand and promote eco-design. Complementary actions to promote greater resource efficiency and circular economy goals are therefore needed to better address climate change, biodiversity loss and pollution. These include: actions to mainstream the circular economy within other policy objectives; exploit synergies with sectors with a disproportionately high resource footprint; strengthen and realign incentives and; leverage demand-side interventions. In addition, monitoring progress towards a circular economy through a wide range of indicators is essential (OECD, 2024^[46]).

Circular economy policies are embedded within broader environmental, economic and social policy frameworks. However, the governance of circular economy strategies commonly sits within the remit of environmental ministries and is often considered as a separate policy objective, offering significant potential to mainstream such considerations into existing policy areas to enhance alignment. This includes mainstreaming circular economy considerations into cross-cutting policies that themselves impact the triple planetary crisis, such as in innovation and trade. Inter-ministerial coalitions could help bridge gaps in how circular economy priorities are addressed with the objective to tackle the triple planetary crisis. Jointly, initiatives like the African Development Bank's African Circular Economy Facility fund provides a targeted opportunity to support developing countries' ambitions in designing circular economy policies and programmes in ways that jointly address climate change, biodiversity loss and pollution.

With respect to innovation, aligning circular economy with innovation policies can stimulate research and development and accelerate the deployment of advanced technologies like digital twins and automated recycling systems. For instance, circular economy policies could promote circularity by setting minimum reuse or recycling targets for plastic products, or by modulating fees based on environmental impacts. Such policies could encourage innovation in product design to reduce waste generation, improve product recyclability and reusability and encourage innovation in waste recycling. Innovations such as material substitution and digitalisation can improve resource efficiency but must be carefully deployed to avoid generating new environmental pressures. For example, substituting mineral resources with bio-based inputs can increase demand for land and biomass, possibly leading to nutrient pollution. Risks of “regrettable substitution” could be anticipated and managed through improving ex-ante assessments that consider hazard, exposure and functionality of chemicals and materials throughout their lifecycles.

Additionally, trade offers the potential to improve the economic viability of circular practices through economies of scale. Despite the domestic nature of circular economy strategies, value chains are inherently global. Trade has an important implication, for instance, for mitigating the criticality of materials required for the energy transition. Trade also plays a crucial role in supporting international markets for end-of-life products and supporting markets for secondary materials. To maximise the potential of trade to unlock circular economy goals, greater alignment of standards and regulations is key. This could entail

clarifying and aligning different definitions and classification systems of waste, secondary materials and end-of-life products. For instance, there are different definitions of “secondary materials” and their relation to the codes used in the customs for classifying products at borders (Harmonised System) are unclear. Considering the potential trade implications of upstream measures targeting choices from resource extraction to production processes (e.g. eco-design) can also help enhance the role of trade in scaling up circular economy solutions.

Food and energy systems together with the built environment and transport jointly account for about 90% of global material demand (UNEP, 2024^[42]). With respect to the energy sector, the large-scale deployment of wind and solar energy generation drives demand for materials, with around 82% of global mining areas targeting materials needed for renewable energy production (Sonter et al., 2020^[47]), which can reduce, fragment and degrade natural habitats, increase pollution and release GHG emissions. The quantity of minerals per megawatt used for wind power and solar PV 1.2 to 14 times larger than for other power generation technologies (IEA, 2021^[48]) place additional pressures on the environment.

The circular economy therefore has significant potential to reduce the environmental impacts of the energy sector. Investments in improving the efficiency of renewable energy generation can reduce the spatial footprint of the infrastructure per unit, thereby reducing pressures on biodiversity and ecosystems. Likewise, circular economy indicators could be incorporated into lifecycle analysis methodologies for renewable energy technologies to more clearly map potential implications for climate change, biodiversity loss and pollution.

Enhanced transparency about the material composition and environmental impacts of products may also facilitate efforts towards improving upstream pollution risks of renewables as well as the downstream management of end-of-life solar panels and wind turbine blades. For instance, the European Union is introducing a Digital Product Passport as part of Ecodesign for Sustainable Products Regulation, which establishes a framework for specifying eco-design requirements on virtually all products placed on the market (European Union, 2024^[49]). Improving end-of-life management of renewables can likewise support more circular economies. Several countries including Germany and France have adopted the EU Waste regulations from Waste from Electrical and Electronic Equipment directives for management of end-of-life solar PV, making manufacturers responsible for the cost, collection and recycling of PVs. Importantly, concomitant considerations of material recovery and resource efficiency are needed. Investments in infrastructure supporting circular business models, beyond waste management, are therefore important. For instance, the Dutch government has supported large-scale production of circular solar cells and panels through the SolarNL project.

There is likewise significant potential for more circular food systems to tackle the triple planetary crisis. For instance, optimising farming techniques, including a shift towards regenerative agriculture techniques – such as silvopasture – can minimise external inputs including fertiliser use while improving carbon sequestration. Additionally, ensuring that food packaging is recyclable and compostable can alleviate GHG emissions and waste associated with the production of single-use packaging and landfilling, while mitigating the risk of biodiversity harms once in the environment.

Switching from a linear economy towards more circular economies in the food sector can also be extended to phosphorus-based products. Phosphorus reuse involves using phosphorus-containing waste directly without significant processing, for example by applying phosphorus-rich manure and compost to land as fertilisers. Phosphorus recycling focuses on recovery from waste materials and transformation into a form that can be used again, often in agriculture, for example through chemical extraction of phosphorus from sewage sludge or phosphorus recovery from sewage sludge ash after mono-incineration.

Furthermore, a more circular approach to food systems can mitigate the amount of food that goes unconsumed. Voluntary collaborations among governments, farmers, suppliers and retailers can create holistic strategies to tackle food loss and waste from farm to fork. Since 2005, the United Kingdom’s UK Food and Drink Pact (formerly, the Courtauld Commitment) has provided guidance to help businesses set

food waste reduction targets, measure food surpluses and waste and act to reduce food waste across the supply chain (WRAP, 2022^[50]). Governments can track progress in meeting targets via food loss and waste indices. Such measures necessarily require complementary initiatives that incentivise sustainable non-food consumption.

There is also an opportunity to strengthen incentives to better manage environmental impacts along the lifecycle of materials from extraction, transport, processing, use and disposal. Realigning incentives with the aim to strengthen efforts to curb production and demand and enhance eco-design are particularly important. For instance, primary materials remain more price-competitive than secondary materials, in part due to support measures such as reduced corporate income tax and concessional investment financing for the extraction of metals. To make circular economy approaches more economically viable, revenues from primary materials taxes could be redistributed in the form of recycling subsidies on the input price of feedstock for recycling processes or on the selling price of recycled commodities. In turn, greater uptake of recycling can significantly offset land use requirements, energy demand, as well as soil, water and air pollution associated with primary materials production. Subsidies could likewise enable firms to increase their spending on research and development, thus improving the likelihood of unlocking key innovations and their future production capacity. Crucially, it is important to align such incentives with addressing rebound effects.

Furthermore, such actions must be considered in the context of whole-of-lifecycle impacts, to avoid burden shifting between end points. For example, while secondary materials tend to be considerably less polluting, hazardous chemicals can become concentrated in recycled products. For recycling to become more viable, there is a complementary need to accelerate the transition to a cleaner energy system and incentivise more sustainable product design.

Changing consumption patterns is at the heart of a circular economy transition in line with the objective of tackling the triple planetary crisis. In turn, the prevailing approach of focusing on supply-side (production) measures must be supplemented with a much stronger focus on demand-side (consumption) measures to help avoid wasteful consumption and shift towards less harmful alternatives. Demand-side measures that focus on reducing structural, financial and psychological barriers while improving choice architecture and the development of markets for recycled products can therefore contribute towards reducing environmental pressures. Availability, affordability and convenience are fundamental to enabling more sustainable household decisions. For example, individuals are unlikely to repair their garments if such services are difficult to find or if repair is not price competitive vis a vis the purchase of new clothing. Similarly, households are more likely to recycle and compost their waste if they have access to convenient curb-side collection services. Other demand-side strategies, such as tax credits for purchasing refurbished and repaired items or volume-based fees for residual and food waste, can incentivise residents to minimise their waste footprint. These instruments are typically implemented at the sub-national level. It is therefore important to anticipate the potential challenges municipalities may face due to resources and capacity limitations to ensure policy effectiveness. Cultural and structural shifts also need to be considered together with individual choices.

Social and distributional considerations

The transition to a more resource-efficient and circular economy – while supporting the objective of tackling the triple planetary crisis – must ensure that no one is left behind. Yet, this focus is not always prominent in circular economy strategies (Barrie et al., 2024^[44]). Availability, affordability and convenience are also fundamental to the uptake of circular economy models. If circular economy policies lead to higher product costs upfront (for example for more durable, repairable goods) then low-income households may face affordability concerns. On the other hand, sharing models such as rental and leasing, that are also part of the circular economy, can help improve affordability by reducing costs.

While circular economy might imply a net increase in jobs through a transition from material intensive sectors such as extractives to more service-oriented sectors that tend to be more labour intensive, there may be job dislocations across occupations and regions, creating winners and losers. In some cases, there may also be concerns about the quality of the jobs that are created. Social protection measures like retraining programs may be deployed to help workers displaced by circular economy policies while redirecting revenues from primary materials taxes to reduce distortionary labour taxes can contribute to social outcomes. At a regional level, channelling circular economy investments into regions that were previously reliant on extractive industries can also help reduce the dislocations that might result from a transition to a more circular economy.

As secondary production tends to be more labour-intensive than primary production, reducing labour taxes could be a way to enhance cost advantages of secondary production. Environmental health and safety may also need particular attention, for example in the case of workers employed in recycling, repair and refurbishment. In many developing and emerging economies these tasks are often conducted by informal workers that are underpaid and under conditions that lack appropriate environmental safeguards. Integrating informal workers within more formalised waste management systems can help improve occupational health and safety and raise incomes.

7.2.6. Rethink food systems

Food systems, which comprise the elements and activities related to producing and consuming food (including land use change), account for around one-third of global GHG emissions (Crippa et al., 2021^[51]). Agriculture and related land use change make up about 65% of such emissions, with the remainder arising from both downstream (e.g. transport, processing, retail, packaging, waste) and upstream (fuel production) activities (OECD, 2023^[52]).

Food systems are also the most significant driver of terrestrial biodiversity loss (Dasgupta, 2021^[53]). Agriculture stands out as the main driver of habitat loss, accounting for a large share of global land use changes, primarily through the conversion of natural ecosystems for crop production and pastures. The expansion of agriculture also harms freshwater and marine ecosystems, including through pesticide use.

While options to reduce greenhouse gas emissions in the food system are plentiful, and in many cases they also have co-benefits in terms of reduced biodiversity loss and lower pollution, their implementation is fragmented and uncoordinated. Such measures also risk trade-offs with other key outcomes such as food security or impact on livelihoods. In general, improvements in environmental outcomes can be achieved through switching to lower-impact food categories and/or lower-impact production methods. The significant heterogeneity within food categories, however, adds further complexity, underscoring the critical importance of evidence in weighing the possible synergies and trade-offs (OECD, 2021^[3]). Agriculture has been so far largely exempted from legally binding targets for greenhouse gas emissions reduction and is often not integrated into national net-zero strategies. For instance, while most countries mention agriculture among sectors considered in their NDCs; only 16 of 54 countries surveyed by the OECD have any form of specific mitigation target for the agricultural sector (OECD, 2022^[26]). Another important policy area concerns integration of food systems into other economy-wide climate policies. For example, agricultural emissions tend to be excluded from most national carbon pricing schemes.

While actions on biodiversity loss are better linked to food systems, synergies and trade-offs between biodiversity and climate actions are not fully accounted for in designing the actions (OECD, 2023^[52]). Increasing intensive land use reduces deforestation but has higher demands on fertiliser and water while increasing extensive land use results in more deforestation. Evaluating these trade-offs requires an integrated approach to policy across the three areas of climate, biodiversity and pollution, which is not fully in place.

Transformation of the food system is essential to address the triple planetary crisis. On climate change, meeting the net zero target will require mitigation in all sectors including food systems, which have been making slower progress relative to other sectors. On biodiversity, continued losses and degradation of ecosystems are closely tied to the current food systems. Pollution related to food systems also accounts for most of the habitat loss and land use changes resulting in deforestation. In terms of pollution, the costs of nitrogen used in agriculture to health and ecosystems are significant. Estimates of the global hidden costs of nitrogen use are around USD 1.5 trillion (or around 1.46% of global GDP) (Lord, 2023^[54]). While the application of nutrients such as nitrogen and phosphorus are important to maintain yields, a large share of these inputs is not taken up by plants. For example, there is considerable global surplus application of nitrogen (around 50% is lost), which can be reduced in surplus regions without endangering food security while improving nitrogen use efficiency (Lassaletta et al., 2014^[55]).

Core policy recommendations and actions

Actions need to be taken to reduce the negative impacts of food systems across climate, biodiversity and pollution in a way that takes account of synergies and addresses trade-offs. For instance, governance issues are present at the global and national levels. The Global Stocktake does not provide targets or guidance for integrating food systems measures in national policies. While the former addresses the vulnerabilities of food production systems to climate change, the role of food systems to mitigate climate change is not included in the Agreement. There has been some progress in including agriculture within the UNFCCC framework through the Koronivia Joint Work on Agriculture, which was designed to advance discussions on how agriculture can contribute to both increased food security and climate change adaptation. It was followed up by a decision at the 2022 COP in Sharm el-Sheikh to develop comprehensive strategies for addressing food security in the face of these challenges. Results from this initiative, however, are yet to be achieved. The Global Stocktake at COP28 in 2023, for the first time, mentions food systems but fails to incorporate a systems approach to address climate change in such systems (WWF, 2024^[56]).

The Kunming-Montreal Global Biodiversity Framework sets clear targets related to agriculture and food systems, but much remains to be done to implement them. Through multistakeholder and collaborative approaches under NDCs, NAPs and NBSAPs, governments can ensure that sectoral policies for climate, biodiversity, and food are aligned and geared towards contributing to the global goals for climate and nature (OECD, 2023^[52]).

At the national level, a food systems approach that recognises the challenges but also sees the opportunities is needed. This requires integrating food systems measures in NBSAPs and NDCs. While most (94%) of 146 updated NDCs mention food, only 3% (5 NDCs) consider measures across several intervention areas in agriculture and food systems (WWF, 2024^[56]).⁷

With respect to regulations and safeguards, concerted action to address food systems emissions requires a focus on both supply and demand (OECD, 2022^[26]). On the supply side, three areas of action stand out: first, reducing direct emissions from agricultural production and elsewhere along food systems value chains, including through enhancing productivity and efficiency of input use; second, reducing emissions from land use change and enhancing carbon sequestration potential; and third, reducing food loss. On the demand side, shifting dietary preferences towards less emissions-intensive products and processes and reducing food loss and waste is paramount.

Another measure that would be effective is pricing emissions from sources in agriculture, which are presently exempt. One recent development is the announcement by Denmark in 2024 (pending parliamentary approval) to impose a tax on livestock related GHG emissions from agriculture from 2030 onwards (The Copenhagen Post, 2024^[57]).

Further opportunities exist to improve land-based area payments to better align with a transition to low-emissions food systems, including through linking such payments to the provision of environmental and ecosystem services such as carbon sequestration through afforestation or land rehabilitation. Such schemes can play an important role but difficulties can arise when they are driven more by government aims and objectives and less by local needs (Pagiola, Agostini and Gobbi, 2004^[58]). This can be avoided by making sure that schemes are based on the participation of all relevant parties and account is taken of how providers will respond to the incentives offered (Wunder et al., 2020^[59]).

On the demand side, reducing food loss and waste is critical. The amount of food lost or wasted is around one-third of all food produced (FAO, 2023^[60]) and generates 8-10% of global GHG emissions (UNEP, 2024^[61]). Policy measures include targeted investments in equipment, training of operators, educational programs for consumers (FAO, 2019^[62]). While these technical solutions have made some impact and are found to be cost-effective, others that focus on changing behaviour have not been evaluated in detail but remain important. 12% of food is wasted in retail and 60% by households (UNEP, 2024^[61]). Promoting/directing behavioural changes and consumer awareness can significantly reduce food waste, including through incentivising changes in retailer and business practices such as reporting and consumer targeting, introducing longer-lasting products or regulating commercial practices that lead to overbuying (OECD, 2022^[26]).

The other demand side measure is dietary change. A transition to plant-based diets is projected to cost USD 30 billion, but the predicted economic benefits of this transition, totalling around USD 1.3 trillion, eclipse these costs (Nature Editorial, 2019^[63]). However, as diets are an integral part of social habits and cultures, changing them is very difficult. Current policies often entail information provision and nudge strategies. There are some signs of a general move to healthier and more sustainable diets but also a global increase in the consumption of meat and dairy is anticipated (OECD/FAO, 2025^[64]).

Research and development may play a potentially sizeable role. In recent decades, large productivity gains have helped to meet increasing global food demand while limiting environmental impacts. There is potential for further gains in productivity that would reduce the demand for land expansion, while also reducing the environmental footprint of agriculture. New genetic technologies offer additional opportunities to advance crop resilience and productivity and could play an important role in reducing food systems emissions (von Braun et al., 2021^[65]). Viable options also exist for reducing livestock emissions. As most emissions come from enteric fermentation, herd genetics and feed and pasture quality are key (OECD, 2022^[26]).

Investments in research and development in agrifood systems are found to have a high return in terms of productivity as well as environmental benefits, higher in some studies than restrictions on land use (Fuglie et al., 2022^[66]). Yet, public investments in agricultural innovation currently remain marginal – equivalent to only 0.54% of the value of agricultural production in 2022-2024 (OECD, 2025^[23]). This will need to be complemented by the adoption of improved practices where significant potential exists and by measures to ensure that access to technologies and professional training is available to vulnerable groups.

Social and distributional considerations

Reforming the food system can result in both positive and negative social and distributional consequences. On the positive side, for example, dietary shifts and reduced pollution can lead to health co-benefits. Reducing food loss and waste, meanwhile, can help reduce hunger and malnutrition by increasing food availability. Further, by optimising fertiliser and pesticide use, policymakers can improve soil and water quality, and lower the costs of water treatment. It is, however, the potential negative side effects that need to be carefully evaluated and managed as part of any food system reform process. Stricter environmental regulations or taxes on high emission foods like meat and dairy can raise retail prices and disproportionately impact low-income households who spend a higher share of their budget on food. If more sustainable and healthier alternatives remain more expensive and/or less available, then it may widen health inequities and have disproportionate impacts on lower income households. Other reforms,

such as reduction of agricultural inputs or meat production could cause income loss or job insecurity among farmers, especially smallholders, employed in input or livestock heavy agriculture. Dietary shifts and measures like border carbon adjustments in high-income countries could also have international distributional effects on farmers in low- and middle-income countries dependent on emissions intensive agricultural exports.

Governments have at their disposal a wide range of tools to help mitigate these adverse social and distributional effects and prevent these issues from becoming an impediment to improving environmental sustainability of food systems. These could include income transfers or food vouchers for low-income groups. Targeted subsidies for healthy, low emission foods are another option while ensuring that these subsidies themselves are not socially regressive if the consumption of such foods is initially concentrated in high income groups. Public procurement policies could also be considered to provide affordable more environmentally friendly meals in establishments like schools and hospitals. Just transition programmes that support retraining of farm workers as diversification of rural economies (e.g. renewables and ecosystem services) can help offset potential income and job losses. Making input subsidies conditional on the adoption of practices like climate and biodiversity smart agriculture – can help reduce nutrient pollution while supporting farmer livelihoods. At the international level, meanwhile, support for trade diversification to reduce reliance on export of single food commodities, use of development assistance and/or climate finance can help support sustainable transition in the food system.

Beyond specific policy instruments, any reforms of the food system must take into consideration the close connection between food and culture, religious beliefs and values. Multi-stakeholder collaboration is key with particular attention to those who are traditionally excluded from decision-making. Given these intertwined interests, the adoption of a “food systems approach” is needed to move forward with coherent and ambitious reform. A food systems approach opens the possibility of using different policy instruments to balance competing interests and values. This entails considering the impacts of all policies affecting food systems on farmer livelihoods, the environment, food security as well as the economy more widely, to foster synergies and avoid or mitigate unintended consequences.

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Notes

¹ The scope of the policies considered are detailed in Annex 2.A. The cut-off date used in the modelling analysis means that the changes in policies and ambition within the updated (2025) nationally determined contributions (NDCs) are not considered under current policies.

² The ten countries included in the analysis are Argentina, Australia, Canada, China, France, India, Indonesia, Japan, Peru, and Uganda (see Chapter 5).

³ Developed countries provided and mobilised USD 115.9 billion in climate finance (supporting developing countries) in 2022, exceeding the annual goal of mobilising USD 100 billion for the first time (OECD, 2024^[68]). Similarly, Target 19 of the Kunming-Montreal Global Biodiversity Framework sets out the goal of mobilising USD 200 billion a year by 2030, including USD 30 billion in international finance from developed countries to developing countries. In 2021, biodiversity-related official development finance is estimated to have reached USD 18.5 billion (OECD, 2023^[20]).

⁴ Also known as the Chemicals and Waste Management Programme, the Special Programme provides funding for strengthening institutions for the sound management of chemicals and waste to support the implementation of the Basel, Rotterdam and Stockholm Convention, the Minamata Convention and the Global Framework on Chemicals.

⁵ Support measures can include direct budgetary transfer, tax expenditure as well as the foregone revenue (e.g. underpricing of a good or a service). Certain types of support measures such as market price support (e.g. minimum price guarantee) for agriculture are foregone revenue rather than a budgetary transfer; these measures therefore cannot be repurposed or redirected but options exist for their reforms and elimination (Matthews and Karousakis, 2022^[67]).

⁶ Furthermore, the cost of producing renewable electricity have declined rapidly in recent years.

⁷ While there may be limited cases of food systems measures in national reporting, these measures may be included in countries' implementation plans.

Environmental Outlook on the Triple Planetary Crisis

Stakes, Evolution and Policy Linkages

Climate change, biodiversity loss and pollution – the three elements of what is now called the triple planetary crisis – are a growing risk to human health, the environment and the economy. While these challenges are intimately linked, policy responses have traditionally operated in silos, presenting an opportunity for more integrated action.

This OECD Environmental Outlook examines the biophysical impacts of the triple planetary crisis before developing projections for the evolution of its interlocking drivers, environmental pressures and states to mid-century. The Outlook also presents an in-depth analysis of the policy linkages among climate change, biodiversity loss and pollution. An analytical framework is first developed to examine synergies and trade-offs between policy responses to the three challenges. This is followed by a first-of-its-kind stocktake examining the extent to which policy linkages are addressed in national documents. This high-level analysis is complemented by deep dives on how key synergies and trade-offs between different objectives manifest during policy design and implementation. Key insights are then synthesised into a policy roadmap to help inform integrated action.



Co-funded by
the European Union



PRINT ISBN 978-92-64-71679-7
PDF ISBN 978-92-64-46691-3



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