ROOTED

Agriculture Rooted in Biodiversity

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Contents

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NBS INVEST
Accelerating Nature Based Solutions in Least Developed Countries

FOODSYSTEMS 2030

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Glossary

Agriculture: The science, art, and practice of cultivating the soil, producing crops, and raising livestock, (Reference FAO) which includes specialized agriculture such as pastoralism, horticulture, vegeculture, and arboriculture (tree crops) (Harris, D.R., Fuller, D.Q. 2014).

Agrobiodiversity: The variety and variability of animals, plants, and microorganisms that are used directly or indirectly for food and agriculture.

Biodiversity: The variability among living organisms from all sources including 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 (Convention on Biological Diversity, Article 2).

Critical Natural Assets: Areas providing irreplaceable local and global ecosystem services or NCPs.

Ecosystems: A dynamic complex of plant, animal, and microorganism communities and their non-living environment interacting as a functional unit (*IPBES 2019*).

Ecosystem services: The material, non-material, and regulating services that ecosystems provide. Also referred to as NCPs.

Nature's Contribution to People (NCP): The benefits people obtain from ecosystems.[1] Also referred to as ecosystem services.

Nature: The natural world with an emphasis on its living components, includes biodiversity, ecosystems (both structure and functioning), evolution, the biosphere, humankind's shared evolutionary heritage, and biocultural diversity (*IPBES 2019*).[2]

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[1] The full IPBES definition is as follows: The benefits people obtain from ecosystems. In the Millennium Ecosystem Assessment, ecosystem services can be divided into supporting, regulating, provisioning and cultural. This classification, however, is superseded in IPBES assessments by the system used under "Nature's contributions to people." This is because IPBES recognizes that many services fit into more than one of the four categories. For example, food is both a provisioning service and also, emphatically, a cultural service, in many cultures.

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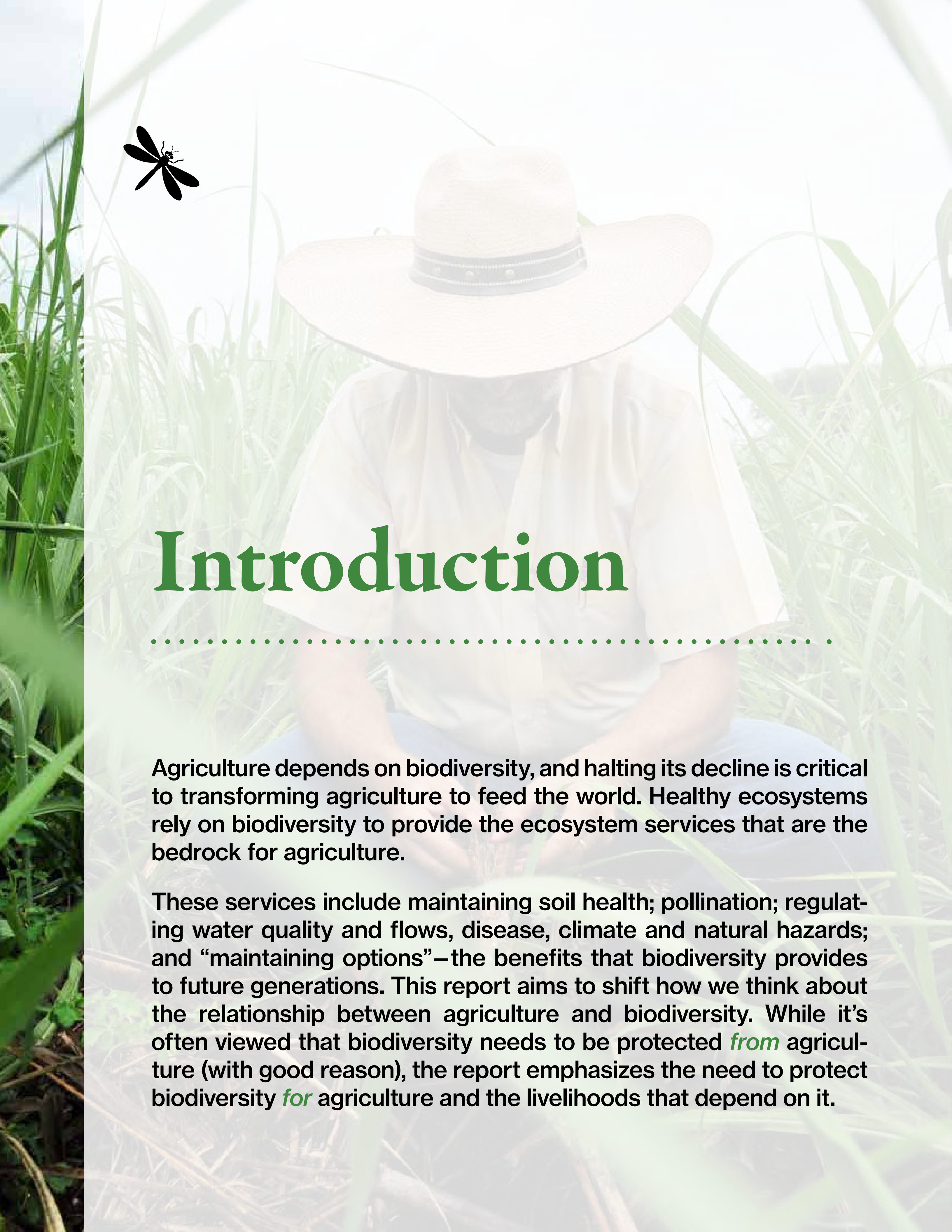
Acronyms & Abbreviations

CA	Conservation Agriculture
CBD	Convention on Biological Diversity
CAFOs	Concentrated Animal Feeding Operations
CNA	Critical Natural Assets
EFA	Economic and Financial Analysis
EU	European Union
FAP	Farming with Alternative Pollinators
FAO	Food and Agriculture Organization of the United Nations
GBF	Kunming-Montreal Global Biodiversity Framework
GHG	Greenhouse-Gas Emissions
INM	Integrated Nutrient Management
IPM	Integrated Pest Management
IPBS	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPLCs	Indigenous Peoples and local communities
IUCN	International Union for Conservation of Nature
LDN	Land Degradation Neutrality
Mha	Million Hectares
NARS	National Agricultural Research Services
NCP	Nature's Contributions to People
NBS	Nature-Based Solution
OECM	Other Effective area-based Conservation Measures (OECMs)
PAs	Protected Areas
PGRFA	Plant Genetic Resources for Food and Agriculture
SAPs	Sustainable Agricultural Practices
SEEA	System of Environment-Economic Accounting
SWC	Soil and Water Conservation
TEEB	The Economics of Ecosystems and Biodiversity
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNEP FI	United Nations Environment Programme Finance Initiative
UNFCCC	United Nations Framework Convention on Climate Change
WCS	Wildlife Conservation Society



Introduction

Agriculture depends on biodiversity, and halting its decline is critical to transforming agriculture to feed the world. Healthy ecosystems rely on biodiversity to provide the ecosystem services that are the bedrock for agriculture.

These services include maintaining soil health; pollination; regulating water quality and flows, disease, climate and natural hazards; and "maintaining options"—the benefits that biodiversity provides to future generations. This report aims to shift how we think about the relationship between agriculture and biodiversity. While it's often viewed that biodiversity needs to be protected *from* agriculture (with good reason), the report emphasizes the need to protect biodiversity *for* agriculture and the livelihoods that depend on it.

The objective of the report is to raise countries' understanding of biodiversity's importance for agriculture and provide the knowledge, policy tools, and investment options to increase biodiversity to meet the growing demand for food and provide healthy diets. The information in this report is a foundation for supporting countries to reform agricultural policies and investments for conservation, restoration, and scaling up the adoption of sustainable agricultural practices for biodiversity. This will also support countries in meeting COP 15 commitments.

The report is geared to government agencies and ministries including ministries of finance, agriculture, water, environment, and land use that are jointly concerned with public policy, planning, and investment for more sustainable agriculture and better biodiversity outcomes, as well as development partners and multilateral development banks supporting governments in this agenda.

In this report, agriculture refers to crop and livestock production. While the report discusses the importance of forest and aquatic ecosystems for agriculture, the report is framed around the importance of biodiversity for agriculture, rather than for forestry and aquaculture production, which are equally significant, but not discussed extensively in this report.

CHAPTER 1 describes how biodiversity provides a foundation for the ecosystem services that support agriculture and explains why biodiversity in both natural and agricultural landscapes must be protected to support agricultural productivity and resilience, locally and globally, for decades to come.

CHAPTER 2 draws on recently published studies on the spatial distribution of biodiversity and ecosystem services to map the threat that agricultural development and climate change pose to biodiversity and ecosystem services in natural and semi-natural areas. It also flags opportunities for restoring natural areas and illustrates how spatial data can inform spatial targeting of conservation, restoration, and sustainable intensification.

CHAPTER 3 delineates the pathways through which unsustainable agricultural practices drive biodiversity loss, and in turn, the loss of ecosystem services supporting agriculture across wide spatial and temporal scales. It describes declining diversity of animal and plant genetic resources for food and agriculture (agrobiodiversity). The report argues for a multifaceted approach to biodiversity conservation involving both land sparing (intensification to reduce land use pressure) and land sharing (enhancing biodiversity within agricultural areas) and identifies the circumstances under which intensification may have "rebound effects" moderating land sparing effects.

CHAPTER 4 identifies sustainable agricultural practices that mitigate agricultural-driven biodiversity loss, and may even improve biodiversity over time. It provides evidence to show that while results are often context specific, these practices generally have win-win outcomes improving both biodiversity and financial returns, albeit often with time lags. This transition period (including possible upfront investment costs) calls for innovative finance, public support, and sustained technical support for farmers as they move to sustainable practices and productivity.

To understand the linkages between agricultural support and biodiversity loss, **CHAPTER 5** presents evidence on the relationship between agricultural support and the number of threatened species and discusses the types of agricultural support that harms or benefits biodiversity. It also describes the biodiversity financing gap and explores the potential to fill this through repurposing agricultural support toward measures that support biodiversity. It discusses the relative benefits of Payments for Ecosystem Services and green subsidies and opportunities for scaling them up. This chapter closes by discussing the emerging bio-credits market and the need for a comprehensive framework for monitoring results and verification for all types of investments supporting biodiversity.

Finally, **CHAPTER 6** provides recommendations on policy and investment for: (i) conservation and restoration of natural areas; (ii) sustainable intensification for biodiversity; (iii) financing sustainable intensification, restoration, conservation supported by case studies in the annexes – including on Payments for Ecosystem Services, sustainable agricultural practices, and restoring and conserving plant genetic resources for food and agriculture.

The report benefits from evidence from a review of scientific and economic literature on agricultural-driven biodiversity loss and sustainable agriculture conducted by CGIAR, and on spatial analysis of the threat to biodiversity and ecosystem services and restoration opportunities conducted by the Wildlife Conservation Society (WCS) for this report.

Summary

Biodiversity Supports Agriculture

Increasing biodiversity and increasing agricultural productivity are complementary objectives, not competing ones.

While agriculture is often viewed as a threat to biodiversity, evidence shows that maintaining biodiversity is critical *for* agriculture.

Biodiversity is a foundation for healthy ecosystems and the ecosystem services they provide support agriculture, for example:

Forming, protecting, and decontaminating soils and sediments (valued at $11.4 trillion annually): Diverse soil organisms improve soil structure, water retention, and nutrient availability.

Freshwater flow, quality, and quantity: Biodiverse forests, grasslands and wetlands regulate water flow and filtration, ensuring reliable and clean freshwater, 72 percent of which is consumed by agriculture.

Pollination and seed dispersal (valued between $235–$577 billion annually): Diverse pollinator communities including over 200,000 species enhance the pollination of crops and reduce pollinator vulnerability to environmental shocks.

Pest and disease control: Natural predators and microbial diversity suppress pest and disease outbreaks.

Regulation of hazards and extreme events; and climate regulation: Biodiverse landscapes (e.g., forests, grasslands) stabilize microclimates reducing damage from storms or heatwaves.

Genetic diversity within crops and livestock which allows for greater resilience to pests, diseases, and changing climate conditions.

Biodiversity at three levels (genetic, species, and ecosystem) work together to provide a multi-dimensional support system for agriculture.

Genetic diversity in crops provides resistance against pests and disease and diverse predator species protect the same crops against pests, while biodiverse ecosystems reduce the risks of disease transmission.

Biodiversity at global, regional, landscape, and local scales including within agricultural areas support agriculture simultaneously.

On a global scale

Large wilderness areas regulate global climate patterns essential for distant agriculture.

Amazon deforestation of 20 to 25 percent could affect rainfall up to 4,500 kilometers away.

At a regional scale

Biodiversity supports agriculture by regulating water resources, climate, and pest populations.

Watersheds ensure reliable water supply and reduce flood damage in agricultural areas, typically 10 to 1,000 kilometers from headwaters.

At a landscape scale

Biodiversity contributes to pollination, pest control, soil health, and carbon sequestration.

Landscape complexity within one kilometer increases natural enemy abundance by 40 to 70 percent.

At a local scale

Biodiversity supports pollinators and pest enemies, and regulates microclimates – including within agricultural areas, habitat patches, riparian vegetation, and forest edges.

Pollination declines by 50 percent at more than 750 meters from natural habitats.

The location and proximity of natural areas to agriculture plays a key role in determining how effectively biodiversity supports agriculture.

Human-modified landscapes that retain at least 20–25 percent of semi-natural habitat can sustain pollination, pest control, and other ecosystem services, while areas with less than 10 percent of habitat experience sharp declines in ecosystem services, with some services disappearing entirely.

Agriculture can also support biodiversity.

Beyond the contribution of sustainable agricultural practices to increasing biodiversity in previously unsustainable systems (which is a core focus of this report) agriculture can contribute to biodiversity in other ways. Animal and plant breeding and selection have created an immense diversity of genetic resources for food and agriculture. Agriculture can also contribute to restoring degraded landscapes such as after mining. Furthermore, about 17 percent of species (from species groups comprehensively assessed on the IUCN Red List) are found in agricultural habitats and 86 species are only found living in agricultural habitats(IUCN 2024).

Agriculture is responsible for nearly 75 percent of negative impacts on land-based biodiversity.

Agricultural expansion has driven biodiversity loss in natural areas

Agriculture fundamentally relies on nature, yet it stands as the primary driver of nature's decline causing nearly 75 percent of negative impacts on land-based biodiversity (UNEP 2024).

Agriculture drives the vast majority of deforestation and related nature loss

86%

of global deforestation between 2001–2022 was due to conversion for crop and cattle production (West et al. 2025)

Agriculture threatens up to 85 percent of species currently at risk of extinction

73%

average drop in monitored wildlife populations which have plummeted globally since 1970 (WWF 2024)*

Trade results in displaced biodiversity impacts; consumption in high-income regions drives deforestation and habitat loss in the Global South

72%

of impacts from agriculture on biodiversity linked to consumption in high-income countries originated from imported goods in 2015**

* Losses were concentrated in certain regions, including 95 percent in Latin America and the Caribbean, 76 percent in Africa, and 60 percent in Asia Pacific (WWF 2024).

** Only 17 percent of the biodiversity footprint in low-income countries was tied to imports (Bjelle et al., 2021).

The farm types driving deforestation differ by region.

Large-scale forest conversion for commodities is evident in the Brazilian Amazon and in Indonesia (World Bank Forest Indicators 2022), for example. Yet, in Africa, smallholder agriculture is the dominant driver of forest conversion (Masolele et al. 2024).

Only about half of deforested land has been used for the expansion of productive agriculture.

The remainder land has been cleared for speculation, caused by agricultural-related fires, remained idle due to land tenure issues, or used for short-lived agriculture and abandoned (Pendrill et al. 2022).

Urgent action to arrest land use change is essential because ecological systems in some natural areas are nearing or have already passed tipping points.

For example, the Amazon rainforest is at risk and could shift from forest to savanna. This shift would cause catastrophic biodiversity loss and disrupt regional and global climate regulation, significantly impacting agriculture reliant on its rainfall patterns (IPCC 2023).

Therefore, strategies for conserving remaining natural areas, restoring degraded ecosystems, and connecting fragmented landscapes discussed in the following section are crucial for maintaining biodiversity and the ecosystem services that support agriculture.

Status of natural areas supporting agriculture

Over half of the areas that provide irreplaceable biodiversity and NCPs, including those that support agriculture, are still largely intact.

Conservation of those areas, hereafter referred to as critical natural assets, is the most cost-effective way to maintain the provision of those NCPs to agriculture. Just under half of critical natural assets are degraded and yet the opportunity remains to ensure that both biodiversity and the NCPs that agriculture depends on are maintained or restored. Action is most urgent where intact or degraded areas are under threat from agricultural development and climate change.

Critical Natural Assets (CNA) are defined as areas providing irreplaceable biodiversity and irreplaceable local and global NCPs, including those supporting agriculture (Chaplin-Kramer et al. 2023; Neugarten et al. 2024). These include 12 NCPs, two that are global (carbon storage and vegetation-regulated moisture retention recycling) and 10 that provide local/regional benefits (crop pollination, flood regulation, sediment retention, nitrogen retention, and fodder production that directly benefit agriculture as well as fuelwood production, timber production, coastal risk reduction, river fish harvest, and access to nature that support food production and rural livelihoods).

Spatial conservation planning based on the status of CNAs can inform decision on conserving and restoring them to maintain the biodiversity and NCPs that support agriculture.

Conservation priorities: Over half of critical natural assets (55.8 percent of CNA or 4.8 billion hectares) remain largely in their original natural or semi-natural state and are global priorities for conservation.

These areas have avoided significant conversion into agricultural landscapes such as croplands or pasturelands, they hold important biodiversity, and their ecosystems are still healthy and somewhat ecologically intact, providing critical NCPs to agriculture.

Conservation priorities under threat: About half of the conservation priority area or just over a quarter of critical natural assets (27.2 percent of CNA or 2.3 billion hectares) is potentially under threat from either agricultural development and or climate change (referred to here as unstable).

The remainder (28.6 percent of CNA or 2.5 billion hectares) is under low threat (referred here as stable).

Restoration priorities: Under half of critical natural assets (44.2 percent or 3.8 billion hectares) are priority areas for restoration.

While currently degraded from their natural condition and converted to cropland or pasture, they represent important opportunities where ecosystem restoration could potentially reestablish vital NCPs, thereby enhancing support for agriculture.

Restoration priorities under threat: About two-thirds of restoration priority areas or just under one-third of critical natural assets (28.6 percent or 2.5 billion hectares) is potentially under threat from either agricultural development or climate change (unstable).

The remainder of the restoration priority area is under low threat (stable).

Conservation, restoration and enhancing connectivity of natural areas

Management approaches for conservation

- **Key measure:** For conservation priorities not under threat (stable) include: ensuring effective existing legal protections, strengthening protected areas and Other Effective area-based Conservation Measures (OECMs); recognizing the governance rights of Indigenous Peoples and local communities (IPLCs). Where Conservation priorities under threat (unstable) measures include rapidly setting up strong legal protections (e.g., new Protected Areas (PAs) or OECMs) on critical "edges" or frontiers where agricultural development is a threat; climate-smart conservation plans; and monitoring systems.

- **Principles:** include ensuring connectivity and minimizing fragmentation; functional integrity of ecological processes such as pollination, nutrient cycling, and water regulation rather than just setting conservation area targets; comprehensive protection of biodiversity (genetic, species, ecosystem) to provide multidimensional support to agriculture; building climate resilience; ensuring access and use rights and equitable governance with IPLC participation; and monitoring biodiversity, NCPs, and threats.

Management approaches for restoration

- **Approaches:** restoring land back toward natural or semi-natural habitat known as ecosystem restoration or managed to maximize ecosystem services from its existing state, so called novel ecosystems.

- **Key measures:** For restoration priorities not under threat (stable) key measures include soil improvement, hydrological restoration, and integrating diverse native vegetation, potentially within agroecological systems aiming for substantial integration (20–25 percent) of natural habitats. For restoration priorities under threat (unstable), strategies must be integrated with measures to mitigate climate change and development pressures (secure tenure, OECMs).

- **Principles:** Ensuring functional integrity; integrating diverse, appropriate, often native species and habitat structures (like hedgerows, buffer strips, agroforestry elements) directly into agricultural landscapes to maximize ecosystem services for agriculture; action at landscape scale and prioritizing areas such as riparian zones, marginal lands, connectivity bottlenecks; equitable governance; and building climate resilience.

- **Restoration Priorities:** Within global restoration priorities, the most effective habitats for both biodiversity and carbon storage are tropical forests and wetlands. Restoring just 15 percent of restoration priorities could avoid 60 percent of expected extinctions while sequestering 299 gigatons of CO_2 (Strassburg et al. 2020).

60%
of expected extinctions could be avoided by restoring just 15 percent of restoration priorities

Enhancing connectivity

Connectivity between conserved natural areas and agricultural areas provides NCPs to agriculture. Maintaining or restoring sufficient natural habitat within agricultural landscapes is critical for ensuring these flows underpin farm stability and resilience.

A minimum threshold of 20–25 percent semi-natural or natural habitat cover per square kilometer is necessary in human-modified landscapes, including agricultural areas to maintain NCP delivery (Mohamed et al. 2024). A global target of restoring and retaining at least 20 percent natural habitat within heavily converted working landscapes (>80 percent conversion) benefits food security, NCP delivery, and links protected areas (Garibaldi et al. 2021).

Investments in restoration and related sustainable land management can yield economic benefits up to $30 for every dollar invested (UNEP 2021). These investments include measures that support connectivity such as integrating habitat features like hedgerows, field margin buffers, and riparian strips within the existing agricultural matrix.

20-25%
semi-natural or natural habitat cover per km^2 is necessary in human-modified landscapes to maintain NCP delivery

Connecting priority restoration areas increases success and can lower costs. Degraded landscapes are often fragmented. Strategies for connecting habitat patches include restoring riparian corridors, establishing ecological corridors, creating stepping-stone habitats, and improving the agricultural matrix itself (e.g., through sustainable practices) (Williams et al. 2024).

Unsustainable agriculture is driving loss of biodiversity that supports agriculture

Unsustainable agricultural practices (other than land use change previously discussed) driving biodiversity loss can be broadly grouped into four categories: (1) land and soil management; (2) agricultural water management; (3) crop nutrition, crop protection and livestock waste management (causing pollution); and (4) genetic diversity in crops and livestock.

Land and soil management

Modern agricultural practices such as monocropping, conventional tillage, and overgrazing are widely used to boost efficiency and productivity, but they come at a significant cost to biodiversity and ecosystem health.

- **Monocropping** undermines biodiversity and ecosystem resilience by reducing genetic diversity, which increases vulnerability to environmental stressors such as drought, pests, and disease.
- **Conventional tillage** damages soil ecosystems, undermines fertility, and disrupts ecosystem services such as water regulation, pest control, and carbon sequestration.
- **Overgrazing** reduces plant diversity, diminishes ecosystem services, and drives long-term degradation of both aboveground and belowground biomass.

Up to 40 percent of the world's land area is degraded, with nearly 100 million hectares degrading further each year (UNCCD GLO2 2022). Land degradation negatively impacts the livelihoods of at least 3.2 billion people. It represents an economic loss of more than 10 percent of the annual global GDP.

Agricultural water management

Over-abstraction of surface and groundwater destabilizes water cycles, depletes resources, and threatens ecosystems globally.

Inefficient irrigation practices lead to waterlogging, salinization, and soil degradation, further harming biodiversity. **Converting and draining wetlands** destroys vital habitats and eliminates the ecosystem services they provide, including flood regulation and carbon storage.

Constructing dams and reservoirs fragments aquatic habitats, alters natural water flows, and reduces connectivity in river systems, leading to widespread ecological consequences. Among the many impacts of these practices, the following are of particular concern:

- **Groundwater-dependent ecosystems are at risk**, with more than half located in regions with declining levels of groundwater (Rohde et al. 2024) and 15–20 percent of watersheds experiencing flows below sustainable levels.

- **Wetlands covering 12.1 million km² provide ecosystem services estimated at $35,000 per hectare per year** (Ramsar 2018; Brander et al. 2024). Natural wetlands declined by 35 percent between 1970 and 2015 while man-made wetlands like paddy fields expanded by 233 percent (Darrah et al. 2019).

- **Connectivity of freshwater ecosystems is declining**. Due to 6,374 large dams, 48 percent of rivers have been altered (Grill et al. 2015; Schmutz et al. 2018). Only 37 percent of rivers longer than 1,000 kilometers remain free-flowing and only 23 percent flow uninterrupted to the ocean.

Nutrient pollution

Nitrogen pollution arises from diffuse sources including fertilizers and manure spread across agricultural fields; and point sources, such as concentrated animal feeding operations, release nitrogen through leaking waste lagoons, overflow events, and poorly managed manure storage facilities. **Human activities add 190 million tons of nitrogen annually far exceeding the planetary boundary for nitrogen**, which is set at 62 million tons per year to avoid harmful environmental impacts (Planetary Health Check 2024).

Phosphorus is a critical nutrient for plant growth, but its overuse in agriculture is the main cause of phosphorus pollution. Human activity contributes 22.6 million tons of phosphorus annually to rivers, lakes, and oceans, more than double the planetary boundary of 11 million tons per year (Planetary Health Check 2024). Agriculture is responsible for over 90 percent of phosphorus pollution.

Excess nitrogen and phosphorus harm ecosystems by overloading water bodies with nutrients causing explosive algae growth resulting in oxygen-depleted "dead zones" where fish and other aquatic life cannot survive. Algal blooms dominated by invasive species outcompete native plants and animals, leading to less diverse ecosystems.

Agrochemical pollution

Pesticide use exceeds countries' ability to test their safety. "The increasing rate of production and releases of larger volumes and higher numbers of novel entities with diverse risk potentials exceed societies' ability to conduct safety related assessments and monitoring" (Persson 2022). Global pesticide use grew by over 20 percent in volume over the last decade, while in low-income countries it increased by 153 percent in the same period (Stattuck et al. 2023).

Intensive monocultures are a major driver of agrochemical use. These systems lack natural pest suppression and crop rotation that regulate pests (Wang et al. 2021; Liu et al. 2022). Similarly, **clearing forests** disrupts natural pest regulation, leaving smallholder farmers vulnerable to pest outbreaks (Ratnadass et al. 2021; Jasrotia et al., 2023). **Overgrazing** degrades pastures, encourages invasive species, and increases pesticide use (Centeri 2022).

Pesticides cause **aquatic toxicity, contaminate water bodies**, harming fish, amphibians, and aquatic invertebrates, and lead to algal blooms (Schepker et al. 2020); they **impact birds**, by disrupting bird reproduction, neurological functions, and reproduction (Marlatt et al. 2022; Mohanty 2024) and **harm pollinators** – neonicotinoids impair honeybee memory, navigation and foraging – and reducing pollination services (Elhamalawy et al. 2024).

Examples of the impacts of unsustainable practices on biodiversity and ecosystem services that support agriculture include:

- **Formation, protection, and decontamination of soils and sediments:** Unsustainable agricultural intensification has reduced soil organic carbon by 50–70 percent compared to natural conditions, with degraded soils showing 15–30 percent lower yields.

- **Freshwater flow, quality, and quantity:** Natural habitat loss reduces water flow, quantity, and quality, and it has increased flood frequency (20–90 percent) while reducing water availability. Agricultural losses from water-related events have increased 65 percent over 50 years, exceeding $300 billion annually.

- **Pollination and seed dispersal:** Wild pollinator declines of 30–50 percent in diversity and abundance, threaten agricultural productivity (Dicks et al. 2021): Wild pollinators declined by over 40 percent in the past decade. Pollination services are valued at $235–$577 billion annually.

- **Pest and disease control:** 20 to 40 percent of crop production is lost to pests annually, with plant diseases costing about $220 billion and invasive insects around $70 billion annually (FAO 2023). Antimicrobial resistance is an existential threat affected by declining microbial diversity, pollution, and antibiotic use.

- **Hazards and extreme events:** Natural vegetation loss and land conversion for agriculture have significantly increased agriculture's vulnerability to hazards and extreme events, with an estimated loss of $3.8 trillion worth of crops and livestock production over the past three decades (FAO 2023).

- **Climate regulation (global and local scales):** Agricultural intensification has reduced carbon storage capacity by 25–50 percent in many regions. Climate-related agricultural losses have increased 150 percent since 1980, exceeding $100 billion annually.

- **Genetic diversity in agriculture:** Agricultural biodiversity has declined significantly, with commercial crop varieties decreasing 75 percent since 1900 and livestock breeds declining at 1 percent annually, threatening global agricultural productivity and stability (FAO 2023).

Land sparing and land sharing

Land sparing (intensifying yields on minimal land to spare natural habitats) offers superior biodiversity outcomes by preserving large, intact habitats, benefiting specialized species and enhancing overall biodiversity and functional diversity, including abundant and rich bird species, when significant portions of land are set aside (Zingg et al. 2024; Palmer 2025).

Land sharing (integrating biodiversity conservation within agricultural landscapes) supports on-farm biodiversity by maintaining ecological connectivity and integrating wildlife-friendly practices, yet generally achieves lower biodiversity conservation outcomes, particularly for species that rely on undisturbed habitats (Estrada-Carmona et al. 2022; Cannon et al. 2019).

A consensus is emerging on the need for context-specific, integrated strategies that combine elements of both approaches to balance conservation and food security effectively. More specifically, the most promising options are keeping large habitat blocks surrounded by diversified farming systems (Kremen & Geladi 2024).

Integrating 20 to 25 percent of natural or semi-natural area into agricultural landscapes is essential for maintaining biodiversity, sustaining ecosystem services, and ensuring agricultural systems function under current environmental pressures (Mohamed et al. 2024).

Between 18 to 33 percent of agricultural lands globally lack the semi-natural habitat per square kilometer needed to support pollination, pest control, climate regulation, prevent soil erosion, and reduce nutrient loss and water contamination (DeClerck et al. 2023).

Complementary regulation and incentives to mitigate land use change are needed to mitigate the risks of rebound effects from intensification. When more efficient use of a resource results in its increased use this is known as a rebound effect. Evidence suggests that land sparing from intensification happens but is patchy and vulnerable to rebound effects (Balmford 2021). Rebound effects are greatest when consumers are most responsive to prices and production is well connected to global markets (high value commodities).

$3.8 trillion

worth of crops and livestock production has been lost over the past 30 years to hazards and extreme events

Agro-biodiversity

Diverse Plant Genetic Resources for Food and Agriculture (PGRFA) are an important aspect of biodiversity and greater investment in both in-situ and ex-situ conservation of genetic material will be important. PGRFA are essential for agriculture to adapt to environmental stresses, climate change, and changing markets. In 2022, 5.7 million accessions were reportedly conserved in 831 gene banks by 114 countries including through the International Treaty Benefit Sharing Fund. Continuing to meet funding commitments is critical. Cooperation between informal farmer seed systems and gene banks to maintain genetic material could be scaled up. Diversity of animal genetic resources for agriculture is increasingly important given the effects of climate change and increasing risk of pandemics. The FAO Animal Diversity Information Systems (DAD-IS) reports that the population status of nearly 60 percent of breeds is unknown, which is a major constraint to their conservation while almost three quarters of breeds of known status are at risk of extinction.

5.7 million

accessions were reportedly conserved in 831 gene banks by 114 countries

From vicious to virtuous: Sustainable agricultural practices mitigate biodiversity loss and support agriculture

It is possible to engage in agriculture in ways that maintain and restore biodiversity and enhance the ecosystem services that optimize and sustain food and agriculture outcomes for the economy, the planet, and its people.

Each of the practices highlighted here – while certainly non-exhaustive – provide evidence on their positive impacts on biodiversity that supports agriculture, on agricultural outcomes themselves, on barriers to adoption, and on their potential viability for farmers. While these results are generally positive in direction across different crops and conditions, the size of the impact – as well as their profitability – is highly context specific. This calls for a systematic "domestication" of the evidence by national agricultural research services (NARS) and their partners, as well as observation and measurement with farmers already adopting similar measures in the area. Much of the below – and much that is not found below – is closely linked (if not outright derived from) Indigenous knowledge with centuries, in not millennia, of observable outcomes. This gives rise to the question of why these practices are not already mainstreamed. Both incentives and non-economic barriers to adoption matter.

Sustainable practices to enhance biodiversity for agriculture

Because **many sustainable practices reverse or resolve multiple types of nature loss at once**, they do not usually serve as a single solution to a single type of problem (e.g., only nutrient pollution or only water conservation). While practices like **micro-irrigation** clearly help resolve agriculturally induced water management issues (by reducing water abstraction, preserving ground water, curtailing nutrient leaching etc.), most sustainable agricultural practices can reverse multiple negative impacts of conventional agriculture in ways that are not immediately apparent but are well documented in the scientific literature. They restore ecosystem services and the agricultural outcomes that depend on them in multiple ways. For instance, as opposed to monocropping, **intercropping** increases species diversity at the field level, improving soil and contributing to greater resilience to stressors. Intercropping also allows for inclusion of certain crops that attract pests away from the main crop or repel them, thereby reducing the need for agrochemicals in this way, the one sustainable practice reverses the impacts of at least three "types" of unsustainable practices: land and soil management, crop protection and genetic diversity.

Similarly heavy hitting, **crop rotation** in the same field over the seasons supports a wider range of soil microorganisms, insects, and other wildlife, promoting biodiversity both in the soil and the landscape, improving pest and weed control. Crop rotation is the building block of several production approaches like Integrated Pest Management (IPM) and it is one of the three pillars of **conservation agriculture**, alongside green manure (see below) and zero tillage.

A third practice that excels in its range of positive biodiversity impacts for agriculture is **agro-silvo-pastoralism**. This approach (of synergistically combining crops, livestock, and forestry) can enhance resilience to environmental stresses by diversifying crops, trees, and livestock breeds. It enhances pest control by attracting and supporting natural predators of crop pests. It can reduce the levels of synthetic inputs needed, which in turn help lower the risk of nutrient and chemical pollution. The evidence shows that it enhances nutrient cycling, regulates water flows, moderates microclimates, and improves climate resilience. **Minimum tillage and no-tillage** (also known as zero tillage) allows for an enhanced number and species of soil arthropods and a greater abundance of microbials, all of which provide natural enemies to detrimental organisms. This gives the crop greater resistance to pests and disease and reduces the need for chemical pesticides and herbicides. Minimum tillage also preserves earthworm populations, which contribute to overall soil structure.

Green manure refers to the planting of cover crops (the terms are used interchangeably). This practice increases biodiversity in the fields and improves soil quality with positive impacts on crop production and crop resilience to stressors. Cover crops also enhance soil microbial biodiversity, favoring fungal biomass and improving nutrient cycling and biological soil health. Applying green manure is therefore a key practice for reducing synthetic inputs, which is used excessively and can cause nutrient pollution. In the effort to mitigate nutrient pollution without loss of productivity, innovations like **biostimulants** do not add nutrients to the soil but enhance nutrient efficiency.

In addition to managed manure, common types of **organic fertilizers** used in agriculture are compost and biofertilizers. Applying biofertilizers enhances the biodiversity in the soil, increasing microbial abundance, which regulates detrimental organisms and improves crop resistance to pests and diseases for the farmer. Its counterpart for pest control, also known as **biocontrol**, refers to a diverse set of nature-based practices based on the use of natural enemies. Contrary to the use of pesticides, which aim to directly eliminate harmful organisms, biocontrol relies largely on inter-species predation and parasitism to contain pest populations within an acceptable level. It is often applied using microbial pathogens and repellents and it preserves a biodiverse ecosystem.

As potent as these practices, and others, have been found to be when analyzed alone, in practice, they are bundled with other sustainable agricultural practices. Studies of these bundles or systems produce similar results – in direction of impact – to studies of stand-alone practices. For instance, four of the practices covered above – crop rotation, intercropping, biocontrol and green manure – combine to form IPM, a holistic approach to pest and disease management which is found to mitigate both the need and impacts of agrochemical pesticides, combining biological, cultural, mechanical, and chemical methods to control pests (IPM).

Integrated Nutrient Management (INM) is also not a single practice, rather it is based on the balanced use of organic and inorganic sources of nutrients (e.g., chemical fertilizers, legume crops, manure, biofertilizers), combined with appropriate soil management practices. INM protects freshwater and biodiversity, positively impacting the ecosystem services to farmers. While nowhere near exhaustive (e.g., farming with alternative pollinators (FAP) is also an intervention framework rather than a single practice), in addition to these systems of approaches are the many permutations of the different practices that farmers adopt. This compounds the complexity arising from the context specificity of impacts of sustainable practices and raises the level of difficulty in generating comparable evidence.

Together these two factors (context specificity and bundling) make it imperative that decisions of transition to sustainable practices be informed by localized demonstration or rigorous measurement of existing local trials to properly gage the impacts on livelihoods and food security – and the transitional support needed by farmers for the landscape, regional, national, and global public good they are providing.

The list goes on. **Mechanical water and soil conservation**, including water harvesting practices and runoff limitation practices limit soil runoff, preserve biodiversity in water bodies, and improve the availability of water for local fauna. Yet other sustainable practices come from the **circular economy framework** and address different – and complementary – impacts on biodiversity in decreasing the amount of land needed for animal feed, **waste to animal feed** mainly impacts biodiversity through reduced land-use change, supporting in the maintenance of habitats for biodiversity. Why, with the evidence around these and other sustainable practices of both ancient and modern origin, are sustainable practices not more widely mainstreamed? A closer look at incentives and other barriers to adoption is needed.

Financial Performance of Sustainable Practices

Of primary importance to livelihoods and food security is the financial viability of transitioning to these practices for farmers.

Most sustainable agricultural practices demonstrate positive financial returns. Crop rotation, mechanical soil and water conservation, improved seed varieties, agro-silvo-pastoralism and agroforestry (i.e., even without livestock) consistently outperform conventional practices in terms of profitability and returns on investment.

Bundling multiple sustainable agricultural practices (SAPs) consistently improves financial performance and reduces variability. When integrated, complementary practices such as minimum tillage, improved seed varieties, soil conservation, and integrated nutrient management (INM) produce stronger, more stable financial outcomes compared to their individual implementation.

Because of their positive impacts on biodiversity which support positive outcomes for agriculture, it is unsurprising that almost all of them can – under at least some circumstances – provide positive financial incentives. **Important to note, however, there are some practices that have neither consistently positive nor consistently negative financial returns, underlining once again the importance of basing investment decision on local context specific research and advice.** Minimum tillage yield outcomes are highly dependent on crop and conditions; intercropping varies with level of farm mechanization; integrated pest management (IPM) cost savings vary as a function of original pesticide use level; and organic fertilizer profitability depends on market price and yield stability. Conservation agriculture similarly shows context-dependent financial performance.

Positive financial incentives to sustainable practices are driven by cost savings from decreased dependency on inputs, and by yield gains. Practices such as organic fertilizer, organic farming, integrated pest management (IPM), and green manure, report a decrease in input costs like fertilizers, herbicides and water usage. Cost variability, however, can be context specific as in the case of sustainable practices that are more labor intensive (e.g., intercropping), for which the cost and availability of labor is a key determinant to ultimate profitability. Second, yields increase over time for many of the practices found in the literature, resulting in increased profitability in the few studies explicitly analyzing financial variables. Finally, price premiums offset yield decreases for organic farming specifically. Organic farming and organic fertilizers generally resulted in decreased yields, however, cost reductions in fertilizer inputs and price premiums for organic products often offset the losses from decreases in yield, and the practices still reported profitable returns in most analyses.

Economic research must pay greater attention to long-term financial performance: While the returns on investment were indeed higher for sustainable practices, payback periods were longer for sustainable practices compared to conventional systems. This therefore impacts the short-term incentives for adoption. Further to profitability, higher initial investments may act as barriers to adoption. For intercropping, integrated farming systems, crop rotation and minimum tillage that require one off or short-term capital investments, costs were higher when compared to conventional practices. Further, many sustainable agricultural practices and bundled systems are complex, with timing, spatial planning, new machines and/or varieties pushing farmers up a steep learning curve. Without sustained (not one-off) technical assistance, that may not be a curve that farmers either can or wish to climb.

In conclusion, sustainable agricultural practices can improve biodiversity and farm incomes, supporting the conclusion that these are not competing objectives. **Investing in sustainable practices, however, is a long-term effort and there is a role for government in overcoming technical barriers to adoption, fostering public private partnerships where possible, and in supporting farmers with the short-term costs of transitioning to sustainable practices.** While the expected (context-specific) returns to sustainable practices will provide financial incentives for farmers' long term adoption, helping to cover transitional costs such as up front capital investment costs and income loss due to time lags to improved yields are justified in the light of the public good being generated by farmers for national – and global – objectives around soil health, climate change and multiplier effects of agricultural sector growth. With this is in mind, the next section explores the financing of efforts to improve biodiversity.

Repurposing agricultural support and financing biodiversity

Biodiversity finance

Biodiversity finance encompasses a wide range of financial instruments whose primary objective or co-benefit is to conserve biodiversity. Biodiversity finance covers financial flows from all actors in biodiversity-relevant sectors – public, private, domestic, and international (OECD 2020).

The World Economic Forum's (WEF) Global Risks Report 2024 ranks "biodiversity loss and ecosystem collapse" as the third biggest long-term global risk. More than 50 percent of the loan portfolio of banking systems in 20 emerging markets were found to be highly exposed to nature related risk (Calice et al. 2023).

About $58 trillion, equivalent to 55 percent of global GDP, is highly or moderately dependent on nature and its services. The WEF estimates that nature-positive transitions could yield up to $10 trillion in annual business value and create 395 million jobs by 2030 (WEF 2020).

Financing flows that are harmful to nature far exceed nature-positive finance. In 2022, global financial investments that harm nature (public and private) were found to be about 30 times the level of investments in nature-based solutions of approximately $200 billion (UNEP 2023).

55%
of global GDP
is highly to moderately dependent on nature and its services

In 2024 the biodiversity financing gap between current levels and what is needed in 2030 was updated and estimated to be about $942 billion per year. Official development assistance (ODA) is growing but not in reach of the GBF's $20 billion 2025 annual target for biodiversity (OECD 2024).

New multilateral funds linked to the Convention on Biological Diversity (CBD) for public and private finance have been created, but funding levels are still low and uncertain. Funding of the Global Biodiversity Framework Fund (GBFF) remains very low with new pledges of $163 million adding to the previous $220 million. At COP 16 a new "Cali Fund" was launched to share benefits from digital genetic information.

Target 18 of the Kunming-Montreal Global Biodiversity Framework aims to cut harmful incentives by at least $500 billion annually by 2030 and increase positive incentives for biodiversity conservation and sustainable use.

Composition of agricultural support and effects on biodiversity

Agricultural support impacts biodiversity by incentivizing the allocation of land, water, and inputs by producers. Much of the current global public support is through instruments and mechanisms that are distortive, contribute to inefficient allocation resources and have a high environmental footprint (Damania et al. 2023).

In 2022, net global producer support and general support to the sector was $513 billion. **More than 80 percent of producer support was linked to production, which distorts land use, the composition of production, and the allocation of water and inputs.** Market price support was the predominant instrument. These support instruments are extremely distortive and incentivize economically inefficient over-production through agricultural expansion or increased input use, threatening biodiversity.

Production-linked subsidies are responsible for the loss of 2.2 million hectares of forest per year (Druckenmiller, H. 2021). If current patterns of support continue, more than 56 million hectares of land are projected to be converted to agriculture between 2020 and 2040, impacting critical reservoirs of biodiversity (Al Mamun et al. 2023).

Input subsidies have large negative spillovers estimated at almost 10 percent of global GDP. More than half of global agricultural production occurs in areas where the marginal benefit of additional fertilizer is negative (Zaveri, E. 2025). Input subsidies reduce on-farm technical efficiency, degrade foundational biodiversity and ecosystem services and have led to overuse. Input subsidies are responsible for up to 17 percent of nitrogen pollution in water.

Decoupled support is least distortive but represents a small share of producer support. **Some components of general support services can help address biodiversity loss.** General services support includes public spending on research, extension, inspections, and infrastructure that improve the enabling environment for adoption of sustainable practices, have a critical role in improving agricultural productivity (Lopez and Galinato 2006; World Bank 2016; Fan et al. 2008) and are expected to reduce potential negative impacts on biodiversity.

Principles for repurposing agricultural support to mitigate biodiversity loss

More efficient use of resources can improve agricultural output without further loss of biodiversity. Improving allocation and management of resources can increase agricultural output by $329 billion and meet the food demand by 2050, while keeping biodiversity at current levels. (Natures Frontier 2023). Repurposing agricultural support for sustainable practices is an important means of bring about improved allocation and management.

Repurposing should firstly decouple support from production and invest these funds in public goods including those that support the adoption of sustainable agricultural practices. In most

cases, production-coupled subsidies have no impact and, in some cases, a negative impact on agricultural productivity growth.

Repurposing should then redirect support to conservation, restoration, and sustainable practices. Agricultural support can be repurposed toward:

i. Payments for Ecosystem Services (PES) or Green Subsidies to farmers to incentivize conservation, restoration or adoption of sustainable practices.

ii. Public goods and services such as research, extension, and infrastructure to create an enabling environment for adoption of sustainable practices.

Repurposing should target sustainable practices that deliver both improved biodiversity and improved productivity to avoid trade-offs with land use change or food security. Identifying repurposing options involves non-trivial trade-offs. Redirecting $70 billion of the global distortive producer support toward greens innovations that both enhance environmental outcomes and raise productivity can drive down food prices by 21 percent, increase crop and livestock production by 16 and 11 percent, and importantly release about 105 million hectares of agricultural land for restoration to natural habitats, with potentially substantial biodiversity benefits (World Bank 2022).

Regulation may be needed to complement incentives when they are insufficient to address the environmental externalities. This will depend on the expected effectiveness of incentive payments, for example: (i) whether incentive is sufficient to incentivize/disincentivize the practice; (ii) the potential environmental costs of non-adoption of the practice; (iii) the costs and feasibility of monitoring compliance with PES conditions; (iv) the costs and distributional effects of incentives vis a vis regulation.

Implementing repurposing through payment for ecosystem services

Payments for Ecosystem Services (PES) can incentivize conservation, restoration and sustainable practices. PES requires certainty of funding and local capacity for monitoring and results verification. In lower-capacity settings, green subsidies (non-conditional transfers aimed at environmental goals) may be a more practical option.

An alternate approach can be a one-off payment to incentivize adoption of sustainable practices. High upfront costs can be a barrier to adoption of some practices, even though they are financially viable in the longer term. One off payments such as matching grants can be used to improve access to these technologies.

Rapidly evolving spatial data and digital technology creates opportunities for scaling up of Payments for Ecosystem Services. Global, national and local spatial data on biodiversity and ecosystem services can improve the technical specificity and spatial targeting of PES.

Monitoring policy and investment impact

Impact monitoring is critical to mainstreaming biodiversity objectives into decision making. Advances in spatial data, digital technology, and valuation of ecosystem services mean that mainstreaming biodiversity will be increasingly feasible. Innovation and technology development offer new and diverse options for biodiversity monitoring. These include: remote sensing, new acoustic and other sensors, eDNA, genetic monitoring tools, ecosystem models, and Artificial Intelligence (Nicolle, W et al. 2024).

There is currently no single, comprehensive tool for monitoring biodiversity outcomes of policy and investment as each tool addresses different aspects of biodiversity. The IUCN Land Health Monitoring Framework (IUCN 2023), analyses 114 indicators and 14 existing tools that cover three levels of biodiversity (genetic, species, ecosystem) at four scales (soil, farm, landscape and national[3]). Existing tools tend to focus on the soil and farm levels and do not properly cover landscape and national levels. In pursuit of a more comprehensive tool, IUCN has published The Guidance Note for Monitoring Land Health in Agricultural Landscapes (2025), designed to operationalize the Land Health Monitoring Framework through a step-by-step process.

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[3] National is not a formal scale to monitor but the sum of landscapes encircled by an administrative border.

Recommendations

Recommendations to support biodiversity for agriculture are organized under three Policy and Investment Packages. These packages recognize the importance of natural areas – including natural habitats within agricultural areas – in maintaining biodiversity as a foundation for the ecosystem services that support agriculture; the need for sustainable intensification to reduce land pressure; the harmful impact of agricultural support for unsustainable practices and the potential to repurpose this support for conservation, restoration, and sustainable agricultural practices including through scaling up of PES and green subsidies; the need to maintain genetic resources for agriculture and the need to establish comprehensive biodiversity monitoring systems as a foundation for all investments in biodiversity.

Policy and Investment Package 1: Conservation and restoration of natural areas

Package 1 aims to employ rapidly evolving spatial data on biodiversity and ecosystem services to support:

- **Spatial prioritization of conservation and restoration** of critical natural assets supporting agriculture by employing evolving spatial data on biodiversity and ecosystem services and ground truthing with IPLCs;

- **Conservation and restoration of critical natural assets** supporting agriculture recognizing the additional effort needed to protect areas under threat from climate change and agricultural development; and

- **Conservation and restoration of natural habitats within agriculture** and building their connectivity with natural areas.

Policy and Investment Package 2: Enabling sustainable intensification for biodiversity

Package 2 aims to address the barriers to adoption of sustainable agricultural practices and support maintenance of agro-biodiversity through:

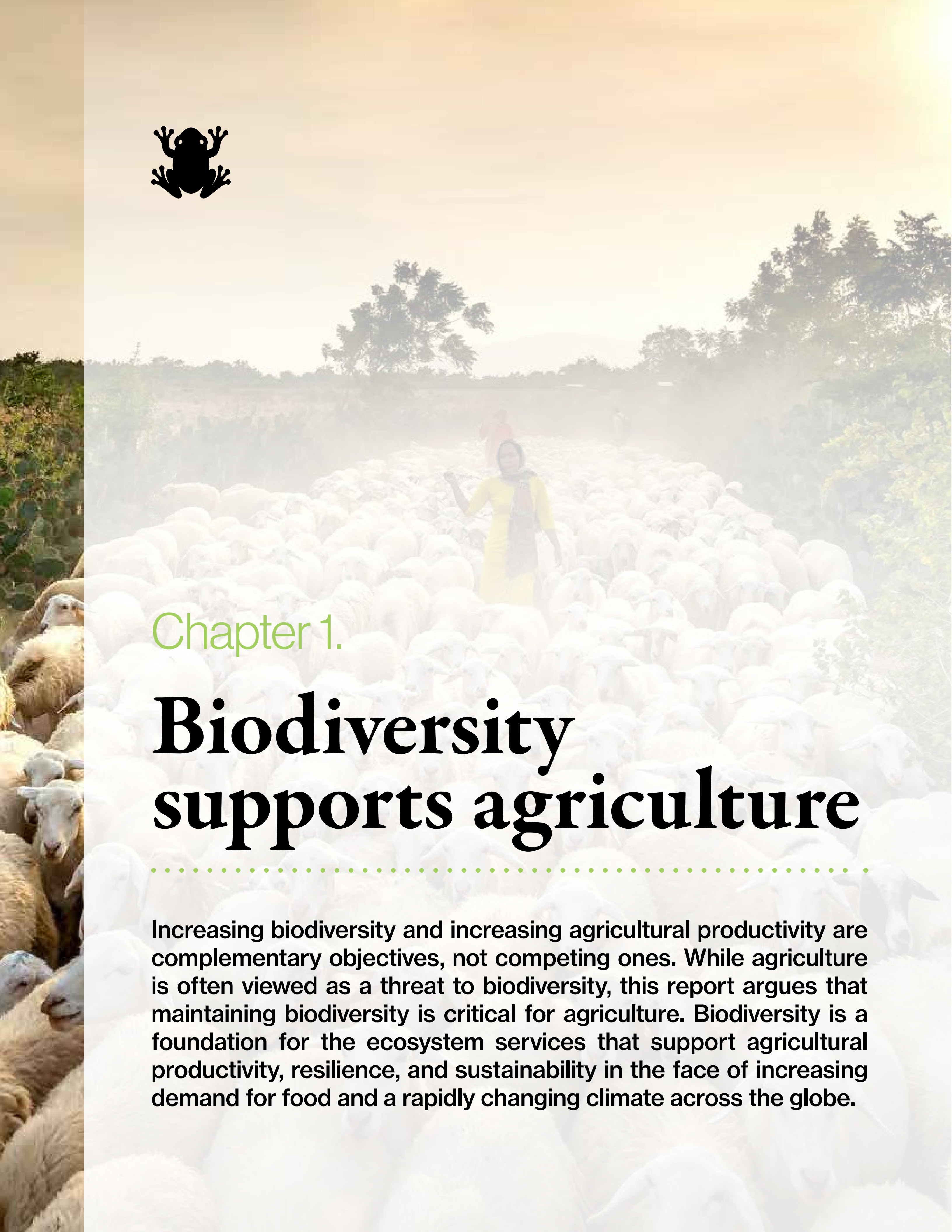
- **Establishment of long-term Biodiversity for Agriculture (B4R) lighthouse programs** dedicated to supporting farmers on adoption of sustainable agricultural practices that improve biodiversity for agriculture including:

  - **Research:** Localized B4R research to provide context specific evidence-based recommendations;
  - **Extension:** integration of biodiversity into extension advice on sustainable practices;
  - **Collaboration** with environmental agencies to build research and extension capacity on B4R;
  - **Incentives** including PES and green subsidies to incentivize adoption of SAPs (linked to package 3);
  - **Investment promotion** for sustainably produced products;
  - **Bioinputs:** Building regulatory frameworks for the emerging bioinputs market to reducing barriers to entry.
- **Genetic Resources:** Support in-situ and ex-situ conservation of plant and animal genetic material for food and agriculture including through scaling up cooperation between farmer seed systems and gene banks.

Policy and Investment Package 3:
Financing sustainable intensification, restoration and conservation

Package 3 aims to mainstream and scale up the provision of public funding for biodiversity and ecosystem services that support agriculture through:

- **Incorporating ecosystem service valuation** investment decisions on conservation, restoration and support for sustainable agricultural practices;
- **Repurposing agricultural support** for the above investments;
- **Scaling up PES** through replication of tested platform such as My Farm Trees;
- **Complementary regulation** such as on land use where incentives are insufficient to meet objectives;
- **Biodiversity monitoring capacity** to inform investment decisions.



Chapter 1.

Biodiversity supports agriculture

Increasing biodiversity and increasing agricultural productivity are complementary objectives, not competing ones. While agriculture is often viewed as a threat to biodiversity, this report argues that maintaining biodiversity is critical for agriculture. Biodiversity is a foundation for the ecosystem services that support agricultural productivity, resilience, and sustainability in the face of increasing demand for food and a rapidly changing climate across the globe.

The discussion of biodiversity and ecosystem services supporting agriculture in this chapter extends to different types of biodiversity (genetic, species, and ecosystem diversity), and different ecosystems including terrestrial and freshwater ecosystems. These exist at different spatial scales (field, farm, landscape) and benefit agriculture across space (locally, regionally, and globally) and time (in the present and distant future). The report discusses biodiversity both within agricultural landscapes (including within crop and livestock – agrobiodiversity) and in surrounding natural landscapes. The term nature is used in this report to encompass biodiversity, ecosystems, ecosystem services, and their interdependence (see glossary for definitions of these terms).

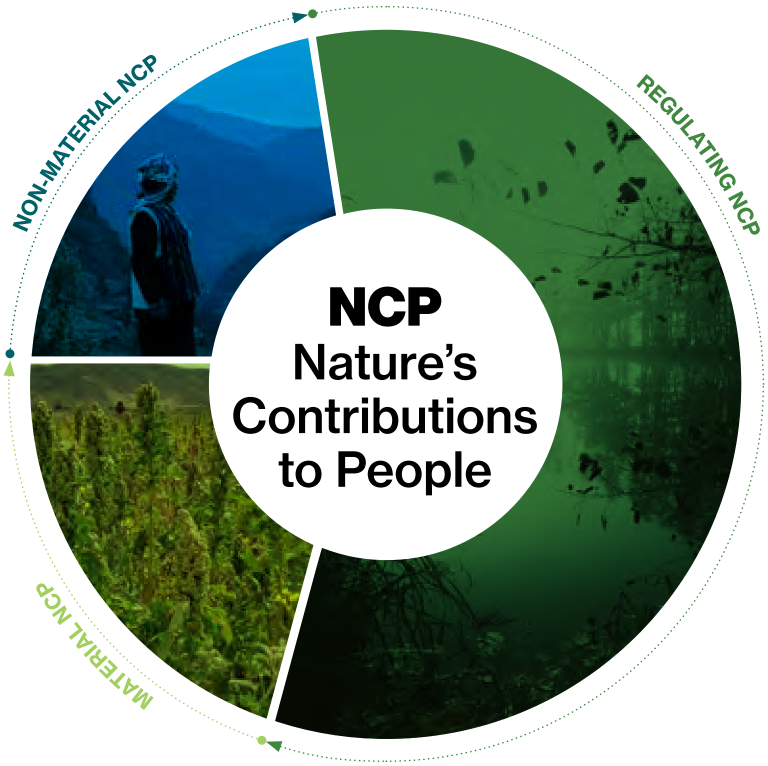
1.1 Biodiversity for ecosystem services

Nature's Contributions to People encompass four categories of ecosystem services, each vital for agriculture (Figure 1). **Regulating contributions** are air quality regulation and climate; water quantity, timing, and quality; forming, protecting, and decontaminating soil; habitat maintenance; pollination and seed dispersal; and regulating hazards and detrimental organisms (e.g., pathogens and pests). These regulatory services create the conditions that make agriculture possible, from stable local climates to fertile soils and reliable water supplies (Managi et al. 2022). **Material contributions** are the products people harvest and use. **Non-material contributions** connect agriculture to cultural identity and knowledge systems, particularly important for traditional farming communities, which maintain critical agricultural biodiversity through their practices. **Maintenance of future options** (see Figure 1) includes preserving genetic diversity and ecosystem functions and is crucial for agriculture's resilience, providing the raw material for crop adaptation to climate change and resistance to emerging pests and diseases and underlines all other Nature's Contributions to People (NCPs) (IPBES 2019, 2024).

Individual species may contribute to agriculture via regulating, material, and non-material contributions across multiple NCPs (Assis et al. 2023). Most species contribute to multiple NCPs. For example, a bat feeds on crop pests, pollinates night-blooming plants, disperses seeds across forests (all regulating services), fertilizes plants through its droppings, and supports cave ecosystem health (material contributions). In turn, agriculture provides foods and practices (e.g., planting and harvesting rituals) that are culturally significant, a non-material contribution. African honey badgers support NCPs by eating crop-damaging pests like root-eating beetles, termites, and rodents; their digging improves soil aeration and water infiltration in fields and across landscapes; and their soil-turning activities support nutrient cycling and seed dispersal. Beekeepers see them as a pest since they can consume honey and they are hunted for bush meat and traditional medicine (Carter et al. 2017).

The three levels of biodiversity (genetic, species, and ecosystem diversity) all contribute to agriculture, immediately and in the future (across temporal scales), locally and over large distances (across spatial scales). At the local scale, these three levels work simultaneously: genetic diversity within crops provides immediate resilience to pests or weather variations and species diversity ensures current pollination and pest control. Ecosystem diversity spans large areas, so local services such as regulating disease transmission are context dependent. These same three levels of biodiversity also secure future benefits: genetic resources remain available for crop breeding, species continue evolving beneficial traits in crop wild relatives, and diverse ecosystems build long-term soil health. Beyond the immediate farm, these benefits extend across large spatial scales: genetic diversity spreads across regions, mobile species like migratory pollinators provide landscape-level services, and ecosystem processes regulate watersheds and climate at regional scales. Biodiversity therefore provides a multi-level, multi-scale support system that simultaneously contributes to agriculture both immediately and for the future, locally and across broader landscapes.

Figure 1. Nature's Contributions to People



Source: (Moreira et al., 2024) based on (Díaz et al., 2018).

NON-MATERIAL NCP

- Learning and inspiration
- Physical and psychological experiences
- Supporting identities

MATERIAL NCP

- Energy
- Food and feed
- Materials, companionship, and labor
- Medicinal, biochemical, and genetic resources

REGULATING NCP

- Habitat creation and maintenance
- Pollination and dispersal of seeds and other propagules
- Regulation of air quality
- Regulation of climate
- Regulation of ocean acidification
- Regulation of freshwater quantity, location and timing
- Regulation of freshwater and coastal water quality
- Formation, protection, and decontamination of soils and sediments
- Formation, protection and decontamination of soils and sediments
- Regulation of hazards and extreme events
- Regulation of detrimental organisms and biological processes

Biodiversity is essential for ecosystem resilience, functioning as a natural safeguard against environmental disruptions or shocks. When a system lacks diversity, environmental shocks like drought, disease, or pest outbreaks can simultaneously affect a large proportion of similarly vulnerable organisms. A plantation forest made of one or two tree species will be highly and uniformly susceptible to bark beetles or fungal pathogens, while a diverse forest contains species with varying resistance levels and recovery mechanisms. To speed recovery, diverse systems can access different resource pools – some species may tap deep groundwater while others use surface moisture. This is crucial in habitats near agriculture: diverse upland forests protect valleys through multiple mechanisms (some trees stabilize soil through deep roots while others intercept rainfall with broad canopies) and diverse grasslands maintain soil stability and water retention.

Box 1
Forests and the hidden power of green water stocks

Vegetation is critical not just for generating rainfall, but also for nurturing “green water” in the soil. While much attention has been paid to forests’ role in producing atmospheric moisture and sustaining precipitation cycles, vegetation also plays a vital role in holding that water in the landscape. Moisture stored in the root zone, referred to as green water stocks – act as a natural buffer that sustains crops during periods of low rainfall and drought.

New evidence shows that these green water stocks significantly enhance agricultural resilience to drought. The recent World Bank report The Economics of a Livable Planet (Damania et al. 2025) presents global findings using satellite-based measures of vegetation, soil moisture, and crop productivity. The analysis shows that agricultural areas adjacent to healthy forested landscapes retain more soil moisture and experience smaller declines in yields during dry spells, compared to areas surrounded by degraded or sparsely vegetated land.

Biodiversity itself appears to strengthen this buffering function. The same analysis finds that natural forests, which host more diverse species and deeper, more complex root networks, outperform monoculture plantations in preserving soil moisture.

Green water is not only about atmospheric flows, but also about stable stocks in the soil, and forests help maintain both. As climate risks grow, this hidden form of water storage may prove to be one of the most cost-effective natural buffers for agriculture.

Damania, R., Ebadi, E., Mayr, K., Russ, J., & Zaveri, E. (2025). The Economics of a Livable Planet. Washington, DC: World Bank.

1.2 Biodiversity and key ecosystem services supporting agriculture

Agriculture relies on biodiversity and the multiple NCPs it provides. This section focuses more deeply on a select group of NCPs, genetic diversity, and then the regulating services, which are most critical to agriculture. Table 1 summarizes some ways biodiversity and key NCPs support agricultural productivity, resilience, and sustainability. For each of the grouped NCPs, a short discussion of selected ways they support agriculture is described below.

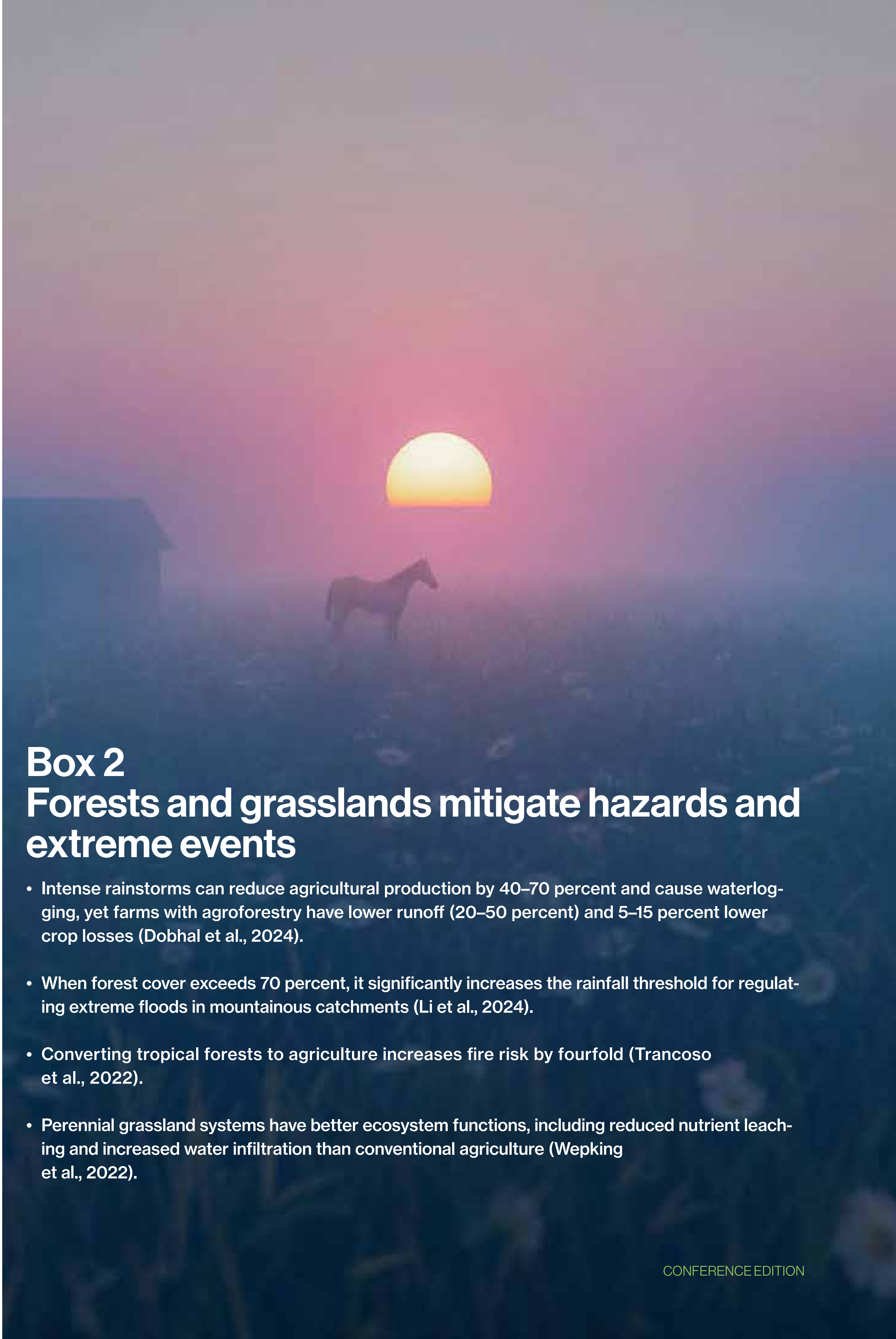
Forming, protecting, and decontaminating soils and sediments: Soil formation and protection services (forming, protecting, and decontaminating soils) was valued at $11.4 trillion annually (McBratney et al. 2017). Soil holds 25 percent of all biodiversity, including bacteria, fungi, insects, and earthworms that drive key soil processes by decomposing organic matter, cycling nutrients, enhancing soil structure, and improving water infiltration and retention (Guerra et al. 2022). Soil-dwelling insects like beetles, ants, and termites improve soil by burrowing, creating channels for air and water movement. Earthworms are sufficiently important that they alone contribute to producing 6.5 percent of four key global grains, 2.3 percent of legumes, and producing up to 10 percent of cereal grains in Africa and 8 percent in Latin America (Fonte et al. 2023). Soil biodiversity enhances nutrient availability, improves soil structure and drainage, limits erosion, and can restore soil quality if it is exposed to chemical and biological pollutants.

Freshwater flow, quality, and quantity underpin agricultural productivity and resilience. Biodiverse ecosystems – including forests, wetlands, and grasslands – regulate water cycles by enhancing infiltration, reducing runoff, and mitigating floods, which stabilizes water availability for irrigation and reduces soil erosion (Cimatti et al. 2023; Meli et al. 2024) Animals of all sizes are “ecosystem engineers,” improving conditions for water flow, recharge, and storage. Areas with higher soil biota (e.g., insects and earthworms) retain water better, recharging groundwater. Forests, particularly native forests, have higher water infiltration rates with less overland flow and erosion and improved water supply (Box 1). Biodiversity also shapes water quality. High plant diversity in wetlands filter pollutants while microbial communities break down contaminants. Diverse forests provide better variety and quality of services, regulating water flow, conserving water, controlling floods, preventing erosion, filtering pollutants, and recharging groundwater aquifers for agriculture (Martínez-García et al. 2022). All of these factors enhance agricultural outcomes.

Pollination and seed dispersal: Wild pollinators have a very high value NCP for agriculture, with a global economic value between $235–577 billion annually (IPBES 2019). Global agriculture increasingly relies on pollination (75 percent of crops), with more area planted with crops that depend at least partially on pollinators (Aizen et al. 2019; FAO 2024). Over 200,000 species are wild pollinators including bees, flies, butterflies, beetles, birds, reptiles, amphibians, and mammals, especially bats (Benton et al. 2021). More pollination by diverse pollinators improves crop quantity, quality, and nutritional value (Chaplin-Kramer et al. 2014; Gazzea et al. 2023; Katumo et al. 2022), increasing yields by 20 to 50 percent in pollinator-dependent crops (Dainese et al. 2019). Many species

Table 1. Benefits of regulating NCPs to agricultural productivity,resilience, and sustainability

	Productivity	Resilience	Sustainability
1. Forming, protecting, and decontaminating soils and sediments	Biodiversity, including soil microbes, fungi, and earthworms, recycles organic matter and forms soils, recycles nutrients, and increases soil fertility. Diverse soil organisms improve soil structure and nutrient availability (e.g., nitrogen and phosphorus), directly boosting crop yields.	Biodiverse soils withstand environmental stresses like droughts, floods, erosion, and nutrient leaching. Soil biodiversity improves water retention and reduces erosion, maintaining soil structure and fertility making agricultural systems more resilient to climate variability.	Biodiversity maintains healthy soils by reducing the need for synthetic fertilizers and pesticides, promoting long-term productivity with lower inputs, and sustaining long-term nutrient cycling, minimizing soil degradation, and reducing agrochemical runoff.
2. Fresh water flow, quality, and quantity	Biodiverse ecosystems regulate water flow and filtration, ensuring reliable and clean water for irrigation and crop growth. Wetlands and riparian buffers, for example, play a key role in maintaining water quality and availability for agriculture.	Natural water regulation systems, such as wetlands, mitigate water scarcity, drought, and flood by stabilizing water tables. They also filter pollution, protecting crops from waterlogging or salinity, helping agriculture adapt to climate variability. All of these maintain or boost productivity.	Biodiverse ecosystems reduce irrigation demands by enhancing water retention and quality, lowering the need for energy-intensive water extraction and conserving water for future use.
3. Pollination and seed dispersal	Pollinators and seed dispersers increase crop yields and genetic diversity, ensuring robust plant reproduction and higher-quality produce. Diverse pollinator communities enhance the pollination efficiency of crops, directly contributing to higher yields.	Pollinator diversity provides redundancy, ensuring both pollination and crop growth even if some species decline or during environmental stresses (e.g., heatwaves), since a wider variety of species provides greater diversity of responses to stressors, a valuable buffer.	Natural pollination reduces reliance on artificial methods (supporting ecosystem health), preserves genetic diversity in wild plant populations, minimizes the need for external inputs, and reduces costs over time.
4. Pest and disease control	Natural predators (e.g., birds, spiders) and microbial diversity suppress pest and disease outbreaks, reducing crop losses. Diverse ecosystems have a variety of pest predators.	Diverse agroecosystems limit pest adaptation and provide biological buffers against pest outbreaks, a vital function given climate change and other shocks (e.g., floods) that increase pest pressures.	Lower pesticide use preserves beneficial insect populations that also support soil health and fertility, lowering input costs, and supporting long-term agricultural sustainability.
5. Hazards and extreme events	Biodiverse landscapes (e.g., forests, grasslands) stabilize microclimates – reducing crop damage from storms, heatwaves, or landslides – and mitigate erosion and flooding, protecting infrastructure and crops.	Diverse ecosystems absorb and dissipate the impacts of extreme weather, reducing damage from hurricanes or preventing soil erosion during heavy rains. Healthy soils that can absorb water and diversify plant root systems and provide vegetation covers help maintain land productivity.	Natural buffers (e.g., mangroves, hedgerows) provide long-term protection against extreme events, reduce costly infrastructure repairs, lower recovery costs, and maintain productivity over time, even under changing climate conditions, thereby supporting agricultural sustainability.
6. Climate regulation (global and local scales)	Biodiverse ecosystems sequester carbon and regulate temperatures in microclimates (local scale), creating optimal growing conditions. For example, shade from diverse tree canopies reduces heat stress in crops enhancing growing conditions and crop yields.	Diverse ecosystems buffer against temperature extremes and weather variability, supporting stable production. For example, diverse vegetation enhances drought tolerance and reduces yield variability, essential for supporting agriculture as climate impacts worsen.	Biodiversity-driven carbon storage mitigates global warming, aligning agricultural systems with climate stabilization goals, reducing energy-intensive interventions, and promoting long-term agricultural viability, aligning with global climate change mitigation through sustainable land use.



Box 2
Forests and grasslands mitigate hazards and extreme events

- Intense rainstorms can reduce agricultural production by 40–70 percent and cause waterlogging, yet farms with agroforestry have lower runoff (20–50 percent) and 5–15 percent lower crop losses (Dobhal et al., 2024).

- When forest cover exceeds 70 percent, it significantly increases the rainfall threshold for regulating extreme floods in mountainous catchments (Li et al., 2024).

- Converting tropical forests to agriculture increases fire risk by fourfold (Trancoso et al., 2022).

- Perennial grassland systems have better ecosystem functions, including reduced nutrient leaching and increased water infiltration than conventional agriculture (Wepking et al., 2022).

disperse seeds by eating and defecating seeds or seeds stick to them and fall off. Diverse pollinators and seed dispersers increase resilience to climate change impacts and shocks.

Biodiversity-driven pest and disease control mitigates agricultural losses by regulating detrimental organisms (e.g., pests, pathogens, vectors) through ecological interactions. Diverse predator-prey networks, including birds, bats, and parasitoids, suppress pest populations. For example, bats eat nocturnal pests and disease-carrying insects. (Buzhdygan & Petermann 2023; Tuneu-Corral et al. 2023). Soil microbial communities further limit diseases by suppressing pathogens and priming plant immunity (Buzhdygan & Petermann 2023). Healthy ecosystems also reduce pathogen spread that affect wildlife, livestock, and humans; healthier, diverse habitats limit the spread of diseases that jump from wildlife to people (zoonotic disease) by maintaining balanced host-pathogen dynamics, reducing transmission events (Plowright et al. 2024). Intact habitats are better than agricultural settings in diluting pathogen loads, which lowers risks of diseases that can affect crops or be passed to humans (Keesing & Ostfeld 2024).

Healthy ecosystems act as a “biological insurance policy” buffering extreme weather events. They do this by moderating temperature fluctuations, reducing runoff during heavy rainfall, and maintaining soil moisture during droughts. Healthy soils retain water so crops withstand dry periods and also absorb excess water during floods (Box 2). Diverse predator communities reduce pests and crop vulnerability during climatic stresses. Agroforestry systems, reduce extreme temperatures by providing shade and windbreaks (FAO 2023).

Biodiversity, through its role in climate regulation, can have local and distant impacts on agriculture. At local scales, biodiversity enhances microclimate regulation by stabilizing local rainfall patterns and temperatures (Cimatti et al. 2023; Oliveira et al. 2022). On a global scale, teleconnections (causal connections between meteorological or environmental phenomena across long distances) link climate and weather patterns across distant regions. When carrying precipitation these are sometimes called “flying rivers”. Forest systems, particularly in tropical regions, influence precipitation patterns and atmospheric circulation of air (Trancoso et al. 2022). For example, water vapor released by forests can influence regional rainfall patterns. Water vapor from the Amazon forest lands as rainfall both locally (e.g., Brazil’s Atlantic Forest region with 70 percent of Brazil’s population) and as far as northern Argentina, Paraguay, Uruguay, and even the U.S. Midwest (Avissar & Werth 2005; Duku & Hein 2023; Ferrante et al. 2023; Sierra et al. 2022). Rainfall moves from the Congo Basin to the Ethiopian highlands, which supplies about 85 percent of the Nile’s headwaters (Gebrehiwot et al. 2019).

Agriculture also supports biodiversity. Over and above the contribution of sustainable agricultural practices to increasing biodiversity in previously unsustainable systems, which is a core focus this report, agriculture can contribute to biodiversity in other ways. Animal and plant breeding and selection have created an immense diversity of genetic resources for food and agriculture. Agriculture can also contribute to restoring degraded landscapes such as after mining. Furthermore about 17 percent of species (from species groups comprehensively assessed on the IUCN Red List) have agriculture documented as a habitat and 86 species have only been found to live in agricultural habitats (IUCN 2024).

1.3 Biodiversity supports agriculture from global to farm scales

The reach of NCPs for agriculture at global, regional, landscape and local scale

Natural areas sustain biodiversity and NCPs that reach across global, regional, landscape, and local scales to sustain agricultural productivity. Nature at each of these interconnected scales contributes to agricultural resilience by regulating climate, supporting pollination, managing water resources, and enhancing soil health. Integrating natural areas into agricultural systems ensures the long-term viability of both. Natural areas and agricultural systems are deeply interconnected across spatial and temporal scales, with benefits at one level reinforcing those at others. For example, global climate regulation drives regional water cycles, which support local pollination and pest control. Examples are provided in Box 3.

Natural areas within or near farms provide immediate and measurable benefits to productivity. Habitat patches, riparian vegetation, and forest edges support wild pollinators and host natural enemies of agricultural pests, reducing pesticide use. Local vegetation regulates microclimates, reducing temperatures by 2–5°C during heat waves preventing crop damage (Wright & Francia 2024). Riparian buffers prevent soil erosion, saving farmers significant costs in nutrient loss and soil restoration (Hernandez et al. 2023). Greater natural habitat correlates with increased biodiversity in croplands, which enhances resilience in crop systems (Dainese et al. 2019; Outhwaite et al. 2022).

Critical thresholds to maintain ecosystem functions

Critical thresholds in ecosystem functioning define the minimum habitat coverage required to sustain NCPs. Habitat loss beyond certain thresholds sharply reduces NCP flows (Palmer et al. 2025). For example, forest patches below critical sizes fail to sustain pollinators and pest predators, directly reducing agricultural productivity (Priyadarshana et al. 2024). NCP flows, especially those at the local scale, decline sharply with distance from natural areas. Pollination drops by 35 percent at 500 meters and 65 percent at one kilometer from habitat patches, while pest regulation follows similar trends, with predation rates declining significantly beyond 500 meters (Garibaldi et al. 2021). Agricultural landscapes with 20–30 percent of natural vegetation consistently support higher levels of ecosystem services, balancing productivity with environmental sustainability (Garibaldi et al. 2021; Mohamed et al. 2024).

Semi-natural habitats covering at least 20–25 percent of human-modified landscapes sustain pollination, pest control, and other NCPs, while areas with less than 10 percent habitat experience sharp declines, with some services disappearing entirely (Priyadarshana et al. 2024). Specific needs vary: pollination and pest control require at least 20 percent habitat, water quality regulation may need as little as 6 percent depending on buffer widths (Mohamed et al. 2024; Priyadarshana et al. 2024). Maintaining a maximum linear distance of 300–500 meters between natural habitats and agricultural fields ensures consistent NCP flows. Working landscapes, including areas used for farming, ranching, and forestry, require a minimum of 20 percent native habitat to ensure biodiversity, NCP flows, and agricultural productivity are secure and to avoid tipping points where ecosystems can no longer recover (Garibaldi et al. 2021; Mohamed et al. 2024).

The location and proximity of natural areas to agriculture plays a key role in determining how effectively NCPs flow to agricultural systems and how they support agricultural productivity and resilience. Strategically placed habitat maximizes benefits, with riparian corridors providing water filtration, flood control, and connectivity (Petit & Landis 2023). Leaving natural habitat on marginal lands, such as steep slopes, reduces trade-offs between agricultural production and ecological function, supports NCPs, and ensures the efficient use of available space (Palmer et al. 2025). Edge effects, created where natural and agricultural systems meet, strongly influence NCP flows. Gradual transitions between forest edges and farmland support higher biodiversity and enhance pollination and pest regulation, whereas abrupt boundaries reduce effectiveness (Bourgoin et al. 2024). Managing edge habitats through hedgerows and buffer zones mitigates negative effects and enhances biodiversity (Albrecht et al. 2020; Estrada-Carmona et al. 2022).

Heterogeneous landscapes, with their mix of habitat types and spatial arrangements, support richer pollinator and predator communities, which directly improve crop productivity. These varied landscapes increase natural enemy populations compared to uniform ones (Garibaldi et al. 2021). This diversity ensures stability in delivering NCPs as different habitats provide complementary resources and resilience under changing conditions (Buchadas et al. 2022; García-Vega et al. 2024b). Semi-natural habitats and smaller fields are particularly effective in enhancing farmland biodiversity (de la Riva et al. 2023; Outhwaite et al. 2022).

The next section explores how these insights inform actions for conserving biodiversity and NCPs, managing agriculture and restoring degraded lands.

Box 3
NCPs for agriculture

Examples of their reach across geographic scales

GLOBAL-SCALE SERVICES

- **Climate regulation through carbon sequestration:** Stabilizes climate patterns for predictable growing seasons. Intact forests sequester 7.6 billion metric tons of CO_2 annually regulating climate worldwide *(Harris et al. 2021; Rockström et al. 2021; Bossio et al. 2020).*

- **Teleconnections (atmospheric rivers):** Large forests supply rainfall to distant agricultural regions, with moisture transfer across continents (e.g., Amazon to Rio de La Plata Basin: approximately 4,000 km). Amazon deforestation of 20-25 percent could trigger tipping points affecting rainfall patterns up to 4,500 km away *(Ellison et al. 2017; Duku & Hein 2023; Flores et al. 2024; Qin et al. 2025).*

REGIONAL-SCALE SERVICES

- **Watershed protection:** Ensures reliable water supply for irrigation and reduces flood damage, typically 10–1,000 km from headwaters to agricultural areas. Large watersheds can influence water regulation up to 2,000 km downstream in major river basins *(Xu et al. 2019; Ilstedt et al. 2016; Filoso et al. 2017; François et al. 2024).*

LANDSCAPE AND FARM-SCALE SERVICES

- **Carbon storage in agricultural landscapes:** Improves soil structure and water holding capacity in adjacent fields. Carbon sequestration in agroforestry systems and field margins extends 10–500 meters from tree lines, with soil carbon enhancement extending 50–250 meters from tree lines and measurable but diminishing effects up to 500 meters *(Ledo et al. 2020; Zomer et al. 2022; Mohamed et al. 2024).*

- **Pollination from adjacent habitats:** Increases crop yields and quality in fields near natural areas. It is most effective within 500 meters of fields (mean: 989m) since most wild pollinators operate within 100–1,500 meters of natural habitats. Needs rich, diverse habitat with native and non-native species. Pollination services

decline by 50 percent at distances >750m from natural habitat, with spatial threshold effects that vary by crop type *(Garibaldi et al. 2013; Albrecht et al. 2020; Martin et al. 2019; Turo et al. 2024; Mohamed et al. 2024).*

- **Pest control from nearby natural areas:** Reduces crop loss or pesticide use and requires a minimum of 20 percent natural habitat (mean: 19 percent). Most effective within 500 meters of fields (mean: 606 meters). Needs complex habitat with diverse native species. Landscape complexity within 1 km radius increases natural enemy abundance by 40–70 percent, with sharp declines beyond 300 meters from habitat edges *(Karp et al. 2013; Boldorini et al. 2024; Tscharntke et al. 2024; Scheper et al. 2023).*

- **Water quality regulation from plants and riparian buffers:** Requires a minimum of 6 percent natural habitat (mean: 6 percent). Most effective when placed on both sides of streams. Needs diverse semi-natural vegetative buffers with native species. Improves irrigation water quality and reduces water treatment costs, with effective filtering typically within 5–50 meters of waterways. Riparian buffers of 30–100m width can remove 70–90 percent of nutrients and sediments from agricultural runoff *(Cole et al. 2020; Qiu et al. 2023; Shi et al. 2024).*

- **Soil conservation and erosion control:** Erosion control typically within 10–100 meters of conservation practices such as vegetative strips that can reduce soil erosion by 70–85 percent within 50 meters downslope. It is most effective when evenly distributed across landscape. Needs diverse, rich semi-natural vegetation cover *(Wu et al. 2020; Wuepper et al. 2020; Meena et al. 2022)*.

- **Natural hazards mitigation from plants:** Most effective at slope base or bottom for landslides. Needs semi-natural vegetation with diverse native species (strong deep-rooted trees and shrubs, spaced young species like poplar and willows, and mixed plantations) *(Pacheco Quevedo et al. 2023; Nel et al. 2014; Fuller & Conley 2024)*.

- **Local genetic exchange:** Maintains local adaptation and genetic diversity in cultivated species. Gene flow between crop varieties and wild relatives typically within 0.5–2 km, most intensive within 500 meters but measurable up to 3 km for wind-pollinated species *(Zuza et al. 2024; Salgotra & Chauhan 2023; FAO 2025).*

Chapter 2.

Conserving, connecting, and restoring natural areas to support agriculture

Increasing biodiversity requires a multifaceted approach involving conservation, restoration, and intensification to reduce land use pressure.

This chapter focuses on conserving, connecting, and restoring natural areas to ensure NCPs flow to agriculture from healthy ecosystems. It examines the natural areas (forests, wetlands, and other natural areas) providing NCPs to agriculture and the extent to which they have been lost or are threatened by agricultural expansion. It then explores opportunities to restore degraded agriculture and pastureland to natural areas. It also addresses the importance of conserving natural habitats within agricultural areas themselves. It underscores the critical role of connectivity, both within fragmented natural landscapes and between natural and agricultural areas. Finally, this chapter discusses spatial conservation planning to prioritize areas for conservation and restoration which also helps identify remaining areas where sustainable intensification can reduce overall land use pressure (land sparing).

2.1 Agricultural expansion has driven biodiversity loss

Agriculture fundamentally relies on biodiversity, yet it stands as the primary driver of declining biodiversity causing nearly 75 percent of negative impacts on land-based biodiversity (UNEP 2024a). Agriculture is essentially undermining the biodiversity and NCPs it depends upon (FAOSTAT). Agriculture threatens up to 85 percent of species currently at risk of extinction (Boakes et al. 2024; Hald-Mortensen 2023). Plant and animal extinctions are estimated to be 10 to 100 times higher than expected primarily due to land use change, habitat fragmentation, and related pressures (Ceballos and Ehrlich 2023; IPBES 2019). Biodiversity losses reached 2–11 percent during the 20th century. Losses continued declining by 2–6 percent each decade over the past 30–50 years. Nearly 1 million species are now at risk (Ceballos and Ehrlich 2023; Pereira et al. 2024; McElwee et al. 2024). Monitored wildlife populations show severe declines, having plummeted by an average of 73 percent globally since 1970 (WWF 2024). Losses were concentrated in certain regions, including Latin America and the Caribbean (95 percent decline), Africa (76 percent), and Asia Pacific (60 percent) (WWF 2024). Crop and forestry biomass cultivation specifically has caused 90 percent of land – use-related biodiversity loss and water stress (UNEP 2024a).

Growing demand for food, changing diets and food loss and waste are driving agricultural expansion undermining the biodiversity and NCPs that agriculture depends upon. Agricultural expansion has been driven by population growth (2.5 billion people in 1950 to 8.0 billion in 2022), increased calorific consumption (2,181 kcal per capita in 1961 to 2,959 in 2021) and increased demand for animal protein (19.5 grams per capita in 1961 to 37 grams in 2021 (Roser, Ritchie, and Rosado 2024). Global food loss and waste are staggering with over 1 billion meals are thrown out per day totaling more than $1 trillion each year and accounting for the equivalent of production from 30 percent of the world's agricultural land and the generation of 8–10 percent of global greenhouse gas (GHG) emissions (UNEP 2024b).

Expansion into marginal lands (e.g., arid regions, steep slopes) not suited for intensive agriculture causes land degradation and biodiversity loss. Marginal lands account for about 29 percent of global cropland. Farming on marginal lands, unsuited for intensive agricultural practices, has low and diminishing returns, yielding just 10–30 percent of potential productivity due to poor soil quality and limited adaptive capacity. Clearing these lands leads to soil losses that are 2–3 times higher than in fertile regions (UNCCD 2022). Estimates suggest that a significant portion of the 1.5 billion hectares of degraded land globally is linked to livestock production and extensification practices. Degraded lands exhibit soil organic matter below 1.5 percent, requiring costly remediation (FAO 2021).

Agriculture drives the vast majority of deforestation and related nature loss. Between 2001 and 2022, 86 percent of global deforestation was due to conversion for crop and cattle production (West et al. 2025). Over the past 60 years, 309 million hectares (Mha) of land have been converted to agriculture. In the tropics, agriculture accounts for 90–99 percent of tropical deforestation (Pendrill et al. 2022). Deforestation rates increased from ~5.1 Mha per year in the early 2000s, peaking between 6.4 and 9.0 Mha annually during the 2010s, when it began to slow (Winkler et al. 2021). Recent data suggests a slowing trend in primary tropical forest loss at 3.7 Mha in 2023 (WRI 2024). Actions that fragment forests (e.g., roads or farms) create edges that reduce forest health, affecting 18 percent (approximately 206 Mha) of remaining tropical moist forests (Bourgoin et al. 2024).

Much of this land use change is relatively recent and is in tropical countries. Land clearing continues at about 3-4 million hectares annually (Bourgoin et al. 2024). Between 2003–2019, global cropland expanded by 9 percent (217 million hectares), with the greatest agricultural expansion in that period in South America (49 percent) and Africa (34 percent) (Potapov et al. 2021). This transformation in tropical South America, Southeast Asia, and Africa has been particularly intense, and its drivers include demand for exports, commercial crops, and smallholder farming (Kadoya et al. 2022). Overall, land-use change for agriculture is large-scale, widespread, severe, often irreversible, and increasing.

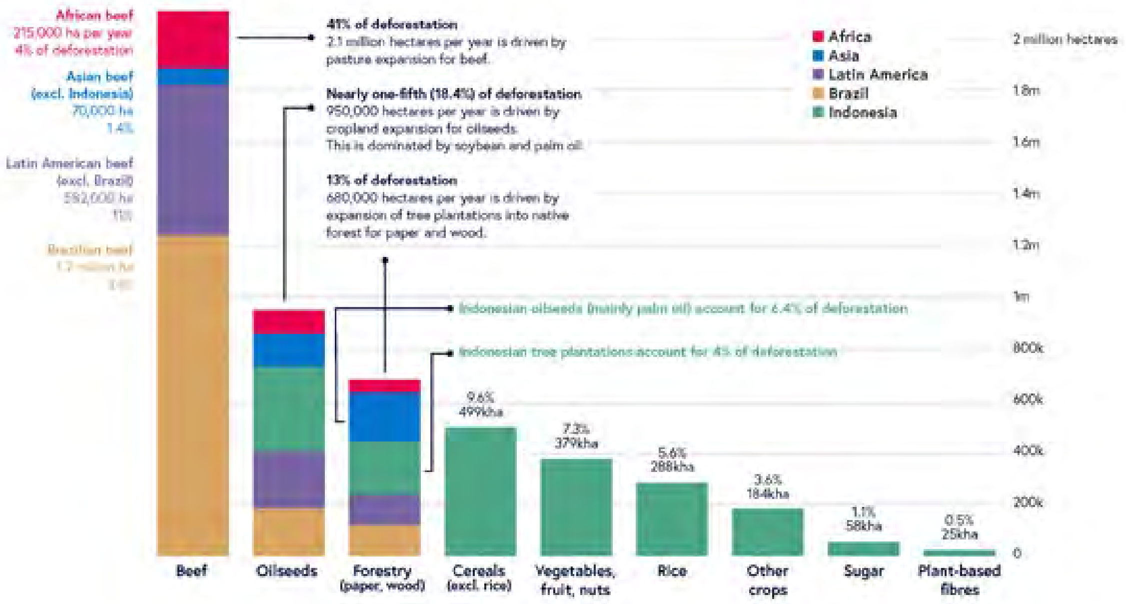
Demand for commodities drives nearly 70 percent of global deforestation, with beef production alone responsible for over 40 percent of deforestation. Figure 2 shows the contribution of different types of agriculture to land clearing in different regions, with high deforestation in Brazil for beef, palm oil (especially in Malaysia and Indonesia), and soy (largely for animal feed) in multiple countries. Palm oil, soy, beef, wood products, and other agricultural commodities from just seven countries accounted for 40 percent of total tropical deforestation between 2000–2011 (Schwarzmueller & Kastner 2022; Ritchie 2019).

International trade plays a significant role in driving biodiversity loss, particularly in tropical regions where agricultural commodities are produced for export. Trade results in displaced biodiversity impacts, where consumption in high-income regions drives deforestation and habitat loss in the Global South. For instance, 72 percent of the agricultural impact on biodiversity linked to consumption in high-income countries in 2015 originated from imported goods. In contrast, only 17 percent of the biodiversity footprint in low-income countries was tied to imports. (Bjelle et al. 2021). Cropland used for export increased from 17 percent in 2000 to 23.4 percent in 2013, with five crops – wheat, soybeans, palm oil, maize, and sugar – accounting for approximately 60 percent of traded calories globally (Schwarzmueller & Kastner 2022; Chaves et al. 2020).

Western Europe, North America, and East Asia are major net importers, while regions with large land resources like Latin America, Southeast Asia, and Oceania are key exporters (Kastner et al. 2021). Major bilateral flows include exports from Brazil and Latin America to the EU, China, and the United States, leading to 103,000, 85,000, and 81,000 hectares of forest loss respectively; exports from Russia were primarily to the EU; and exports from Oceania and Southeast Asia were mainly to

China (Kan et al. 2023). China is a dominant importer, with more diversified source regions compared to the EU and United States.

Figure 2. Contribution of commodities to deforestation by region and commodity



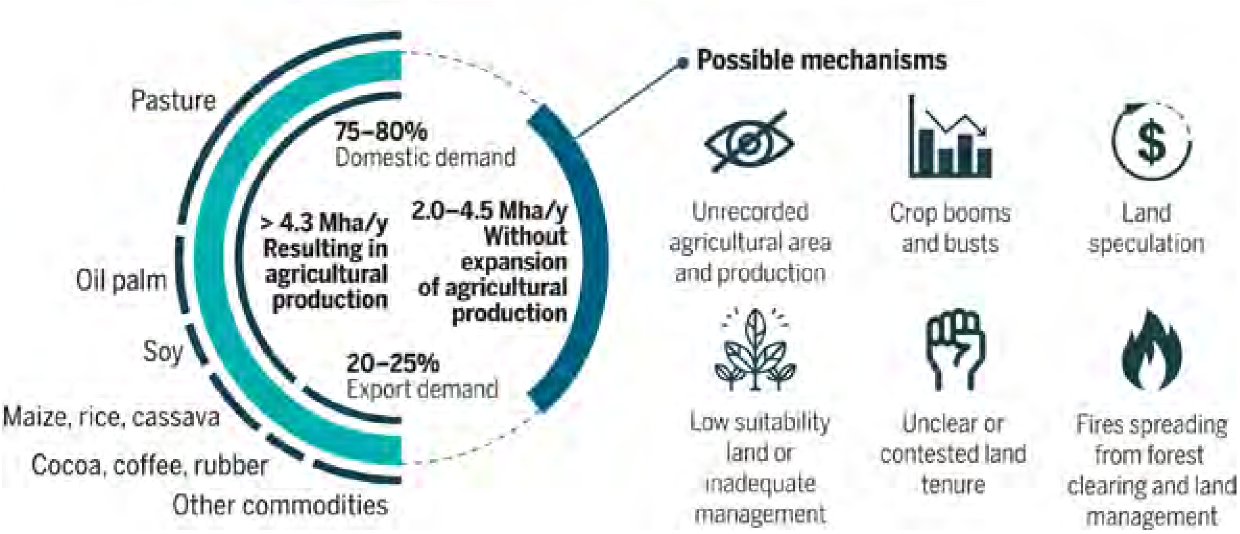
Source: Ritchie, H. (2019), Cutting down forests: what are the drivers of deforestation, Our World in Data, [online]

The farm types driving deforestation differ by region. Commercial agriculture is responsible for 40 percent of tropical deforestation, and this land tends to stay in commodities (FAO 2020). Large-scale conversion of forests for commodities is evident in the Brazilian Amazon (7.3 Mha of forest loss 2016–2021) and in Indonesia (4.1 Mha of forest loss 2016–2021) (World Bank Forest Indicators 2022) for example. Yet in Africa, smallholder agriculture is the dominant driver of forest conversion (Masolele et al. 2024).

Large areas of land deforested for agriculture sit idle after clearing. Only about half (45–65 percent) of deforested land has been used for the expansion of productive agriculture, with the remainder cleared for land speculation, left idle due to land tenure issues, used for short-lived agriculture and then abandoned, or damaged by fires from forest clearing and land management (Pendrill et al. 2022). The initial clearing of forests causes over 90 percent of biodiversity loss and water stress related to land use change (Bhandary, Deb, and Sharathi Dutta 2023; Terpstra, Marquitti, and Vasconcelos 2024). Cumulatively, 101 Mha of cropland was abandoned globally between 1992–2020 (Zheng et al. 2023).

Urgent action to arrest land use change is essential because ecological systems in some natural areas are nearing or have already passed tipping points. Tipping points are critical thresholds beyond these which ecological or climatic changes become irreversible, leading to cascading impacts across systems with potentially devastating consequences for regional climates, water availability, and agriculture (IPCC 2023). For example, the Amazon rainforest is at risk and could shift from forest to savanna. This shift would cause catastrophic biodiversity loss and disrupt regional and global climate regulation, impacting agriculture (IPCC 2023). Similarly, abrupt changes in major rainfall patterns, such as the monsoons vital for agriculture across Asia and Africa could potentially result from exceedance of climate and land use change thresholds.

Figure 3. Agriculture-driven deforestation



Source: Pendrill et al. 2022.

Strategies for conserving remaining natural areas, restoring degraded ecosystems, and connecting fragmented landscapes are crucial for determining the fate of cleared land and mitigating negative impacts on the biodiversity and NCPs that support agriculture.

2.2 The status of natural areas supporting agriculture

Critical Natural Assets (CNA) are the planet's most essential natural areas, irreplaceable for maintaining global biodiversity, climate stability, and the NCPs underpinning agricultural productivity (Box 4). This section examines the current status of CNAs, assesses their condition, the threats they face from agricultural expansion and climate change.

CNAs can be categorized as either Conservation Priorities or Restoration Priorities based on their current condition, which helps us identify appropriate management approaches needed to sustain the agricultural benefits they provide:

- **Conservation Priorities are CNAs that largely remain in their original natural or semi-natural state.** Many of these are still healthy ecosystems that are somewhat ecologically intact because they still hold important biodiversity. These CNAs represent the planet's most critical functioning ecosystems actively delivering essential NCPs like climate regulation, water filtration, and pollination that benefit agriculture and human well-being. They have largely avoided significant conversion into agricultural landscapes such as croplands or pasturelands.

- **Restoration priorities are CNAs with restoration potential that have already been converted to agriculture or pasture yet are still delivering NCPs.** These areas are global priorities for ecosystem restoration (Strassburg et al. 2020). While currently degraded from their natural condition, they represent important opportunities where targeted restoration efforts could potentially re-establish vital NCP functions and services, thereby enhancing support for agriculture and biodiversity conservation in the future. Table 2 shows the total global area of conservation or restoration priorities to support agriculture.

Table 2. Percent and area of total global CNA that are conservation or restoration priorities

CONSERVATION PRIORITY
56 percent of CNA (~5.1 billion ha)
RESTORATION PRIORITY
44 percent of CNA (~4.0 billion ha)

CNAs can also be categorized as either Stable or Unstable based on the threat to these areas from agricultural expansion or climate change (Box 5). This classification can be applied to both Conservation Priorities and Restoration Priorities.

Box 4

Defining Critical Natural Assets

Critical Natural Assets (CNA) are defined as areas providing irreplaceable local and global NCPs (Chaplin-Kramer et al., 2023; Neugarten et al., 2024). These include 12 NCPs, two that are global (vulnerable terrestrial ecosystem carbon storage, and vegetation regulated moisture retention recycling) and ten that provide local/regional benefits (crop pollination, flood regulation, nitrogen retention, sediment retention, fodder production, fuelwood production, timber production, coastal risk reduction, river fish harvest, and access to nature). These natural and semi-natural locations collectively provide 90 percent of the total global supply of these NCPs. In addition, for this report we have added irreplaceable biodiversity values, such as habitats supporting rare and endangered species or exhibiting high ecological integrity, since they are fundamental to resilience and maintaining ecological health. Methodologically, this involved spatially combining data from three peer-reviewed global datasets representing key priorities for: 1) ecosystem services (Chaplin-Kramer et al., 2023), 2) carbon storage (Noon et al., 2022), and 3) biodiversity conservation (Allan et al., 2022). This integrated approach identifies the highest priority areas critical across these multiple dimensions of natural value.

The two threat assessments, for agriculture and climate change, were combined to identify the CNA threat, categorized as Stable or Unstable. CNAs facing low threats from both agricultural expansion and climate change were classified as "Stable," while those facing high threats from either factor were deemed "Unstable".

Agricultural expansion represents a near-term risk of habitat conversion, while climate change involves more pervasive, longer-term impacts from altered environmental conditions. Agricultural expansion poses a significant short-term risk, threatening approximately **12 percent of CNAs** (1.1 billion hectares). Climate-change is estimated to threaten a vast area of CNA – roughly **33 percent of CNAs** or 3.0 billion hectares over the next 50 years (under a moderate scenario). Furthermore, climate change can act as a threat multiplier, particularly impacting CNA areas already converted for agriculture. This increases the risk that these lands become unsuitable for farming, potentially leading to the loss of both the underlying natural asset functions and agricultural productivity.

Table 3 summarizes the characteristics of the four categories of CNA based on their condition (Conservation Priority/Restoration Priority) and threats to them (Stable/Unstable) and Figure 4 shows their spatial distribution.

Table 3. Characteristics of CNA Categories based on condition (Conservation Priority/Restoration Priority) and stability (stable/unstable)

PRIORITY	STABLE	UNSTABLE
CONSERVATION	**29 percent (2.6 billion ha)** • High ecological integrity & intactness • Likely remote or well-managed lands • May overlap with PAs & Indigenous lands. • Low current/projected threats (climate, development)	**27 percent (2.5 billion ha)** • High, current ecological integrity & intactness • Critical areas for biodiversity & carbon under pressure • Facing short-term threat from agriculture & long-term threat from climate change
RESTORATION	**16 percent (1.4 billion ha)** • Currently low value agriculture or pastureland • Identified as a restoration priority • Low future threats: climate, agriculture • Ecological recovery with intervention	**28 percent (2.6 billion ha)** • Currently low-value agriculture or pastureland. • Identified as a restoration priority • Facing high future threats (climate, agriculture) so requires intervention • High potential for restoration gains & avoided future losses if managed

Management approaches for maintaining, connecting, and restoring these four categories of critical natural assets emerge from their categorization by condition and threat. Table 4 summarizes these approaches which are discussed in detail in sections section 2.3-2.5 below.

Figure 4. Conservation and restoration priorities

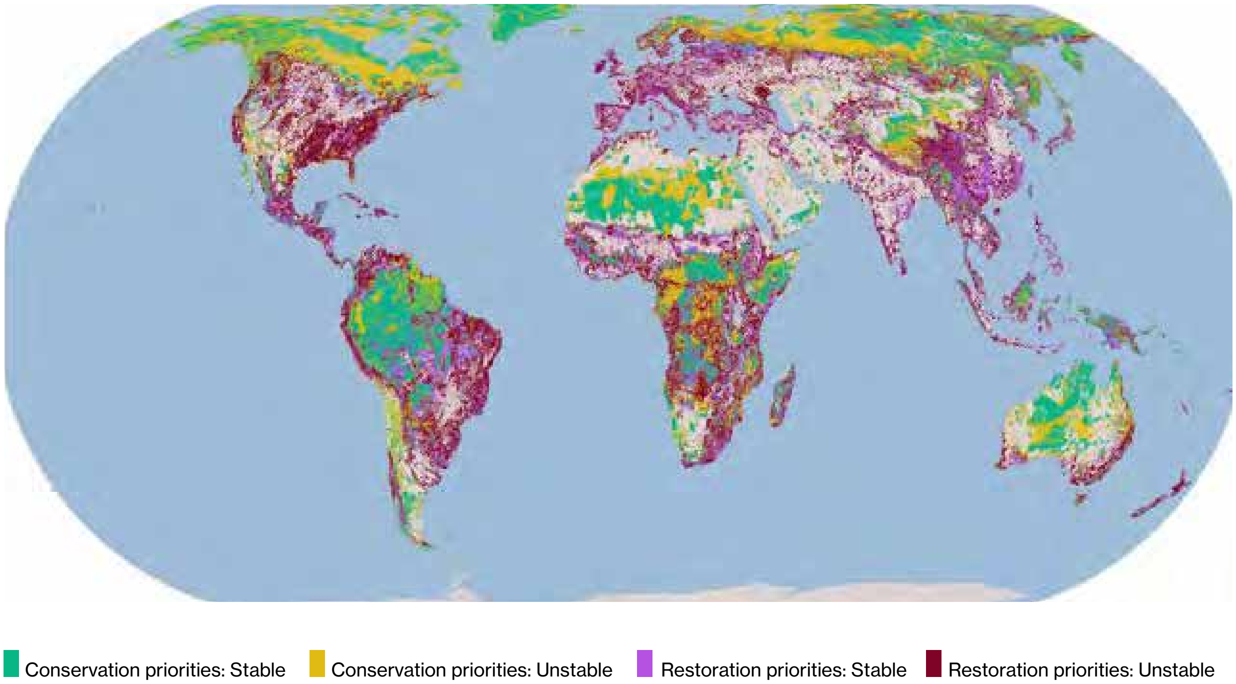


Table 4. Summary of key management approaches for each CNA category

PRIORITY	STABLE	UNSTABLE
CONSERVATION	• Maintain existing ecological processes • Strengthen/formalize protection (PAs, OECMs, recognize IPLC rights/governance) • Active resource management where needed (e.g., invasive species, fire regimes) • Community engagement & stewardship • Monitor conditions	• Proactive protection against threats (e.g., establish new PAs/OECMs quickly) • Climate-smart conservation planning (boost resilience, facilitate species movement, reduce hazards) • Secure land tenure/rights to prevent conversion • Adaptive management based on threat monitoring
RESTORATION	• Prioritize ecological restoration activities • Implement actions like soil improvement, erosion control, reforestation/revegetation • Focus on hydrological & biodiversity restoration • Integrate with sustainable land use planning in surrounding landscape (e.g., agroecology)	• Implement long-term restoration programs • Integrate climate adaptation explicitly into restoration design & goals • Monitoring and adaptive management to respond to changing conditions • Address drivers of degradation & future threats simultaneously • May require higher investment but offer high potential returns (restoration and avoided loss)

Note: Other Effective Area Based Conservation Measures (OECM). Protected Areas (PA).

2.3 Conserving natural areas to support agriculture

Conserving the world's remaining intact natural landscapes stands as the most effective, and often most cost-efficient, strategy for maintaining CNAs essential for agriculture. Preventing these relatively intact CNA ecosystems from being converted or degraded is critical, as subsequent restoration is often technically challenging, significantly more costly, and may never fully recover original biodiversity and thus the NCP functions (Mori and Isbell 2024). Conservation of these areas should focus on functional integrity, scale, proactive threat management, equitable governance, and climate resilience. Conservation should be guided by the principles discussed below and align with global targets like the 30×30 target via the Kunming–Montreal Global Biodiversity Framework (2022) – committing parties to protect and conserve at least 30 percent of land, inland water, and sea areas by 2030 under the Convention on Biological Diversity (CBD), and the United Nations Conventions on Climate Change (UNFCCC), and to Combat Desertification (UNCCD).

CNAs that are Conservation Priorities and Stable, require a focus on long-term conservation and monitoring. Key actions include ensuring effective existing legal protections, strengthening Protected Areas, recognizing and supporting Other Effective area-based Conservation Measures (OECMs), and recognizing the governance rights and conservation success of Indigenous Peoples and local communities (IPLCs) whose territories often overlap with these stable CNAs. Where needed, active resource management (e.g., controlling invasive species, maintaining natural fire regimes) helps sustain the flow of benefits, while community engagement builds local stewardship needed for long-term resilience.

CNAs that are Conservation Priorities and unstable, require urgent climate-smart action that envisages and rapidly responds to development to avoid fragmentation or further degradation. Key actions include rapidly setting up strong legal protections (e.g., PAs or OECMs) where needed on the most critical "edges" or frontier areas where agricultural development is likely to pose challenges and try to convert these lands. Climate-smart conservation plans are essential; they should be designed to boost ecosystem resilience, reduce climate-related hazards, and help species move as conditions change. Dedicated monitoring systems are also needed to guide adaptive management, to ensure these CNAs keep functioning and providing benefits under pressure.

Management approaches can be guided by the following illustrative principle to help ensure these intact areas remain ecologically functional, diverse, and capable of delivering sustained NCPs like climate regulation, water cycling, pollination, and pest control, which directly support food systems.

a) **Focus on functions and integrity:** Ensure conserved areas deliver necessary NCP flows vital to agriculture by protecting functional integrity of ecological processes e.g., pollination, nutrient cycling, water regulation). Metrics must reflect function, not just area (an "empty forest" lacks function).

b) **Conserve comprehensive biodiversity:** Protect the full range of biodiversity (genetic, species, ecosystem) to underpin ecological functions, NCP delivery, and resilience to shocks.

c) **Ensure sufficient scale, size and internal connectivity:** Prioritize large, unfragmented intact areas, minimizing internal fragmentation (e.g., from infrastructure) to support viable populations, large-scale processes, and reduce vulnerability.

d) **Prioritize irreplaceable and threatened assets:** Focus conservation on areas critical for significant biodiversity, threatened species, vulnerable ecosystems, or unique NCP provision where loss would be irreversible or disproportionately impactful for agriculture.

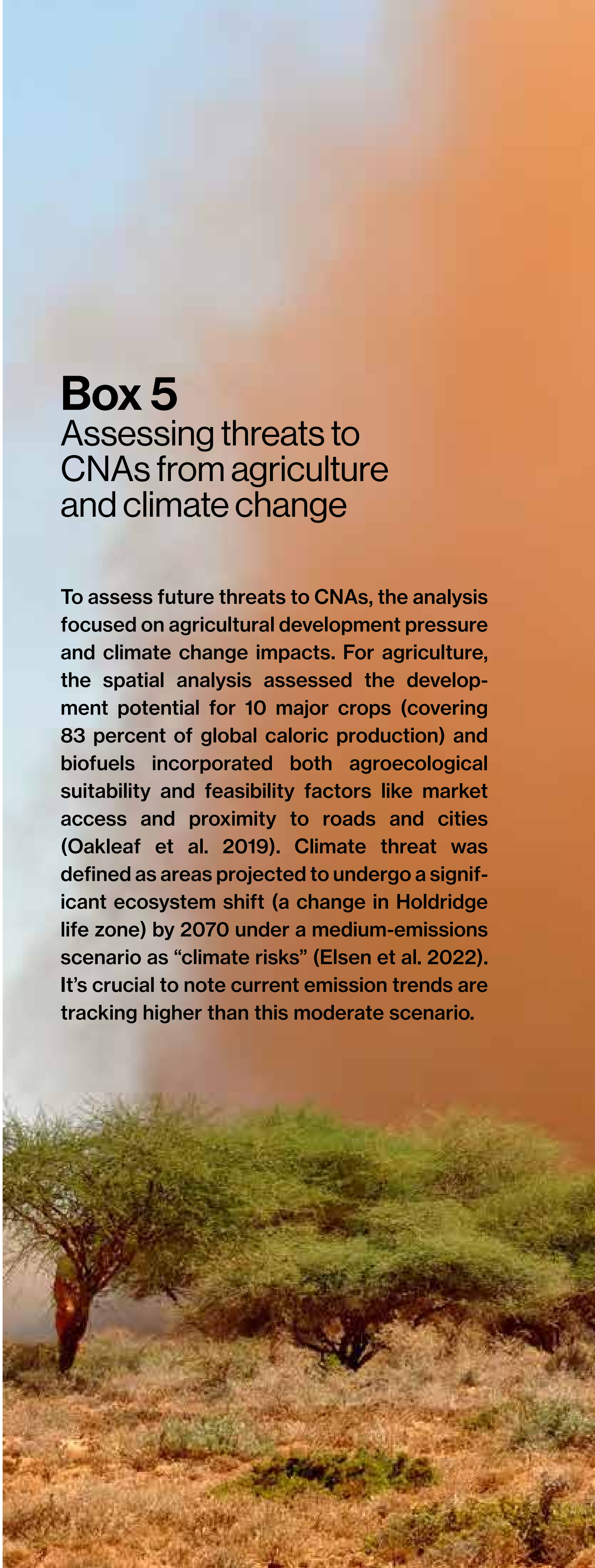
e) **Proactive management of threats:** Prevent degradation through timely conservation, which is more effective and less costly than restoration. Actively manage key threats (e.g., invasive species, altered fire regimes, illegal activities) where necessary to maintain integrity, even in stable areas.

f) **Build ecological redundancy:** Promote multiple similar functional habitats or populations across landscapes, providing insurance against localized disturbances and buffer NCP delivery.

g) **Secure effective and equitable governance:** Ensure long-term security of intact areas through effective and appropriate governance mechanisms (e.g., PAs, OECMs, recognized IPLC territories), respecting rights and ensuring equitable participation and benefit-sharing.

h) **Enhance climate resilience:** Conserve climate refugia within intact areas and manage them to bolster intrinsic resilience to climate impacts (e.g., drought, fire), facilitating adaptation.

i) **Implement monitoring and adaptive management:** Establish long-term monitoring of biodiversity, ecosystem function, and threats within intact areas to inform adaptive management strategies, ensuring continued effectiveness under changing conditions.



Box 5

Assessing threats to CNAs from agriculture and climate change

To assess future threats to CNAs, the analysis focused on agricultural development pressure and climate change impacts. For agriculture, the spatial analysis assessed the development potential for 10 major crops (covering 83 percent of global caloric production) and biofuels incorporated both agroecological suitability and feasibility factors like market access and proximity to roads and cities (Oakleaf et al. 2019). Climate threat was defined as areas projected to undergo a significant ecosystem shift (a change in Holdridge life zone) by 2070 under a medium-emissions scenario as “climate risks” (Elsen et al. 2022). It’s crucial to note current emission trends are tracking higher than this moderate scenario.

Conserving Stable CNA which remains largely intact aligns directly with global conservation commitments, particularly Target 3 of the Kunming-Montreal Global Biodiversity Framework. This target mandates nations to halt and reverse biodiversity loss, ensuring that by 2030 at least 30 percent of terrestrial areas are effectively conserved through ecologically representative, well-connected, and equitably governed systems. Achieving this goal relies on a combination of formally Protected Areas, recognized Indigenous territories, and OECMs – areas like certain watersheds or community forests managed for sustained biodiversity outcomes even outside formal protection. The vital role of lands governed by Indigenous Peoples and local communities (IPLCs) is increasingly recognized, as these areas often demonstrate high conservation effectiveness (UNEP-WCMC and IUCN 2024; Li et al. 2024; Balmford et al. 2019). While conserving these areas is the priority, substantial CNA areas have already been degraded and their restoration is discussed in the next section.

2.4 Restoring natural areas to support agriculture

Given significant global land degradation, ecological restoration of CNA already converted or degraded is critical for securing NCPs supporting agriculture. Land degradation negatively impacts the livelihoods of at least 3.2 billion people. It represents an economic loss of more than 10 percent of the annual global gross product due to disruption of biodiversity and ecosystem services. Up to 40 percent of the world's land area is degraded, with nearly 100 million hectares degrading further each year (UNCCD GLO2 2022). This includes at least 33 percent of global croplands (FAO 2021), which is a reflection of the drivers of biodiversity loss discussed in Chapter 3.

Ecosystem restoration supports the recovery of ecosystem services that support agriculture. **Agricultural restoration** rehabilitates degraded agricultural land back to improved agricultural land focusing for example on soil health; **ecosystem restoration** restore degraded agricultural land back toward natural or semi-natural habitat; while the **novel ecosystem restoration** aim to maximize ecosystem services from the land in its existing state recognizing that restoration back to its original state may not be possible.

This section primarily focuses on ecosystem restoration which are often former natural areas within or adjacent to agricultural landscapes, to restore ecosystem services critical for agriculture. This aligns with approaches like establishing hedgerows, riparian buffers, agroforestry systems, or restoring wetlands within the agricultural matrix (Edwards and Cerullo 2024; de la Riva et al. 2023; Mutillod et al. 2024). Agricultural restoration is discussed separately in chapter 4 along with other sustainable agricultural practices.

Restoring ecological function within and around agricultural landscapes directly enhances farm resilience and productivity while contributing to broader environmental goals (Edwards and Cerullo 2024; de la Riva et al. 2023). Integrating biodiversity through habitat restoration or diversification practices often improves agricultural outcomes by enhancing critical NCPs (e.g., pollination, pest control, water regulation). While converting productive land back to a natural habitat involves trade-offs due to lost production, the net effect on farm productivity, profitability, and resilience can be positive due to enhanced NCPs, reduced input costs, and diversified income, though outcomes are context specific.

Global analyses (Strassburg et al. 2020) highlights the potential impact of targeted restoration. Restoring just 15 percent of converted lands identified as priorities could avoid 60 percent of expected extinctions while sequestering 299 gigatons of CO_2. The analyses focused only on land converted to croplands and pastures because these lands were already altered, offering clear potential for recovering biodiversity and storing carbon. The analysis identified priority areas to avoid species extinctions and maximize carbon sequestration. It selected restoration of the most effective habitats for both biodiversity and carbon, which were primarily wetlands and tropical forests. Minimizing overall costs, including lost agricultural income and implementation expenses, was also a prioritization criterion. Biome-specific differences were considered to ensure restoration across multiple biomes. Since large areas of land have been cleared for agriculture or pasture and then abandoned, there are significant restoration opportunities, especially where contiguous with existing CNA. Figure 5 shows the results of the analysis of priority restoration areas. There are four billion hectares of CNA that are restoration priorities, as shown earlier in Table 3 and Figure 4.

CNAs that are restoration priorities and stable: These areas are degraded but face relatively low future threats from agricultural expansion or climate change. Restoration here represents a significant opportunity, focusing on enhancing NCPs crucial for both global benefits (if there are large contiguous areas) and adjacent agriculture (water regulation, soil health, pollination). Key measures include soil improvement, hydrological restoration, and integrating diverse native vegetation, including within agroecological systems aiming for substantial habitat integration (e.g., 20–25 percent) to rebuild natural assets.

CNAs that are restoration priorities and unstable: These degraded areas face high future threats from intensive agriculture or climate change, demanding urgent, climate-smart interventions. Restoration strategies must be adaptive, integrated with measures to mitigate pressures (e.g., secure tenure, OECMs), and focus on building climate resilience. While investment may be higher, the return includes avoiding significant future losses. These areas are likely to be fragmented and the benefits are likely to be greater if implemented at landscape scales.

The following illustrative principles guide efforts to ecosystem restoration to restore biodiversity, and the delivery of NCPs within and around agricultural landscapes.

a) **Prioritize functional biodiversity:** Restoration actively rebuilds essential NCPs (e.g., pollination, pest control, water regulation, soil health). Integrating diverse, appropriate (often native) species and habitat structures (like hedgerows, buffer strips, agroforestry elements) directly into the agricultural matrix will enhance overall farm system resilience and productivity.

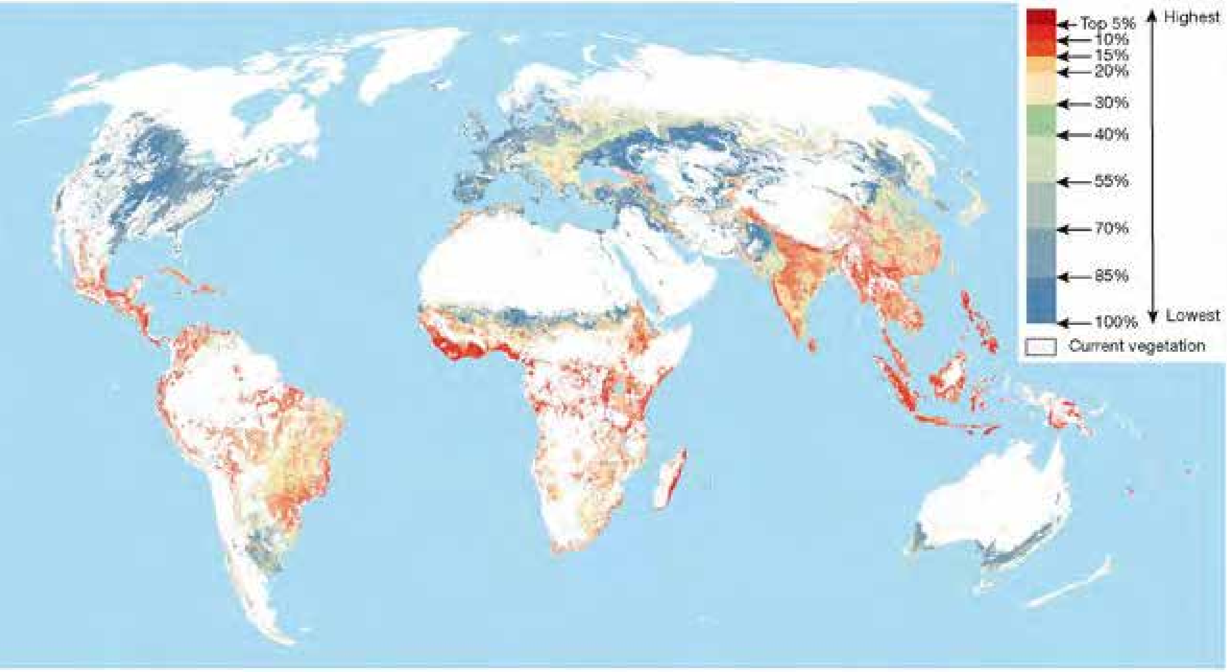
b) **Adopt a landscape-scale, targeted approach:** Effective restoration requires planning and action at the landscape level, not just site-by-site. This involves prioritizing areas such as degraded riparian zones, marginal lands, connectivity bottlenecks and considering the spatial arrangement of different land uses and habitats to get the most benefits from restoration to NCPs and agriculture.

c) **Build climate resilience:** Restoration must anticipate and adapt to climate change by selecting climate-appropriate species and methods, protecting potential climate refugia within agricultural landscapes, enhancing connectivity to allow for range shifts (change in species distribution in response to environmental changes), and designing restored agroecosystems to better withstand climate stressors like drought or extreme weather.

d) **Ensure equitable governance and Participation:** Restoration within agriculture directly affects livelihoods, so must meaningfully involve land managers, Indigenous Peoples, and local communities in site selection and management. Efforts must respect land tenure and rights, incorporate local and traditional knowledge, and strive for equitable sharing of costs, benefits, and decision-making power.

International frameworks recognize the urgency of addressing land degradation. The United Nations Convention to Combat Desertification (UNCCD), alongside the Conventions on Biological Diversity (CBD) and Climate Change (UNFCCC), forms a cornerstone of global environmental governance. Many countries have committed to achieving Land Degradation Neutrality (LDN) targets under the UNCCD, aiming to balance anticipated land degradation with land restoration efforts. These commitments provide a policy framework encouraging nations to prioritize and invest in restoring degraded lands, including CNA critical for agriculture and water security, thereby contributing to national development goals and global sustainability targets.

Figure 5. Global priority areas for ecosystem restoration (Strassburg et al. 2020)



2.5 Enhancing connectivity to support agriculture

Connectivity is crucial maintaining the flow of NCP across landscapes. Linking habitats allows species movement, gene flow, and movement to adapt to changing conditions like climate change. This functional connectivity maintains large-scale ecological processes vital for agriculture. Without connectivity, even conserved or restored patches become isolated islands, diminishing their long-term value and resilience.

Maintaining or restoring sufficient natural habitat within agricultural landscapes is critical for establishing connectivity between conserved natural areas and agricultural areas and for the provision of NCPs to farms. A minimum threshold of 20–25 percent semi-natural or natural habitat cover per square kilometer is necessary in human-modified landscapes, including agricultural areas (Mohamed et al. 2024). This level maintains key regulation NCPs such as pollination, pest and disease control, water quality regulation, and soil erosion control. Below this threshold, NCP provision declines significantly, nearly disappearing below 10 percent habitat cover (Mohamed et al. 2024). A global target of restoring and retaining at least 20 percent natural habitat within heavily converted working landscapes (>80 percent conversion) benefits food security, NCP delivery, and links protected areas (Garibaldi et al. 2021).

Achieving connectivity involves integrating habitat features like hedgerows, field margin buffers, and riparian strips within the existing agricultural matrix. Investments in such restoration and sustainable land management can yield substantial economic benefits, up to 30 US dollars for every US dollar invested (UNEP 2021). Connectivity needs vary; pollinators may use small habitat patches and hedgerows, while larger ecosystem engineers (species significantly shaping their environment, like large herbivores influencing vegetation or predators controlling prey populations) require larger corridors to maintain broad ecological functions benefiting agriculture.

Connecting restoration priorities enhances restoration success and can lower costs. Degraded landscapes identified as restoration priorities are often fragmented. Strategies to connect isolated habitat patches include restoring riparian corridors, establishing ecological corridors, creating stepping-stone habitats, and improving crop diversity. Importantly, connectivity can facilitate natural regeneration, especially using existing remnants as seed sources. This offers significant potential for large-scale, cost-effective recovery and carbon benefits, particularly in the tropics (Williams et al. 2024). Protecting and restoring riparian networks is also crucial for linking habitats across landscapes.

This chapter explored how conversion of natural areas for agriculture has driven biodiversity loss, how spatial analysis can inform conservation, restoration and connectivity solutions to mitigate or reverse losses. Chapter 3 now turns to agricultural areas and how unsustainable practices have driven biodiversity loss and the consequences for ecosystem services supporting agriculture.

Chapter 3.

Unsustainable agriculture drives loss of biodiversity needed to support agriculture

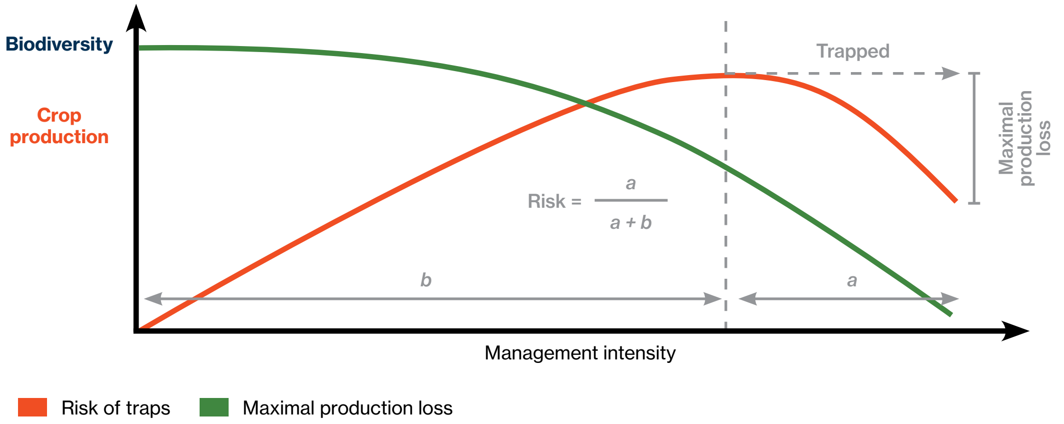
Intensive and extensive agricultural systems are driving biodiversity loss through intensification and extensification “traps.”

3.1 Intensification and extensification traps

"Intensification traps" happen when unsustainable intensification practices initially boost yields but then cause nature loss, both directly and indirectly, resulting in lower agricultural productivity and resilience, higher use of inputs, and systems become stuck in a counterproductive cycle (Burian et al. 2024; Kremen et al. 2024). These traps have a non-linear response to inputs as shown in Figure 6. Yield improvements plateau or decline past critical thresholds as biodiversity-mediated benefits collapse, particularly in systems that rely on intact ecological processes, such as pollinators, healthy soils, and pest predation (Hald-Mortensen 2023; Butt et al. 2023; Boakes et al. 2024). When these are destroyed, yields decline so substitutes for NCPs (e.g., pesticides, fertilizers, and manual pollination) are used, but they are costly and worsen inequities and sustainability (Hald-Mortensen 2023).

Indirect feedback loops, such as reduced rainfall, higher temperatures from deforestation, and increased GHG emissions, further entrench these traps (Butt et al. 2023; Boakes et al. 2024). The use of inputs to intensify continues to disrupt biodiversity that disrupts yield-enhancing processes and further undermines regulating NCPs, creating a "double loss" of biodiversity and yield despite escalating inputs (Burian et al. 2024; Kremen et al. 2024). Simulations suggest that all high-intensity systems risk entering such traps as agricultural damage to biodiversity cascades into broader declines in ecosystem functions critical to productivity (Burian et al. 2024; Kremen et al. 2024).

Figure 6. Intensification traps in agricultural landscapes



Source: Burian et al., 2024

"Extensification traps" are most common on grazing land when there is declining productivity and negative environmental impacts. As farmers expand into marginal lands to increase production, they often encounter lower yields and higher costs, creating a cycle of dependency on further land expansion rather than improving existing agricultural practices. Yet much of this land is marginal, so after crop yields decline it is used as rangeland for grazing livestock. Globally, up to half of rangelands are degraded, posing a severe threat to food security and the well-being of billions of people (about 20 percent of the world's population) who depend on these ecosystems for their livelihoods (UNCCD 2024). As these low-input, extensive systems become less productive and degrade, they face increased vulnerability to natural hazards (floods, drought, fire) linked to increasing climate change impacts.

3.1.1 How "traps" affect biodiversity and NCPs

The following section summarizes how biodiversity and ecosystem services are progressively impaired as ecosystems erode under both intensive high-input agricultural regimes and extensive systems. The section focuses on regulating NCPs, also including genetic diversity given its importance to agriculture. Summarized information and examples for both intensification and extensification traps are shown in Table 5.

Forming, protecting, and decontaminating soils and sediments: Unsustainable agricultural intensification has reduced soil organic carbon by 50–70 percent compared to natural conditions, with degraded soils showing 15–30 percent lower yields. At the field scale, reduced soil biodiversity leads to decreased nutrient cycling, poor soil structure, and increased vulnerability to erosion. At landscape scales, these effects manifest as reduced water retention capacity, increased flooding risk, and decreased resilience to climate extremes. Global soil degradation costs reach 6.3–10.6 trillion annually, representing 10–17 percent of global GDP (Brauman et al. 2020) related to local-scale ecological impacts. Excessive nitrogen inputs alter microbial communities and reduce long-term soil fertility (Hald-Mortensen 2023).

Freshwater flow, quality, and quantity: Natural habitat loss reduces water flow, quantity, and quality and it has increased flood frequency (20–90 percent) while reducing water availability (WMO 2023). Agricultural losses from water-related events have increased 65 percent over 50 years, exceeding $300 billion annually (FAO 2024). Climate change is amplifying these impacts, making natural water regulation increasingly important for agricultural resilience. Regions with intact ecosystems show significantly better agricultural performance during extreme weather events.

Pollination and seed dispersal: Wild pollinator declines of 30–50 percent in diversity and abundance, particularly severe in intensively farmed landscapes, threaten agricultural productivity (Dicks et al. 2021). Pollination services are valued between $235–577 billion annually (IPBES 2019). Yields, fruit set (transition from flower to young fruit), and quality are typically 50 percent lower without diverse wild pollinator communities (Reilly et al. 2024). Substituting manual pollination or relying solely on managed honeybees is neither feasible at large scales nor economically viable. Vulnerability concentrates in regions with high pollinator-dependent crop production and reduced natural habitat (Aizen et al. 2019) with disproportionate nutritional impacts on populations dependent on pollinator-mediated crops for micronutrients (Chaplin-Kramer et al. 2014; Murphy et al., 2022).

Pest and disease control: The potential for pest control, indicated by the diversity and abundance of pest enemies, is uniformly worsening across agricultural landscapes. While pest-driven damage shows relatively stable patterns, vector-borne disease incidence is worsening, with regional differences in health impacts (FAO 2021; Zeische et al. 2023). Clearing forests can increase soil pathogen abundance (Qu et al. 2024), creating cascading effects through agricultural systems. Economic costs related to pest-driven damage are uniformly worsening (estimated at over $423 billion in 2019), particularly affecting regions with simplified agricultural landscapes and reduced natural habitat corridors (Sanchez et al. 2022; Ma et al. 2025). Intensification involves greater pesticide use, which alters pest control regimes, harm soil microbiota, and more than 10 percent of net annual-applied pesticides stay in soil, seven percent leach to aquifers, and others enter the food chain (Brunelle 2024). Agricultural drivers have been linked to approximately 50 percent of zoonotic emerging infectious diseases since 1940 (Rohr et al. 2019). Some examples of the impact of land use change and agricultural practices on biodiversity and disease regulation are shown in Box 6.

Hazards and extreme events: Extreme weather events are increasing and drive hunger, food insecurity, and malnutrition in all its forms. Natural vegetation loss and land conversion for agriculture have significantly increased agriculture's vulnerability to hazards and extreme weather events, with an estimated loss of $3.8 trillion worth of crops and livestock production over the past three decades (FAO 2023). Agricultural systems in regions with degraded natural habitats are particularly susceptible to extreme events. Removing natural buffers, such as forests and wetlands, seriously reduces nature's ability to mitigate floods, droughts, and storms. Intact habitats near farms can buffer many elements of weather events. Climate change is intensifying the frequency and severity of extreme events (WMO 2024).

Climate regulation: Agricultural intensification has reduced carbon storage capacity by 25–50 percent in many regions. Climate-related agricultural losses have increased 150 percent since 1980, exceeding $100 billion annually. Agricultural intensification has severely disrupted natural climate regulation both globally and at the local scale. Agriculture has significantly contributed to rising GHG emissions (Sutton, Lotsch & Prasann 2024; FAO 2021). Diverse agricultural landscapes show 20–40 percent better yield stability during extreme weather events (Renard et al. 2023, Estrada Carmona 2022). These patterns demonstrate critical thresholds in ecosystem functioning, where loss of natural vegetation can trigger abrupt changes in local climate regulation services.

Interdependent impacts and tipping points

There is a "polycrisis" underway that spans multiple development challenges, all of which are closely linked to biodiversity and ecosystem loss. These include reduced freshwater availability and quality, declining agricultural yields, increasing land degradation, intensifying climate change impacts, and rising extreme natural hazards (IPBES 2019; IPCC 2023). These interconnected issues worsen public health risks and undermine global food security.

These crises are deeply interconnected, with negative feedback loops at multiple scales, from local to global. Biodiversity loss, land degradation, and climate change are mutually reinforcing, creating cascading effects that destabilize ecosystems and agricultural systems alike (Chaplin-Kramer et al. 2021). Pollinator declines may become abrupt and irreversible if critical thresholds are

Table 5. Examples of agriculture’s impact on regulating NCPs: magnitude, impact, intensive replacement, and i

	Magnitude	Agricultural impact
1. Forming, protecting, and decontaminating soils and sediments* (UNCCD GLO2 2022; Guerra et al. 2022; Fonte et al. 2023)	About 3.3 billion hectares globally are degraded and the amount is increasing yearly. The distribution by region is estimated at 1.4 billion ha in Asia, 1.0 billion ha in Africa, 0.4 billion ha in Latin America and the Caribbean, 0.35 billion ha in Europe and 0.25 billion ha in North America , with smaller areas in Oceania.	Soil biodiversity loss reduces nutrient cycling and organic matter decomposition, leading to less fertile soil, more erosion, degraded soil structure, fewer nutrients, and less nitrogen and phosphorus resulting in lower crop yields. Soils retain less water, increasing drought vulnerability.
2. Fresh water flow, quality, and quantity (FAO 2024; WMO 2023; Meli et al. 2024; Martínez García et al. 2022)	Globally, 40 percent of irrigated croplands already face water stress due to ecosystem decline.	Degraded ecosystems disrupt water flow, filtering, and retention. Water scarcity, salinization, and pollution reduce irrigation reliability, lowering crop productivity and quality. Poor water quality (e.g., salinization, agrochemical runoff) reduces crop yields.
3. Pollination and seed dispersal (IPBES 2019; Aizen et al. 2019; Dainese et al. 2019; Reilly et al. 2024)	Pollinator decline threatens 75 percent of crops that depend on animal pollination; wild pollinator populations declining by over 40 percent in the past decade.	Reduced pollination efficiency lowers yields of fruits, vegetables, oilseeds and nuts by up to 30 percent. Seed dispersal loss further disrupts ecosystem regeneration, weakening agroecosystem stability.
4. Pest and disease control (FAO 2023; Keesing and Ostfeld 2024; Bernis Fonteneau et al. 2024)	Between 20 percent to 40 percent of global crop production is lost to pests annually, with annual global plant diseases costing about $220 billion and invasive insects around $70 billion. Less diverse habitats reduce natural pest regulation (predatory insects, birds, and soil microbes) by 30 percent in many regions.	Fewer natural predators increase pest outbreaks and pathogens, lower crop resilience and increase crop losses (up to 20 percent in some regions); increased pesticide use raises costs and harms beneficial species.
5. Hazards and extreme events (UNCCD GLO2 2022; IPBES 2022; Dobhal et al. 2024; Li et al. 2024)	Up to 40 percent in natural flood control and drought-mitigation capacity in crucial agricultural landscapes.	increases frequency and severity of floods, droughts, heat and storm events, damaging crops, faster soil erosion, and higher post-event recovery costs; higher vulnerability leads to higher yield instability.
6. Climate regulation: Global and local scale (IPCC AR6 WGII 2022; Duku and Hein 2023; Weiskopf et al. 2024)	Lower carbon sequestration from degraded ecosystems accelerates climate change, with 7–10 percent lower crop yields per 1°C of warming. Fewer trees increase heat stress: coffee and cocoa drop by 20–30 percent. Less microclimate regulation. Global heat increases and water regulation decreases, affecting weather.	Heat stress, erratic rainfall, and temperature extremes reduce yields; long-term warming threatens crop viability. Heatwaves disrupt planting cycles, while soil carbon loss reduces nutrient availability. Planting schedules become less predictable.

ntensification and extensification traps

Intensification replacement	Intensification trap	Extensification trap
Greater reliance on synthetic fertilizers (costly, energy-intensive); soil amendments (e.g., compost) to rebuild fertility. Machinery causes soil compaction so less healthy soils.	Need for ever-increasing fertilizer use harms soil biodiversity, with higher input costs and risk of soil acidification and worsening soil health. Nutrient leaching and agrochemical runoff degrade downstream ecosystems.	Lower productivity on marginal lands and poor soils leads to cycle of land conversion; increased erosion, with leads to sedimentation in water, affecting flow, quality, and affecting freshwater biodiversity.
Energy-intensive water extraction (e.g., groundwater pumping); constructed wetlands or filtration systems (high cost). Depleting aquifers and raising production costs. Chemical additives to improve quality.	Unsustainable practices in agriculture are pervasive; increasing scarcity; nutrient and sediment loadings from farmlands contribute to degraded water quality in over 40 percent of monitored river systems globally.	Expanding farmland into natural areas increases water consumption and disrupts ecological water flows; deforestation leads to local water regime change, increasing droughts.
Artificial pollination (labor-intensive) or managed honeybees; genetic engineering of self-pollinating crop habitat restoration for pollinators.	Commercial pollinators in some areastransfer diseases or compete with wild pollinators; high labor cost if people pollinate; cycle of escalating input costs and declining ecological function.	Lower crop density reduces pollinator abundance, affecting crop yield. If habitat clearing is extensive, fewer seeds and dispersers, so less diversity in regrowth, leading to simplification and reduced NCPs.
Synthetic pesticides cause environmental harm and occasional biological agents can have unanticipated effects; integrated pest management (IPM) requires labor and monitoring.	Less crop diversity increases plant disease risk; pesticide use suppresses target pests, diminishing beneficial organisms; this accelerates pest resistance and undermines natural biological control; pesticides harm soil organisms; cycle of escalating pest pressures as pests evolve and input volumes rise.	Expanding into natural habitats can increase human-wildlife conflict and increase risk for zoonotic disease transmission from wild animals to livestock – or vice versa, harming wildlife.
Engineered solutions (e.g., levees, terracing) are expensive to build and maintain; irrigation systems.	Loss of natural buffers like wetlands exacerbate climate vulnerability to floods, droughts, and soil erosion. Replacing natural buffers with infrastructure is costly, and in turn erodes remaining habitat complexity, creating negative feedback loops.	Simpler and less healthy ecosystems are less able to regulate extreme events. Farming on marginal or steep lands increases disaster vulnerability, lower capacity to recover from losses, so new clearing.
Artificial climate control (e.g., greenhouses, energy-intensive irrigation); and longer-term, reforestation and agroforestry that partially restore climate regulation functions but rarely match the capacity of intact natural ecosystems.	Less productivity and increasing reliance on synthetic inputs such as fertilizer use that contributes to nitrous oxide emissions, a potent GHG.	Land use change (e.g., deforestation) and habitat loss, releasing stored carbon in biomass and soils; soils degrade and are less able to sequester carbon.

Box 6

Examples of impact of agricultural-driven land use change and intensification on disease regulation

South Asian vultures and diclofenac: In Southeast Asia, significant declines in Gyps vulture populations resulted from vultures feeding on cattle carcasses that had been treated with the anti-inflammatory drug diclofenac (Swan et al. 2006). From a population previously in the tens of millions, a >90 percent reduction was seen in some species since the 1990s. Consequently, millions of tons of carcass were left uneaten every year, creating a breeding ground for infectious disease, encouraging rodents and causing an increase in the feral dog population, with human deaths rising by four percent (or 100,000 people per year) in districts where birds once thrived, costing the economy $69 billion per year. One study estimated that the feral dog population increased by five million resulting in 38 million additional dog bites and 47,000 extra deaths from rabies costing $34 billion (Burfield and Bowden 2022).

Nipah virus in Malaysia: Change in forest ecosystem due to deforestation and wildfires in Malaysia reduced resource availability for bats, likely resulting in bats seeking out food in artificial environments. Large-scale pig farming was taking place in areas around fruit orchards with limited biosecurity. Partially eaten fruit contaminated by flying fox bats (the reservoir for Nipah virus) entered pig sties, resulting in transmission of Nipah virus to pigs, and then onward from pigs to farmers (Eco Health Alliance 2024)

Poultry production and avian influenza around wetlands: The rapid expansion and intensification of poultry production, often in the absence of adequate biosecurity, has led to the mixing of wild and domestic poultry, resulting in reassortment of avian influenza viruses and in some cases leading to the development of highly pathogenic strains of avian influenza – presenting risks to humans, domestic poultry, and wild bird populations (Eco Health Alliance 2024).

crossed, threatening agricultural yields and food security (Comford et al. 2023). Global trade further amplify these risks by spreading the impacts of local environmental degradation to distant regions (Eberle et al. 2023).

Climate change is a potent risk multiplier that exacerbates these crises. It amplifies biodiversity loss, land degradation, and food insecurity through rising temperatures, shifting rainfall patterns, and extreme weather events (IPCC 2023). Droughts, which account for 65 percent of agricultural disaster losses, are projected to intensify, particularly in vulnerable regions like the Mediterranean and Central Asia, further destabilizing food systems (IPBES 2024). Rising temperatures are expanding pest habitats and threatening staple crops, while rainfall disruptions make it harder for farmers to plan planting and harvesting cycles (IPCC 2023). Climate change impacts are likely to exceed 2°C, triggering stronger climate extremes.

Urgency is essential because many systems are nearing or have already passed tipping points. Tipping points represent critical thresholds where ecological or climatic changes become irreversible, leading to cascading impacts across systems (IPCC 2023). For example, the Amazon rainforest is at risk of shifting from forest to savanna, which would result in catastrophic biodiversity loss and disrupt regional and global climate regulation (IPCC 2023). These irreversible changes happen once thresholds are reached, with consequences across ecological, human, and economic systems. For instance, key pollinator declines would result in steep declines in crop yields, threatening food security (IPBES 2024). Acting now is critical to avoiding irreversible damage and building resilience across systems.

3.1.2 Land sparing or land sharing

How to reconcile agriculture and ecological integrity has led to a debate over land use strategies: land sparing (intensifying yields on minimal land to spare natural habitats) versus land sharing (integrating biodiversity conservation within agricultural landscapes). Land sparing offers superior biodiversity outcomes by preserving large, intact habitats, benefiting specialized species and enhancing biodiversity and functional diversity, when significant portions of land are set aside (Zingg et al. 2024; Palmer 2025). Land sharing supports on-farm biodiversity by maintaining ecological connectivity and integrating wildlife-friendly practices, yet achieves lower biodiversity conservation outcomes, particularly for species that rely on undisturbed habitats (Estrada-Carmona et al. 2022; Cannon et al., 2019). Land sharing can contribute to ecosystem services such as pollination, pest control, and soil health, which benefit both biodiversity and agricultural productivity (Kamau et al. 2023).

Neither land sparing nor land sharing alone fully resolves the tension between biodiversity conservation and agricultural productivity. While land sparing can support biodiversity through habitat preservation, it risks neglecting biodiversity within agricultural systems (Estrada-Carmona et al. 2022). As Kremen (2015) suggests, “the dichotomy of the land-sparing/land-sharing framework limits the realm of future possibilities to two, largely undesirable, options for conservation.” A consensus is emerging on the need for context-specific, integrated strategies that combine elements of both land sparing and land sharing to balance conservation and food security effectively. They work synergistically and are not mutually exclusive. More specifically, the most promising options are keeping large habitat blocks surrounded by diversified farming systems (Kremen & Geladi 2024).

Integrating 20 to 25 percent of natural or semi-natural area to maintain biodiversity and sustain ecosystem services is critical to ensuring agricultural systems function under current environmental pressures (Mohamed et al. 2024). **However, 18 to 33 percent of agricultural lands globally lack the semi-natural habitat per km² needed to support pollination, pest control, climate regulation, prevent soil erosion, and reduce nutrient loss and water contamination** (DeClerck et al. 2023). Semi-natural features, such as hedgerows, wetlands, and natural buffers, reduce the impacts of agricultural intensification that drives biodiversity loss through land conversion and monoculture (Wang & Pfister 2024; Scheper et al. 2023). Habitat heterogeneity is linked to higher species richness and greater ecosystem resilience (Maskell et al. 2023; Estrada-Carmona et al. 2022). Increasing landscape complexity enhances the overall functionality of agricultural ecosystems (Frank et al. 2024; Vandendriessche et al. 2024). Retaining at least 10 percent of semi-natural habitat enhances pest control by acting as reservoirs for beneficial species (Guo et al. 2022; Mazón et al. 2024). Mixed cultivation systems near semi-natural areas improve wild pollinator diversity (Shi et al. 2023). Semi-natural habitats also support natural enemies of pests, strengthening biocontrol and making them critical to sustainable farming systems (Luliano et al. 2024).

Sustainable intensification, which combines yield improvements with minimized environmental impacts, has been proposed as a hybrid approach to reconcile trade-offs between land sparing and land sharing (Kamau et al. 2023). Land sparing relies on agricultural intensification to increase yields on existing farmland, which could free land for conservation. However, this approach risks rebound effects (discussed below), where higher efficiency drives further agricultural expansion, especially in middle-income countries (García et al. 2020; Tscharntke et al. 2024). Land sharing sacrifices yield potential by prioritizing wildlife-friendly farming, making it less productive in many contexts (Saydeh & Bissonnette 2023). Extensification often degrades habitats and threatens NCPs.

Rebound effects

The risks of rebound effects from intensification mean that complementary regulation and incentives to mitigate land use change caused by rebound effects are needed. When more efficient use of a resource results in its increased use, this is known as a rebound effect. In the case of intensification, savings from more efficient land use can incentivize producers to convert more land to agriculture, moderating the land sparing effect of intensification, also known as “imperfect” land sparing. When rebound effects are so extreme that intensification results in more land use change this is a case of Jevons Paradox. In contrast, the Borlaug effect describes how more efficient land use will result in reduced conversion of land for agriculture or “perfect” land sparing. (Balmford 2021).

Rebound effects are greatest when consumers are most responsive to prices (price elastic demand) and intensification results in lower product prices, when intensification is labor or capital saving, and for intensification of products well connected to global markets. Rebound effects are greatest for price-elastic products such as beef, biofuels, coffee or cocoa, and least for price-inelastic products such as cassava or other staples. Large-scale analyses investigating trends in yields and forest area changes suggest that land sparing from intensification happens but is patchy and vulnerable to rebound effects (Balmford 2021). Annex 1 provides a more detailed discussion on influences on rebound effects.

3.2 Unsustainable agricultural practices driving biodiversity loss

Unsustainable practices alter ecosystem conditions driving changes in biodiversity and reducing the ecosystem services that support agriculture. These practices impact biodiversity through multiple pathways. Figure 7 provides a generalized summary of the pathways through which agricultural practices affect biodiversity and ecosystem services. This is a simplified illustration and there is significant variation in these pathways depending on the drivers involved, with multiple feedback loops amplifying the effects.

Ecosystem conditions altered by unsustainable practices often result in more homogeneous communities composed of fewer beneficial species. For example, waterlogging reduces soil oxygen levels, impairing the survival of aerobic soil organisms while favoring anaerobic species. This shift in soil biodiversity disrupts nutrient cycling, increases GHG emissions, and reduces agricultural productivity, demonstrating how alterations to ecosystems can cascade through biodiversity and ecosystem functions. Homogenization of species also weakens ecosystem resilience to environmental shocks.

Unsustainable agricultural practices (other than land use change discussed in chapter 2) driving biodiversity loss can be broadly grouped into four categories: Land and soil management; agricultural water management; crop nutrition, crop protection and livestock waste management; and genetic diversity in crops and livestock. This section describes the global extent of these practices, pathways through which they impact biodiversity, and subsequent impacts on ecosystem services that support agriculture.

3.2.1. Land and soil management

Modern agricultural practices such as monocropping, conventional tillage, and overgrazing come at a significant cost to biodiversity and ecosystem health. These practices destabilize ecological balances, reduce the diversity of plants, animals, and soil organisms, and weaken the ecosystem services that agriculture depends on.

Monocropping

Monocropping undermines biodiversity and ecosystem resilience by reducing genetic diversity, which increases vulnerability to environmental stressors such as drought, pests, and disease resulting in greater reliance on synthetic inputs to maintain yields. Monocropping dominates global food production and calorie supply. Monocropping offers short-term economic advantages, including streamlined cultivation, fertilization, agrochemical application, and harvesting but comes with significant costs to biodiversity. At the soil level, monocropping homogenizes microbial communities impairing nutrient cycling and disease suppression and deselects beneficial organisms like nitrogen-fixing bacteria while allowing pathogenic species to thrive. Beyond soil impacts, monocropping

Figure 7. Pathways to impact on biodiversity and ecosystem services

1 **Change in ecosystem state**

- Bio-physical and chemical composition of soils
- Chemical composition, thermal state
- Hydrological flows (level, consistency, seasonality)
- Sediment flows
- Pollutant flows

2 **Pathways to impact on biodiversity**

- Selective pressure
- Plant/animal physiology and susceptibility to stressors
- Changes in connectivity affects breeding, feeding, migration, pollination and flowering
- Changes in refuges, predation threat, symbiotic relationships

3 **Impact on biodiversity**

- Loss of genetic material/species
- Change in composition of genetic material/ species
- Homogenization and reduced specialization of species
- Invasion by species
- Changes in habitat composition, predator-prey relations

4 **Pathway to impact on ecosystem services**

- Nutrient cycle
- Water cycle
- Climate cycle
- Energy flows

5 **Impact on ecosystem services**

- Air, soil, water regulation
- Habitat maintenance
- Climate regulation, resilience to hazads
- Pollination, pest and disease regulation

Unsustainable agricultural practices cause changes in the state of the ecosystem such as aerobic conditions in soil or river flows.

These conditions can affect species physiology and feeding habitats for example, creating selective pressure.

Changes the composition of species often results in less diverse communities and fewer beneficial species.

As species composition changes, so does their function in nutrient cycles, water and climate cycles.

This in turn affects ecosystem services such as soil formation and climate regulation that support agriculture.

reduces structural complexity in landscapes, limiting habitat for fauna such as small mammals and arthropods, which are vital for food web stability and pest regulation. Habitat homogenization also disrupts water regulation, nutrient recycling, and pollination, further diminishing ecosystem services essential for sustainable agriculture (Sanchez 2022; Priyadarshana et al. 2024).

Conventional tillage (plowing)

Conventional tillage damages soil ecosystems, undermines fertility, and disrupts ecosystem services such as water regulation, pest control, and carbon sequestration. This practice, which remains dominant globally, especially in parts of Africa, accelerates soil erosion, with sediment loss rates averaging 9.5 ± 1.2 megagrams/hectare/year (Novara et al. 2019). It reduces soil biodiversity by disturbing habitats, exposing soil organisms to predation, and compacting soil, which limits the mobility of both macrofauna like earthworms and beetles and microfauna such as nematodes (Briones and Schmidt 2017). Beneficial organisms, such as arbuscular mycorrhizal fungi critical for nutrient uptake and soil structure are fragmented allowing harmful organisms to proliferate (Roger-Estrade et al. 2010). Pest regulation declines as the balance between beneficial and parasitic nematodes shifts in favor of plant-parasitic species (van Capelle et al. 2012). Conventional tillage contributes significantly to soil carbon loss, with annual emissions estimated at 10.3 to 15.2 teragrams of carbon (Yu et al. 2020).

Overgrazing

Overgrazing reduces plant diversity, diminishes ecosystem services, and drives long-term degradation of both aboveground and belowground biomass. By defoliating plants and altering root systems, overgrazing weakens plant competitiveness, reduces species diversity, and promotes invasive species and weeds. Reduced vegetation cover and litter accumulation accelerate soil degradation by depleting organic carbon, nitrogen, and phosphorus stores. Belowground biomass declines as plants allocate resources to shoot recovery, altering root morphology and impairing water and nutrient uptake (Guo et al. 2012; Li et al. 2021). This disrupts soil microbial communities and weakens nutrient cycling, creating a feedback loop were declining root biomass further limits plant growth, exacerbating ecosystem degradation. Bird species like grouse, which depend on native vegetation, are particularly vulnerable (Ajayi et al. 2023; Guido & Pillar 2017). Similarly, butterfly species reliant on low-intensity grasslands decline due to habitat homogenization. Larger, generalist species dominate these degraded environments, further reducing biodiversity and weakening pollination services. Overgrazing impacts aquatic ecosystems through soil compaction, increased runoff, and nutrient loading from manure causing eutrophication. Burning grasslands fragments habitats and causing local extinctions.

3.2.2. Agricultural water management

There are four critical aspects of agricultural water management that drive biodiversity loss and disrupt ecosystems: over-abstraction, irrigation management, converting and draining wetlands, and constructing dams and reservoirs. Over-abstraction of surface and groundwater destabilizes water cycles, depletes resources, and threatens ecosystems. Inefficient irrigation practices lead to waterlogging, salinization, and soil degradation, further harming biodiversity. Converting and draining wetlands destroys vital habitats and eliminates the ecosystem services they provide, including flood regulation and carbon storage. Constructing dams and reservoirs fragments aquatic habitats, alters natural water flows, and reduces connectivity in river systems, leading to widespread ecological consequences.

Over abstraction of water

Human-induced disturbances to both blue water (surface and groundwater) and green water (soil moisture in the root zone) have exceeded safe planetary limits, threatening terrestrial and aquatic ecosystem health. Excessive abstraction of blue water for irrigation, combined with mismanagement of green water, has degraded ecosystems globally, disrupting water cycles, reducing climate resilience, and intensifying water stress in vulnerable regions, posing significant risks to long-term environmental and agricultural sustainability (Planetary Health Check 2024).

Irrigation is the primary driver of global freshwater use, representing approximately 70 percent of total withdrawals and 85–90 percent of consumptive water use (water not returned to its source). Global freshwater withdrawals increased from 500 billion m^3 in 1990 to nearly 3.9 trillion m^3 by 2017 (Ingrao et al. 2023). Half of irrigation water use is unsustainable, particularly in regions like the Indo-Gangetic Basin and North China Plain, where blue water abstraction has degraded local and downstream water flows. In India, free energy incentives encourage groundwater overexploitation for irrigation, further depleting aquifers (Sidhu et al. 2020).

Groundwater is heavily overexploited, with 15–20 percent of watersheds experiencing flows below sustainable levels (de Graaf et al. 2019). If current trends persist, up to 80 percent of watersheds could fail to meet environmental flow requirements, threatening aquatic biodiversity and ecosystem services. Groundwater-dependent ecosystems cover over a third of global drylands and include biodiversity hotspots with more than half located in regions with declining groundwater levels (Rohde et al. 2022).

Livestock production exacerbates over abstraction, primarily through cultivating water-intensive feed crops, which account for 41 percent of agricultural water use (Heinke et al. 2020). Producing animal-based calories requires significantly more water than plant-based food (Mekonnen & Hoekstra 2010). Regions such as northern India and the central United States face severe water stress due to livestock-related demands.

Irrigation management

Irrigation management practices drive biodiversity loss through poor scheduling and the use of low-quality irrigation water. Poor water distribution practices exacerbate over-abstraction. The use of brackish or wastewater for irrigation introduces harmful salts and contaminants into soils and water systems, causing widespread ecological harm. These mismanagement practices are particularly detrimental in regions heavily reliant on irrigation, where water stress and biodiversity loss are closely linked.

Waterlogging, a common consequence of flood irrigation and poor scheduling, disrupts soil ecosystems and alters plant physiology, reducing biodiversity and ecosystem services. Anoxic soil conditions impair photosynthesis, root development, and plant morphology while altering soil microbial communities. Beneficial aerobic organisms, such as nitrifiers, earthworms, and nematodes, decline in waterlogged conditions, while denitrifying and methanogen bacteria increase, contributing to higher methane and nitrous oxide emissions (Singh 2015; Li et al. 2021). These shifts impair nutrient cycling, nitrogen fixation, and cause temporary toxicity from elements like iron and magnesium.

Salinization often occurs along with waterlogging, and it exacerbates soil degradation. It affects approximately 11 percent of global irrigated land (77 percent of which is in Asia), reducing soil biodiversity and agricultural productivity (FAO 2021a). Salinity induces osmotic stress and ion toxicity, harming nitrogen-fixing microbes and increasing the solubility of heavy metals, which disrupts soil ecosystems (Zhang et al. 2019; Haj-Amor et al. 2022). The increasing use of low-quality water, such as saline water or untreated wastewater, worsens these impacts, particularly in arid regions where farmers have limited alternatives.

Converting and draining wetlands

Wetland loss has been extensive, with natural wetlands declining by 35 percent between 1970 and 2015, while human-made wetlands like paddy fields have expanded by 233 percent (Darrah et al. 2019). Coastal and inland wetlands are among the most biologically productive ecosystems, covering 12.1 million km² globally and providing an estimated $35,000 per hectare annually in ecosystem services (Ramsar 2018; Brander et al. 2024). Agriculture is likely to have negative effects on more than 50 percent of Wetlands of International Importance[4]. More than 20 percent of the world's Wetlands of International Importance are affected by dams, 20 percent by drainage and more than 20 percent by livestock farming, agricultural and forestry effluents or land conversion (Ramsar Convention on Wetlands 2021).

Wetland degradation is harming biodiversity and ecosystem services vital for agriculture, including flood regulation, nutrient cycling, and carbon sequestration. Wetlands are under threat from agriculture which affect their hydrology, sediment transport and salinity. Converting wetlands into arable or aquaculture disrupts biodiversity. High water levels kill critical vegetation while drying events prevent submerged species from thriving. Birds suffer from fluctuating water levels, which affect foraging and nesting habitats (Orsholm and Elenius 2022; Malekian et al. 2022). Using wetlands for water storage alters flow patterns, reducing downstream ecosystem health (Verhoeven et al. 2006; Chuma et al. 2022). Wetlands store 30 percent of the Earth's soil carbon (Moomaw et al. 2018) but wetland conversion for agriculture has turned these ecosystems into net sources of greenhouse gases, with drained peatlands contributing 4 percent of anthropogenic emissions (Leifeld et al. 2019). Nitrogen and phosphorus pollution lead to eutrophication of wetlands (Ramsar Note 13).

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[4] Those designated as Wetlands of International Importance or with data updated since 2015.

Dams and reservoirs

Nearly half of all rivers globally have been altered by dams, with only a third remaining free flowing along their entire length. 58,700 large dams[5] (Perera et al., 2021) and millions of smaller dams and reservoirs disrupt river systems. Over 60 percent of rivers have been fragmented by dams and only 23 percent flow uninterrupted to the ocean (Grill et al. 2019; GWP & IWMI 2021).

The primary mechanism through which dams and reservoirs impact biodiversity is through changes in flow regimes and reduced connectivity between aquatic habitats. Dams reduce the connection between groundwater and surface water (vertical connectivity) and between rivers and their floodplains and wetlands (lateral connectivity). Habitats are homogenized as flowing water (lotic environments) is replaced with still water (lentic environments). The amount, velocity, timing, and turbulence of water flows is altered, affecting breeding, feeding, migration, and refugia for aquatic organisms, reducing species diversity and abundance and favoring invasive species. Flood frequency and magnitude are altered impacting the richness of plant and aquatic species that rely on seasonal flooding and promoting non-native species which thrive in stable conditions. Reduced flood magnitude and frequency diminishes terrestrial vegetation diversity in floodplains (Rolls and Bonds 2017; Rolls et al. 2012; Yamanaka et al. 2020; Hayes et al. 2017).

Annex 2 summarizes impacts of agricultural water management on biodiversity and ecosystem services and illustrates the protection status of groundwater dependent ecosystems, threats to wetlands of international importance and the status of global water connectivity.

3.2.3. Crop nutrition, pests and disease, and waste management (pollution)

Nutrient pollution: Nitrogen and phosphorus

This section highlights the ecological consequences of nutrient overload and its threat to long-term environmental sustainability.

Agriculture has profoundly disrupted the nitrogen cycle, primarily through fertilizer use and livestock intensification. Human activities add 190 million tons of nitrogen annually – an amount equal to all natural sources combined. This far exceeds the planetary boundary for nitrogen, which is set at 62 million tons per year to avoid harmful environmental impacts (Planetary Health Check 2024). Fertilizer use is the largest source of nitrogen pollution, followed by manure from livestock operations and nitrogen-fixing crops.

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[5] Defined as structures exceeding 15 meters in height or with a storage capacity of three million cubic meters

Nitrogen pollution arises from diffuse and point sources. Diffuse sources include fertilizers, manure spread on fields, and nitrogen-fixing crops from which nitrogen leaches into groundwater or runs off into water bodies. Point sources, such as concentrated animal feeding operations (CAFOs), release nitrogen through leaking waste lagoons, overflow events, and poorly managed manure storage facilities. In areas with porous soils or high water tables, nitrogen from these operations easily contaminates drinking water and aquatic ecosystems.

Farming practices, such as monocropping and deforestation, further amplify nitrogen pollution. Monocropping depletes soil nutrients, requiring heavy nitrogen inputs to sustain crop yields. Deforestation removes nutrients stored in vegetation and soil organic matter, which are quickly lost through erosion and leaching. Farmers often rely on fertilizers to compensate for these losses. Overgrazing concentrates manure and urine in small areas, overwhelming the land's ability to absorb nutrients. Soil compaction caused by livestock reduces water infiltration, increasing runoff and accelerating nitrogen losses to nearby ecosystems.

Phosphorus is a critical nutrient for plant growth, but its overuse in agriculture is the main cause of phosphorus pollution. Today human activity contributes 22.6 million tons of phosphorus annually to rivers, lakes, and oceans—more than double the planetary boundary of 11 million tons per year (Planetary Health Check 2024). Agriculture is responsible for over 90 percent of phosphorus pollution, primarily through the use of fertilizers made from mined rock phosphate and manure application.

The impacts of phosphorus pollution vary across regions and river basins. China (35 percent), Spain (13 percent), India (11 percent), Brazil (8 percent) and Russia (5 percent) were the largest contributors to the phosphorus load from agriculture (Figure 8) (Mekonnen et al. 2018). Phosphorus use rates are strongly increasing, particularly in parts of South America, India, China, and Southeast Asia. In contrast, parts of Europe show a notable reduction in phosphorus use over the same period, likely due to improved agricultural practices and regulations. (Planetary Health Check 2024).

Excess nitrogen and phosphorus harm ecosystems by overloading water bodies with nutrients. (eutrophication). This nutrient overload causes explosive algae growth, known as algal blooms, which block sunlight and deplete oxygen in the water as the algae die and decompose. The result is oxygen-depleted "dead zones" where fish and other aquatic life cannot survive. These zones significantly reduce biodiversity, as species that cannot tolerate low oxygen levels either die or migrate.

Nutrient pollution gives invasive species a competitive advantage. Algal blooms dominated by invasive species, such as cyanobacteria, outcompete native plants and animals, leading to less diverse ecosystems. Cyanobacteria can also release toxins that harm fish, birds, and other wildlife. On land, nitrogen pollution acidifies soils, disrupting soil microbial communities and reducing plant diversity. Acidified soils lose beneficial microbes and become more vulnerable to pests and diseases, further degrading ecosystem health and reducing agricultural productivity.

Annex 3 summarizes a recent study (Schulte-Uebbing 2022) that establishes regional spatially explicit boundaries for agricultural nitrogen use to limit terrestrial biodiversity loss.

Nutrient pollution: Examples

- **Monocropping:** Repeated planting of the same crop depletes soil nutrients, increasing reliance on nitrogen fertilizers (Mukhovi and Jacobi 2022).

- **Groundwater contamination:** High nitrate levels result from excessive fertilizer use and poorly managed manure systems, particularly near drinking water sources (Kou et al. 2021).

- **Acidified soils:** Nitrogen pollution acidifies soils, reducing plant diversity, harming beneficial microbes, and degrading ecosystem health.

- **Livestock systems:** Overgrazing and concentrated manure deposits lead to nitrogen runoff into rivers, lakes, and groundwater.

- **Phosphorus pollution:** Agriculture is responsible for 90 percent of phosphorus pollution. Cereals contribute 55 percent of fertilizer-related inputs, while fruits and vegetables dominate manure-related phosphorus inputs (Mekonnen et al. 2018).

- **Dead zones:** Nutrient runoff from agricultural fields along the Mississippi River has created one of the world's largest dead zones, spanning 245,000 km^2 in the Gulf of Mexico (Dodds 2006).

- **Algal blooms:** High nutrient levels promote cyanobacteria, which outcompete native species and reduce biodiversity. Algal blooms in Lake Victoria threaten fish species like Nile perch and tilapia and reduce food availability for birds such as African fish eagles and herons (Nyamweya et al. 2023).

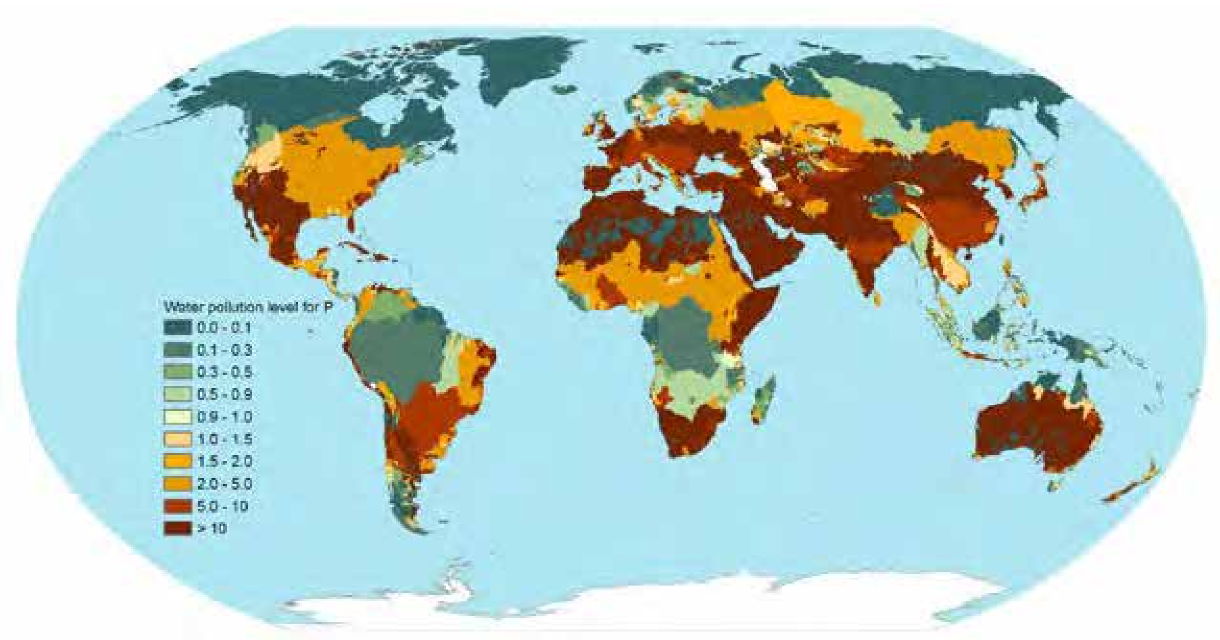
- **Deforestation and erosion:** Forest clearing removes stored nutrients, which are lost through erosion and leaching, creating greater dependence on fertilizers (Maestre, F. T. et al. 2024).

Agrochemical pollution

"Humanity is currently operating outside the planetary boundary for introduction of novel entities." "The increasing rate of production and releases of larger volumes and higher numbers of novel entities with diverse risk potentials exceed societies' ability to conduct safety related assessments and monitoring." (Persson 2022). Novel entities refer to substances and materials that are either entirely new to the environment or introduced in forms and quantities that have no natural precedent. These include synthetic organic pollutants, radioactive materials, genetically modified organisms, nanomaterials, microplastics, and heavy metals released through human activity. This section focuses on agrochemical use which disrupts ecosystems by contaminating soil, water, and air, poisoning non-target species, and reducing biodiversity.

Global pesticide use has grown sharply, increasing by over 20 percent in volume over the last decade, with low-income countries experiencing a staggering 153 percent rise in pesticide use during the same period (Stattuck et al. 2023). However, data reporting particularly from low- and middle-income countries is leading to underestimates in global pesticide use. High-income countries with intensive agriculture have also reported less reliable data in recent years, further complicating efforts to monitor pesticide usage accurately (Stattuck et al. 2023).

Figure 8. Water pollution levels per river basin related to human-induced P loads from the agricultural, industrial, and domestic sectors. Period: 2002–2010.



Source: *Mekonnen et al. 2018*

Pesticides are categorized by their target organisms and chemical composition. Major categories include organophosphates, organochlorines, carbamates, and synthetic pyrethroids. These chemicals are also classified as systemic or non-systemic. Systemic pesticides are absorbed into plant tissues, offering prolonged pest protection but posing risks to non-target species and beneficial insects. Non-systemic pesticides act on contact and remain on plant surfaces, requiring reapplication after pest resurgence or new plant growth (Ahmad et al. 2024; Ambaye et al. 2024).

How long pesticides persist in the environment varies widely, with some classified as persistent organic pollutants (POPs) due to their long half-lives. For example, organochlorine pesticides like DDT have half-lives of up to 15 years, leading to bioaccumulation and long-term risks (Rasool et al. 2022), accumulating in the food chain and causing long-term ecological harm. Pesticides contaminate waterways through agricultural runoff, affecting aquatic organisms and contribute to nutrient overloads that cause algal blooms. These chemicals also harm birds, pollinators, and soil invertebrates, disrupting ecosystems and reducing biodiversity. Insecticides like neonicotinoids impair honeybee navigation, reproduction, and foraging efficiency, reducing pollination and undermining agricultural productivity.

Intensive monocultures, forest clearing and overgrazing all contribute to increased pesticide use. Intensive monocultures lack the natural pest suppression and crop rotation benefits that help regulate pest populations. Continuous monoculture farming increases pests and weeds, requiring increasing pesticide and herbicide use (Wang et al. 2021; Liu et al. 2022). Examples include maize farming in Sub-Saharan Africa and soybean production in Brazil. Forest clearing for agriculture disrupts pest regulation. This leaves smallholders vulnerable to pest outbreaks and increasing pesticide use (Ratnadass et al. 2021; Jasrotia et al. 2023). This is especially common on forest frontiers like the Amazon Basin. These farmers often lack access to adequate training on safe pesticide application, exacerbating the risks to both human health and the environment (Ratnadass et al. 2021; Jasrotia et al. 2023). Overgrazing degrades pastures, encourages invasive species, and increases pesticide use to manage weeds and restore grasslands (Centeri 2022). Examples include overgrazing in the Sahel region and the Great Plains of North America.

Pesticides cause aquatic toxicity and impact birds: Pesticides contaminate rivers, lakes, and wetlands, harming fish, amphibians, and aquatic invertebrates, and lead to algal blooms through nutrient leaching (Schepker et al. 2020). Insecticides disrupt bird reproduction, neurological functions, reduce egg production, hatching success, and overall population dynamics (Marlatt et al. 2022; Mohanty 2024). Examples include the decline of bald eagle populations due to DDT exposure in the United States.

Neonicotinoids are the world's fastest growing and most widely used class of insecticides, targeting a broad spectrum of sucking and some chewing insects. Neonicotinoids account for 25 percent of the global insecticide market and are widely used in crops like maize, canola, and soybeans (Thompson et al. 2020). These chemicals are widely valued for their systemic action, long-lasting efficacy, and presumed lower toxicity to non-target organisms compared to older insecticides like organophosphates or carbamates. Their versatility and effectiveness have led to their widespread use, particularly as seed treatments, but also via aerial or ground sprays, chemigations, or injections (Goulson 2013; Simon-Delso et al. 2015).

Despite their advantages, neonicotinoids have been found to contaminate soils, water bodies, and non-crop plants, exposing non-target organisms to acute and chronic toxicity. Neonicotinoids persist in soils for over 1,000 days, accumulating with repeated use and contaminating nearby ecosystems (Bonmatin 2015). They are often used alongside other pesticides that act synergistically to amplify their toxicity. Neonicotinoids frequently exceed EU water safety limits in streams and wetlands, harming aquatic invertebrates and disrupting ecosystems (Pietrzak 2020). Honeybees are exposed to neonicotinoids through seed drilling dust, contaminated nectar, and pollen, leading to impaired navigation, memory, foraging efficiency and colony decline reducing pollination services (Elhamalawy et al. 2024; Simon-Delso et al. 2015).

3.3 Agrobiodiversity

Agricultural biodiversity has declined significantly, with commercial crop varieties decreasing 75 percent since 1900 and livestock breeds declining at 1 percent annually, threatening global agricultural productivity and stability (FAO 2023). This genetic uniformity increases vulnerability to pests and diseases. Smallholder farmers face particular risks as they depend on agricultural biodiversity for resilience, with implications for nutrition security in regions relying on local crop diversity

(Storkey et al. 2024). Loss of genetic diversity represents a permanent reduction in future adaptation options, particularly crucial given climate change. Impact distribution is uneven, particularly affecting smallholder farmers in developing countries. Genetic resources underpin $150 billion annually in global agricultural output (Dwivedi et al. 2024).

Plant Genetic Resources for Food and Agriculture (PGRFA)

Globally, crop species, varieties of species and their crop wild relatives and the genetic and phenotypic variation within them have declined or have been lost. IPBES reports that the pool of genetic variation, which underpins food security has declined. Globally, of about 6,000 plants cultivated for food, only 200 species have significant production levels and nine species account for 66 percent of all crop productions (maize, rice, wheat, potatoes, cassava, soybeans, sugar cane, sugar beet and oil-palm). A meta-analysis (Khoury et al. 2014) of 139 published studies, covering 50 years found that over 95 percent of all the studies reported diversity change, and almost 80 percent found evidence of loss. The key drivers of loss are high dependence of unsustainable intensification such as agrochemicals which often favor genetic uniformity; land use change and associated loss of wild species, and the fast decline of IPLC food systems which use hundreds of edible species; and the homogenization of diets.

Formal and informal seed sectors can contribute to greater diversity. Informal farmers' seed systems, (informal sector), are characterized by a diversity of traditional and modern varieties that are often highly adapted in-situ for specific agroecological conditions and tend to breed for varietal heterogeneity reflecting a mosaic of heterogeneous landscapes. This informal in situ conservation allows crops to evolve within changing environments but there are also risks of plant degeneration and loss of varieties through a series of biotic and abiotic stresses.

Formal seed systems tend to breed for homogeneity and selection of the genotype best adapted to uniform controlled growing conditions. Homogeneity is also a requirement for varietal registration. Ex situ conservation includes collection, characterization, regeneration and exchange with gene banks. In 2022, 5.7 million accessions were reportedly conserved in 831 gene banks by 114 countries and 17 regional and international research centers. These accessions do not represent neglected and under-utilized species (NUS) and crops' wild relatives which are underrepresented.

The International Treaty Benefit Sharing Fund has enabled multi-stakeholder partnerships of 500 institutions for 81 projects in 67 countries and have reached 1 million farmers in developing countries. The Food and Agricultural Organization's (FAO) International Treaty for Plant Genetic Resources for Food and Agriculture facilitates international cooperation for the conservation and sustainable use of all PGRFA for 150 countries, plus the European Union. The Treaty has a multilateral system (MLS) of access and benefit-sharing (ABS), whereby countries agree to virtually pool and share plant materials of 64 major crops and forages covering about 2.3. million PGRFA samples, with over 6.1 million exchanged globally. The Treaty also has a working model of benefit sharing in harmony with the Convention on Biological Diversity and its Nagoya Protocol and the Global Biodiversity Framework. However, the MLS does not capture Neglected and Under-Utilized Species (NUS).

A new development is the digital sequence information (DSI) of gene function, position and expression. This allows laboratories to develop and patent products and plants through DSI without necessarily the physical access biological plant materials. DSI adds new critical tools and complex dimensions to access and benefit sharing of PGRFA.

Animal genetic resources for food and agriculture

Diversity of animal genetic resources provides options to deal with future climate and disease threats. Diversity of animal genetic resources for food and agriculture, which includes mammalian and avian species, is increasingly important given the effects of climate change and increasing risk of pandemics. A genetically diverse population is less likely to be affected by disease as some breeds may have some resistance, or are less affected by drought as diverse breeds have unique feeding habits (ILRI 2006).

The population status of nearly 60 percent of breeds is unknown while almost three quarters of breeds of known status are at risk of extinction. There are around 8800 livestock breeds of 38 different species in the world (Cao et al 2021) and Domestic Animal Diversity Information System (DAD-IS) (FAO). The unknown status of breeds is a major constraint to their protection. Except for the wild boar, the ancestors and wild relatives of major livestock species are either extinct or highly endangered which is a major difference from crop species, many of whose wild ancestors still exist (ILRI 2006).

The erosion of genetic diversity of domestic species has been exacerbated by crossbreeding and the introduction of exotic breeds has contributed to erosion of local breeds in developing countries. Other causes include the neglect of multi-purpose animals and selection of a narrow selected of breeds for intensive systems, natural disasters, and a lack of breed characterization and economic valuation (ILRI 2006).

The preferred method of conserving animal genetic resources is preservation of live animals, which allows breeds to continue to evolve with their environments. In vitro conservation including cryopreservation the process of freezing genetic material – and DNA banking – is an important back-up when conservation of live animals is not possible or cannot protect a large enough population size (ILRI 2006).

The following section explores sustainable agricultural practices to mitigate the agricultural- driven biodiversity loss described above while supporting agricultural productivity.

Chapter 4.

Sustainable agricultural practices mitigate biodiversity loss and support agriculture

Agricultural practices can maintain and restore biodiversity, thus optimizing food and agriculture outcomes for the economy, the planet, and its people. In brief, there is a better way.

4.1 Technical assessment of sustainable agricultural practices

Defining a better way

Sustainable agriculture practices are here defined as technologies and approaches that either mitigate selected types of nature loss that result from unsustainable practices and systems, or that enhance positive impacts on nature. Through various channels, all sustainable practices discussed in this section improve the biodiversity underpinning ecosystem services to agriculture and human livelihoods. A practice is considered sustainable if, additionally, there is evidence around potential economic viability – at least under certain conditions – in support of livelihoods of diverse farmers, including smallholders. A non-exhaustive, list of sustainable practices is discussed below (and a link to detailed notes on each practice is provided here in the online version). Most of the sustainable practices discussed are implemented in "bundles" or alongside other practices in a complementary package. Whereas a number of these practices below are discussed as standalone practices, their impact is often optimized when bundled (e.g., zero-tillage vs zero-tillage+intercropping). Wherever possible, details around bundling accompany the discussion on sustainable agricultural practices. In some instances, there are "bundles" that combine quite specific, highly complementary practices together *by definition* as in "integrated pest management" (IPM), where if one or more component practices are absent, it is no longer is considered IPM. Agro-silvo-pastoralism and integrated nutrient management fall under this category as well. Finally, it is clear that many of the practices below – singled out for their evidenced positive impact on agriculture livelihoods and sustainability – are the same practices often found in different combinations under classifications like "climate-smart agriculture," "nature-based solutions," "regenerative agriculture" and "agroecology." Individual sustainable agricultural practices are not grouped as such in this discussion to maintain the focus on the scientific evidence of their individual (and bundled) impact on farmers rather than on grouping nomenclature.

From vicious to virtuous

Each of the practices highlighted here address one or more of the types of nature loss resulting from unsustainable agriculture. In doing so, they address the biodiversity and ecosystem services critical for agricultural productivity and livelihoods. Two of the broadest-reaching sustainable agricultural practices in this regard include **intercropping** and **crop rotation**. They are among the low hanging fruit or "heavy hitters" of sustainable agricultural practices.

Just as **monocropping** negatively impacts biodiversity in soil microbial communities, thereby reducing crop resilience to environmental stress, **intercropping** – the practice of growing two or more crops in proximity within the same field – increases species diversity at the field level, improving soil and contributing to greater resilience to stressors. Intercropping also allows for inclusion of certain crops that attract pests away from the main crop or repel them with allelopathic compounds (e.g., marigolds release chemicals that deter nematodes and can be intercropped with tomatoes). This in turn permits a reduction in the amount of agrochemical use needed for pest and weed control, further reducing threats to biodiversity through reduced pollution. Intercropping results in input-use efficiency for more than just pesticides, since a reduced amount of water and fertilizers are needed. Growing different plant species with different roots helps to efficiently use the water at various depths, reducing the need for irrigation. Crops with different root depths also access different soil layers for nutrients, reducing the need for nutrient addition (fertilizer) and thereby reducing the risk of nutrient pollution. In addition, nutrient complementarity is achieved when nitrogen-fixing plants, like legumes, replenish the soil with nitrogen, fundamental for the subsequent crop.

The nutrient cycling that comes from complementarity of subsequent crops is also a feature, by definition, of **crop rotation** when leguminous plants are included in the rotation. Rotating crops in the same field over the seasons supports a wider range of soil microorganisms, insects, and other wildlife, promoting biodiversity both in the soil and the landscape, improving pest and weed control relative to monocropping and monoculture. By alternating different plant species, crop rotation breaks the pathogen life cycles, reducing their prevalence, and minimizing the need for chemical pesticides – and the risk of chemical pollution. Weed management is also enhanced through crop rotation because different crops compete with weeds in various ways. Crop rotation disrupts weed growth patterns, reducing weed prevalence and the reliance on herbicides. Overall, crop rotation has the advantage of improving resilience of crops by reducing risks related to crop failure due to pests, disease, or adverse weather conditions, providing more stable yields and incomes for farmers.

The basic practice of crop rotation (which has been around since Roman times) and intercropping have the opposite impact on biodiversity of that caused by monoculture and monocropping described in the section above. Why, then, are these practices not more universal? Limited land availability, lack of equipment, insufficient knowledge/knowledge transfer, and the complexity of implementation are common barriers shared by intercropping and crop rotation. In addition, smallholder farms often prioritize staple food production to meet immediate household needs, leaving little room for either or both practices. This becomes more acute in the case of intercropping systems involving agroforestry (where trees are the secondary crop) where there is a lag before tree crops bring income, and the farmer loses out[6]. Further, experience has shown that seed availability for optimal rotational crops, such as legumes, may be restricted. On the demand side, if market demand for specialized crops introduced in rotation or into intercropped fields is low, then so are market incentives for the farmer to adopt. Furthermore, diversified rotations and intercropping techniques can be complicated since optimal timing and spatial configurations can be extremely localized (i.e., from farm to farm).

Most, if not all, sustainable agricultural practices are optimized when bundled with other practices. Crop rotation is the building block of several production approaches like Integrated Pest Management (IPM), and it is one of the three pillars of conservation agriculture, alongside green manure (see below) and zero-tillage. Perhaps the most enduring image conjured up by the word “agriculture” is that of a farmer tilling the soil. Tilling controls weeds and improves both soil aeration and water

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[6] It is important to note that other intercropping systems, like maize-legume and maize-legume-forage (“push-pull”) are already widely practiced in many parts of Africa South of the Sahara. Likewise, it is estimated that 30-50 percent of global cassava production is intercropped. In such cases, the question is not one of adoption but of enhancement, or optimization, of an existing practice.

filtration. Deep plowing and excessive tilling, however, lead to soil degradation by increasing susceptibility to erosion (Kimaro et al. 2005), soil runoff (Guto et al. 2011), and by reducing microbial diversity and activity (Kladivko 2001). For this reason, minimum tillage and no-tillage (also known as **zero-tillage**) promotes less disruptive agricultural management by eliminating traditional plowing practices with the use of direct seeding. To be effective, direct seeding is preceded by other land preparation practices, including chemical or mechanical weed control (e.g., slashing), removal of the previous crop residues, or cover crops (see below) to create a mulch layer. Crop residues are retained to ensure complete soil coverage and seeding is then done directly through the mulch layer. Minimally disturbing the soil allows for an enhanced number and species of soil arthropods and a greater abundance of microbials, all of which provide natural enemies to detrimental organisms. This gives the crop greater resistance to pests and disease and reduces the need for chemical pesticide and herbicide. Minimum tillage also preserves earthworm populations, (Rasmussen 1999) which contribute to overall soil structure. Minimum tillage is also promoted as a method to reduce air pollution, for instance in India, where previously farmers used to burn rice straw but now apply direct seeding on cut crop residues that are spread as mulch. By retaining crop residues on the soil surface, zero-tillage promotes the activity of decomposers. These organisms break down organic matter, speeding up the release of essential nutrients and assist in greater nutrient cycling. Finally, by leaving the soil relatively undisturbed, carbon dioxide emissions are reduced, contributing to climate change mitigation. Since the practice is often used in monoculture systems and combined with chemical weeding, extensive use of herbicides is an observed limitation (Lu et al. 2022). Herbicide (ab)use can be moderated by bundling minimum tillage along with other agricultural practices like crop rotation (Colbach & Cordeau 2022) and within the context of conservation agriculture. To summarize, the effectiveness of zero-tillage in enhancing biodiversity of soil microbes (and insects) is increased when applied together with crop rotation and soil organic cover (i.e., green manure).

Green manure has similar broad-based impacts across several drivers of biodiversity loss described above. Evidence shows that these sustainable agricultural practices help reduce nutrient and chemical pollution while rebuilding soils and improving water retention. Green manure refers to the planting of cover crops (the terms are used interchangeably), on fallow fields in the period between the harvest of one crop and the sowing of the next. The practice increases biodiversity in the fields and improves soil quality with positive impacts on crop production and crop resilience to stressors – both aspects of key concern for farmer livelihoods. Green manure impacts the soil's physical, chemical, and microbial characteristics. The mechanical action made by the cover crop's growing roots and the increased organic matter reduce soil compaction and soil's bulk density (Haruna et al. 2020) and improve water infiltration (Haruna et al. 2020; Blanco-Canqui & Ruis 2020). Cover crops can further improve physical soil health by acting as a shield, preventing erosion caused by heavy rainfall and wind (Haruna et al. 2020; Blanco-Canqui & Ruis 2020; Blanco-Canqui et al. 2015) and in temperate zones, crops grown during the winter intercept excess rainwater, rendering it available during warmer and dry seasons (Blanco-Canqui et al. 2015). By incorporating new and residual nutrients into the soil from the cover crops, there are greater nutrients available in the soil for the commercial crops that follow (Fontaine et al. 2020). Cover crops also enhance soil microbial biodiversity, favoring fungal biomass and improving nutrient cycling and biological soil health (Muhammad et al. 2021). Applying green manure is therefore a key practice for reducing synthetic inputs, which if used excessively can cause nutrient pollution. It also reduces the risk of chemical pollution because cover crops provide habitat for a diverse range of beneficial insects and other organisms (Fiorini et al. 2022; Elhakeem et al. 2019), contributing to ecosystem resilience and helping control pest populations naturally (Gurr et al. 2012). Similarly, increasing the diversity of crop species grown in farmers' fields throughout a growing season provides a nature-based solution to weeds, reducing the need for pesticide and herbicide. Just as in crop rotation, cover crop species belonging to the leguminous family foster a particular soil microbial biodiversity that enables the capture of nitrogen from the atmosphere, making it available for plants. Evidence is mixed but exists for yield increases in the commercial crop, through nitrogen fixation (Fageria et al. 2005). Reliance on synthetic fertilizers may also diminish through cover crops (Zablotowicz et al. 2011). These two factors can lead to lower costs and higher output for farmers. In addition, the higher microbial abundance from cover cropping also increases the sequestration of carbon dioxide from the atmosphere, reduces GHG emissions from agricultural sources, thus helping to mitigate climate change (Blanco-Canqui et al. 2015; Kaye & Quemada 2017). Contrast these benefits with the unsustainable alternative of leaving land fallow without vegetation cover that can lead to erosion, surface runoff, freshwater contamination, etc.

Along with biocontrol, three of the practices covered above – crop rotation, intercropping, and green manure – combine to form a holistic approach to pest and disease management referred to as **integrated pest management (IPM).** The detrimental effects of addressing pest management solely with pesticides reviewed in the previous section led to the development of alternative approaches, like biocontrol and organic agriculture. Biological pest control, also called biocontrol, refers to a diverse set of nature-based practices based on the use of natural enemies. Contrary to the use of pesticides, which aim to directly eliminate harmful organisms, biocontrol relies largely on inter-species predation and parasitism to contain pest populations within an acceptable level. It is often applied using microbial pathogens and repellents and it preserves a biodiverse ecosystem, creating an equilibrium between pests and antagonists that is favorable to the latter. Biocontrol is a toolkit for alternative pest management, often adopted as part of IPM approaches (Naranjo et al. 2015) and organic agriculture systems (Baker et al. 2020).

IPM is more of an overarching approach than biocontrol and benefits from accommodating other sustainable practices like **alternative pollinators**.[7] It offers a viable solution combining biological, cultural, mechanical, and chemical methods to control pests (IPM) (Stenberg 2017; Barzman et al. 2015; Flint & van den Bosch 1981). By reducing the reliance on chemical pesticides, IPM aims to minimize adverse environmental impacts, promote biodiversity, and safeguard the health of ecosystems and human populations. It involves the prevention and suppression of pest habitats through agronomic practices like crop rotation, intercropping, and sanitation measures. It involves regularly monitoring pest populations and using threshold levels to determine when control measures are needed, thus avoiding unnecessary pesticide applications. It has recourse to mechanical control, such as barriers, traps, and manual removal of pests, and prioritizes biological control over chemicals to decrease pest populations. It aims to limit – not necessarily reduce completely – the use of chemical pesticide to necessary levels.

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[7] Integrating farming with alternative pollinators and IMPM generates significant benefits due to the synergies between these practices.

In limiting these, **IPM** can support a wider variety of pollinators. Pollination is a recognized ecosystem service, and its economic value has been assessed numerous times (Hein 2009; Khalifa et al. 2021; Breeze et al. 2016). However, there is a rapid biodiversity decline in terms of wild pollinators, which is caused by human activities (Drossart & Gérard 2020), most prevalent of which is the intensive and improper use of agrochemicals (Kluser & Peduzzi 2007). While there are regulations to limit the most pollinator-damaging pesticides in many parts of the world, this does not exist or is difficult to enforce in others. As a result, **farming with alternative pollinators (FAP)** is more of an intervention framework than a single practice. It is an attempt to protect pollinators and enhance biodiversity at the landscape level by establishing a marketable habit using enhancement plants such as flowering shrubs, trees, crops, herbs, and medicinal plants on around the field and by establishing ecological corridors between fragmented natural habitats and agricultural sites. FAP aims at delivering both economic and ecological benefits. In increasing biodiversity of off-field and in-field diversified crops and trees, FAP carries the same beneficial ecosystem services seen in other landscape biodiversity-enhancing measures. Namely, by enhancing the number and species of pests' natural enemies, and by creating habitats for pollinators and other beneficial insects, farmers experience greater crop resistance to pests and disease (Christmann et al. 2021) and greater agrisystem resilience. Importantly, in numerous field trials FAP led to higher yields compared to controls (Sentil et al. 2022; Christmann et al. 2017). Like waste-to-animal-feed approaches (below), FAP requires landscape-level coordination that can be complex and relies on widespread collaboration and coordination.

Like IPM, **Integrated Nutrient Management (INM)** is not a single practice, rather it is based on the balanced use of organic and inorganic sources of nutrients (e.g., chemical fertilizers, legume crops, manure, biofertilizers), combined with appropriate soil management practices and – importantly – the knowledge to tailor the combination of interventions to local agroecological conditions. While biostimulants do not add nutrients to the soil (and are, therefore, not technically a fertilizer), their role in enhancing nutrient efficiency makes them part of the INM toolbox. For instance, research shows some seaweed extracts contain plant growth regulators, vitamins, minerals, and other bioactive compounds that act as biostimulants (Mughunth et al. 2024). Approaches for balanced nutrient application also tend to include innovations such as remote sensing and tailored decision-support systems. In addition to nutrient management, soil management practices under INM improve soil nutrient retention and absorption and improve soil quality and health (Aulakh 2010; Selim 2020), also important components. Examples include terracing, alley cropping, and green manures like mulching and cover crops. INM prevents overdosage and protects freshwater and biodiversity, positively impacting the ecosystem services to farmers. Evidence shows that INM can lead to an increase in soil organic matter content, moisture-retention capacity, and water infiltration rate while reducing soil bulk density (Biswas & Dutta 2020). Importantly, not only does INM lower farmer costs for a given yield, it slows the mineralization of organic matter, enhances nutrient use efficiency, and provides higher nutrient availability in the soil because of reduced nutrient leaching and runoff (Kakraliya et al. 2017), leading to higher yields (Kannan et al. 2013; Kakraliya et al. 2017; Panigrahi et al. 2022; Rahman et al. 2013; Liu et al. 2013). Finally, INM mitigates climate change by reducing nitrogen losses (Graham et al. 2017) and enhancing soil carbon sequestration (Bayu 2020), while reducing GHG emissions from fertilizer production. As with any bundle, constraints to adoption are greater than the sum of their parts. That is, in addition to the constraints known for the individual practices that combine to make up INM (e.g., cost constraints on chemical fertilizer or transport issues of heavy manure), an added constraint is the know-how on the best combination of these for a given site (Ma et al. 2013).

Akin to intercropping and crop rotation, agro-silvo-pastoralism is a practice with broad biodiversity impacts. It combines crops, trees, and livestock breeds within a single system. As a result, ecosystem services such as enhanced carbon sequestration, greater nutrient cycling, and soil conservation contribute to climate regulation and soil restoration. A diversified landscape created by agro-silvo-pastoralism that integrates animals contributes to crop protection and weed control. That is, the diversified landscape in agro-silvo-pastoral systems enhances pest control by attracting and supporting natural predators and parasitoids of crop pests. This ecological complexity disrupts pest life cycles and reduces pest populations (Nobilly et al. 2023). These ecosystem functions combined can reduce the levels of synthetic inputs needed, which in turn help lower the risk of nutrient and chemical pollution. Regarding food security, greater species diversity in agro-silvo-pastoral systems expands agricultural provisioning since croplands, animal grazing, and trees are all involved in the delivery of food and materials for human consumption. In addition, agro-silvo-pastoral systems can improve the provision of feed required for animal production (Venkatesh et al. 2024). In sum, by diversifying crops, trees, and livestock breeds, agro-silvo-pastoral systems can enhance resilience to environmental stresses and improve land productivity (Kumar et al. 2024), key to improving agricultural livelihoods. This is because agro-silvo-pastures enhance nutrient cycling through various mechanisms: livestock grazing redistributes nutrients and adds organic matter through dung and urine (Barros et al. 2018), trees contribute to the enhancement of soil organic matter and soil nitrogen through leaf litter and atmospheric nitrogen-fixing (Hoosbeek et al. 2018), and the agro-forestry components improve soil properties by mitigating the risk of soil erosion inherent to intensive farming systems (D'Angelo et al. 2000; Hancock et al. 2020). In terms of resilience, the product diversification inherent in silvo-pastoral systems, as opposed to monocultures and intensive livestock systems, acts as a risk mitigation strategy for smallholder farmers and communities and guarantees sustainable provision of food over time. This improves the food availability dimension of food security (FAO, IFAD, & WFP 2013). Finally, climate regulation is an important aspect of this practice. The agroforestry component can regulate water flows, moderate microclimates, and improve climate resilience. On the one hand, carbon sequestration by trees mitigates climate change by directly lowering greenhouse gases in the atmosphere (Montagnini & Nair 2004). In terms of resilience, the diverse nature of agro-silvo-pastoral systems makes them well-suited to cope with climate variability and extreme weather events.

In light of these benefits, there is a public goods aspect to resolving financial constraints that have been documented as barriers to adopting some of these practices (see Chapter 6). For agro-silvo-pastoralism, the existence of maintenance costs and high labor intensity during the initial installation phase are significant adoption barriers despite positive evidence on impacts (Lee et al. 2020; Opdenbosch & Hansson 2023). Evidence about factors determining the adoption of cover crops comes mostly from the United States, the European Union, and China, with very little evidence from the Global South. Studies suggest the main barriers are economic. While yields of commercial crops have been seen to rise – and use of costly chemicals to fall – there is also evidence of falling yields in other studies (Deines et al. 2023). More importantly, the fact that cover crops are usually not sold can drive negative impacts on the overall productivity of farming systems, creating financial concern (Deines et al. 2023). For other practices, such as integrated pest management (IPM), lack of adoption is often attributable to insufficient bundling with targeted dissemination and underinvestment in extension services to equip farmers with the necessary technical know-how to successfully implement IPM (Creissen et al. 2021; Lane et al. 2023; Parsa et al. 2014; Timprasert et al. 2014). For IPM (and sometimes organic agriculture), there is the additional challenge of requiring collective action, as IPM effectiveness on one plot is limited if neighboring parcels do not also adopt similar pest control practices (Parsa et al. 2014). Another constraint to adopting bundled approaches like IPM and integrated nutrient management (INM) is complexity. The efficacy of INM, in particular, depends on having highly site-specific recommendations based on local soil, climate, and crop requirements. Universal recommendations are therefore difficult to formulate and data intensive. This technical complexity has proven to limit adoption in regions like China, where uptake remains low due to inadequate technical knowledge and incentives (Aryal et al. 2021; Ma et al. 2013).

Micro-irrigation reduces irrigation water quantities preserves groundwater natural replenishment rates and curtails soil runoff and nutrient leaching, thereby protecting biodiversity in water bodies and soils from contamination (Reid et al. 2019). For farmers, this translates into greater ecosystem resilience, improved soil health, and reduced weed proliferation due to limited water availability at the soil surface, indirectly helping crops resist pests and disease (Madramootoo & Morrison 2013). Micro-irrigation can often achieve the same or even higher yields compared to traditional irrigation systems, lowering costs and increasing water use efficiency per plant (Cheng et al. 2021; Zhang et al. 2022; Wang et al. 2022). However, high upfront and maintenance costs, lack of technical knowledge, and inadequate support programs remain substantial barriers to adoption, particularly for smallholders (Chandrakanth et al. 2013; Kumar et al. 2008). Given these challenges, mechanical soil and water conservation practices complement micro-irrigation by enhancing agricultural productivity at the farm level (Hornum et al., 2023; Wanvoeke et al. 2016). Among these practices, water harvesting and runoff limitation methods, such as terracing, stone lines, tied ridges, and semi-circular bunds, are especially effective (Mekdaschi Studer & Hanspeter 2013). By limiting soil runoff, biodiversity in water bodies is preserved, and water harvesting practices increase local water availability for fauna, thereby maintaining habitats and improving agro-ecosystem resilience (Norfolk et al. 2012; Hedhili et al. 2023). Additionally, preventing soil erosion substantially improves soil health (Rajbanshi et al. 2023). Interestingly, the main constraints to adoption of **mechanical soil and water conservation practices** are not primarily financial, although that remains a factor, but rather linked to issues around land tenure and land rights (Ali et al. 2014; Lovo 2016; Deininger et al. 2008; Aker & Jack 2023).

Finally, other sustainable practices come from the circular economy framework and address different – and complementary – impacts on biodiversity. **Waste to animal feed** is the practice of diverting food waste to animal feed. It is collected from sources such as the food processing industry or households, sorted to remove any non-edible or contaminated materials and then processed to make it easier to incorporate into animal feed (e.g., dehydration, ensiling). In decreasing the amount of land needed for animal feed, the main impact on biodiversity comes through land-use change, supporting in the creation and maintenance of habitats for biodiversity. By reducing food waste in landfills, this practice also reduces emissions, contributing to climate and air quality regulation i.e., to public goods. Since the primary impact is through land-use change, a common recommended counterpart is **sustainable manure management**, which does less for land-use change but contributes to pollution reduction and soil restoration – therefore enhancing the circular bioeconomy effects of waste to animal feed alone. Sustainable manure management plays a key role in the circular economy transition by converting organic matter from agri-food systems into energy through biogas plants or – where high technology is prohibitive – into a form easy to apply to soil for soil enhancement through composting. As such, manure compost is one of several possible **organic fertilizers** (see below). While these are two very different activities, they both reverse the negative impacts of manure mismanagement reviewed above by avoiding excessive application of manure in the field. In addition to the circular benefits of producing energy to replace fossil fuels (Tamburini et al. 2020), the practice improves soil and water quality (Tamburini et al. 2020; Lin et al. 2022) and facilitates nutrient cycling. For farmers this means reduced energy costs, improved soil health, and greater agroecosystem resilience.

Composting elements of **manure** management are often bundled with biocontrol (above) as a building block of organic agriculture, alongside other **organic fertilizers**[8]. In addition to managed manure, common types of organic fertilizers used in agriculture are compost and biofertilizers. Compost is made from decomposing and stabilizing different organic substrates, like crop residue and household waste. Biofertilizers contain beneficial microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, that enhance nutrient availability and promote plant growth. Their application enhances the biodiversity in the soil, increasing microbial abundance, which leads to the regulation of detrimental organisms and the improvement of crop resistance to pest and diseases for the farmer. Organic fertilizers increase soil organic matter, and they can prevent soil degradation and groundwater pollution by avoiding salinization and possible nutrient leaching and runoff (Savci 2012). They can also work as soil amendments, improving soil structure (Shepherd et al. 2002; Lekfeldt et al. 2017) and increasing its water retention (Ahmad et al. 2008) and organic matter content. Finally, the reduction of the displacement of chemical fertilizer with organic fertilizers reduces carbon dioxide emissions, attributable to the production of chemical fertilizers (Ball et al. 2004). Finally, replacing synthetic fertilizers with organic ones has even been reported to increase the quality of the agricultural produce in terms of protein and various nutrients for human health (Kurniawati et al. 2023). The key constraints to adoption are financial and socio behavioral. First, synthetic fertilizers are often cheaper per unit of nutrient, which can lead farmers to stay with synthetic fertilizers if the alternative does not have a similar nutrient content (Tur-Cardona et al. 2018) yet comes with higher cost, including higher labor-intensity. Second, organic fertilizers produced from waste can be perceived negatively by farmers who are worried about foul odors (Case et al. 2017) and possible soil contamination (Chen et al. 2020). Finally, the constraints around the movement of organic fertilizers are found to be significant in some countries (Daadi & Latacz-Lohmann 2021; Alewell et al. 2020).

In a similar vein, activities for both **composting and biogas production** are considered labor-intensive, which means that farms in regions facing labor availability constraints are less likely to adopt **sustainable manure management practices** (Cai et al. 2019a; Cai et al. 2019b). The impact of sustainable manure management is almost universally positive, but the size of impact varies considerably under different conditions. When compared to its capital and labor costs, if the analysis is purely financial, its attraction can therefore vary widely. Low adoption also appears to be linked to the perceived lack of environmental awareness in this framework (Cai et al. 2019b), although it is an open question whether poorer farmers in the Global South should pay for public goods. The adoption of waste to animal feed is a further step removed from the farm, it requires landscape coordination and

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[8] Distinct from biofertilizers, and outside the circular economy framework, are biostimulants. Biostimulants enhance a plant's natural processes rather than providing nutrients, like fertilizers. Examples range from seaweed extracts which are receiving increasing scientific and agronomic attention all the way to microorganisms like bacteria and fungi. On the latter, in particular, there remains some controversy in the literature with respect to their nitrogen fixing claims. What is better evidenced are benefits to yields and output quality.

appropriate facilities and processes that go beyond the capacity of any individual farm or household. Widespread adoption therefore requires regulation and investment that few countries have so far undertaken given the scope of the endeavor, despite its manifold benefits.

Table 6 summarizes the potential and application of these sustainable agricultural practices. **Annex 4** provides a glossary of agricultural practices and their impacts on biodiversity.

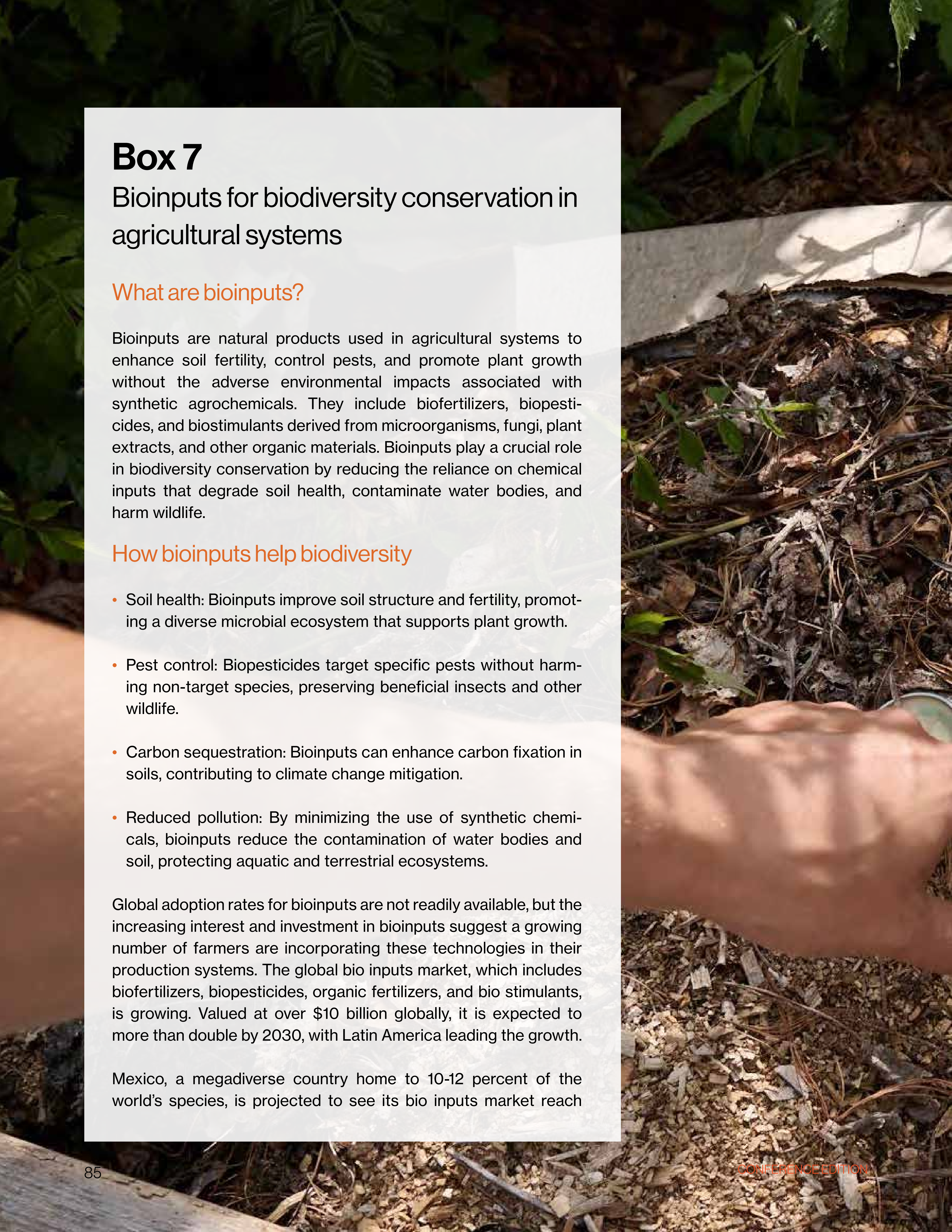
Decades of research and innovation – as well as centuries of Indigenous knowledge and know-how – have produced a plethora of sustainable agricultural practices. The non-exhaustive expose above focuses on practices that address agricultural productivity and resilience for smallholders and hold potential for livelihood-viability for farmers, at least under some conditions.

Table 6. Potential and application of sustainable agricultural practices

If the problem to be solved is....	...the sustainable practices that can help are:	
Nutrient and chemical pollution of soils and waterways, destroying biodiversity needed for ecosystem services essential to agricultural productivity, incomes and resilience then....	• Minimum tillage • Bio control • Organic fertilizer • Green manure • Micro irrigation • Agro-silvo-pastoralism	• Farming with Alternative Pollinators • Sustainable manure management • Integrated Nutrient Management • Integrated Pest Management • Crop rotation • Intercropping
Land-use change that is destroying habitats of critical biodiversity for agricultural productivity, resilience, and livelihoods then....	• Green manure • Mechanical soil and water conservation • Agro-silvo-pastoralism	• Waste-to-Animal Feed • Crop Rotation • Intercropping • Multipurpose trees
Soil degradation, undermining agricultural productivity and livelihoods, then solutions to boost biodiversity that can restore the structure and health of soils can include....	• Minimum tillage • Organic fertilizer • Green manure • Mechanical soil and water conservation • Agro-silvo-pastoralism	• Sustainable manure management • Integrated Nutrient Management • Crop rotation • Intercropping • Multipurpose Trees
Invasive species are choking productivity-enhancing biodiversity then....	• Bio control • Integrated Pest Management	• Crop r otation • Intercropping

4.2 The economics of adoption of sustainable agricultural practices

The **sustainable practices** discussed above were selected also considering their potential for economic feasibility for farmers, either inherently or with appropriate incentives and/or reforms. Research and evidence on economic and financial analysis (EFA) variables are not as thick on



Box 7

Bioinputs for biodiversity conservation in agricultural systems

What are bioinputs?

Bioinputs are natural products used in agricultural systems to enhance soil fertility, control pests, and promote plant growth without the adverse environmental impacts associated with synthetic agrochemicals. They include biofertilizers, biopesticides, and biostimulants derived from microorganisms, fungi, plant extracts, and other organic materials. Bioinputs play a crucial role in biodiversity conservation by reducing the reliance on chemical inputs that degrade soil health, contaminate water bodies, and harm wildlife.

How bioinputs help biodiversity

- Soil health: Bioinputs improve soil structure and fertility, promoting a diverse microbial ecosystem that supports plant growth.

- Pest control: Biopesticides target specific pests without harming non-target species, preserving beneficial insects and other wildlife.

- Carbon sequestration: Bioinputs can enhance carbon fixation in soils, contributing to climate change mitigation.

- Reduced pollution: By minimizing the use of synthetic chemicals, bioinputs reduce the contamination of water bodies and soil, protecting aquatic and terrestrial ecosystems.

Global adoption rates for bioinputs are not readily available, but the increasing interest and investment in bioinputs suggest a growing number of farmers are incorporating these technologies in their production systems. The global bio inputs market, which includes biofertilizers, biopesticides, organic fertilizers, and bio stimulants, is growing. Valued at over $10 billion globally, it is expected to more than double by 2030, with Latin America leading the growth.

Mexico, a megadiverse country home to 10-12 percent of the world's species, is projected to see its bio inputs market reach

nearly $2 billion by 2032, growing annually at 13 percent. The rise in biopesticides demand, which accounts for 79.5 percent of the domestic market of bio inputs, alongside the growing popularity of bio stimulants and biofertilizers, drives this growth. The expanding organic farming sector in the country, which has seen a 30 percent increase in land under organic production since 2018, further boosts bio input adoption.

At the farm level, surveys across 22 countries in Latin America suggest that producers see bioiputs as an opportunity to reduce production costs and enhance agricultural yields. However, barriers to adoption are multiple.

Farm-level adoption challenges

- Knowledge and training: Farmers need education on the benefits and application of bioinputs.
- Regulatory barriers: Complex registration processes for bioinputs can hinder their adoption.
- Financial constraints: Initial investment costs for bioinputs can be prohibitive for smallholder farmers.
- Market availability: Limited availability and inconsistent quality of bioinputs

Economic viability of bioinputs by type

- Biofertilizers: These are economically viable as they can be produced locally using organic waste, reducing dependency on expensive synthetic fertilizers.
- Biopesticides: While effective, their production requires specific knowledge and technology, making them more costly than conventional pesticides. However, their long-term benefits in reducing pest resistance and environmental damage can offset initial costs.

the ground as would be desired but there are enough studies that provide data on the costs and returns of these practices to warrant their inclusion in decisions around sustainable agriculture. Furthermore, a recent meta-analysis (Rosenstock et al. 2025) found a statistically significant increase in profits (and costs) across all sustainable practices considered in their linear mixed effects model. Unfortunately, if a given site or situation only merits the implementation of some practices and not others, such an outcome is not enough to inform investment or policy decision. It does, however, reinforce the direction of profitability and revenues found in the literature on individual practices. **Annex 5** provides a glossary of the economic variables for which evidence was sought in the peer-reviewed literature on the economic and financial returns of sustainable agricultural practices including: benefit to cost ratio; cost; internal rate of return; net present value; payback period; product price; profit; revenue; pesticide use; water use; fertilizer use; yield. It covers as many of the practices discussed above as possible and includes relevant results from other complementary practices – such as improved seeds and genetic diversity. Most of the literature documents economic information for single practices with the greatest focus on a minimum tillage and organic fertilizers, with several practices having only one analysis each (biocontrol, Farming with Alternative Pollinators, green manure, and waste to animal feed). Yet others, notably, micro irrigation and multipurpose trees, were not discovered in the literature reviewed. Asia had the highest number of analyses, followed closely by Africa, and then Europe, North America, and South America. The available evidence on bundled practices is relatively less, with "climate-smart agriculture "and "organic farming" having received the most attention.

Not every variable in Annex 5 is available in every study and the definition of variables across studies varies as well. Given these caveats, existing rigorous evidence can be used for indicative purposes and the summaries of curated studies are available and should be assessed for applicability to specific investment decisions of a given practice. The overview of the evidence, rather, serves to provide indicative trends in the economic and financial returns of (largely) individual sustainable agricultural practices. One thing that the evidence makes clear is that programs that aim to implement and scale sustainable practices should undertake context-specific EFA as a matter of priority (see Chapter 6 recommendations).

Evidence-based returns on sustainable agricultural practices

Most sustainable agricultural practices demonstrate positive financial returns under at least some of the conditions studied. While not all studies documented all indicators such as profits, benefit cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and payback periods, these generally favored sustainable agricultural practices, as did the meta-analysis cited above. More specifically, first there are practices for which returns are consistently higher as compared to conventional agriculture. Practices such as crop rotation, mechanical soil and water conservation, improved seed varieties, agro-silvo- pastoralism and agroforestry (i.e., even without livestock) consistently outperformed conventional practices in terms of profitability and returns on investment. Even among all these positive outcomes, however, certain economic indicators could vary according to local conditions and affect the magnitude, but (often) not the direction, of impact. For instance, intercropping systems' financial return outcomes varied largely due to yields in Tanzania. That is, while costs increased across the board in Tanzania, yield outcomes varied by site, causing profitability to vary, albeit in size and not direction (NPV and IRR always remaining higher in all cases than that of conventional agriculture)[9].

Bundling multiple sustainable agricultural practices (SAPs) was also found to consistently improve profitability and reduce variability across financial indicators by harnessing complementarities among individual practices. When integrated, complementary practices such as minimum tillage, improved seed varieties, soil conservation, and integrated nutrient management (INM) produce stronger, more stable financial outcomes compared to their individual implementation. For instance, studies in South Asia demonstrate that bundling minimum tillage with stress-tolerant improved seed varieties in rice-wheat systems increased yields by 16–17 percent, more than offsetting a modest 6 percent rise in costs, ultimately enhancing profitability relative to conventional methods. Additionally, some studies looked at differently named categories of practices, such as either "CSA" or organic farming, and these also outperformed, although what different studies considered to be CSA or organics varied, complicating an overview result, and reinforcing the utility in looking at individual practices or bundles as units of different categories and approaches.

Next, there are practices that show variability of financial outcomes. That is, practices for whom different indicators were neither consistently positive – as above – nor consistently negative. This ambiguity holds valuable information. First, it reinforces the critical point that financial and economic analyses specific to local conditions must be conducted with care. Second, the variability itself holds information on the determining factors on the size and direction of financial returns to farmers. Table 7 shows the sources of variability in outcomes drawn from empirical studies that showed variation in the profitability/unprofitability of some sustainable agricultural practices.

Observed variability in the financial returns of some sustainable practices therefore point to the most germane factors in considering profitable adoption of given sustainable agricultural practices. Some practices under study had profitability outcomes that clearly varied with the use of complementary practices (e.g., minimum tillage). In others, crop type or farm system were key. For example, minimum tillage in Ghana showed negative NPV and IRR due to declining watermelon yields, while wheat under minimum tillage in the same country had a positive NPV and IRR. Conservation agriculture (CA), which integrates practices like no or reduced tillage, cover crops, and crop rotation, similarly displays highly context-dependent economic performance. CA tends to reduce variable costs by saving labor and fuel, but farmers might need to invest in specialized machinery and face a learning curve. Short-term yields can decline initially, especially if weed or nutrient management is suboptimal in early adoption phases. In small-scale or manual farming settings, maintaining yields has often proven challenging. As a result, external support through training or subsidies often plays a critical role: studies have shown that without such support, initial losses may occur, whereas payments can buffer farmers until soil health improvements translate into higher yields. Over time,

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[9] There were other practices with positive financial returns, but whose results were based on only a single analysis. This is the case for outcomes for biocontrol and farming with alternative pollinators, both of which were positive based on the single study included in the peer reviewed literature review in Italy and China respectively. In some single study practices, outcomes showed mixed results depending on crop or livestock variety (a factor): Yield under green manure varied depending on crop type in Canada. Waste-to-animal feed showed mixed results in Ghana, with an increase in the number of sheep but no observed change for cattle.

CA typically improves soil structure and moisture retention, potentially boosting yields and profitability, although outcomes continue to vary widely by crop and environment. In the case of integrated farming systems in India, the value of NPV varied depending on the combination of crops grown in the integrated system and on the size of the farm. In other cases, cost variability was the driver.

Table 7. Variability of outcomes

Practice	Key financial metrics	Sources of variability	Time horizon consideration
Single practices			
Minimum tillage	NPV, IRR, cost	Yield outcomes are highly dependent on crop and conditions; Upfront costs can be high, which may hinder profitability until soil structure or moisture management improves so that the point in time at which the study took place impacts the picture on returns to the practice	Profitability improves over time or with support
Intercropping	NPV, profit, cost	Yield responses vary by crop; level of mechanization inversely affects costs (if farms depend largely on labor, then implementation raises costs, less so in mechanized systems) some systems* yield strongly positive returns	Often requires multi-year adjustment before consistent positive financial outcomes are realized
Integrated pest management (IPM)	Cost savings, yield, IRR	Reduces pesticide use so costs vary as a function of original pesticide use; results also depend on pest control effectiveness and farmer training	Cost-effective in longer term with investments in training
Integrated nutrient management (INM)	Yield, input cost, NPV	Replaces at least some inorganic input with organic, lowering costs; soil quality improves slowly (3+ years with consistent application)	Short-term profitability maybe limited; positive over time with correct implementation and capacity building and support
Organic fertilizers	Profit, cost savings	Lower input costs; profitability depends on market price and yield stability	Moderate to long-term benefit. Typically reach consistent profitability after several years (often 3–5), as soil fertility builds, yield stabilizes, and market premiums are realized
Bundled practices			
Conservation agriculture (bundled minimal tillage + cover cropping + rotations)	BCR, NPV, costs, yields	Mixed results; reduced variable costs (saving labor and fuel), but farmers might need to invest in specialized machinery and face a learning curve challenging in small scale or manual farming settings	2–5-year horizon often needed for results

* The literature shows that diversified subsistent and semi-commercial (Ghana and Tanzania) and supported by studies in Viet Nam and Uganda

Costs varied widely by the type of practice and the type of cost, ranging from installation costs, operating costs, maintenance costs or input costs. The stage at which the costs were incurred also played a role in the outcomes of costs for SAPs. Practices such as organic fertilizer, organic farming, integrated pest management (IPM), green manure, and sustainable manure management reported a decrease in input costs like fertilizers, herbicides and water usage. **This reduction in the**

dependency on inputs was the main driver of the reduction in total costs for sustainable agricultural practices that reduce dependency on synthetic inputs. For instance, while costs consistently decrease with the use of IPM and INM, the realized levels of cost savings depends on how much inorganic and chemical input was used conventionally in a given locale for a given crop. The same goes for the additional work involved in intercropping, with labor costs increasing inversely with the level of mechanization in a given baseline conventional farming system. A very important driver, however, is that of yield variability.

Unsurprisingly, yield responses to sustainable agricultural practices are a key determinant of their financial viability. As with conventional agriculture, crop type, environmental conditions, farm size and farming systems were factors that determined the outcomes of yield. Of note is the role of improved seed in further raising the returns to biodiversity-friendly practices. As expected, the yield performance of sustainable practices is influenced by weather affecting the magnitude and sometimes direction of benefits as compared to conventional agriculture. In Nepal, rice grown under zero tillage benefitted from monsoon rains, which provide sufficient nutrients despite reduced soil disturbance under minimum tillage. Wheat yields, however, decline under zero tillage during the drier winter season, when the absence of rain means that the soil aeration and water infiltration does not take place at all. Some studies have shown that using improved seed varieties together with crop rotation showed the most consistent positive trends in yield. Organic farming and organic fertilizers generally resulted in decreased yields, however, cost reductions in fertilizer inputs and price premiums for organic products often offset the losses from decreases in yield, and the practices still reported profitable returns in most analyses. For example, ancient wheat varieties in Italy and medicinal plants in Mongolia commanded higher market prices which offset the costs of lower yields. Although many studies did not report on temporal dimensions of yield, the few that did, found that **yields increase over time, in part driving the result on profitability over time discussed above**. In India, organic farming had higher yields than conventional systems using synthetic fertilizers over a seven-year period. Similarly, integrated nutrient management (INM) and sustainable manure management in Kenya showed steady yield increases over a 21-year period. This suggests the probability of potential of long-term productivity improvements when SAPs improve soil health, that needs to be considered in EFAs. It also suggests risks and vulnerabilities associated with short-term losses must be carefully weighed and mitigated.

Results vary importantly for net present value for all these factors but importantly due to discount periods: Longer periods favor higher returns for sustainable practices, reflecting investments in biodiversity and soil. While NPVs were generally higher for sustainable agricultural practices, as compared to conventional agricultural practices (SAPs), **the payback periods were longer compared to conventional systems**, meaning it takes more time for farmers to recoup their investments. In Indonesia, organic farming has a payback period of eight years. In Tanzania, Ng'ang'a et al. (2020) report a payback period of five years for early maturing soybeans and seven years for late maturing soybeans. Practices studied under (varying) bundles of CSA practices are also characterized by longer payback periods in comparison to conventional methods. The payback period for CSA practices ranges from 2–4 years, while conventional practices typically have a shorter payback period of 1 year. This trend indicates that while SAPs offer long-term financial benefits, **higher initial investments may act as barriers to adoption**. It also indicates that conventional economic and financial analyses should factor in declining soil fertility under conventional practices that degrade soil over time, whilst EFAs should correctly capture rising productivity over the same time period. One study from the EU finds that support to the profitability of farmers in the short run for conservation agriculture, secures long term food security through preserving soil fertility and soil productivity and this needs to be reflected in calculating overall investment returns. Specifically, that profitability or other financial indicators varied over time with returns increasing over conventional agriculture only after a certain (longer) time period has elapsed. As such, considerations like levels of extreme poverty and/or fragility might inform decisions against adoption, just as managing transitional losses might be more attractive where soil health and soil restoration for future agricultural productivity gains is high on the agenda.

This temporal dimension plays also into the cost question. For sustainable agricultural practices requiring one-off or short-term capital investments, implementation costs were higher when compared to conventional practices. This appears true for intercropping, integrated farming systems, crop rotation and minimum tillage. In the absence of input-related savings, implementation costs can sometimes be a barrier to adoption. In Tanzania, for example, maize-soybean intercropping incurred higher implementation costs than the business-as-usual scenario, with installation costs being the largest expense, followed by maintenance and operational costs. Despite higher long-run returns, adoption was problematic. This result is repeated throughout Sub-Saharan Africa, where farmers were found unlikely to adopt sustainable manure management as the increased initial costs of implementation compared to their current practice of applying fertilizer to the soil was a barrier for risk-averse farmers. Crop rotation also saw increased implementation costs in Viet Nam, Uganda, and Tanzania. Despite higher initial costs for these practices, profits were generally greater than for conventional practices. In the case of minimum tillage, high upfront investment costs for labor and equipment led to negative NPV and IRR, while declining short term yields meant that costs could not be covered without a subsidy in Italy and Germany.

Both bundling and unpacking are key to making use of what is known about the financial and economic potential of sustainable agricultural practices. In terms of unpacking, the best use to be made of the evidence that does exist is not to make spurious generalizations – which the above tries to avoid – but to look at the limited number of rigorous EFA analyses, made easily accessible in this link – to see if similar conditions and lessons apply to an investment under consideration. In the case of organics, for instance, there is robust evidence on the decrease in input costs which boosts farmer profitability overall despite frequent results on decreased yield. If, however, food availability is a concern at scale, then unpacking the drivers of profitability is important: Yield (output) loss is a consideration in the decision to invest in organic fertilizers when the short-term quantity of food available is a concern. In other cases, sustainable agricultural practices have been shown to better meet urgent food needs over conventional. For example, zero tillage fields can be harvested before conventionally tilled fields, helping to mitigate food shortages and raise incomes in lean pre-harvest times.

Finally, as mentioned, bundled practices generate the most consistent (across studies) returns. Table 8 looks at the outcomes of studies found on bundled practices. While the discussion above reflects the wide variety of results on the economic outcomes of (mainly) single practices, of immediate note in **Table 8** is the rise in consistency (similar colors) across different study outcomes on the same variables, regardless of the composition or type of bundle and regardless of geographic location.

Table 8. EFA outcomes from bundled practices: Direction of change compared to conventional practices

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Bundled practices	Indicator	Country	Crop type
Mechanical soil and water conservation, minimum tillage, improved seed variety	BCR	Pakistan	🟩 Cotton Wheat | Rice Wheat | Maize Wheat
Improved seed variety, mechanical soil and water conservation	Profit	India	🟩 Rice Wheat
Mechanical soil and water conservation, minimum tillage, improved seed variety	Profit	Pakistan	🟩 Cotton | Wheat
Improved seed variety, mechanical soil and water conservation	Cost	India	🟥 Rice Wheat
Mechanical soil and water conservation, minimum tillage, improved seed variety	Cost	Pakistan	🟨 Rice Wheat
Mechanical soil and water conservation, minimum tillage, improved seed variety	Cost	Pakistan	🟨 Rice Wheat
Integrated nutrient management, mechanical soil and water conservation, minimum tillage, improved seed variety	Revenue	Pakistan	🟩 Rice Wheat
Crop rotation, agro-silvo-pastoralism	Yield	Canada	🟩 Potato Beans
Improved seed variety, minimum tillage	Yield	India	🟩 Rice Wheat
Mechanical soil & water conservation, minimum tillage, improved seed variety	Yield	Pakistan	🟩 Rice Wheat
Sustainable manure management, mechanical soil and water conservation	Yield	Tanzania	🟩 Banana | Maize | Beans
Mechanical soil and water conservation, improved seed variety, intercropping	NPV	Malawi	🟩 Maize Pigeon pea
Minimum tillage, intercropping, improved seed variety	NPV	Mozambique	🟩 Maize Pigeon pea
Mechanical soil and water conservation, improved seed variety, intercropping	NPV	Zambia	🟩 Maize Pigeon pea
Minimum tillage, crop rotation, improved seed variety	IRR	Malawi	🟩 Maize Ground nuts
Minimum tillage, crop rotation, improved seed variety	IRR	Mozambique	🟩 Maize Soybean Beans
Improved seed variety, crop rotation	IRR	Zambia	🟩 Maize Soybean

Cotton Wheat Maize Rice Potato Banana Beans Pigeon pea Ground nuts Soybean

For instance, similar bundles for different countries and even different crops, all resulted in similarly positive returns across economic variables.

Conclusion

164.156.The evidence on economic and financial returns to sustainable agricultural practices, as compared to conventional agriculture, is available from most regions in the world and for a variety of crops. Most sustainable practices show positive overall returns under given conditions and in different countries. Bundling multiple practices seems to make these positive outcomes more consistent. The evidence also shows that for some practices, the impact on profitability and livelihood can vary in direction – bringing gains or losses depending on local conditions. The best use of the evidence available, therefore, is to reference the specific conditions under which different practices have been tested for livelihood viability, in order to inform each investment-specific economic and financial analysis. Overall, there is sufficient evidence of positive livelihood potential, however, to support the consideration of the sustainable agricultural practices discussed here. The second important conclusion from the empirical evidence is that sustainable agricultural practices often present short-term trade-offs, when initial yield losses or high start-up costs depress production and profitability, respectively. In these cases, strategies to manage these trade-offs are necessary (see Chapter 6).

Scientific evidence establishes the beneficial linkage between sustained and improved biodiversity and ecosystem services that support agricultural productivity and livelihoods. Furthermore, these are often profitable under the right conditions. The answers to the obvious question as to why all agriculture is not conducted using sustainable agricultural practices can also be inferred from the evidence reviewed. These include (i) the temporal dimensions of both upfront investment needs and time-lagged yield improvements; (ii) the complexity of implementation and learning curves; and (iii) underlying incentives.

The (i) temporal dimension related to those practices with high up front (private) investment needs speaks to access to finance instruments that understand the time lagged nature of returns and can work with farmers on repayment schedules, as well as risk sharing facilities for financial services providers. Even when upfront investment costs can be met, the impact of time lagged returns on short run incomes, vulnerability and food security are an important factor in widespread adoption. Compensating farmers for their transitional losses has a strong public goods dimension given national productivity, climate resilience and landscape restoration goals, as well as biodiversity externalities. Further, in the case of food insecurity and high vulnerability, in kind compensation for any temporary yield losses would be needed to overcome legitimate hesitation in rural households to convert to sustainable agricultural practices. These measures point to the need and potential for repurposing and subsidies (see Chapter 5) to compensate farmers for short term losses undertaken for long term national goals. Repurposed expenditure can also be directed to public investments like better roads to reduce transport costs to market. One last temporal aspect relates the next main category of barriers to entry – implementation complexity – and it refers to the need for a long-haul perspective. While the evidence attests to low hanging fruits in the immediate term in several sustainable practices (e.g., a second remunerative crop with intercropping), significant superior returns to the agricultural sector and the livelihoods it supports – as well as positive externalities – are achievable over a period of time ranging from 2 to 21 years.

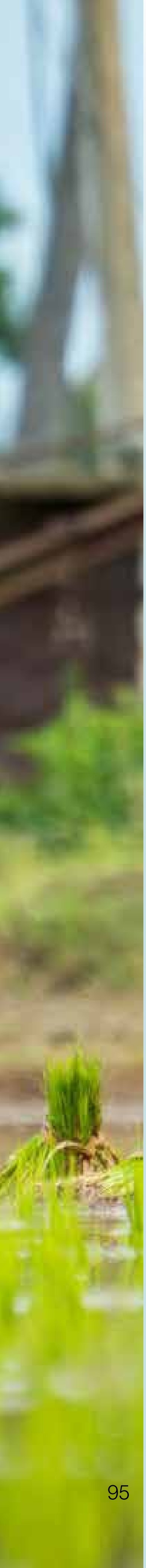
The evidence points to multiple sustainable practices requiring strong and sustained technical support for farmers. This implies a number of shifts in traditional extension strategies and in the strategies of the development partners and donors that support them. Extension strategies need to be cost effectively designed to address the need for multiple, repeated and frequent instruction over the seasonal and multi-year implementation of some sustainable agricultural practices. To the extent that these use improved genetics and equipment, leveraging private sector extension advisory from these input providers, as well as deploying the wealth of digital and AI tools being developed will be essential so that farmers have consistent support and accompaniment. In turn, this requires the extension and advisory strategy to include strong capacity and training support for the public extension workforce on the empirical and productive link between biodiversity conservation, agricultural productivity and livelihood gains. The "why" of significant change as well as training in the change itself needs to happen at the level of extension and advisory professionals and can be incentivized through learning-leaves, country-to-country internships and field visits and other stimulating capacity provision. Further upstream still, agricultural educational curriculum in university and colleges need to be updated with the why and wherefore of these sustainable agricultural practices and their future demand to attain national goals. This "modern" turn holds potential to interest a generation of youth widely aware of climate change threats and the need for environmental stewardship of the land. All of this implies a program, spanning decades and even – in the case of higher education – generations. While a number of sustainable practices result in immediate yield gains and/or cost reductions ("quick wins"), even these only achieve their truly superior returns when all practices in their 'bundle' have time to come to fruition. The current focus on quick wins, while remaining important to incentivize and encourage change, needs to be reconsidered in light of the need for sustained time and attention to making biodiversity driven agricultural productivity and resilience a reality. **Box 8** provides a case study on integrated nutrient management.

Annex 4 provides case studies on mechanical soil and water conservation and crop rotation.

4.3 Restoration for agricultural production

Degraded lands are an untapped resource for production agriculture. Restoration of agricultural land can enhance biodiversity by sparing land and reducing pressure for land use change. Although degraded lands generally support less biodiversity than natural areas, they can support biodiversity levels similar to or even above those of surrounding managed landscapes. The restoration of the Loess Plateau in China is one of the most significant and successful examples of large-scale restoration. This project, supported by the World Bank, addressed severe land degradation and improvement of agricultural productivity in one of China's poorest regions (see restoration case studies **Annex 8**).

Restoration of land is a slow process (Wu et al. 2018). The benefits of restoration occur over an extended period so long-term as well as shorter term benefits must be considered (Mansourian and Elias 2024). Global land restoration efforts and plans should therefore invest sufficient time allowing programs to attain their goals.



Box 8: Case study

Integrated nutrient management in India's rice-wheat belt

Location	Impact period	Relevance
Haryana and Punjab, India	11 years	Policy makers, agricultural extension services, donor organizations, smallholder farmers in intensive cropping regions

Key results at a glance				
22 percent average yield increase in rice-wheat systems over a decade	Enhanced soil organic carbon by 25-30 percent across study plots	Reduced synthetic nitrogen use by 15-20 percent with no yield penalty	Improved soil fauna biodiversity, particularly earthworms and microbes	Higher water-use efficiency and reduced input costs by 10-15 percent

In the intensively farmed Indo-Gangetic Plain, decades of over-reliance on chemical fertilizers degraded soils and reduced yields in rice-wheat cropping systems. To reverse this, the Indian Council of Agricultural Research (ICAR) and local Krishi Vigyan Kendras (farm science centers) implemented Integrated Nutrient Management (INM) through participatory trials. Farmers combined organic inputs – such as farmyard manure, crop residues, and green manures – with balanced chemical fertilizer use and crop rotation involving legumes. This holistic soil fertility management approach not only boosted yields and farmer incomes but also played a pivotal role in reversing biodiversity loss and enhancing ecosystem services essential for long-term agricultural productivity.

INM directly mitigated biodiversity loss by restoring soil health. Reduced use of synthetic nitrogen and better organic matter incorporation increased soil microbial and macrofaunal communities. This underground biodiversity improved nutrient cycling and soil structure, enhancing water retention and root health.

Crucially, the diversification of crop rotations – such as integrating pulses – supported aboveground biodiversity by breaking pest cycles, reducing chemical pesticide reliance, and increasing floral diversity. These changes improved key ecosystem services like pollination, water flow regulation, and habitat maintenance, reinforcing agricultural resilience under climate stress.

Policy takeaway

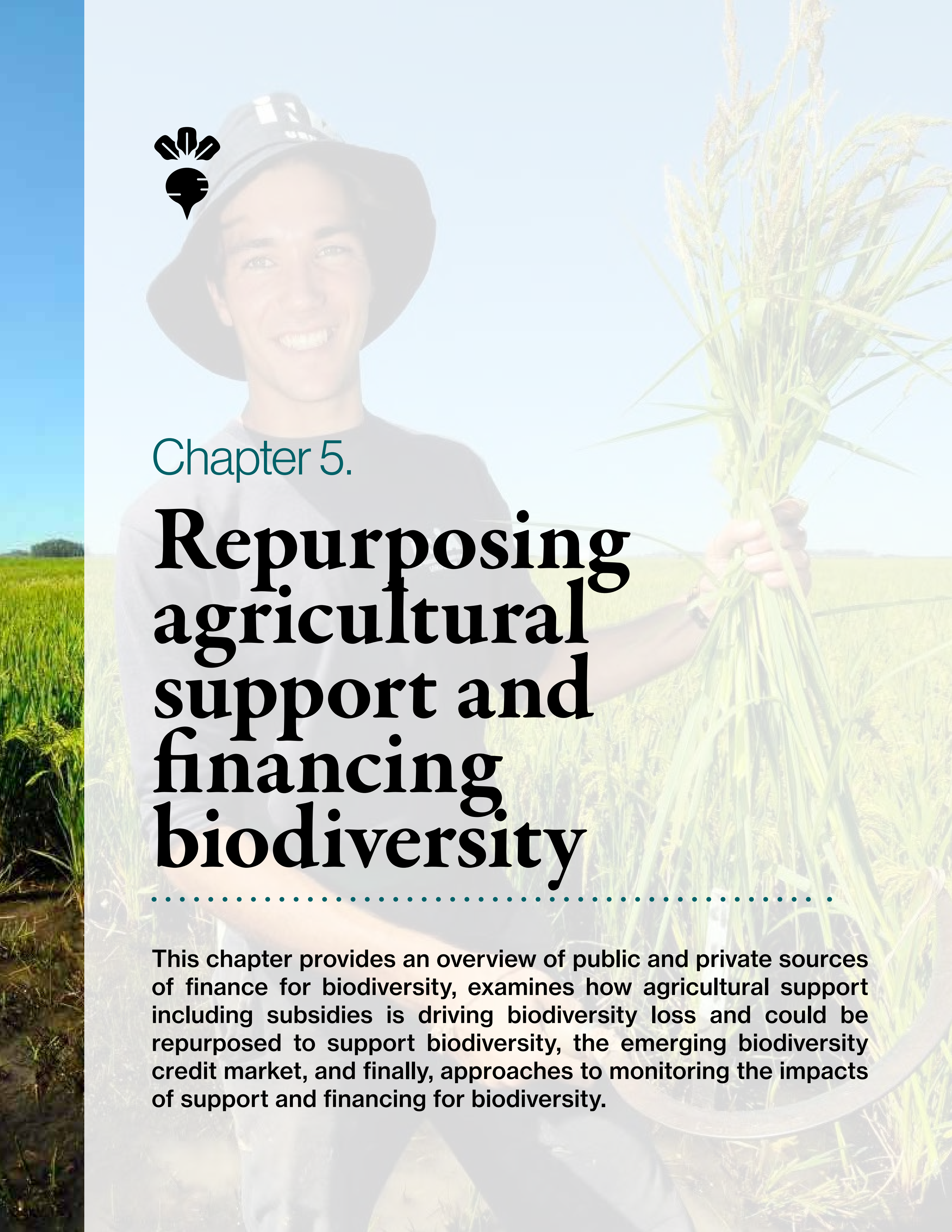
Integrated Nutrient Management should be embedded in national soil health and agricultural extension programs, with incentives for diversified rotations and organic input use to sustain yields and biodiversity jointly.

Reference: Indian Council of Agricultural Research (ICAR), 2019. Synthesis Report on Long-Term Fertilizer Experiments and Integrated Nutrient Management in the Indo-Gangetic Plains.

Silvo pastoralism is an example of an agricultural production system that can contribute to the restoration of agricultural land. This is an innovative approach to cattle ranching that integrates planting of trees, shrubs, and grasses among fodder crops to create sustainable and productive environments. Through restoration efforts by the World Bank, the Loess Plateau, an area of dry powdery wind-blown soil in China's Northwest, was transformed into productive agricultural lands, restoration of natural resources and ecosystem services that led to increase in food production and employment generation.

Degraded surface mines can potentially be restored for biomass production but appropri**ate approaches for enhancing biodiversity in such degraded areas are poorly understood.** By using degraded surface mines for biomass production, they have potential to deliver considerable ecosystem services and environmental and socioeconomic benefits. Selective plantation, application of various soil amendments to the topsoil, and use of native species can enhance recovery of mine degraded land, stress tolerance, climate resilience and maximized ecosystem services (Ahirwal and Pandey 2020).

Indigenous Peoples and communities are central to success restoration approaches. The role of Indigenous knowledge is exemplified by Yacoub Sawdogos' application of the "zai" technique for restoration (see Great Green Wall Initiative case study Annex 8).



Chapter 5.

Repurposing agricultural support and financing biodiversity

This chapter provides an overview of public and private sources of finance for biodiversity, examines how agricultural support including subsidies is driving biodiversity loss and could be repurposed to support biodiversity, the emerging biodiversity credit market, and finally, approaches to monitoring the impacts of support and financing for biodiversity.

5.1 Biodiversity finance

Biodiversity finance encompasses a wide range of financial instruments whose primary or secondary objective or co-benefit is to conserve biodiversity. According to the OECD, biodiversity finance covers financial flows from all actors in biodiversity-relevant sectors – public, private, domestic, and international (OECD 2020).

Finance solutions include diverse instruments including loans, grants, debt/equity, debt-for nature swaps, fiscal mechanisms (subsidies), market mechanisms (payments for environmental services, credits), results-based payments, regulatory fines, risk management instruments and guarantees, as well supply-chain finance.

Despite nature and biodiversity's significant value to the economy, current financing flows that are harmful to nature far exceed nature-positive finance. In 2022, global financial investments that harm nature (public and private) were found to be about 30 times the level of investments in nature-based solutions of approximately $200 billion to implement national biodiversity strategies and action plans (UNEP 2023).

The Kunming-Montreal Global Biodiversity Framework (GBF) adopted in 2022 sets ambitious targets, yet these are well below the estimated need to halt biodiversity loss. These include:

- Bridging the biodiversity financing gap of $700 billion per year;
- Reforming $500 billion of harmful incentives by 2030;
- Mobilizing at least $200 billion per year by 2030;
- Increasing official development assistance per year to $20 billion by 2025 and $30 billion by 2030.

Biodiversity finance falls far short of requirements. In 2024 the biodiversity financing gap between current levels and what is needed in 2030 was updated and estimated to be about $942 billion per year. This is the case even though annual financial flows for biodiversity are increasing with an estimated $208 billion in 2022-83 percent of which is provided by the public sector (Bromley 2024).

Official development assistance (ODA) is growing but not in reach of the GBF $20 billion 2025 annual target for biodiversity (OECD 2020). Debt-for-nature swaps, in which emerging economies can restructure debt at a lower interest rate or longer maturity on the condition of allocating proceeds to biodiversity, have seen significant growth in the last few years with record levels of sovereign debt of $2.3 billion canceled in 2023 (Bromley 2024). The issuance of biodiversity bonds[10] have also grown substantially reaching $152 billion in 2023.

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[10] Referring to any sustainable bond with a terrestrial and aquatic biodiversity conservation use of proceeds of biodiversity KPI.

New multilateral funds linked to the Convention on Biological Diversity (CBD) for public and private finance have been created, but funding levels are still low and uncertain. Funding of the Global Biodiversity Framework Fund (GBFF) remains very low with new pledges of $163 million adding to the previous $220 million. At COP 16 a new *Cali Fund* was launched to share benefits from digital genetic information. Under the agreed-upon guidelines, large companies using digital sequence information on genetic resources (DSI) such as pharmaceutical, cosmetics, biotechnology, and agribusiness sectors (animal and plant breeding) should contribute 1 percent of their profits or 0.1 percent of their revenue to the fund. At least half of the funding is expected to support the self-identified needs of Indigenous Peoples and local communities. A new Brazil-led *Tropical Forests Finance Facility* (TFFF) backed by five countries (OECD 2024) at COP16 will reward developing countries for keeping forests.

Leveraging private sector finance

There is a strong economic case for investing in biodiversity that provides a rationale for public finance. Economies and livelihoods depend on nature, and biodiversity enables nature to be productive, resilient, and adaptable. About $58 trillion, equivalent to 55 percent of global GDP, is highly or moderately dependent on nature and its services many of which are public goods (Evison et al. 2023).

There is also a strong financial case that should drive further private finance, but information and market failures need to be addressed to realize this potential. The World Economic Forum's (WEF) Global Risks Report 2024 ranks "biodiversity loss and ecosystem collapse" as the third biggest long-term global risk. More than 50 percent of the loan portfolio of banking systems in 20 emerging markets were found to be highly exposed to nature-related risk (Calice et al. 2023). At the same time there are also significant opportunities to invest. The WEF estimates that nature-positive transitions could yield up to $10 trillion in annual business value and create 395 million jobs by 2030 (OECD 2024).

The World Bank has proposed a two-pronged approach to biodiversity finance: greening finance through better management of biodiversity risks and financing green by monetizing financial returns from ecosystem services.

- **Greening financing: The private sector needs to incorporate biodiversity risks into investment decisions through measurement and reporting.** The Taskforce on Nature-related Financial Disclosures (TNFD) has developed recommendations on disclosures, taking a "double materiality" approach that requires companies to both disclose the nature-related risks they face and the company's impact on nature (TNFD 2024). Although there is progress with over 400 companies having started reporting or committed to reporting under TNFD by 2025, a recent analysis of the 200 largest lenders to at-risk sectors for biodiversity shows that three-quarters have no or only weak publicly stated environmental lending policies related to the risk areas of deforestation, water use, and pesticides (TNFD 2024; Bromley 2024). Country policies can enhance the scale and quality of "greening finance" by providing relevant regulatory frameworks, disclosure, and due diligence requirements and taxonomies to mandate greater compliance while also providing data, evidence on good practice, and promoting multi-stakeholder dialogue all with a view to lowering the cost of complying with good practice and facilitating adoption at scale.

- **Financing green: Most biodiversity-targeted private finance instruments ("financing green") are growing from infancy stages.** Impact investing, some of which has focused on biodiversity-positive outcomes, exceeds $1 trillion (Hand et al. 2022). Some specialized investors in agriculture incorporate biodiversity in their investment criteria.[11] At least 14 funds, representing about $1.6 billion in assets directly fund biodiversity and natural capital, a growing number, but still tiny compared to at least the 1,100 climate funds with around $350 billion in assets (Stewart 2022). Less than 1 percent of the green debt market is allocated toward biodiversity conservation (Williams et al. 2022). Public funding can support evidence to inform pipeline development, data availability, and good practice development for measurement, reporting, and verification (MRV). In view of biodiversity conservation's large public benefit, targeted public funds including blended finance or guarantees from MIGA or IFC are also warranted to de-risk private investments.

The GBF objectives on financing include a specific focus on agricultural incentives. Target 18 of the Kunming-Montreal Global Biodiversity Framework aims to cut harmful incentives by at least $500 billion annually by 2030 and increase positive incentives for biodiversity conservation and sustainable use. The next section takes a closer look at how agricultural support incentives are causing biodiversity loss and how their repurposing could help to mitigate land use change and unsustainable agricultural practices driving biodiversity loss.

Biodiversity credit markets discussed further in Annex 9 are an emerging results-based finance tool that has gained increasing attention. While interest in biodiversity credits has picked up since the agreement of the GBF and several initiatives have been launched to aid biodiversity credit market development, the demand for credits has been slow to develop and corporate demand has lagged behind expectations. Meeting such criteria for environmental integrity is already highly challenging for carbon credits and will be more complex for biodiversity credits with a much a heavier data burden. Market governance bodies are not yet established, which risks the integrity of the biodiversity outcomes.

5.2 Agricultural support that threatens biodiversity

Agricultural support impacts biodiversity by incentivizing the allocation of land, water, and inputs by producers. Much of the current global public support is through instruments and mechanisms that are distortive, contribute to inefficient allocation resources and have a high environmental footprint (Natures Frontier 2023).

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[11] For instance, Agricultural Capital and SLM Partners.

Composition of agricultural support and its effects on biodiversity

In 2022, net global producer support and general support to the sector was $513 billion. Countries use a broad range of instruments to support agriculture. Figure 9 shows the composition of support across broad categories over the 2000–2022 period. For 78 countries[12] around 78 percent of the support was through budgetary outlays (which include producer subsidies for input and output or income transfers, general support including spending on research, extension, and infrastructure) while the remaining 22 percent was through non-budgetary measures[13] (which includes non-budgetary support is through market price support using policy instruments, like price control or trade tariffs, which influence the farmgate price (the price of the products sold directly from the farm).

More than 80 percent of producer support was linked to production, which distorts land use, the composition of production, and the allocation of water and inputs. These support instruments are extremely distortive and incentivize economically inefficient over-production through agricultural expansion or increased input use, threatening biodiversity. Market price support was the predominant instrument used – this was followed by coupled budgetary support such as input subsidies for fertilizer, energy, water, and credit among others. Support to specific commodities also distorts relative incentives across crops and can lead to monoculture, negatively impacting biodiversity.

Production-linked subsidies are responsible for the loss of 2.2 million hectares of forest per year (Druckenmiller, H. 2021). If current patterns of support continue, more than 56 million hectares of land are projected to be converted to agriculture between 2020 and 2040, impacting critical reservoirs of biodiversity (Gautham et al. 2022).

Input subsidies have large negative spillovers estimated at almost 10 percent of global GDP. Input subsidies on fertilizers have led to overuse where more than half of global agricultural production occurs in areas where the marginal benefit of additional fertilizer is negative (Zaveri 2025). Input subsidies are responsible for up to 17 percent of nitrogen pollution in water (ibid). Agriculture also accounts for 70 percent of all freshwater withdrawals, and poorly targeted energy and production subsidies have led to depletion of groundwater. For instance, output subsidies have led to a 30 percent overproduction of water-intensive crops in India (Rodella et al. 2023).

Decoupled support is least distortive but represents a small share of producer support. Some components of general support services can help address biodiversity loss. Decoupled support does not distort relative incentives across various inputs or encourage over or under-use of inputs.

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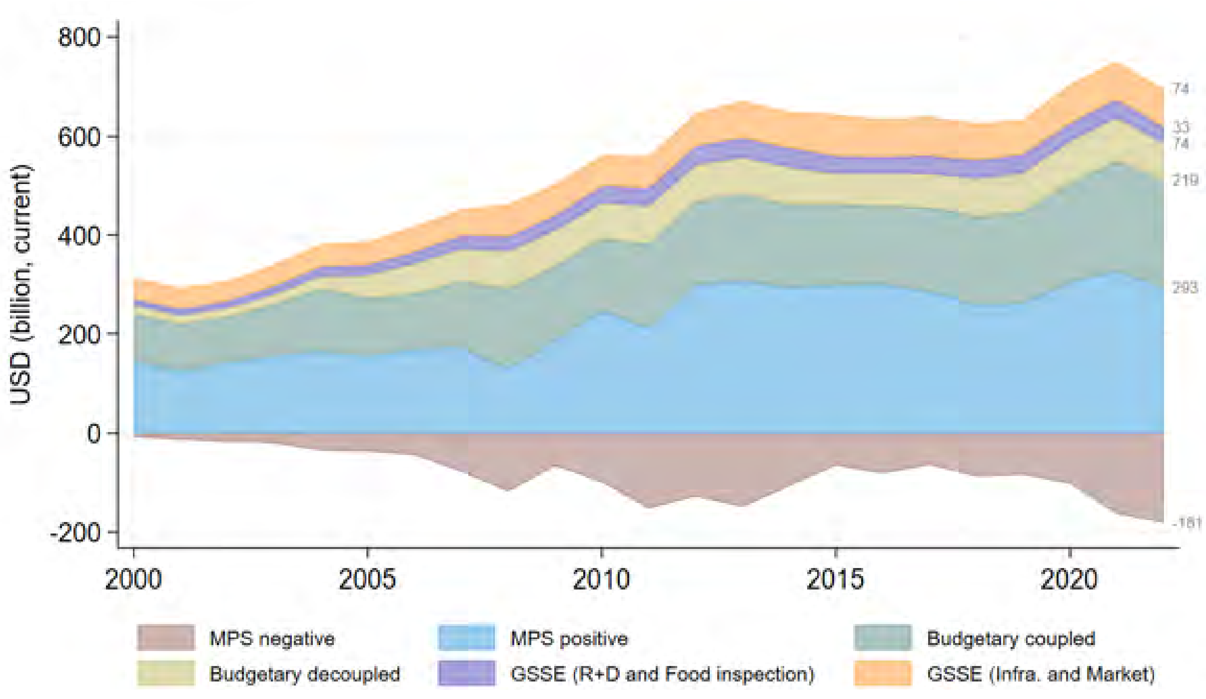
[12] These estimates are based on three primary data sources – OECD, FAO-MAFAP, and IADB. The primary source of Data is OECD which produces an annual estimate of agricultural support for 54 countries which includes OECD, EU and 11 emerging countries. We include additional data to this series from FAO-MAFAP. Data on additional countries from Latin America and Caribbean countries comes from IADB. The OECD methodology is used as the benchmark as it has the largest coverage, and data from MAFAP and IADB is mapped onto it to make the data homogeneous. Number of countries per year is not constant.

[13] This is the total of market price support, budgetary support and general support services, excluding consumer support.

General services support includes public spending on research, extension, inspections, and infrastructure that improve the enabling environment for adoption of sustainable practices. These investments have a critical role in improving agricultural productivity (Lopez and Galinato 2006; World Bank 2016; Fan et al. 2008) and are expected to reduce potential negative impacts on biodiversity.

Spending on infrastructure and marketing support can either cause or mitigate biodiversity loss. The impacts of general support services expenditures on infrastructure, like roads or irrigation, and marketing and promotion services on biodiversity are case specific. Infrastructure investment can divert investment away from natural areas with high biodiversity value and encourage sustainable intensification elsewhere. But investments without consideration for biodiversity outcomes can expose natural areas to development and cause habitat fragmentation. The share of general support services as part of total agricultural support increased in the last decades, largely due to development and maintenance of rural infrastructure (Figure 9).

Figure 9. Annual agricultural support by component (2000 – 2022, USD current)



Note: Time series constructed using all data available for each year, ranging from 52 countries in 2000/2004 to 84 countries in 2017.

5.3 Repurposing agricultural support to mitigate biodiversity loss

Improving the allocation and management of resources can increase agricultural output by $329 billion and meet the food demand by 2050, while keeping biodiversity at current levels

(Natures Frontier 2023). More than half of the increase in the value of agricultural output would be driven by improving technical efficiency, especially in low-income countries where there is significant potential to close productivity gaps. There is an opportunity to increase land use efficiency across all income groups and regions. Most low- and middle-income countries achieve less than half of their potential agricultural output, while rich countries on average are close to 70 percent of their potential agricultural output.

Principles for repurposing agriculture support for biodiversity

Repurposing agricultural support must meet multiple objectives including biodiversity outcomes to support agriculture: Overall, public policy and expenditures should reduce market distortions to support the optimal allocation of resources, improve access to information and knowledge that leads to optimal composition of what is produced and how it is produced, and encourage investments to increase productivity. Repurposing must contribute to multiple objectives including raising farm incomes, improving food security, and improving environmental outcomes including climate change adaptation and mitigation and greater biodiversity that is a foundation for the ecosystem services that support agriculture.

Repurposing should firstly decouple support from production. In most cases, production-coupled subsidies have no impact and, in some cases, a negative impact on agricultural productivity growth. Decoupled payments are less distortive, better at enhancing productivity, and twice as efficient in transferring resources to farmers (Dewbre 2002). Evidence and experience from Latin America (López & Galinato 2007), Africa (Pernechele et al. 2021; Goyal & Nash 2016), Asia (Blanco Armas et al. 2012), and Europe (Garrone et al. 2019) demonstrate that investments in public goods delivers the best outcomes in terms of productivity growth, poverty reduction, and reduced land use change that can benefit biodiversity.

Repurposing should then redirect support to conservation, restoration, and sustainable practices. Agricultural support can be repurposed toward (i) incentives to farmers for conservation, restoration or adoption of sustainable practices that increase productivity, support climate change adaptation and mitigation, and mitigate biodiversity loss through Payments for Ecosystem Services (PES); (ii) public goods and services such as research, extension, and infrastructure to create an enabling environment for adoption of sustainable practices; and finally if required to facilitate the reform, (iii) income support to farmers to ease the transition as coupled subsidies are removed or phased out and enable inefficient producers to exit the sector, making reform more politically feasible.

Repurposing support toward investments that are targeted at productivity-enhancing and environmentally friendly technologies holds the greatest potential for delivering a healthy planet, without compromising on economy, and people. Repurposing should target sustainable practices that deliver *both* improved biodiversity *and* improved productivity to avoid trade-offs with land use change or food security. Identifying repurposing options involves non-trivial trade-offs. A recent World Bank report shows that while removing producer support globally will reduce projected land use change by 50 percent, it will come at the cost of real farm incomes, agricultural output, and cost of food. Similarly, making support conditional to production methods that reduce negative spillovers on the environment at the expense of output will lead to an increase in global food prices and might draw additional land into agriculture. However, redirecting $70 billion of the global distortive producer support toward greens innovations that both enhance environmental outcomes and raise productivity can drive down food prices by 21 percent, increase crop and livestock production by 16 and 11 percent respectively, and importantly release about 105 million hectares of agricultural land for restoration to natural habitats, with potentially substantial biodiversity benefits (World Bank 2022).

Improving the targeting of subsidies and provision of complementary knowledge can contribute to improved biodiversity. Where removing input subsidies is not feasible or desirable, improving their design by improving targeting and complementing them with advice to improve efficiency of application can reduce impacts on biodiversity. For example, replacing universal fertilizer subsidies with smart subsidies that target farmers whose fertilizer use is suboptimal and complementing this with extension advice to improve the application efficiency can reduce impacts on biodiversity.

Implementing repurposing can be challenging and experience suggests several factors influence the political feasibility and effectiveness of reforms:

- **Establishing credibility and winning public trust**. It is important to reassure the public that repurposing is not about removal of much-needed support, but about improving the effectiveness of support in raising farmer incomes and lowering prices for consumers, while safeguarding biodiversity that is critical for agriculture.

- **Sequencing reforms measures to avoid large shocks that can stall or reverse reforms.** It is important to consider the distributional impacts and ensure a “just” transition that enable households to adjust to repurposing through social protection and building capacity to pursue alternative livelihoods. e.g., Improved targeting of fertilizer subsidies may exclude inefficient users from programs but they might also be the poorest.

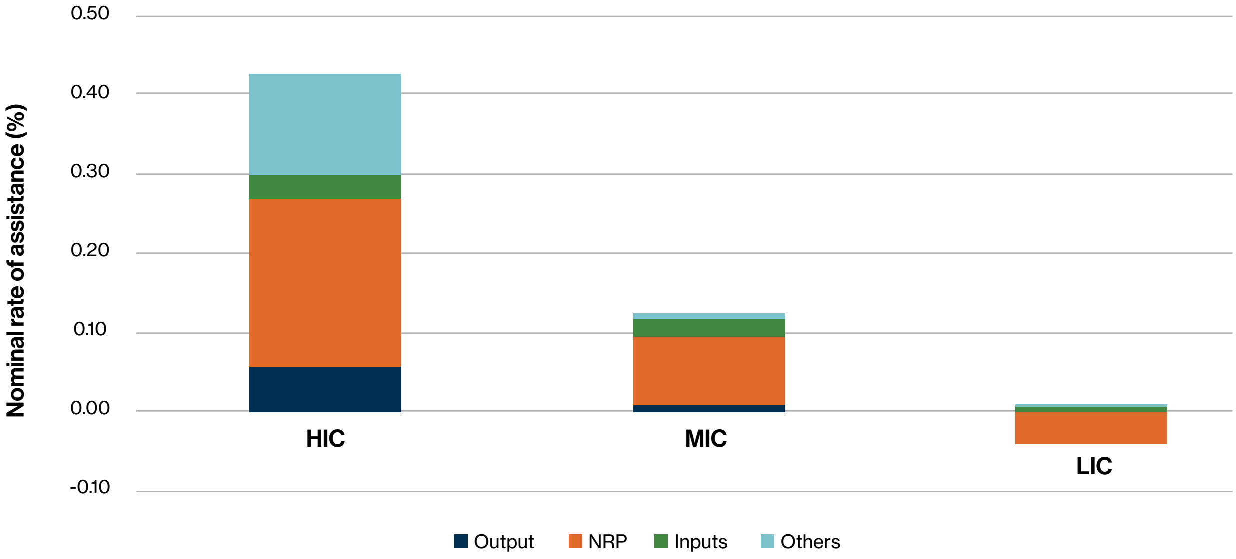
- **Ensuring policy coherence.** Subsidies are only one side of the coin. For example, countries deploy trade measures such as export restrictions or tariffs to reduce the price of staples for net consumers, which is a disincentive to producers, while at the same time using subsidies to incentivize farmers to increase production.

Regulation may be needed to complement incentives when they are insufficient to address the environmental externalities. For instance, repurposing subsidies and market price support might not be enough to prevent additional land from being drawn into agriculture as better technology or road infrastructure might lower the cost of deforestation and expand the agricultural frontier. In such circumstances, zoning and land use regulation, certification of inputs that can be used, and limits on extraction of groundwater may be needed.

Whether regulation is needed to complement incentives will depend on the expected effectiveness of incentive payments. These include: (i) whether PES uptake or the level of green subsidy is expected to be sufficient to incentivize/disincentivize the practice; (ii) the potential environmental costs of non-adoption of the practice; (iii) the costs and feasibility of monitoring compliance with PES conditions; (iv) the costs and distributional effects of incentives vis a vis regulation. Regulation is likely to be necessary where incentives for sustainable intensification have rebound effects that moderate or reverse the intended reduction in land use change or water abstraction.

The precise mix of policies will depend on the country's context and objectives. There is significant heterogeneity in support provided by countries (Figure 10). For instance, high-income countries provide more subsides as a share of agricultural output and tend to use decoupled instruments. Low- and middle-income countries predominantly provide support through production-coupled instruments. Moreover, a substantially large share of low- and middle-income countries utilize tariffs and trade barriers to influence the market price.

Figure 10. Producer support by income category



Note: Nominal Rate of Assistance (NRA) is an indicator that measures policy support provided to farmers individually, both in the form of price incentives generated by trade and market policies (quantified by the nominal rate of protection) and by fiscal subsidies provided to producers of a specific commodity (FAO et al. 2022).

Source: AgIncenitves Consortium

Implementing repurposing through Payments for Ecosystem Services (PES)

This section discusses PES as a tool for incentivizing sustainable practices to support biodiversity that can be funded from repurposing.

PES can incentivize conservation, restoration and sustainable practices. PES can incentivize farmers to transition toward a more sustainable agriculture system that delivers nature-positive outcomes including for biodiversity and pay them for these services where markets are too nascent or nonexistent for these services to be monetized. Farmers can be paid for conservation (payment for not deforesting or polluting, retiring marginal land, establishing connectivity and eco-corridors, protecting natural areas in agricultural landscapes), restoration (restoration of degraded lands back to agriculture or semi-natural state), and adoption of sustainable practices. Annex 10 describes US, UK and EU experience in PES.

The beneficiary of environmental services should ideally pay for the service. Perpetual payments are appropriate when a practice, such as watershed restoration, may not be financially feasible for a farmer but generates benefits for the public or private downstream users such as a water utility. Ideally those who benefit from the resulting environmental services should make the payment for environmental service but where the benefits are essentially public, which is usually the case, it is more appropriate for the government to make the payment. The case of Aquafondo in Peru (Annex 11) is an interesting example of a PES scheme that was intended to be privately funded.

PES requires certainty of funding and local capacity for monitoring and verification. When these programs involve perpetual payments, they require long-term commitment and certainty of funds to create creditability among farmers and lead to large-scale adoption. In addition, these programs require rather complex monitoring and verification systems. Hence, the fiscal and technical capacity of the country can play a critical role in the success of such programs.

PES delivers better environmental outcomes than other tools but requires strong implementation capacity. A recent CGIAR study (Alliance of Biodiversity International & CIAT 2023) compares the impact of PES and green subsidies on farm incomes and environmental outcomes (Annex 11). While both PES and green subsidies enhance smallholder income, PES delivers better environmental outcomes because of its conditional and performance-based design. However, PES requires greater investment in MRV and institutional support. In lower-capacity settings, green subsidies (non-conditional transfers aimed at environmental goals) may offer a more practical entry point, especially when paired with technical assistance, capacity building, and phased implementation.

An alternate approach to perpetual PES can be a one-off payment to incentivize adoption of sustainable practices. High upfront costs or lack of knowledge can be a barrier to adoption of some practices even though they are financially viable in the longer term (Chapter 4). Subsidies can be used to improve access to these technologies through mechanisms such as matching grants, which are a one-time transfer, instead of a perpetual payment over time. Monitoring and verification needs are very minimal and not conditional on certain outcomes that can be costly and hard to measure.

Rapidly evolving spatial data and digital technology creates opportunities for scaling up of PES. (Annex 11). Global, national and local spatial data on land use, climate biodiversity and ecosystem services can improve the technical specificity and spatial targeting of PES (for example which tree species for agroforestry are most effective in delivering the desired ecosystem services in a particular location). Improved digital technology and potentially artificial intelligence allows for more complementary advice, payment, and monitoring and verification, as illustrated by the My Farm Trees platform (Annex 11), which pays farmers for gathering planting material for agroforestry. Remotely verifying results could potentially be replicated for PES for other practices that deliver biodiversity and ecosystem services such as in situ maintenance of plant genetic material or improved soil management practices.

5.4 Monitoring policy and investment impact on biodiversity

Impact monitoring is critical to mainstreaming biodiversity objectives into decision making. Beyond the need for MRVs to develop the biodiversity credit market (Annex 9), which are specific to the target impacts of each credit product, there is also a need for tools that measure the broader impacts of public policy and investment on biodiversity and value subsequent impacts on ecosystem services and resulting benefits to agriculture.

Impact monitoring and valuation is rapidly evolving, making mainstreaming increasingly possible. Our incomplete understanding of how improved biodiversity affects the functions of ecosystems, impacts on ecosystem services, and benefits to agriculture, constrains current monitoring and valuation of biodiversity impacts. But advances in spatial data, digital technology, and perhaps most importantly, valuation of ecosystem services such as through the System of Environmental Economic Accounting – Experimental Ecosystem Accounting (SEEA EEA), mean that mainstreaming biodiversity into decision making will be increasingly feasible.

Building capacity in ecosystem accounting is an essential foundation for improved valuation of impact. An essential foundation for valuing the impacts of improved biodiversity on ecosystem services is establishing inventories of ecosystems, ecosystem services databases, and building the capacity to integrate this information into policy and public investment decision making.

There is currently no single, comprehensive tool for monitoring biodiversity outcomes of policy and investment as each tool addresses different aspects of biodiversity. The IUCN Land Health Monitoring Framework (IUCN 2023), analyses 114 indicators and 14 existing tools that cover three levels of biodiversity (genetic, species, ecosystem) at four scales (soil, farm, landscape and national[14]) (Figure 11). Each application of the Land Health Monitoring Framework notably entails identifying the type of agricultural ecosystem present in the landscape under assessment following the IUCN Global Ecosystem Typology (IUCN 2025a). This step ensures that monitoring is tailored to ecological context and supports harmonization with SEEA EEA by facilitating consistent reporting of ecosystem extent, condition, and services.

There are significant gaps in existing indicators and tools. The IUCN study finds that: (i) “existing tools tend to focus on the soil and farm levels and do not properly cover landscape and national levels”; (ii) “tools to measure planned biodiversity (biodiversity changes resulting from changes in practices) at the three levels exist only at the farm level, and not at the soil or the landscape level” and (iii) “none of the tools cover genetic diversity at the landscape or national level, for either associated or planned biodiversity”. (IUCN 2023). The IUCN study identified the combination of indicators that can provide the best information on agrobiodiversity with the lowest effort and ranked them in

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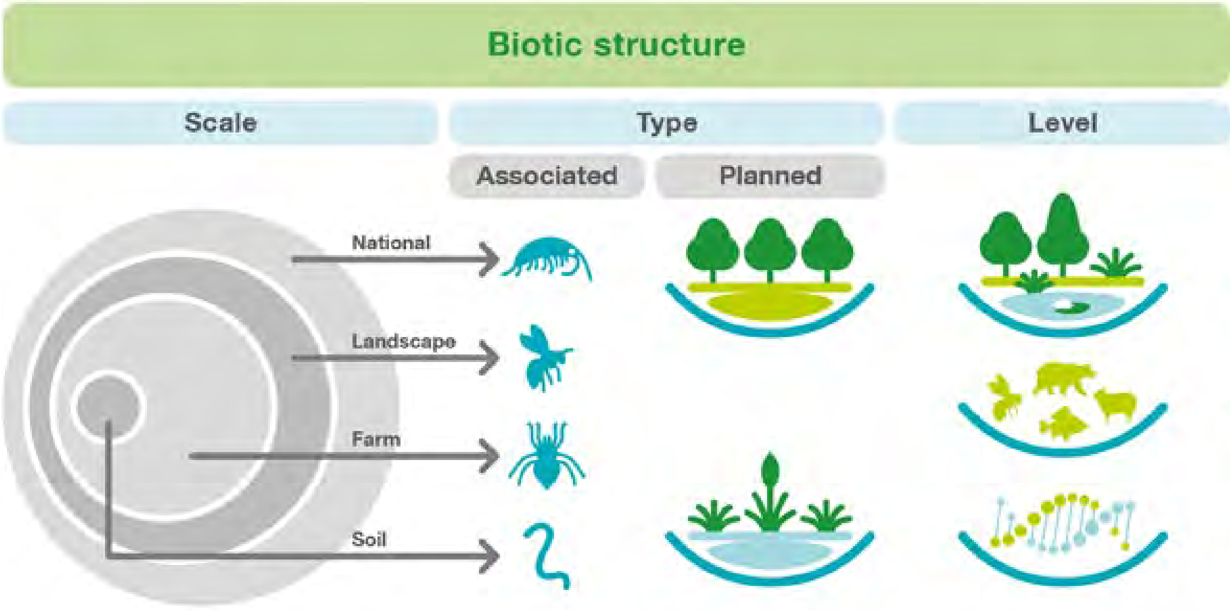
[14] National is not a formal scale to monitor but the sum of landscapes encircled by an administrative border.

terms of the richness of information they provide (Annex 13). Digital collections that measure biotic structure were then identified across each scale and level of biodiversity (Figure 12).

Figure 11. Three dimensions of biotic structure (arrangement of living organisms): Scale, type and level

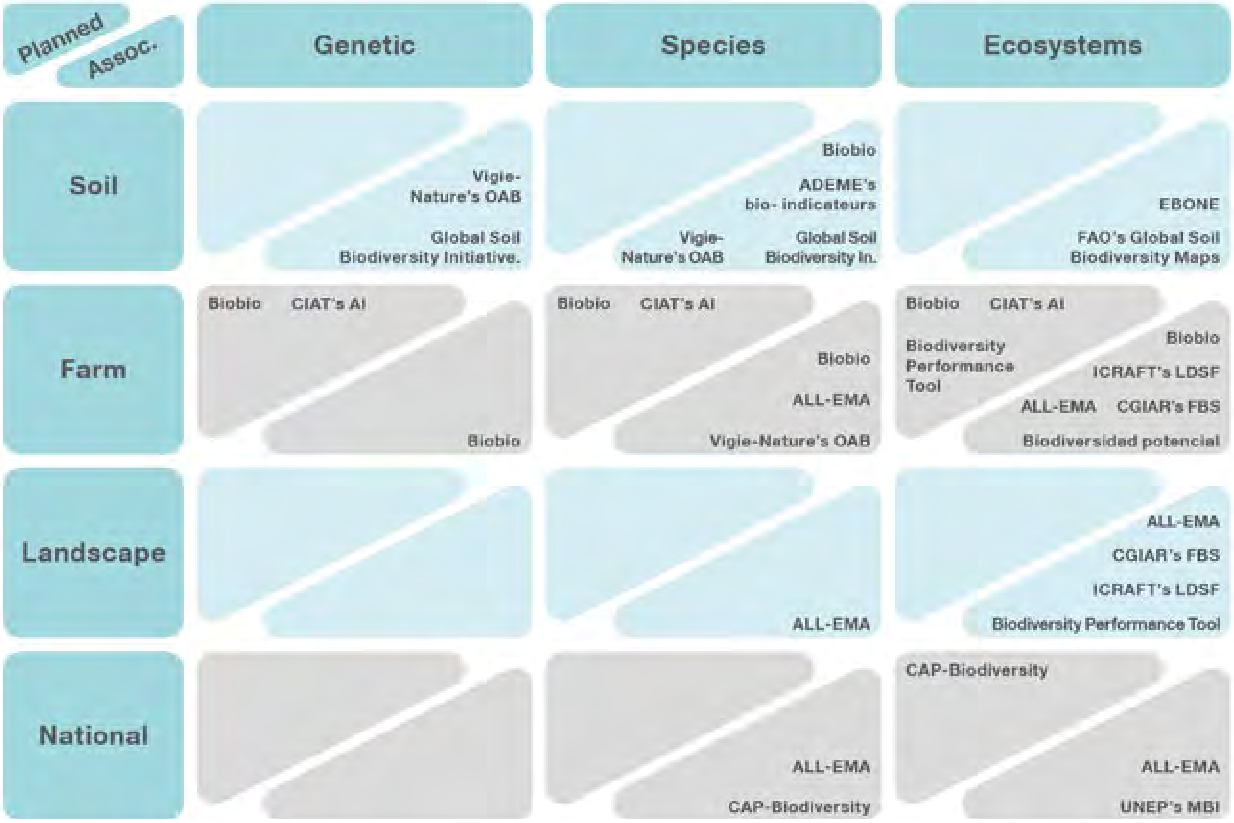


A comprehensive monitoring tool would benefit from more indicators relating to species that have a critical role in ecosystem services for agriculture. These include species indicators for vascular plants that are important for biological pest control; wild bees associated with effective pollination; spiders, which are essential invertebrate predators; butterflies that carry pollen between plants that are far apart; birds that act as predators, pollinators, scavengers, seed dispersers, and ecosystem engineers; and bats that play an essential role in arthropod suppression, seed dispersal, and pollination (IUCN 2023).

Monitoring keystone species can inform the monitoring of ecosystem services that support agriculture. For example, abundance of earthworms and nematodes can be used as an indicator of the decomposition of organic matter across different agricultural contexts. The IUCN Land Health Monitoring Framework (2023) identifies these species for a wide range of ecosystem services.

Available resources and expertise may be a constraint to using some indicators. The IUCN study showed that "80 percent of fauna indicators and 74 percent of habitat indicators are assessed in the field, while nearly 87 percent of ecosystem functions and ecosystem services are assessed through lab and remote sensing"; methods which require greater resources and technical capacities. These requirements may limit the choice of indicators, as well as the scope and comprehensiveness of monitoring.

Figure 12. Digital collections that measure biotic structure



Planned Assoc.	Genetic	Species	Ecosystems
Soil	Vigie-Nature's OAB Global Soil Biodiversity Initiative.	Biobio ADEME's bio- indicateurs Vigie-Nature's OAB Global Soil Biodiversity In.	EBONE FAO's Global Soil Biodiversity Maps
Farm	Biobio CIAT's AI Biobio	Biobio CIAT's AI Biobio ALL-EMA Vigie-Nature's OAB	Biobio CIAT's AI Biodiversity Performance Tool Biobio ICRAFT's LDSF ALL-EMA CGIAR's FBS Biodiversidad potencial
Landscape		ALL-EMA	ALL-EMA CGIAR's FBS ICRAFT's LDSF Biodiversity Performance Tool
National		ALL-EMA CAP-Biodiversity	CAP-Biodiversity ALL-EMA UNEP's MBI

There is a need to develop a comprehensive tool drawing on existing indicators. Replication of the eDNA tool developed by IUCN's eBioAtlas project for soil biodiversity in agricultural landscapes using soil samples and the Cool Farm Tool to measure variety and breed diversity could contribute to monitoring at both genetic, species, and ecosystem level.

In pursuit of a more comprehensive tool, IUCN has published a complementary guidance note. The Guidance Note for Monitoring Land Health in Agricultural Landscapes (IUCN 2025b), designed to operationalize the Land Health Monitoring Framework through a step-by-step process. The guidance helps define monitoring goals, select appropriate indicators, and align biodiversity monitoring with broader sustainability strategies. It is currently being further tested and refined in sustainable agriculture projects. In parallel, a Land Health Monitoring Platform prototype is under development that aims to consolidate key tools, indicators, and decision-support resources.

Chapter 6.

Recommendations

This chapter presents three Policy and Investment Packages to support biodiversity for agriculture.

The three packages presented recognize the importance of natural areas in maintaining biodiversity as a foundation for the ecosystem services that support agriculture; the need for sustainable intensification to reduce land pressure; the harmful impact of agricultural support for unsustainable practices and the potential to repurpose this support for conservation, restoration, and sustainable practices including through scaling up of PES and green subsidies; and the need to establish comprehensive biodiversity monitoring systems as a foundation for all investments in biodiversity.

Policy and investment package 1:
Conservation and restoration of natural areas

Package 1 recognizes the importance of natural areas, natural habitats in agricultural areas and the connectivity between them, in maintaining biodiversity as a foundation for ecosystem services that support agriculture building on the discussion in Chapter 2. It takes advantage of opportunities created by advances in spatial data on biodiversity and NCPs and threats to them for more effective targeting of conservation and restoration and spatial data.

Package 1 aims to: (i) employ rapidly evolving spatial data for **spatial prioritization of conservation and restoration** of critical natural assets supporting agriculture; (ii) **conserve and restore critical natural assets** supporting agriculture recognizing the additional effort needed to protect areas under threat from climate change and agricultural development; and (iii) **conserve and restore natural habitats within agriculture** and build their connectivity with natural areas.

Objective: Enhance biodiversity and NCPs supporting agriculture from natural areas

Policy/ Investment	Action
Spatial planning for conservation and restoration	• Employ evolving spatial data on biodiversity and NCPs supporting agriculture to identify spatial priorities for conservation and restoration. Conduct ground truthing with IPLCs.
Conservation of natural areas supporting agriculture	• **Conservation of stable priority areas:** Maintain biodiversity and NCP provision of intact critical natural assets by strengthening protection (PAs, OECMs), IPLC rights and governance (CREMAs for example) resource management (invasive species, fire regimes) and monitoring their condition. • Conservation of Unstable Priority Areas: Proactive protection of critical natural assets against development threats through zoning to establish new PAs/OECMs; climate smart conservation planning to boost resilience, facilitate species movement and reduce hazards; and monitoring climate and development threats. See zoning case study in **Annex 13**.
Restoration of natural areas supporting agriculture	• **Restoration of Stable Priority Areas:** Restore biodiversity and NCP provision from degraded CNAs through restoration such as soil improvement, erosion control, reforestation/revegetation. • Restoration of Unstable Priority Areas: Implement long-term restoration programs as above with explicit integration of climate adaptation into restoration design and monitoring.
Restoration of natural habitats in agricultural areas	• Identify most cost-effective land to restore within agricultural areas, prioritizing land which is marginally productivity or unused, providing greatest connectivity, or bordering natural areas, protecting riparian ecosystems and hydrological functions.

Policy and investment package 2:
Enabling sustainable intensification for biodiversity

Policy and Investment Package 2 addresses the barriers to adoption of sustainable agricultural practices by farmers including (i) insufficient **localized research** on the feasibility of sustainable practices and bundles of practices as the basis for extension; (ii) insufficient **biodiversity and agroecology expertise within extension services**; (iii) insufficient access to finance to meet the upfront costs of adoption and cash flow needs until sustainable practices yield financial benefits; and (iv) insufficient **incentives to reward farmers for public goods** (e.g., better downstream water quality as a result of healthier ecosystems). All of the above require a long-term commitment because of the time lag to realization of the full benefits of sustainable practices, hence the emphasis on long-term planning and funding in package 2. Package 2 also recognizes the potential of **farmer seed systems – gene bank cooperation** to maintain plant genetic resources for food and agriculture.

Package 2 aims to (i) establish lighthouse programs providing support to farmers on Biodiversity for Agriculture (B4R) – the program would initially focusing on selected SAPs that benefit most from biodiversity, including: localized research to provide context specific evidence-based recommendations; extension advice on B4R; building biodiversity and ecology expertise into research and extension services; PES and green subsidies to incentivize adoption of SAPs; and investment promotion for sustainably produced products; (ii) reduce barriers to entry in the emerging bio-inputs market; and (iii) support in-situ and ex-situ and conservation of plant and animal genetic material for food and agriculture including through scaling up cooperation between farmer seed systems and gene banks.

Objective: Support adoption of sustainable practices for biodiversity
Policy/Investment: Lighthouse program on Biodiversity for Agriculture (B4A) to coordinate research, extension and landscape planning for selected sustainable practices (SAPs)
B4A Lighthouse Program: Ministries of Agriculture and Environmental co-launch a 10-15 year lighthouse program on sustainable practices, for selected sectors best served by biodiversity health. Convene indigenous, local, national, regional and international experts to select SAPs with the highest scientific evidence of impact on stated objective. Identify complementary performance-based donor funding predicating future NARS funding. Establish specific scaling objectives for the program in terms of sustained adoption. Lighthouse program to include: • **Applied Research on B4R:** A 10-year program of applied research on B4A on selected SAPs » National research institutions to lead, leveraging expertise on local suitability of SAPs. » Local, regional, global experts to develop localized evidence-based recommendations » Include standardized financial and economic analysis to facilitate comparison. » Include research impact assessment

Objective: Support adoption of sustainable practices for biodiversity

Policy/Investment: Lighthouse program on Biodiversity for Agriculture (B4A) to coordinate research, extension and landscape planning for selected sustainable practices (SAPs)

- **Extension on B4R:** Farmer support program and curricula for selected SAPs
  - Develop curricula for training of trainers, extension advice and farmer field schools.
  - Consult with private sector, farmer inc. women and youth for inclusive scaling of SAPs.
- **Collaboration with environment ministries and academia to build capacity on biodiversity**
  - Capacity building for agri-research and extension staff on biodiversity and ecology.
  - Appointment of biodiversity and ecology expertise into research and extension.
- **Farmer incentives** provision of incentives from PES and green subsidies (see package 3)
  - For SAPs that are financially viable for farmers long term but with high upfront costs
  - For SAPs delivering public goods
  - Repurposing agricultural support can contribute to funding the lighthouse program.
- **Investment promotion** in premium markets for sustainable produce
  - Conduct market research for sustainably produced products (e.g., organic) with national comparative advantage to tap premium markets and sustainable trade legislation
  - Support marketing infrastructure, information, and voluntary certification.

Objective: Create condition for development of bio-input markets

Policy/Investment: Reduce barriers to entry in bio-inputs market.

- Build regulation of bio-inputs to allow entry of bio-inputs into countries and fill gaps in regulation of traditional agrochemicals
- Establish taxonomy of bio-inputs as a basis for regulation
- Building testing capacity for agrochemicals (to reduce harmful competition) and bio-inputs.

Objective: Support maintenance of agrobiodiversity

Policy/Investment: Support in-situ and conservation of plant and animal genetic material for food and agriculture (PGRFA)

- Develop partnerships between gene banks and community seed funds to exploit the potential of farmer seed systems to maintain genetic material in-situ and share with gene banks (see case studies in **Annex 15**)
- Support local seed companies that create markets for locally adapted varieties saved by farmer seed systems (e.g., matching grants to facilitate access to finance for improved seeds facilities
- Conduct an inventory of breeds and assess extinction risks.

Policy and investment package 3:
Financing sustainable intensification, restoration and conservation

Policy and Investment Package 3 aims to mainstream and scale up the provision of public funding for biodiversity and ecosystem services that support agriculture through (i) **ecosystem service valuation** and incorporation into feasibility studies for investment in conservation, restoration and sustainable agricultural practices; (ii) **repurposing agricultural support** for these investments; (iii) **scaling up payments for ecosystem services** and (iv) building **biodiversity monitoring capacity** to inform investment decisions drawing on the discussion in Chapter 5.

Objective: Integrate the Value of Ecosystem Services into Public Investment Decisions

Policy/Investment: Incorporate ecosystem service valuation into decisions on public investment in sustainable practices

Apply ecosystem service valuation to decisions on public funding of sustainable practices

- Build local inventory of ecosystems and local capacity in ecosystem service valuation
- Build capacity in ecosystem valuation tools and integration into economic analysis (TEEB*, True Cost Accounting**)
- Identify causal links btw. agricultural practices, biodiversity, and ecosystem services.
- Apply ecosystem service valuation into feasibility studies of sustainable practices.

Objective: Repurpose Agriculture Support Toward Sustainable Practices, Conservation and Restoration

Policy/Investment: Decouple agricultural support from input and output markets

Decouple agricultural support from production including:

- Market price support
- Input subsidies
- Commodity specific output subsidies

Policy/Investment: Repurpose support for agriculture to incentivize sustainable intensification, conservation and restoration

Repurpose public expenditure savings from decoupling to fund package 1 and 2:
- Conservation and restoration of CNA threaten by development and climate change
- Public goods and services to support adoption of sustainable practices
- PES to incentivize sustainable practices
- Green subsidies to incentivize sustainable practices where PES capacity limited

Manage the transition:
- Sequence reforms to avoid income shocks to farmers.
- Provide transitional income support to farmers to cushion income shocks.
- Improve targeting of subsidies that cannot be repurposed immediately.

Provide complementary regulation **where incentives alone will not meet objectives:**
- Regulation of land conversion, water abstraction, and use of harmful agrochemicals for example are typically needed in combination with incentives.

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* The Economics of Ecosystems and Biodiversity

** An approach that reflects the real costs of producing food including hidden environmental, social and health costs.

Objective: Scale up Payments for Ecosystem Services

Policy/Investment: Build spatial data

Collaborate with research, academic and development partners to build global, national and local spatial data on biodiversity and ecosystem services as a foundation for PES.

Policy/Investment: Scale up use of tested PES tools

Scale up application of tested tools such as the My Farm Tress Platform that pays farmers for planting native tree species and adopting sustainable agroforestry practices and uses evolving digital technology and spatial data to reduce operating costs and improve targeting.

Policy/Investment: Replicate tested PES tools for more SAPs

Collaborate with research, academic and development partners to replicate tested tools that use improve digital technology and spatial data, to develop and scale up PES tools for a wider range of sustainable agricultural practices.

Objective: Develop capacity to monitor biodiversity to inform investment decisions

Policy/Investment: Capacity for using innovation for biodiversity monitoring

Develop capacity within Environment and Agriculture ministries and partners organizations for using existing technology for biodiversity monitoring at genetic, species and ecosystem level including remote sensing, acoustic sensing, eDNA, artificial intelligence and ecosystem modelling.

Policy/Investment: Framework for biodiversity monitoring for agriculture

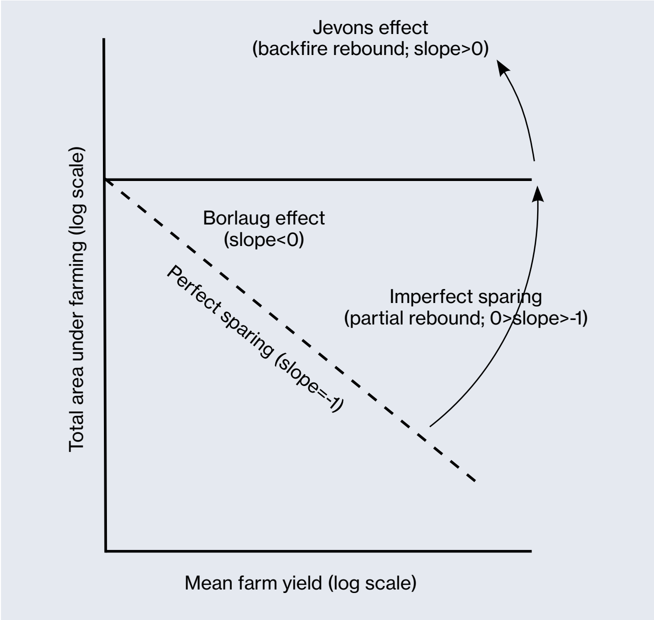
Participate in the ongoing development of biodiversity monitoring frameworks and tools in natural and agricultural landscapes at genetic, species and ecosystem level and test through ongoing investment projects to build capacity and inform investments.

Annexes

Annex 1. Rebound effects of agricultural intensification

When more efficient use of a resource results in its increased use, this is known as a rebound effect. In the case of intensification, savings from more efficient land use can incentivize producers to convert more land to agriculture, moderating the land sparing effect of intensification. Rebound effects mean that land sparing is "imperfect" such that the reduction in land use change is less than the proportionate increase in yield (Figure A1.1). When rebound effects are so extreme that intensification results in more land use change this is a case of Jevons Paradox, but this is rare (Bamford 2021). In contrast, the Borlaug effect describes how more efficient land use will result in reduced conversion of land for agriculture or "perfect" land sparing (Figure A1.1) (Balmford 2021).

Figure A1.1 Perfect and imperfect land sparing



The extent to which intensification causes rebound effects is product and context specific (Figure A1.2) (Paul 2019) provides a conceptual framework to illustrate the multiple influences that determine the extent of rebound effects from intensification. These include direct economic effects (changes in production and consumption caused by reduced costs); indirect effects (changes in producer investment due to cost savings); economy-wide effects (changes in consumption as a result of economic growth where intensification happens at scale); and social-psychological effects/changes in consumer perceptions of the product and its environmental impact.

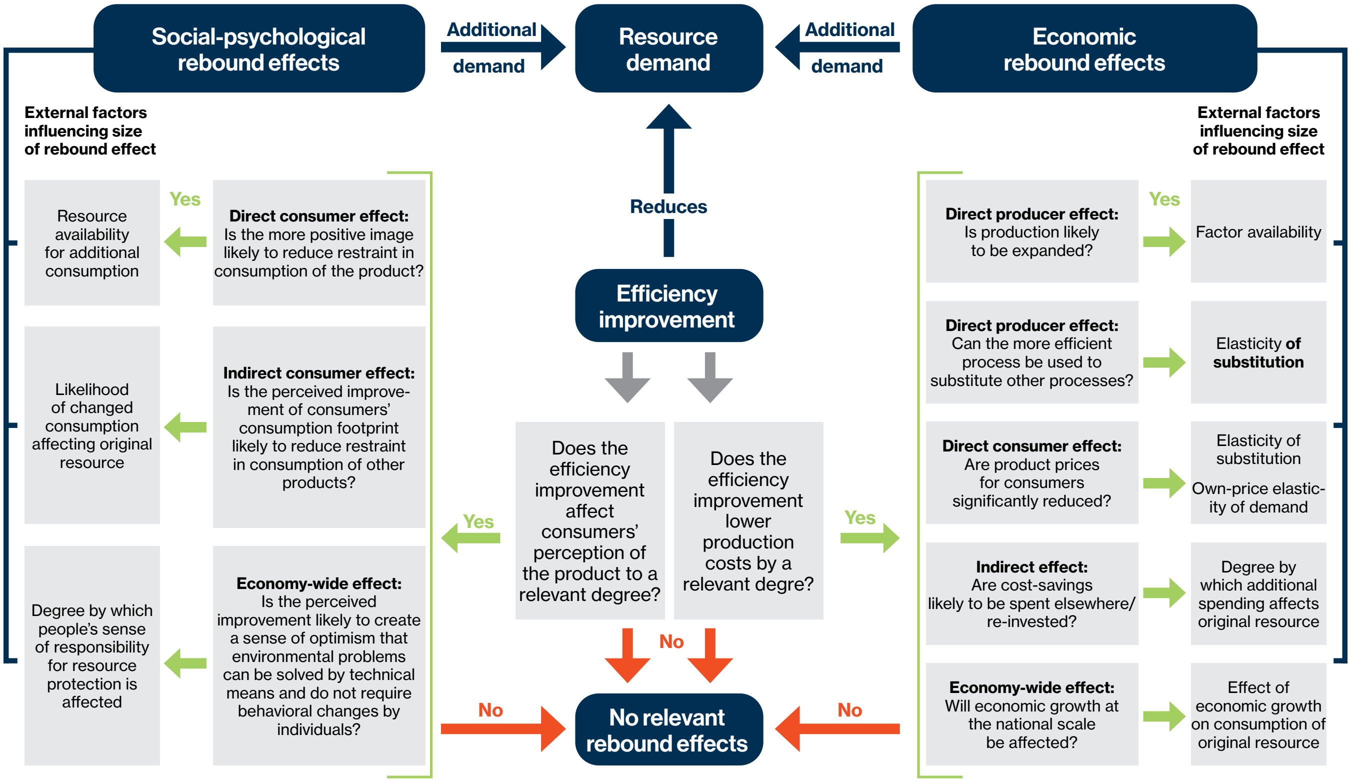
Rebound effects are greatest when consumers are most responsive to prices (price elastic demand) and intensification results in lower product prices, when intensification is labor or capital saving, and for intensification of products well connected to global markets. Thus, rebound effects are greatest for price-elastic products such as beef, biofuels, coffee or cocoa, and least for price-inelastic products such as cassava or other staples. For products well connected to global markets, increased efficiency stimulates exports (García et al. 2020; Pratzer et al. 2023; Villoria 2019). Intensification can also result in increased field rents, potentially motivating farmers to extend their cultivation into additional natural areas (Phelps et al. 2013) (Balmford 2021).

Large-scale analyses investigating trends in yields and forest area changes suggest that land sparing from intensification happens but is patchy and vulnerable to rebound effects (Balmford

2021). In Malawi, farmers from groups that received more subsidies for fertilizer for intensification under the Food Input Subsidy Program deforested less than farmers from other groups who received less subsidies (Abman and Carney 2019; Fisher and Shively 2007). In the Philippines, irrigation schemes for lowland rice in Palawan increased demand for labor, drawing it from other areas where deforestation was slowed (Shively 2001; Shively and Pagiola 2004). In Zambia, providing improved seed reduced deforestation on less acidic soils by half (Pelletier et al. 2020; Balmford 2021).

The risks of rebound effects from intensification mean that complementary regulation and incentives to mitigate land use change caused by rebound effects are needed. Measures to mitigate rebound effects include zoning to regulate access to and development of natural and semi natural areas; subsidies or taxes to disincentivize land use change; conditional credit or market access; or location of strategic commodity infrastructure and advisory services away from natural areas threatened by development (Bamford 2021). The effectiveness of these measures will partly depend on the participation of local governance structures and communities in their design and awareness of their purpose.

Figure A1.2 Efficiency improvement and occurrence of rebound effects



Efficiency improvement and occurence of rebound effects. Rebound effects will not occur unless the efficiency improvement affects economic performance or consumer perception of final products. Blue boxes list factors that strongly influence the size of the rebound effect (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Annex 2. Impacts of agricultural water management on biodiversity

Table A2.1 summarizes impacts of agricultural water management on biodiversity and ecosystem services.

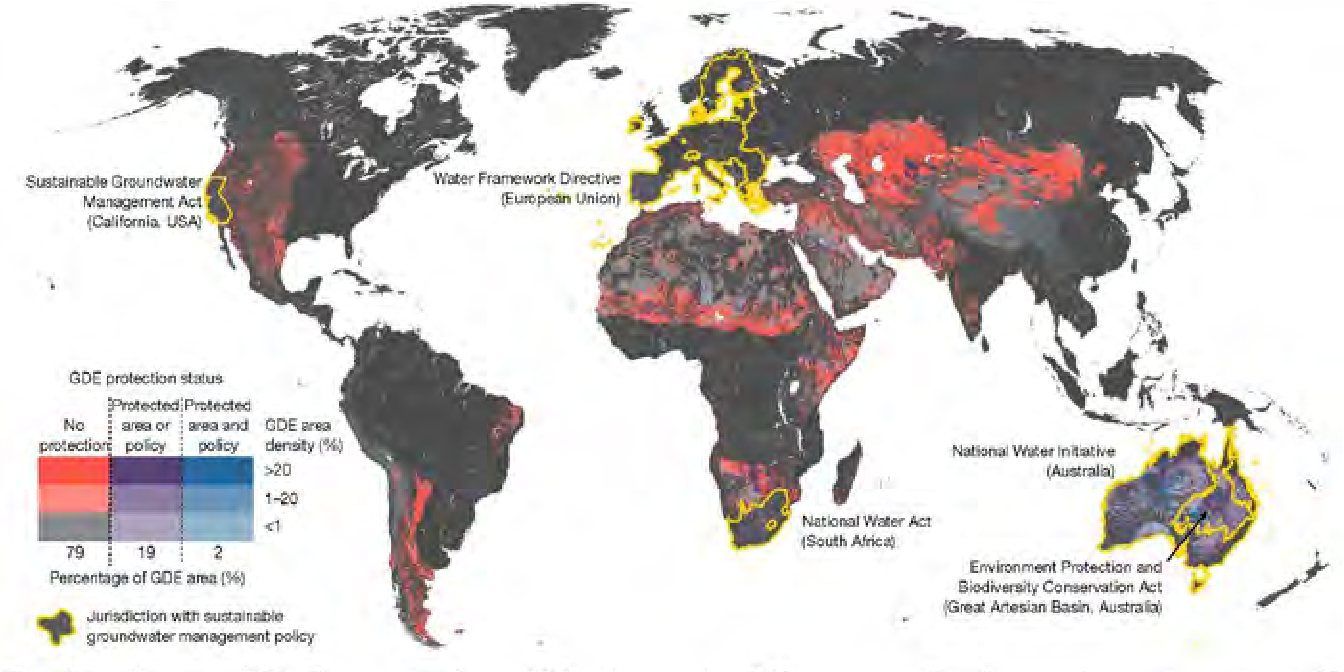
Table A2.1 Impacts of agricultural water management on biodiversity

Category	Drivers	Impacts	Examples of affected regions or systems
Blue water overuse	Irrigation expansion, excessive surface and groundwater withdrawals	Reduced streamflow, seawater intrusion, habitat degradation, loss of aquatic biodiversity	Nile River, Indus River, Indo-Gangetic Basin
Green water mismanagement	Poor soil moisture retention, deforestation, unsustainable land use practices	Reduced soil fertility, disrupted biogeochemical cycles, lower crop resilience	Sub-Saharan Africa, South Asia
Groundwater overextraction	Intensive irrigation, lack of regulation, energy subsidies	Aquifer depletion, reduced streamflow, loss of groundwater-dependent ecosystems (GDEs)	India, Pakistan, Middle East, northern China
Unsustainable irrigation	High water withdrawals, inefficient irrigation methods, reliance on freshwater sources	Depleted local water supplies, downstream flow reduction, eutrophication	U.S. High Plains, California’s Central Valley, North China Plain
Livestock water use	Water-intensive feed crop production, direct water supply for livestock	Increased water stress, unsustainable resource use, biodiversity loss	Northern India, Middle East, Central United States
Waterlogging	Flood irrigation, poor irrigation scheduling	Decline of aerobic organisms (nitrifiers, earthworms), methane emissions, nitrogen cycle disruption	Global irrigated areas, particularly in poorly managed systems
Salinization	Over-irrigation, use of saline or brackish water	Osmotic stress, reduced soil biodiversity (nitrogen-fixing microbes), heavy metal solubility, favoring invasive species	11 percent of global irrigated land; 77 percent in Asia (Pakistan, India, China)
Low-quality irrigation water	Reliance on saline groundwater, untreated wastewater	Soil salinity, sodicity, heavy metal accumulation, aquifer contamination, reduced biodiversity	Bangladesh, India (Punjab, Haryana, Gujarat, Rajasthan, and Uttar Pradesh), Pakistan
Wetland conversion and drainage	Agricultural expansion, aquaculture, fertilizer use, water storage reservoirs	Decline in wetland biodiversity, eutrophication, invasive species proliferation, shifts in species composition	East Africa (Anyiko wetland, Lake Victoria), India, Latin America, and the Caribbean
Wetland habitat loss	Altered hydrological regimes, wetland drainage, habitat simplification	Loss of critical vegetation, reduced habitat for birds and invertebrates	Flooded paddy fields in Asia and Sub-Saharan Africa; global wetlands
GhG emissions from wetlands	Peatland drainage, agricultural conversion	Wetlands turned from carbon sinks to sources; methane and nitrous oxide emissions	Drained peatlands globally; 4 percent of global anthropogenic emissions

Category	**Drivers**	**Impacts**	**Examples of affected regions or systems**
Dams and river alterations	Construction of large and small dams, regulated water releases, sediment trapping	Reduced connectivity (vertical, lateral, longitudinal); disrupted nutrient and sediment transport; habitat homogenization	Global rivers: 48 percent altered (Figure A2.3); Mohanpur Dam (India) reduced floodplain wetlands by 66 percent
Fragmentation of rivers	Dams and reservoirs blocking river continuity, flow regulation, reduced flood magnitude	Impeded fish migration, reduced terrestrial and aquatic biodiversity, increased dominance of invasive species	Over 60 percent of rivers fragmented globally; only 23 percent of rivers flow uninterrupted to the ocean
Flow regulation and eutrophication	Altered flow variability, reduced turbulence, increased thermal/chemical stratification	Changes in species diversity, habitat homogenization, increased predation risks, dominance of non-migratory and invasive species	Reservoirs globally favor non-migratory species; reduced variability impacts terrestrial vegetation richness

Figure A2.1 shows the protection status of groundwater dependent ecosystems. Figure A2.2 summarizes threats to wetlands of international importance and Figure A2.3 illustrates the status of global water connectivity.

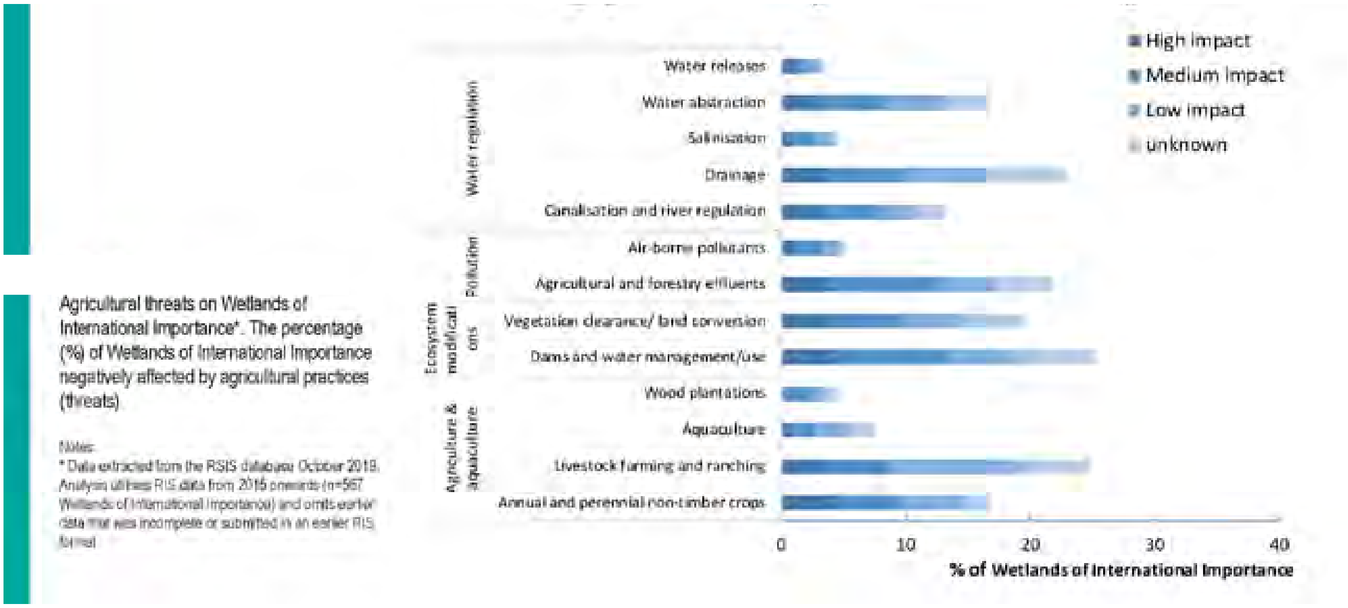
Figure A2.1 Protection status of GDEs



Note: The proportion of mapped GDEs with no protection (red) is 79 percent, with the remaining 21 percent having some degree of protection (blue and purple). GDEs shown in purple exist on protected areas or in jurisdictions with sustainable groundwater management policies. GDEs shown in blue are protected by both measures (protected area and sustainable groundwater management policy), GDE area density is shown in this figure at 30 are second resolution (roughly 1km grids).

Source: Rohde, M.M., Albano, C.M., Huggins, X. et al. Groundwater-dependent ecosystem map exposes global dryland protection needs. Nature 632, 101–107 (2024). https://doi.org/10.1038/s41586-024-07702-8

Figure A2.2 Agricultural threat to wetlands of international importance

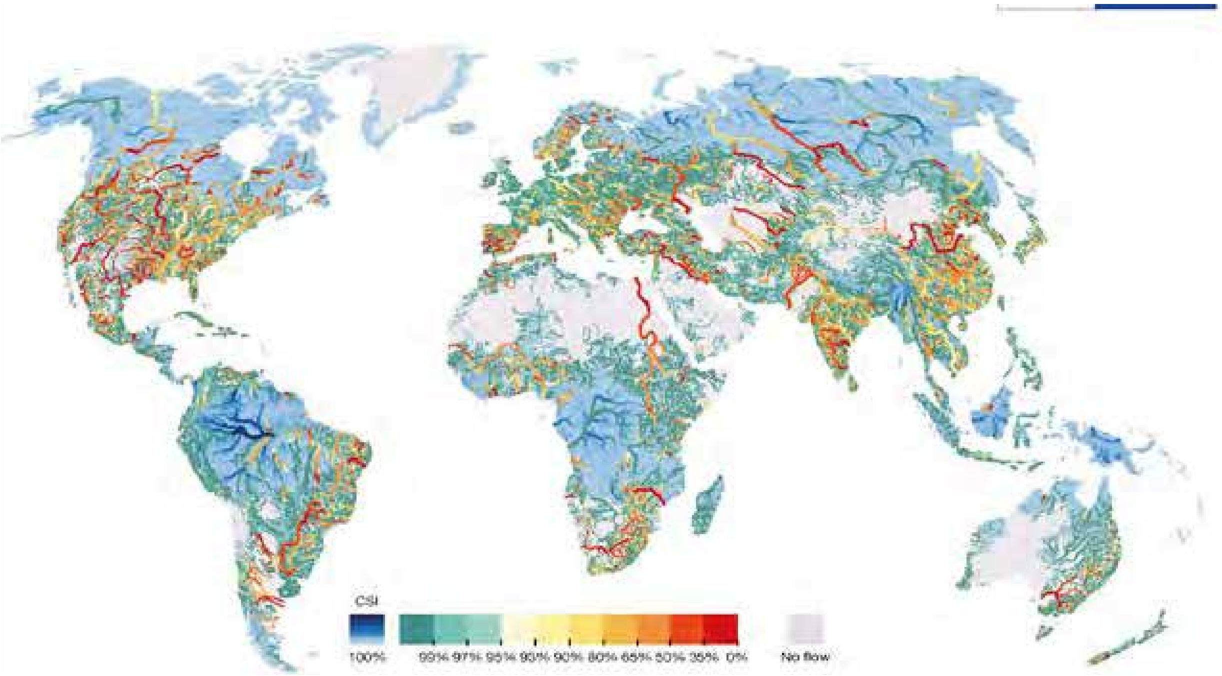


Agricultural threats on Wetlands of International Importance*. The percentage (%) of Wetlands of International Importance negatively affected by agricultural practices (threats)

Notes:
* Data extracted from the RSIS database October 2019. Analysis utilises RIS data from 2016 onwards (n=567 Wetlands of International Importance) and omits earlier data that was incomplete or submitted in an earlier RIS format

Source: Ramsar Convention on Wetlands. Briefing Note 13.

Figure A2.3 Global river connectivity status



Source: Grill et al., 2019

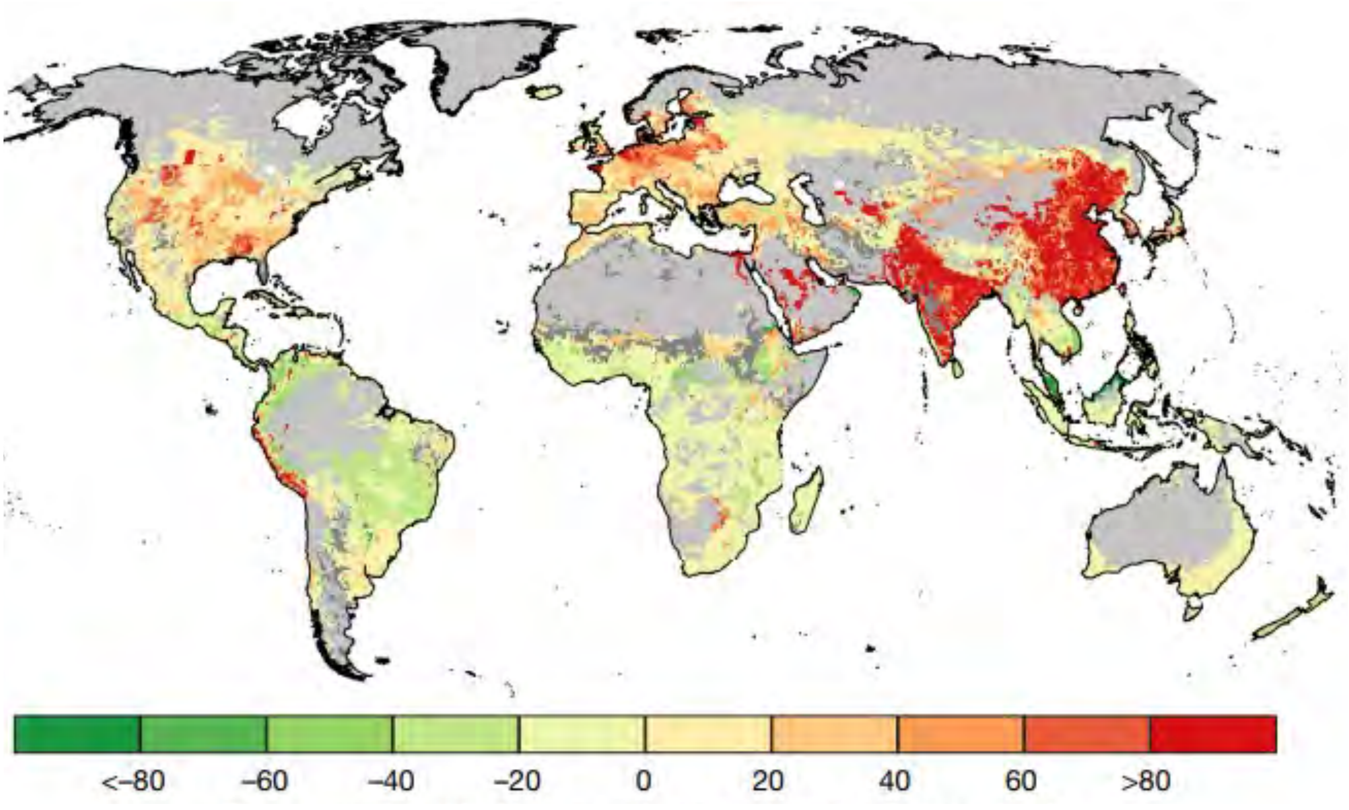
Note: The blue shade indicates the magnitude of the river discharge, and the darker blue shade indicates the discharge of high magnitude from larger rivers.

Annex 3. Agricultural nitrogen pollution: From planetary to regional boundaries

A recent study (Schulte-Uebbing 2022) establishes spatially explicit regional boundaries for agricultural nitrogen to achieve (a) critical N deposition to limit terrestrial biodiversity loss (b) critical N load to surface water to limit eutrophication; and (c) and critical N leaching to groundwater to meet drinking water standards.

Figure A3.1 shows the spatial variation of global exceedance of nitrogen thresholds. The aggregated global surplus boundary with respect to all thresholds is 43 megatons of nitrogen per year, which is 64 per cent lower than the current (2010) nitrogen surplus (119 megatons of nitrogen per year). Allowing the nitrogen surplus to increase to close yield gaps in regions where environmental thresholds are not exceeded lifts the planetary nitrogen boundary to 57 megatons of nitrogen per year.

Figure A3.1 Spatial variation in global exceedance of nitrogen thresholds



Exceedance of critical N surplus by current surplus (kgN ha^{-1} yr^{-1})

Water quality requires the strongest reductions in global N surplus: from 119 MtN yr−1 to 92 MtN yr−1 (boundary including possibilities for intensification in areas of no threshold exceedance). Respecting N surplus boundaries to avoid threats to terrestrial biodiversity requires a global reduction of 15 percent (to 101 MtN yr−1), whereas the N surplus boundary to avoid exceedance of health-impacting nitrate concentrations in groundwater (117 MtN yr−1) is close to the current surplus. Respecting all three thresholds simultaneously leads to a much lower global boundary of 57 MtN yr−1.

The study finds both N overuse and room for intensification of agricultural nitrogen. For example, to respect all three N-related thresholds, the N surplus needs to decrease by 77 percent (from 99 MtN yr−1 to 23 MtN yr−1) in regions where at least one threshold is exceeded but can increase by 70 percent (from 20 MtN yr−1 to 34 MtN yr−1) in regions where no threshold is exceeded.

The study finds that increasing nitrogen use efficiency (NUE) from to about 0.77 could be enough to meet a minimum crop demand of the current global population in a balanced diet scenario. However, current global crop production is not compatible with N boundaries, even with increased NUE.

Annex 4. Glossary of sustainable agricultural practices

This section summarizes findings on biodiversity benefits and time horizons to improved productivity from the literature review on financial and economic analyses of sustainable agricultural practices conducted for this report.

Table A4.1 Key biodiversity benefits from sustainable agricultural practices

Practice/ approach	**Definition/ key focus**	**Key biodiversity benefits**	**Typical constraints**
Intercropping Single practice	Growing two or more crops in proximity in the same field to boost soil health, pest control, and resource use efficiency.	• Improves soil microbial diversity & beneficial insects • Reduces chemical inputs (less pesticide/ fertilizer) • Rooting at multiple depths optimizes water/nutrient uptake, lowering pollution	• Complexity of timing/management (spatial layouts) • Some farmers focus on staple crops only • Seed availability & possible low demand for additional crops
Crop rotation Single practice	Alternating different crops over multiple seasons in the same field, often including legumes.	• Breaks pest/weed cycles, reducing reliance on pesticides/herbicides • Enhances soil biodiversity • Stabilizes yields over time (more resilience to disease/weather)	• Knowledge-intensive (optimal rotation design) • Market constraints for specialized crops • Smallholders may have limited land, prioritizing staple crops
Minimum/ zero tillage Single practice	Reduces or eliminates plowing by direct seeding into mulch or residues, minimizing soil disturbance.	• Protects soil structure & arthropods • Lowers soil erosion & runoff • Potentially cuts GHG emissions by carbon sequestration in undisturbed soil	• Often reliant on herbicides if rotation/ cover cropping are not robust • Special equipment/residue management needed • Knowledge-intensive adoption
Green manure/ cover crops Single practice	Planting cover crops between harvests to replenish nutrients, protect soil, and foster beneficial organisms.	• Builds soil organic matter, microbial diversity, and nutrient cycling • Reduces erosion, chemical pollution • Can fix nitrogen (legumes), lowering synthetic fertilizer use	• Not usually a cash crop (adds costs, not direct revenue) • Higher management complexity • Seed cost & local acceptance can be issues
Biocontrol Single practice	Using natural predators, parasites, or pathogens to keep pest populations below damaging levels (sometimes part of IPM or organics).	• Substitutes chemical pesticides, protecting pollinators & beneficial insects • Helps maintain ecological balance; good for long-term pest resistance	• Predator-pest dynamics can be slow or variable • Requires knowledge of local natural enemies • Often more effective with collective adoption or in broader IPM
Integrated Pest Management Bundle (multi-practice approach)	Combines cultural, biological, mechanical, and chemical controls to manage pests only as necessary.	• Minimizes pesticide use and pollution • Maintains beneficial insects and wild pollinators • Reduces harmful impacts on ecosystems & human health	• Requires training and ongoing monitoring • Collective action helps (neighbors) • May be complex to implement without strong extension services or threshold monitoring

Practice/ approach	Definition/ key focus	Key biodiversity benefits	Typical constraints
Farming with Alternative Pollinators Framework/ approach	Establishing pollinator-friendly habitats and corridors, diversifying off-field and in-field plantings.	• Enhances populations of native pollinators, boosting yields • Reduces pesticide reliance, preserving beneficial insects • Encourages farmland biodiversity at the landscape scale	• Requires large-scale/landscape coordination. • Need for knowledge on habitat/flower strip management. • Possibly higher labor and localized design
Integrated Nutrient Management Bundle (multi-practice approach)	Balancing organic (manure, compost, cover crops) and inorganic fertilizers, plus appropriate soil management, for site-specific nutrient optimization.	• Cuts over-fertilization, protecting water bodies and soil fauna • Improves soil structure and microbial life • Often lowers input costs and can raise yields	• Very knowledge/data-intensive (soil tests, local adaptation) • Transport/labor issues (manure) • Complexity of combining multiple sub-practices effectively
Agro-silvo-pastoralism Framework/ approach	Integrates crops, trees, and livestock in a single system, maximizing ecological synergies (carbon sequestration, soil health, diverse income).	• Boosts nutrient cycling & carbon storage • Diversifies production, mitigating risk • Enhances biodiversity (natural predators, pollinators, soil microbes)	• Complex setup & higher labor costs • Upfront investments, especially if waiting on tree crops • Requires technical knowledge & possibly multi-year horizon
Mechanical water/soil conservation Single practice	Methods like terracing, bunds, water harvesting, or ridges to reduce runoff and store water.	• Minimizes soil erosion & sedimentation • Protects downstream aquatic biodiversity • Improves water availability for local fauna, building resilience	• Often labor/capital-heavy (terracing • Land tenure issues may discourage structural changes • Solutions can be extremely location-specific
Micro-irrigation Single practice	Precision watering (drip, sprinkler) directly to plant roots, reducing water usage, leaching, and runoff.	• Conserves groundwater & aquatic biodiversity.Can achieve similar or higher yields with less water • Reduces nutrient leaching that harms aquatic ecosystems	• High initial / maintenance costs • Technical knowledge & extension support needed • May need subsidies or financing for smallholders
Waste-to-animal feed Single practice	Diverting food waste from landfills or processing facilities to produce livestock feed.	• Decreases land needed for feed crops (less habitat conversion) • Avoids landfill emissions (methane) • Can pair with manure	• Large-scale coordination/ regulation often lacking • Sorting & processing can be costly • Farmers need consistent, safe feed supply
Sustainable Manure Management Single practice	Converting/composting manure for soil application or biogas, rather than overloading fields or waterways.	• Cuts nutrient runoff & pollution. • Builds soil structure & fertility. • Biogas generation reduces fossil fuel use.	• Labor-intensive & potential odor/health concerns. • Transport costs & limited acceptance by some communities. • Often reliant on extension/training.
Organic Fertilizers Single practice	Use of compost, manure, or biofertilizers (microbes/fungi) to boost soil fertility rather than synthetic fertilizers.	• Increases soil microbial biodiversity. • Limits chemical leaching into water. • Improves soil structure & water retention.	• Synthetic fertilizers often cheaper & more nutrient-dense. • Logistics for compost/manure. Social perceptions (odor, contamination fears).

Table A4.2 Sustainable agricultural practices. time horizon to improved productivity

Practice	Key financial metrics	Sources of improved productivity	Time horizon
Single			
Improved seed varieties	Yields/ Returns	Improved varieties increase productivity, raising profits primarily via higher yields. . Effectiveness depends on matching varieties to local conditions (to realize their yield potential).	Immediate – yield and profit gains are realized within the same cropping cycle of adoption (studies did not report a need for multi-year adjustments).
Integrated farming system (diversified multi-component farm)	NPV	Diversification across crops and livestock generally improves profitability and resilience. However, optimal returns depend on a suitable integration design and farm scale. Often entails higher implementation costs (more components to establish), so realizing synergies is key to profitability.	Long-term – involves multi-year investments and management across enterprises; while initial costs are high, NPV is positive over time and farmers benefit in the longer run.
Crop rotation	NPV; profit; ROI	Rotating crops improves soil fertility and breaks pest/disease cycles, which over time boosts yields and reduces need for synthetic inputs. However, farmers face higher upfront costs in initial years. (longer-term analyses show positive NPV).	Medium-term – benefits often become evident after a full rotation cycle or two. Initial investment is higher, but net gains accrue within a few years as soil productivity improves.
Biocontrol (natural pest predators)	Yield; Revenue	Demonstrated in a specific case where bats predated on pests in organic apple orchards, resulting in measurable yield and income gains. This single-case evidence indicates that enhancing natural pest control can improve profitability by reducing crop losses to pests without additional input costs. The context is narrow (fruit orchard pest control), but it suggests that similar biocontrol measures (e.g., encouraging insectivorous birds or bats) can provide economic benefits when pest pressure is significant.	Immediate – the positive impacts on yield and revenue were realized on an annual basis. There is no lengthy delay for benefits; once the biocontrol agent (bats) is established, each season reflects the improved pest control in higher outputs and profits.
Bundled			
Climate-Smart Agriculture (CSA) (bundled practices)	Profit; payback period	While it delivers greater profits over time (by boosting yields and reducing climate risks), it often requires higher upfront investment and changes in management. This leads to a slower return on investment: farmers must wait a few seasons for net gains. The need for up-front resources and knowledge can be a barrier, but once adopted, CSA systems improve yield stability and long-run profitability.	Short-to-medium term – benefits are not immediate but are realized within a few years. Payback for CSA investments ranges around 2–4 years, indicating that farmers typically see positive net returns after several harvests. Long-term, CSA provides sustained financial benefits alongside enhanced resilience, but it requires a multi-year outlook to justify the initial costs.
Organic farming (bundled organic system)	Yield; payback period	During the conversion to organic, yields often dip initially, and full productivity may take years to recover. However, organic farmers benefit from sharply reduced input costs (no synthetic fertilizers or pesticides) and price premiums for organic products, which together tend to offset the lower yields. Most studies find organic systems become profitable, albeit over a longer horizon, thanks to improved soil health and market premiums. For example, cases of ancient wheat in Italy and medicinal plants in Mongolia showed that higher market prices compensated for yield declines. Overall, organic farming consistently showed positive returns in the majority of analyses once these factors are accounted for.	Long-term – requires a multi-year transition period. Profitability is often only fully realized after several years of organic management: one needs to account for the 2–3- year conversion phase and additional years for soil fertility to build up. Empirical evidence shows better economic performance of organic vs conventional after around 5–7 years. Many organic systems have a high initial payback period (around 8 years in one case), meaning farmers must be patient to reap the financial benefits of going organic.

Annex 5. Economic indicators in economic and financial analysis studies reviewed in Chapter 4

Economic Indicator	Description
Benefit-Cost-Ratio (BCR)	The ratio of the benefits to the costs of the investment in the practice.
Cost	Definitions of costs varied across papers. However, most defined costs as all input costs, excluding labor.
Fertilizer use	The total amount of fertilizer used, typically expressed in kg/ha.
Internal Rate of Return (IRR)	The discount rate at which the NPV is equal to zero.
Net Present Value (NPV)	The current value of the investment's costs and benefits over a specified time period.
Payback period	The number of years it takes to break even.
Pesticide use	The total amount of pesticides used, typically expressed in kg/ha.
Price	The market price of agricultural products. This may increase due to premiums from organic production, for example.
Profit	The difference between revenue and cost. In most cases the profit is gross profit as labor costs were not accounted for.
Revenue	Income generated by agricultural production.w
Water use	The total amount of water used.
Yield	The quantity of crop or multiple crops produced.

Annex 6. Sustainable agricultural practices

Case study: Mechanical soil and water conservation

Long-term soil and water conservation success

Location	**Practice**	**Impact period**	**Relevance**
Anjenie Watershed, Ethiopia	Stone bunds, terraces, vegetative barriers	Over 15 years	Smallholder farming systems in semi-arid regions

Key results at a glance				
25 percent increase in crop yields	Reduced sedimentation in water bodies	Recovered vegetation and enhanced biodiversity	Improved soil moisture retention and structure	High local ownership and sustained community engagement

A compelling example of sustainable land restoration and agricultural resilience is found in Ethiopia's Anjenie watershed, where long-term investment in mechanical soil and water conservation (SWC) practices has produced transformative outcomes for both people and nature. In this highland area, where steep slopes and erratic rainfall had long threatened agricultural viability, the consistent application of SWC measures such as stone bunds, terracing, and vegetative barriers over more than a decade has led to a dramatic reversal of land degradation.

Originally characterized by severe soil erosion, nutrient depletion, and declining yields, the Anjenie watershed experienced a restoration process that combined physical conservation infrastructure with community participation and traditional ecological knowledge. According to a study by Adgo, Teshome, and Mati (2013), crop yields in treated plots increased by up to 25 percent compared to adjacent, untreated areas. The improvements stem from enhanced moisture retention, stabilized topsoil, and reduced runoff, all of which contribute to a more productive and resilient farming environment.

Beyond boosting agricultural productivity, the intervention yielded substantial ecological co-benefits. Sediment load in water channels decreased, improving downstream water quality and reducing the need for expensive desilting operations. Vegetation cover in the area was significantly restored, supporting the return of beneficial biodiversity – including insect pollinators and birds that contribute to ecosystem stability.

The success of this initiative also hinges on strong community engagement and capacity-building. Local farmers were not passive recipients but active co-creators of the conservation strategy. Their traditional land knowledge was incorporated into modern SWC designs, enhancing the relevance, acceptability, and long-term sustainability of the practices. The case also illustrates how addressing structural barriers – such as insecure land tenure and lack of technical training – is critical to ensuring adoption and impact.

The Anjenie watershed experience underscores the potential for mechanical SWC practices to generate multiple wins: reversing land degradation, supporting biodiversity, enhancing water security, and improving rural livelihoods. It provides a replicable model for semi-arid regions facing similar environmental and socioeconomic challenges.

Policy takeaway

Scaling up such interventions requires integrated land and water management strategies, tenure security, and long-term support for farmer-led innovation.

Source: Adgo, E., Teshome, A., & Mati, B. (2013). Impacts of long-term soil and water conservation on agricultural productivity: The case of Anjenie watershed, Ethiopia. Agricultural Water Management, 117, 55–61. https://doi.org/10.1016/j.agwat.2012.10.026

Case Study: Crop rotation

Crop rotation revives soil and biodiversity in Canada's Northern Great Plains

Location	Practice	Impact period	Relevance
Northern Great Plains, Canada	Diversified crop rotation	Over 30 years	Smallholder and commercial grain farmers in semi-arid and temperate regions

Key results at a glance				
35 percent reduction in synthetic nitrogen fertilizer use	25 percent increase in crop yield stability	40 percent decrease in pesticide application	Enhanced soil microbial diversity and organic carbon levels	Improved water infiltration and reduced erosion rates

A long-term study in the Northern Great Plains of Canada has provided one of the most comprehensive and convincing demonstrations of how diversified crop rotation can transform agricultural ecosystems. Led by Agriculture and Agri-Food Canada, this 30+ year field study assessed the agronomic, economic, and ecological impacts of rotating wheat, pulses (e.g., peas, lentils), and oilseeds (e.g., canola), compared to monoculture wheat systems.

The evidence shows that diversified crop rotation goes far beyond a yield-enhancing strategy. It is a foundational ecological practice that revitalizes soil biology, enhances nutrient cycling, and strengthens the resilience of farming systems to biotic and abiotic stressors. Over three decades, these rotational systems have helped build robust soil microbial communities and stabilized yields while minimizing input costs. One of the most striking findings was the reduced reliance on synthetic fertilizers and pesticides, accompanied by increased profitability.

A key feature of this success was the mitigation of biodiversity loss and its direct enhancement of agricultural ecosystem services. The introduction of legumes improved soil microbial biodiversity by nurturing nitrogen-fixing bacteria and increasing organic matter. This enriched below-ground biodiversity fostered better soil structure, moisture retention, and disease suppression, all of which support consistent and higher crop yields. Additionally, less pesticide reliance enabled beneficial insects and pollinators to thrive, while reduced fertilizer runoff helped maintain aquatic biodiversity in nearby water bodies. These improvements in habitat maintenance, pollination services, and water quality directly benefited agricultural productivity and ecosystem resilience.

The study emphasized that rotational diversity interrupts pest and disease cycles, reduces soil erosion, and enhances water use efficiency. Importantly, it also found that incorporating legumes significantly lowered greenhouse gas emissions by reducing the need for nitrogen fertilizers and by sequestering carbon in enriched organic matter.

Policy takeaway

Crop rotation must be recognized as a core ecological strategy in sustainable agriculture policies. Incentives and advisory services should support farmers to transition from monoculture to diversified rotations, integrating legumes and regionally adapted crops that build ecosystem services.

Source: Smith, E. G., Zentner, R. P., Campbell, C. A., Lemke, R., & Brandt, K. (2017). Long-term crop rotation effects on production, grain quality, profitability, and risk in the Northern Great Plains. Agronomy Journal, 109(3), 957–970 https://doi.org/10.2134/agronj2016.07.0420

Annex 7. Bioinputs for biodiversity conservation in agricultural systems

What are bioinputs?

Bioinputs are natural products used in agricultural systems to enhance soil fertility, control pests, and promote plant growth without the adverse environmental impacts associated with synthetic agrochemicals. They include biofertilizers, biopesticides, and biostimulants derived from microorganisms, fungi, plant extracts, and other organic materials. Bioinputs play a crucial role in biodiversity conservation by reducing the reliance on chemical inputs that degrade soil health, contaminate water bodies, and harm wildlife.

How bioinputs help biodiversity

- **Soil health:** Bioinputs improve soil structure and fertility, promoting a diverse microbial ecosystem that supports plant growth.

- **Pest control:** Biopesticides target specific pests without harming non-target species, preserving beneficial insects and other wildlife.

- **Carbon sequestration:** Bioinputs can enhance carbon fixation in soils, contributing to climate change mitigation.

- **Reduced pollution:** By minimizing the use of synthetic chemicals, bioinputs reduce the contamination of water bodies and soil, protecting aquatic and terrestrial ecosystems.

Global adoption rates for bioinputs are not readily available, but the increasing interest and investment in bioinputs suggest a growing number of farmers are incorporating these technologies in their production systems. The global bio inputs market, which includes biofertilizers, biopesticides, organic fertilizers, and bio stimulants, is growing rapidly. Valued at over $10 billion globally, it is expected to more than double by 2030, with Latin America leading the growth. This expansion is driven by increasing consumer demand for organic food and sustainable farming practices, which encourage farmers to adopt eco-friendly alternatives to chemical inputs. Stricter government regulations on chemical use, combined with the efficiency and yield-enhancing benefits of bioinputs, further accelerate their adoption.

Bioinput research, commercialization, and adoption have benefited from supportive enabling environments in many countries. In Mexico, the government's flagship rural development program, "Production for Well-Being", includes technical assistance for smallholder farmers to produce bioinputs. In Colombia, the National Policy on Agricultural Inputs promotes bioinput use and production through research investments. In Brazil, specific laws and regulations create a streamlined, supportive environment for bioinput registration and use. India has implemented a wide range of measures to promote bioinputs, including publicly funded research, public-private partnerships for commercialization, farmer subsidies, credit facilities, and training programs.

Mexico, a megadiverse country home to 10–12 percent of the world's species, is projected to see its bio inputs market reach nearly $2 billion by 2032, growing annually at 13 percent. The rise in biopesticides demand, which accounts for 79.5 percent of the domestic market of bio inputs, alongside the growing popularity of bio stimulants and biofertilizers, drives this growth. The expanding organic farming sector in the country, which has seen a 30 percent increase in land under organic production since 2018, further boosts bio input adoption. This growth is supported by investments from both local companies and international players like Syngenta and Adama Agricultural Solutions, creating jobs and contributing to economic development. Favorable factors such as low agricultural labor costs and government initiatives like the "Production for Well-Being" program also play a key role in Mexico's market expansion. The increasing use of bio inputs is concentrated in the northern region and is mostly driven by large scale farming producing high value export crops.

At the farm level, surveys across 22 countries in Latin America suggest that producers see bioiputs as an opportunity to reduce production costs and enhance agricultural yields. However, barriers to adoption are multiple.

Farm-level adoption challenges:

- **Knowledge and training:** Farmers need education on the benefits and application of bioinputs.

- **Regulatory barriers:** Complex registration processes for bioinputs can hinder their adoption.

- **Financial constraints:** Initial investment costs for bioinput production and application can be prohibitive for smallholder farmers.

- **Market availability:** Limited availability and inconsistent quality of bioinputs in the market can deter farmers from adopting them.

Economic viability of bioinputs by type and region

By type:

- **Biofertilizers:** These are economically viable as they can be produced locally using organic waste, reducing dependency on expensive synthetic fertilizers.

- **Biopesticides:** While effective, their production requires specific knowledge and technology, making them more costly than conventional pesticides. However, their long-term benefits in reducing pest resistance and environmental damage can offset initial costs.

- **Biostimulants:** These products enhance plant growth and resilience, potentially increasing yields and reducing the need for other inputs, making them economically attractive either alone or in combination with traditional fertilizers.

By region:

- **Latin America:** Countries like Mexico, Brazil and Colombia are investing in bioinput adoption through training, education, and credit instruments. The World Bank's projects in these countries support the transition to bioinput-based systems.

- **India:** India has seen significant uptake of bioinputs, particularly biofertilizers, due to government subsidies and support programs. The economic viability is enhanced by the large-scale production and availability of raw materials.

Action to promote bioinput adoption

Regulation:

- **Simplify registration processes:** Develop specific assessment procedures for bioinputs to reduce entry barriers and facilitate market access. Consider unique risk profiles for industrial versus smallholder bioinputs production.

- **Intelligent control:** Implement guidelines for the safe self-production of bioinputs, particularly for high-risk products.

Research and development:

- **Strengthen R&D infrastructure:** Invest in research centers and universities to enhance technical training and develop new bioinput technologies. Encourage public-private partnerships to speed commercialization.

- **Participatory research:** Promote documentation of field trials and participatory research, for example with trade associations, to provide evidence on bioinput impacts and effectiveness. This approach has boosted adoption in Mexico's avocado industry.

Financing the transition:

- **Credit instruments:** Integrate existing credit instruments with bioinput promotion programs to support farmers financially.

- **Investment support:** Provide funding for R&D projects, pilot tests, and infrastructure development to facilitate bioinput production and adoption.

Addressing farmer adoption challenges:

- **Education and training:** Conduct training programs and awareness campaigns to educate farmers on the benefits and application of bioinputs.
- **Market development:** Support the creation of local bioinput production facilities to ensure consistent quality and availability.
- **Risk mitigation:** Develop financial mechanisms to compensate farmers for potential yield fluctuations during the transition to bioinput-based systems.

By implementing these recommendations, governments and the private sector can promote the adoption of bioinputs, contributing to biodiversity conservation in agricultural systems around the globe.

Source: FAO (2024). Bioinputs: Investment Opportunities in Latin America.

Annex 8. Restoration case studies

Restoration of Loess Plateau, Northwest China

The Loess Plateau, in China's Northwest, was known for its dry, powdery, wind-blown soil. Centuries of overuse and overgrazing has led to some of the highest erosion rates in the world, resulting in widespread poverty and environmental degradation. The region faced severe soil erosion, reduced agricultural productivity, and frequent sandstorms affecting downwind urban areas. The World Bank supported two major projects to transform the Loess Plateau degraded area into a region of sustainable agricultural production.

Costs and economic impact

The total cost of the restoration projects was substantial, but the investments yielded significant economic and environmental returns:

- **Investment:** The projects restored 4 million hectares of land, more than doubling the incomes of local farmers and reducing erosion by 100 million tons of sediment annually.

- **Economic benefits:** The projects lifted more than 2.5 million people out of poverty, increased grain production from 365 kg to 591 kg per year, and increased employment by 17 percent.

- **Environmental benefits:** The restoration efforts improved soil health, reduced erosion, ensured cleaner water, and sequestered carbon. Vegetation cover in designated restoration areas increased by 99 percent due to the Grain for Green program, which prohibited grazing in these areas.

- **Social impact:** The projects aimed to strengthen household stability and reduce migration to cities by improving local livelihoods. The restoration of the Loess Plateau led to remarkable improvements in both the environment and the livelihoods of the local population:

- **Incomes:** Households saw their incomes increase from about $70 per person per year to about $200.

- **Vegetation cover:** The perennial vegetation cover increased from 17 to 34 percent.

- **Sediment control:** The flow of sediment into the Yellow River was reduced by more than 100 million tons each year, reducing the risks of flooding and improving water quality.

Conclusion

The restoration of the Loess Plateau is a prime example of how large-scale ecological restoration can lead to significant economic, environmental, and social benefits. The World Bank's support and the Chinese government's commitment to sustainable land management played crucial roles in the success of this project.

The Great Green Wall Initiative (GGWI): A remarkable restoration story

Desertification, drought, and land degradation have been common features of the Sahel region of Africa, which stretches from Senegal in the west to Djibouti in the east. However, amidst these challenges, remarkable stories of resilience and innovation have emerged: the Yacouba Sawadogo from Burkina Faso and the Keita Project in Niger. Both initiatives have played pivotal roles in the Great Green Wall Initiative (GGWI), a pan-African effort to combat desertification and restore degraded landscapes.

Yacouba Sawadogo and the Zai Technique

Faced with the relentless advance of the desert and the degradation of his farmland in the 1980s, Yacouba Sawadogo, a farmer from Burkina Faso, turned to traditional agricultural techniques to reclaim the land. Sawadogo referred to as “the man who stopped the desert” used the “zai” technique, a method of planting crops in small pits to capture water and nutrients. Over time, vast areas were re-greened, transforming barren landscapes into productive farmland.

- **Water harvesting:** Zai pits are small (20-30 cm diameter, 10-15 cm deep), circular holes dug at regular intervals across the field.

- **Organic matter:** Pits are filled with organic matter- compost or manure, retaining moisture and providing nutrients.

- **Planting:** Seeds are planted in the pits benefiting from water, and nutrients.

The Keita Project in Niger

A large-scale land restoration initiated in early 1980s in Niger, aimed at combating desertification and improve the livelihoods of local communities through sustainable land management practices.

- **Reforestation:** Millions of trees stabilize the soil, reduce erosion, and create favorable microclimate for agriculture.

- **Water management:** Small dams, terraces, and other water-harvesting structures capture and store rainwater, making it available for agricultural use during dry periods.

- **Soil conservation:** Contour plowing, mulching, and cover crops employed to improve soil fertility and prevent erosion.

- **Community involvement:** Success largely due to active participation of local communities. Farmers trained in sustainable land management practices played a key role in project implementation.

The Keita Project demonstrates that large-scale land restoration efforts could be successful when based on local knowledge and active participation of communities.

The Great Green Wall Initiative (GGWI)

Both Yacouba Sawadogo's work, and the Keita Project have become integral parts of the Great Green Wall Initiative (GGWI). Launched in 2007 by the African Union, the GGWI aims to create a mosaic of green and productive landscapes across the Sahel region, stretching from Senegal to Djibouti and covering approximately 100 million hectares of degraded land.

Objectives of the GGWI

- **Combat desertification:** By restoring degraded lands and promoting sustainable land management practices, the GGWI seeks to halt the advance of the desert.

- **Enhance food security:** Improved agricultural practices and increased vegetation cover can boost crop yields and provide more reliable sources of food for local communities.

- **Mitigate climate change:** Reforestation and land restoration efforts can sequester carbon, helping to mitigate the impacts of climate change.

- **Promote biodiversity:** The creation of green corridors can provide habitats for wildlife and promote regional biodiversity.

The successes of Yacouba Sawadogo and the Keita Project have inspired and informed the broader efforts of the Great Green Wall Initiative, offering hope for a more sustainable and resilient future for the Sahel region. Through continued innovation, collaboration, and commitment, the dream of a re-greened Sahel is becoming a reality.

Annex 9. Biodiversity credits

Biodiversity credit markets are an emerging results-based finance tool that have gained increasing attention. Multiple public and private initiatives have formed in the last few years to shape a growing and credible market.

However, there is no universally agreed definition of biodiversity credits[15]. The Biodiversity Credit Alliance (BCA)[16] recently proposed the following definition (BCA 2024):

“A biodiversity credit is a certificate that represents a measured and evidence-based unit of positive biodiversity outcome that is durable and additional to what would have otherwise occurred.”

The outcomes for which a biodiversity credit is issued can be achieved through activities that generate three different types of complementary results:

- **Uplift:** The improvement in biodiversity from interventions such as ecological restoration indicated by a change in the structure, composition, and function of the target ecosystem or species populations, or reduction in threat measures.

- **Avoided loss:** The prevention of decline in biodiversity resulting from project interventions such as preservation or land designation indicated by the prevention of changed structure, composition, and function of the target ecosystem or species populations, or prevention of increase in threat measures.

- **Maintenance:** The maintenance of intact biodiversity through interventions such as conservation management plans, strengthened Indigenous rights, and sustainable financing of conservation, indicated by the prevention of changed structure, composition and function of the target ecosystem or species populations, or prevention of an increased threat.

Biodiversity outcomes are highly diverse and location specific. Unlike carbon credits, biodiversity credit outcomes are highly site specific, and impact depends upon the ecological and economic context of the location. Whereas a ton of CO_2e reduced in a city location will have the same impact on the global climate outcome as a ton of CO_2e reduced in a rural setting elsewhere, this is not the case with biodiversity credits. Furthermore, there are a multitude of different biodiversity outcomes. Whereas for greenhouse gas emissions (GHG) the uniform metric of CO_2e has been applied as a unit that allows fungibility of emission reductions (e.g., CO_2, methane, N_2O) and underpins a global market for fungible carbon credits, no such equivalence unit easily presents itself for biodiversity outcomes.

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[15] In some initiatives, biodiversity credits are referred to as biodiversity certificates.

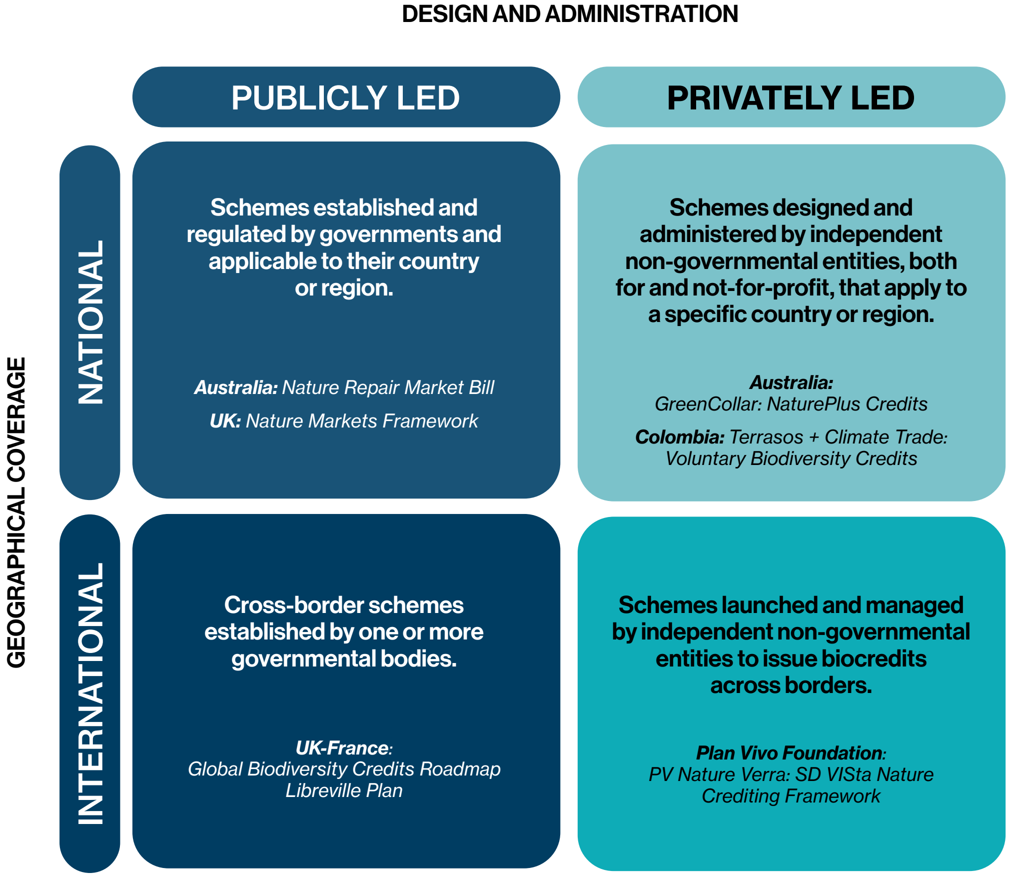
[16] The Biodiversity Credit Alliance (BCA) is a partnership facilitated by UNDP and UNEP FI, working to help steer the development of a credible and scalable biodiversity credit market which is based on a framework of high-level, science-based principles. It was formed at COP 15.

Voluntary biodiversity credits should ideally enhance biodiversity rather than offset losses. In view of the essentially local nature and specificity of biodiversity outcomes and the non-substitutability of ecosystems, most initiatives recommend developing credit markets as a means to enhance – and claim – contributions to achieving biodiversity outcomes, not to offset an "equivalent" biodiversity loss.

Schemes differ in their geographic scope and the role of the public and private sectors. Publicly led schemes provide incentives and/or regulations that shape supply and demand (BCA 2023b). Private sector-led schemes are voluntary in nature. Figure A9.1 provides an overview of four types of biodiversity credit schemes. This section focuses on voluntary private sector-led international schemes.

Demand for credits is currently low, in particular corporate demand, due to a lack of equivalency and market complexity. While interest in biodiversity credits has picked up since the agreement of the GBF and several initiatives have been launched to aid biodiversity credit market development, the demand for credits has been slow to develop and corporate demand has lagged behind expectations. Several projects have struggled to sell their credits (Colombo 2024a). Agrifood companies have not so far been prominent actors in the biodiversity credit market.

Figure A9.1 Categorization of biodiversity credit schemes by scope and public-private sector roles (Palmegiani, I. et al, 2023).



DESIGN AND ADMINISTRATION

GEOGRAPHICAL COVERAGE

	PUBLICLY LED	PRIVATELY LED
NATIONAL	**Schemes established and regulated by governments and applicable to their country or region.** ***Australia:*** *Nature Repair Market Bill* ***UK:*** *Nature Markets Framework*	**Schemes designed and administered by independent non-governmental entities, both for and not-for-profit, that apply to a specific country or region.** ***Australia:*** *GreenCollar: NaturePlus Credits* ***Colombia:*** *Terrasos + Climate Trade: Voluntary Biodiversity Credits*
INTERNATIONAL	**Cross-border schemes established by one or more governmental bodies.** ***UK-France:*** *Global Biodiversity Credits Roadmap* *Libreville Plan*	**Schemes launched and managed by independent non-governmental entities to issue biocredits across borders.** ***Plan Vivo Foundation:*** *PV Nature Verra: SD VISta Nature Crediting Framework*

Market size estimates are highly variable and weak due to lack of system infrastructure. A review in early 2023 found $8 million pledged for crediting schemes covering more than 800,000 ha (Bloomberg NEF 2023). The WEF analyzes estimates that global demand for biodiversity credits could reach $2 billion in 2030 and $69 billion in 2050 if markets develop positively but may range between $760 million in 2030 and $6 billion in 2050 if progress is less effective (WEF 2023a). Whereas 86 percent of large companies have set climate strategies, just 5 percent have nature or biodiversity strategies with few noting biodiversity credits (WEF 2023a).

Emerging quality criteria for biodiversity credits are not yet well defined. There is broad consensus that credits must be durable, evidence based, underpinned by transparent and robust MRV, and be additional to other credits to avoid double counting. Meeting such criteria for environmental integrity is already highly challenging for carbon credits and will be more complex for biodiversity credits with a much heavier data burden.

Market governance bodies are not yet established, which risks the integrity of the biodiversity outcomes. Integrity challenges have led to the establishment of the Integrity Council for the Voluntary Carbon Market introducing Core Carbon Principles to strengthen climate outcomes and project credibility. The lack of agreed integrity standards in the market could leave it vulnerable to disreputable businesses that oversell and underdeliver on biodiversity outcomes and at the same time hold back serious operators who are looking to build a sustainable business model. Establishing a minimum standard for what a biodiversity credit needs to be, with an attached label or certificate, is essential to underpin longer-term stable market development.

Independent validation will be essential to build buyer confidence (IAPB 2024a). More than two-thirds of credit issuers surveyed in 2024 indicated that credits issued under their schemes were verified by an independent third party, the remaining issuers planning the same (Waterford, L. et al. 2024).

Clarifying claims is key to unlocking corporate demand. Mandatory/compliance markets – national and under the UN Framework Convention on Climate Change (UNFCCC) – aimed toward achieving net zero, were critical in driving development of the voluntary carbon market, but there is no equivalent compliance mechanism for biodiversity. For corporate voluntary demand to grow, clarity on how to account for credits and on which claims can be made against the purchase of credits (Colombo 2024b) is needed, as an equivalent of a “net-zero” commitment does not currently exist.

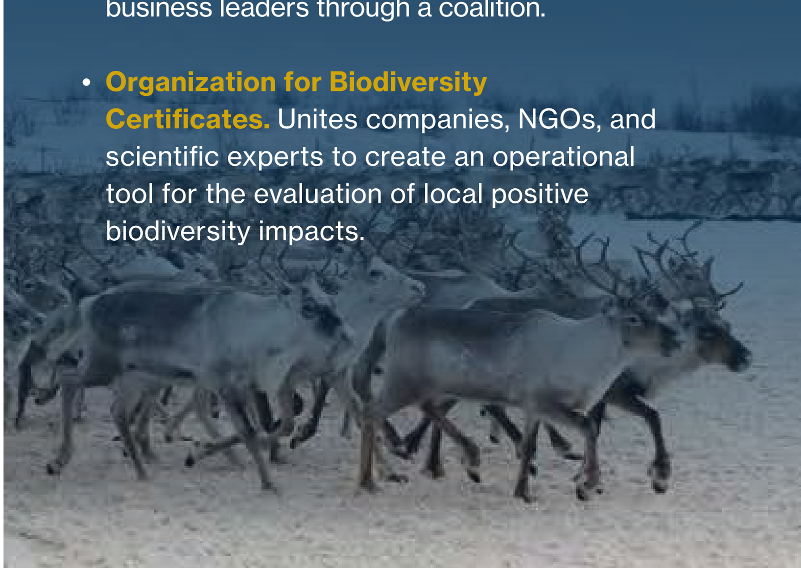
Market governance bodies are not yet established, which risks the integrity of the biodiversity outcomes. Integrity challenges have led to the establishment of the Integrity Council for the Voluntary Carbon Market introducing Core Carbon Principles to strengthen climate outcomes and project credibility. The lack of agreed integrity standards in the market leaves space for “nature cowboys” who oversell and underdeliver on biodiversity outcomes and at the same time holds back serious developers who are looking to build a sustainable business model. Establishing a minimum standard for what a biodiversity credit needs to be, with an attached label or certificate, is essential to underpin longer-term stable market development.

Box A9.1
Initiatives to foster the development of biodiversity credit markets

Several initiatives have emerged that aim to accelerate development and foster quality.

These include:

- **Biodiversity Credit Alliance (BCA).** A partnership formed at COP 15 and facilitated by UNDP and the UNEP Finance Initiative (FI) working to help steer the development of a credible and scalable biodiversity credit market based on a framework of high-level, science-based principles.
- **International Advisory Panel on Biodiversity Credits (IAPB).** An independent initiative established by the United Kingdom and France launched at COP16 to facilitate the creation and growth of high integrity biodiversity credit markets.
- **WEF Nature Markets and Biodiversity Credits Initiative.** Aims to establish a global system that integrates nature-based solutions into the economy, particularly through biodiversity credits and other mechanisms using a collaborative approach. Engages key business leaders through a coalition.
- **Organization for Biodiversity Certificates.** Unites companies, NGOs, and scientific experts to create an operational tool for the evaluation of local positive biodiversity impacts.



In addition to specific biodiversity credits, carbon credits offer opportunities to channel financing to achieve biodiversity outcomes. There is strong scientific evidence of biodiversity and climate feedback loops (Poertner et al. 2021). Many carbon market interventions offer implicit or explicit biodiversity benefits, in particular in agriculture, including among others improved soil management, grazing and livestock management, water management, and composting (Steele, P. et al. 2023). Co-benefits, including biodiversity co-benefits, already allow carbon credits to command a price premium. Some carbon credit buyers even noted that biodiversity benefits were the primary reason for a credit purchase (Ecosystem Marketplace 2024). Leading carbon market standards have already developed and are further strengthening their biodiversity-related labels, such as Verra with SD Vista and Plan Vivo, which is even branching out to offer a specific biodiversity standard, PV Nature.

There are opportunities to stack or bundle carbon and biodiversity credits but standard procedures are languishing. In many contexts, market proponents look to merge biodiversity credits with carbon through stacking (developing separate credit types from the same land) or bundling (showing multiple benefits within a single credit) (see, for instance, IABP 2024b). The combination of these approaches continues to evolve as they face challenges with transaction costs, proving additionality, and considerable ecological complexities in attributing credit outcomes (von Hase, Amrei and Cassin 2018). The rules of stacking and bundling in the biodiversity credit market are not uniform across standards and schemes, which could limit supply.

Credits need to be generated and used in line with the rights and needs of Indigenous Peoples and local communities. Indigenous Peoples (IPs) and local communities (LCs) are principal stewards of biodiversity and are both dependent upon and affected by changes in nature. Indigenous Peoples, while a small part of the world's population, have protected significant proportions of global biodiversity[17]. The CBD and its Nagoya Protocol highlights the significance of equitable benefit sharing and respect for the traditional knowledge held by IPLCs. In a recent market actor survey, three-quarters of respondents said that IPs and LCs are involved in credits generated from land or waters where IPs and LCs have a continuous connection or legal interest, a growing trend. The extent of involvement differs, with the most common form being project implementation, benefit sharing, or mechanisms that remunerate stewardship (Waterford, L. et al. 2024). Tenure rights have been highlighted as a critical factor for project success (IAPB 2024b). External investors need to engage with Indigenous Peoples and local communities both to respect rights and ensure justice, but also to effectively manage risks related to biodiversity credit investments (BCA 2023a).

MRV (Measurement, Reporting and Verification) is critical not only to ensure the credible functioning of a (voluntary, global) biodiversity credit market but also to stimulate demand. Possible measurement approaches differ depending upon the type of credit and the standard. Some of the principal approaches are outlined in Table A9.1 (BCA 2024).

Table A9.1 A non-exclusive and non-exhaustive list of how the different credit types and the activities that generate credits can be measured (BCA, 2024)

Uplift	Avoided loss or maintenance
1. Quantified change in one or more measures of biodiversity (quantified measures across a basket of underlying project-specific metrics, quantified measures in the dominant characteristics of ecological integrity, quantified measures of species or ecosystems of conservation or cultural importance). 2. Quantified measures of reduction in threats with evidence of a causal relationship between threat risk reduction and biodiversity uplift.	1. Quantified prevention of detrimental change in one or more measures of biodiversity. 2. Quantified improvement in management effectiveness with evidence of a causative relationship between improved management effectiveness and biodiversity maintenance. 3. Quantified measures of reduction in demonstrable, imminent threats with evidence of a causal relationship between threat risk reduction and avoided loss of biodiversity.

Reliable MRV is an essential building block to any credit system but despite early progress on MRV approaches, there is a lack of clear alignment. A recent survey identified nine distinct methodologies under development to quantify biodiversity gains with considerable heterogeneity among the approaches and assumptions in what is measured. The methodologies include those developed by MNHN, Wallacea Trust/Plan Vivo, Value Nature, Ecosystem Restoration Standard (ERS), Terrasos, SD VISta Nature Framework, Pivotal future, Qarlbo and EKOS. A broad array of methodologies may be needed as no one will perform adequately in all contexts given the wide range of biodiversity and ecosystem outcomes. The survey noted that common definitions would be beneficial for comparison of metrics (Zadek, S et al. 2023). **Table A9.2** outlines the major distinctions in indicators and examples of their application by various biodiversity credit organizations.

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[17] While the often-cited claim that 80 percent of the world's biodiversity is found in Indigenous territories has been found to not be based upon evidence, the essential roles of Indigenous Peoples in global biodiversity conservation have been recognized in several studies. See Fernandez-Llamazares et al. 2024.

Table A9.2 Indicators across methodologies under development (from Zadek, S. et al, 2023)

Species-level indicators	Measuring indicators that directly reflect abundance and/or diversity of species or their populations (e.g., ecological studies, bioacoustics). Example: Wallacea Plan Vivo, Pivotal future, and ERS methodologies derive a global biodiversity metric from species-level biodiversity metrics.
Ecosystem level indicators	Measuring indicators corresponding to ecosystem characteristics (e.g., tree species diversity, soil carbon concentration). Examples: (1) MNHN Carbone 4 OBC methodology uses a metric that is similar to the MSA.m2 (Mean Species Abundance), assessing the global integrity of an ecosystem on a scale where 0 corresponds to the absence of biodiversity and 1 corresponds to an intact ecosystem*; (2) ValueNature defines "hectares of protected/restored land" and derives an annual ecosystem integrity index from a global biodiversity metric incorporating species and landcover change metrics and including a temporal criterion (specifying that protection/restoration should last for 10 years with a 30 years permanence window).
Practice specific indicators	Measuring indicators relative to management practices (e.g., pesticide use, soil management). Examples: MNHN-Carbone 4-OBC.
Pressure specific indicators	Examples (1) Terrassos' biodiversity credit corresponds to 30 years of conservation and/or restoration of 10m2 of a threatened ecosystem; (2) Ekos also express the results in terms of areas and has a special focus on pests and weeds.

* This metric provides a way to quantitatively assess the state of biodiversity within a given ecosystem, offering insights into how much an ecosystem has been impacted by various factors relative to its pristine state.

Source: Zadek, S. et al, 2023

Biodiversity credits based on measuring activities to reduce threats, rather than measuring biodiversity impacts, can be appropriate in some contexts. Ideally, credits should be based upon methodologies that measure a change in biodiversity. Methodologies that use indicators of threat reduction of physical habitat conditions should, where possible, include at least some measurement of changes in biodiversity. Measures of threat reductions may be most valid where there is strong scientific evidence of causal relationships that can allow estimation of a quantitative change in biodiversity with a quantitative change in threat or physical measures (BCA 2024).

Innovation and technology development offer new and diverse options to meet biodiversity monitoring requirements with varying temporal and spatial scales. These include : (i) Remote sensing: gathering environmental data at a distance, e.g., through satellites or aircraft; (ii) New sensors: creating novel datasets by deploying camera traps, bioacoustics sensors, and GPS trackers; (iii) eDNA: using genetic material in the environment, such as DNA fragments shed by some species in water or soil samples to analyze ecosystems; (iv) Genetics: tools to monitor and maintain genetic variation in populations; (v) Modeling: techniques to study and predict the behavior of environmental systems, such as population dynamics, habitat changes, and species interactions; (vi) Software/Packages: open-access computer packages and apps for collection of field data; and (vii) Artificial Intelligence (AI): algorithms for making predictions, or decisions, based on detecting species from vast quantities of data (Nicolle, W et al. 2024).

Annex 10. Payments for Ecosystem Services: Case studies in the United States, United Kingdom, European Union and Peru, and the CompensACTION study

Payments for Ecosystem Services in the United States

In the United States, the **Conservation Reserve Program** (CRP), was established in 1985 to reduce soil erosion on highly erodible cropland and curb surplus commodities. Today, CRP has expanded to include water quality protection and wildlife habitats and as of 2022, 8.9 million hectares of land have been enrolled. CRP encourages agricultural producers to retire environmentally sensitive land from production and establish cover crops that control erosion, improve water quality, and develop wildlife habitat. The CRP includes highly erodible cropland planted in four of the past six years, marginal pasture suitable for riparian or water-quality purposes, ecologically significant grasslands with forests or shrubs, and farmable wetlands with related buffers. Land is selected using the Environmental Benefits Index (EBI) to rank and prioritize offers, directing funding to applications that promise the highest ecological returns, and are assessed on wildlife habitat, water quality, on-farm soil-retention and air quality benefits. Participants enrolled in CRP receive annual rental payments, cost-share assistance, and incentive payments (USDA a). Rental payments for land that was converted from production to conservation under the general CRP program were an average of $81.88 for the entire country in 2020 (USDA b). Contracts for projects are 10 to 15 years (USDA c). Participants can also receive maintenance incentive payments of up to $5 per acre per year for certain continuous sign-up practices, 50 percent cost-sharing for establishing approved cover, and additional financial incentives of up to 20 percent of the annual payment for specific continuous sign-up practices.

In 2021, the USDA also committed $10 million to partner organizations for CRP monitoring, assessment, and evaluation of the environmental benefits of CRP. Since its inception, the CRP has prevented more than 9 billion tons of soil from eroding and reduced nitrogen and phosphorus runoff by 95 percent and 85 percent, compared to annually tilled cropland. By establishing conservation covers such as grasses and trees on environmentally sensitive lands, CRP has created critical habitats that benefit bees, pollinators, and various bird species, including ducks, pheasants, turkey, bobwhite quail, prairie chickens, and grasshopper sparrows (USDA d). CSP participants experience tangible benefits, including increased resilience to weather and market volatility, reduced reliance on agricultural inputs, and improved wildlife habitat conditions (USDA e).

Other similar programs in the United States include the **Conservation Stewardship Program** (CSP), that offered payments for implementing conservation practices covering 28.3 million hectares of agricultural land and forest in 2022. Participants are required to enroll their entire agricultural operation and meet a stewardship threshold, addressing at least two natural resource concerns at enrollment and committing to addressing an additional concern by the contract's end. CSP offers up to 10 percent of costs for new practices, 100 percent of costs for conservation enhancements, and 125 percent if costs for crop enhancements.

The **Environmental Quality Incentives Program** (EQIP) provides both financial and technical support on 46.5 million hectares for installing or adopting conservation practices relating to agriculture, forestry, or livestock production. EQIP provides financial assistance for participants to hire technical assistance for Conservation Evaluation and Monitoring Activities (CEMA) that can support management strategies (USDA f). EQIP offers up to 75 percent of the estimated cost for adoption of new practices.

Payments for Ecosystem Services in the United Kingdom

Following Brexit, the United Kingdom is transitioning from the European Union's (EU) Common Agricultural Policy (CAP) to the Environmental Land Management (ELM) scheme, rooted in the principle of "public money for public goods." This framework comprises the **Sustainable Farming Incentive** (SFI), **Countryside Stewardship** (CS), and **Landscape Recovery** (LS). We focus on SFI and CS as LS has more of a focus on landscape restoration and not specifically targeting farmers (DEFRA a).

The two schemes aim to link payments directly to environmental benefits such as preserving wildlife-rich habitats, improving water quality, boosting flood and drought resilience through nature-based solutions, expanding and managing woodlands, and reducing carbon emissions while increasing climate resilience through actions such as soil, water, and peatland management (DEFRA b). The SFI covers 358,000 hectares, while the new CS scheme encompasses 948,000 hectares under mid-tier management and 466,000 hectares under higher-tier management. Requirements and payments vary by component of the ELM in the United Kingdom, but all participants must go beyond basic regulatory standards and demonstrate meaningful contributions to public goods, including cleaner water, reduced carbon emissions, and healthier wildlife habitats. In an SFI program, participants receive an SFI management payment for the first 50 hectares they enter, set at £40 per hectare in the first year and £20 per hectare for the following two years (DEFRA c). CS offers capital grants that are three-year agreements to achieve specific environmental benefits across four categories: boundaries, trees, and orchards; water quality; air quality; and natural flood management. There is a list of 70 capital items that are available (DEFRA d). The Natural England-led Agri-Environment Evidence Program seeks to monitor and evaluate existing agri-environment schemes, including CS (DEFRA e). Uncertainties around the long-term funding of ELM have created hesitancy among farmers, particularly as they transition from CAP-style subsidies. A common issue in ELM is the uncertainty surrounding the tax treatment of income from environmental schemes. Though still under development, ELM is expected to deliver long-term benefits by rewarding farmers for improving soil health, water quality, and biodiversity. Farmers participating in the SFI pilot have reported increased biodiversity, with more insects, birds, and small mammals supported by habitats like tall vegetation, trees, and flowers.

Payments for Ecosystem Services in the European Union

Under the Common Agricultural Policy (CAP), the European Union supports agri-environment-climate measures tied to biodiversity protection, soil conservation, and emissions reduction (Schaub et al. 2023). There are many avenues through which funding is awarded to farmers for environmentally positive actions but the scheme that we focus on here is the eco-scheme. Agricultural practices eligible for eco-schemes must address climate, environment, animal welfare, or antimicrobial resistance; align with national or regional priorities; exceed baseline regulatory requirements; and contribute to the EU Green Deal targets (European Commission). The practices need to go beyond legislative requirements for each country, which are detailed in the CAP strategic plans. Applications are open annually. Each member state is required to make eco-schemes available to at least two areas of action from a list of practices such as organic farming, integrated pest management, agroecology, and high nature value farming (ibid).

The CAP offers multiple methods for direct payments to be granted to farmers for adopting sustainable agricultural practices. The target areas and payment scheme vary by country. However, at least 25 percent of the national direct payment budget must go toward the eco-schemes during the 2023–2027 period (European Commission 2023). The CAP uses a common monitoring evaluation framework (CMEF) that uses 28 agri-environmental indicators to assess environmental impact. This is complemented by independent evaluations and studies assessments. The Integrated Administration and Control System (IACS) relies on interlinked digital tools and databases, including the Land Parcel Identification System (LPIS) to accurately recognize agricultural land parcels; a geo-spatial application (GSA) that enables beneficiaries to mark areas they request aid for; and the area monitoring system (AMS), which tracks farm practices to streamline checks; and animal registration. A major challenge is the administrative complexity involved in these programs, which often deter participation, particularly for smallholders and resource-limited farmers. Extensive paperwork, compliance requirements, and ambiguous guidelines can make enrollment and monitoring processes cumbersome (Pe’er et al. 2017).

Generally, studies show that CAP has had a positive effect on employment. There is a debate surrounding the CAP’s impact on the environment. Despite having at least 25 percent of CAP’s budget dedicated to environmental schemes, the EU court of auditors finds there is a lack of quantified estimates from member states (USDA g).

Peru’s Water Fund project (Aquafondo) 2024

Purpose and relation to biodiversity: Aquafondo was established in 2010 as a public-private water fund to address Lima’s water scarcity by conserving and restoring the Rimac, Lurin, and Chillon river watersheds. It enhances watershed sustainability through nature-based solutions, such as restoring ancient water filtration canals (amunas), thereby supporting both biodiversity conservation and sustainable water management.

Institutional structure: Initially a private initiative, Aquafondo evolved into a hybrid model after regulatory reforms in 2015. It operates through a multi-level governance structure, including a Board of

Directors representing public and private entities, a technical committee providing oversight and expertise, and partnerships with community organizations and water utilities, notably Lima's water utility (Sedapal). To ensure accountability, FONDAM, an organization experienced in managing conservation funds, oversees the administration of donations and collaborates with government agencies and local communities.

Funding flow: Aquafondo originally relied on philanthropic and private sector contributions. A major shift occurred in 2015 when Peru's water regulator, SUNASS (Superintendencia Nacional de Servicios de Saneamiento), mandated that water utilities allocate a portion of their revenues to watershed conservation. This change provided Aquafondo with a stable funding mechanism, transforming it from a privately funded initiative to a key implementer of public conservation investments.

Impact: The initiative successfully restored pre-Incan amunas, increasing water infiltration to over 520,000 m^3, benefiting both agriculture and urban water supplies. It has strengthened participatory governance in watershed management and influenced national policy by integrating nature-based solutions into water sector planning. Aquafondo has received multiple environmental awards, highlighting its impact on water security.

Success factors: Key success factors include strong community engagement, integration of Indigenous knowledge, and alignment with government policy reforms. However, long-term financial sustainability remains a challenge, as private sector contributions have not met expectations. Scaling the model requires balancing standardization with local adaptability.

CompensACTION research initiative

(De Blas, D.E.; Dittmer, K.; Costa Jr., C. 2025)

Study objective and design. This study, developed under the CompensACTION research initiative by the Alliance of Biodiversity International and CIAT, explores how different financing mechanisms – payments for Ecosystem Services (PES), subsidies, loans, and investments – affect smallholder income while promoting ecosystem conservation and restoration in the Global South. The analysis, based on a targeted literature review of impact evaluation studies and aligned with the broader goals of CompensACTION, considers how these mechanisms serve as climate-friendly incentives, support diversified livelihoods, generate co-benefits, and mobilize resources and actors at scale. Only studies focused on smallholders in the Global South were included for contextual relevance.

Definitions: PES and subsidies. PES involves conditional compensation (cash, in-kind, or technical assistance) linked to verified improvements in ecosystem services, with contractual obligations and enforcement mechanisms. In contrast, subsidies are non-conditional transfers, typically aimed at productive, economic, or environmental goals, but not tied to direct performance outcomes.

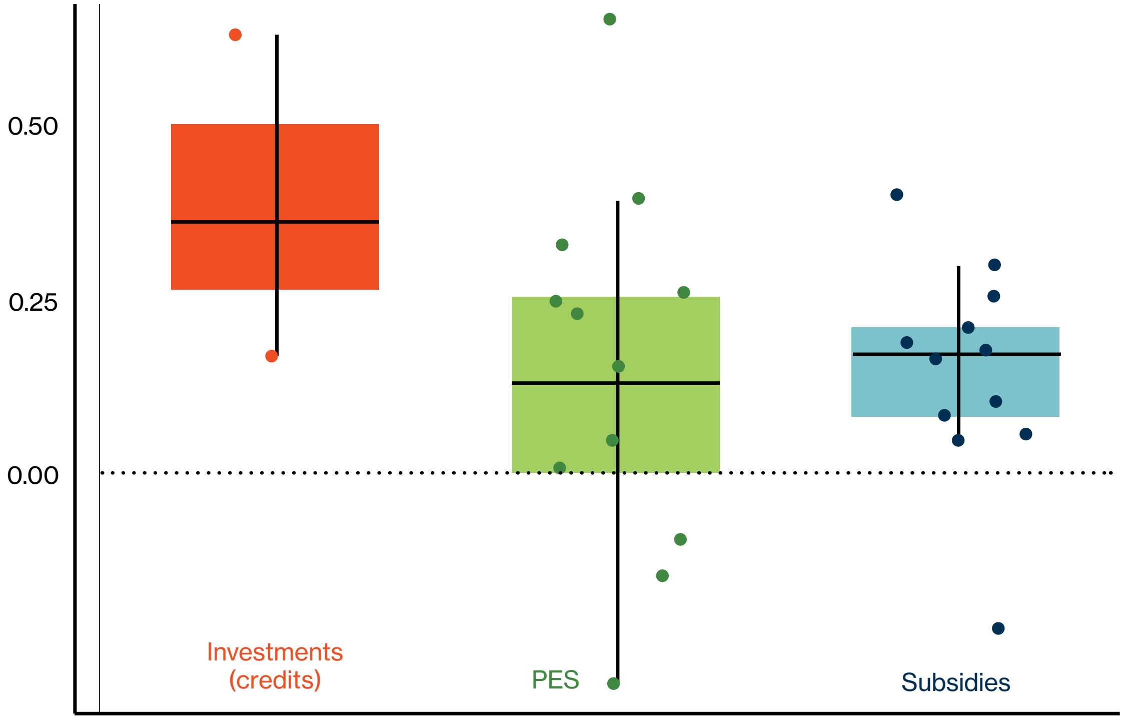
Ecosystem service objectives. PES schemes mainly target forest conservation, erosion control, and carbon sequestration, often with implicit biodiversity goals. Subsidies tend to focus on soil and fertility conservation, with broader objectives and less emphasis on measurable environmental performance. This reflects a key design distinction – PES emphasizes results, while subsidies often support practices with indirect benefits.

Contributions to farm income. From the 31 studies analyzed, both PES and subsidies show similar income impacts, typically under 15 percent of total farm income. Loans and investments tend to deliver higher returns. These findings suggest that PES and subsidies can enhance income, but should be seen as complementary tools, not primary income sources. Figure A10.1 shows the effect of PES on incomes compared to subsidies and investments.

Enabling conditions for PES. Although not the study's focus, existing evidence highlights key conditions for effective PES: robust MRV systems, strong institutional capacity, and political commitment. Integrating PES with income diversification strategies – like agroforestry or access to carbon markets – can improve adoption and long-term impact.

Conclusion. While both PES and subsidies enhance smallholder income, PES stands out when environmental outcomes are prioritized, thanks to its conditional and performance-based design. However, PES requires greater investment in MRV and institutional support. In lower-capacity settings, subsidies may offer a more practical entry point, especially when paired with technical assistance, capacity building, and phased implementation. The choice between PES and subsidies should be guided by local context, cost-effectiveness, and long-term sustainability goals.

Figure A10.1 Hedges' g effect size on net additional agricultural income by type of mechanism (n=31)



Annex 11. Payments for Ecosystem Services: My Farm Trees platform

My FarmTrees (MFT) empowers smallholder farmers to sustainably generate incomes for seed collection and propagation of native trees to scale nature-positive management such as multipurpose trees.

Digital adaptation-finance gateway for smallholder landscapes

MFT is an inclusive, digital, incentive-based platform that supports community-led tree planting and forest-landscape restoration. It mobilizes innovative climate adaptation finance by combining Payments for Ecosystem Services (PES) with digital verification tools that transparently track the full supply chain for restoration activities, from seedling to tree survival, and ecosystem outcomes. Farmers use a mobile application that fuses science-backed, highly targeted planting advice with photo-based survival proofs; every tree therefore acquires a timestamped, geolocated "ecosystem-service" identity that can live on a ledger. Because the cost of monitoring, reporting, and verification (MRV) is decreased, micro-scale restoration outcomes become verifiable at a price point compatible with smallholder finance.

Financial innovation

MFT is focused on expanding the scope of its financial applications as an inclusive, digital, incentive-based platform that supports community-led tree planting and forest-landscape restoration. Critically, the project introduces new forms of collateral to overcome a key barrier to inclusive agricultural finance: most smallholders cannot secure loans due to lack of traditional guarantees (e.g., land titles). MFT tackles this by turning each surviving tree or quantified carbon gain into a verifiable, tradable asset on its blockchain-based monitoring, reporting, and verification (MRV) system. Thus, farmers gain access to preferential loans and insurance products, while lenders become more willing to invest knowing loans are backed by quantifiable ecosystem assets. This approach unlocks and potentially integrates new capital streams (from carbon markets, impact investors, etc.) and reduces transaction costs by standardizing contracts and verification through digital tools, making adaptation finance more scalable and attractive. MFT aims to support multiple financing approaches:

- Blended finance for restoration outcomes (combining public, private, and climate-based funding).
- Digitally tracked PES programs that pay for verified ecosystem service outcomes.
- Risk mitigation instruments (e.g., loan guarantees or insurance schemes).
- Climate-smart fiscal incentives, where MFT's data informs subsidies or tax relief for adaptation activities.

By enabling degraded land restoration (including Farmer Managed Natural Regeneration where appropriate), improving soil health, and increasing resilience to climate shocks, MFT contributes to climate adaptation, biodiversity protection, and carbon sequestration.

A digital public good for scalable, inclusive restoration

- **For farmers:** MFT empowers millions of smallholders with free access to a trusted, science-based platform that ensures they benefit directly—through digital payments, verified seeds, and long-term livelihood gains.

- **For governments, donors, and companies:** MFT provides an open, transparent system to channel incentives, track outcomes, and align local action with global climate, biodiversity, and land restoration goals.

- **For society:** MFT serves as a public digital infrastructure that democratizes restoration, combining cutting-edge science (species diversity, carbon, water, soils) with digital innovation (blockchain traceability, remote sensing, QR-coded seedlings) to safeguard ecosystems as a shared planetary resource.

The platform is funded by the Global Environment Facility, implemented by IUCN, and executed by the Alliance of Biodiversity International and the International Center for Tropical Agriculture (CIAT).

Research that will be generated from My Farm Trees

- **Restoration science at scale**: Data on species performance, tree survival, and growth across climates, soils, and farming systems, based on provenance (seed zone) and diversity.

- **Socio-economic insights:** Understanding how direct incentives, digital wallets, and transparent payments influence farmer behavior, adoption, and equity.

- **Biodiversity & ecosystem services:** Evidence on how diverse species portfolios contribute to carbon sequestration, water regulation, soil health, and pollinators and diet diversity.

- **Digital innovation & governance:** Lessons on how blockchain, QR-coded seedlings, and AI-powered monitoring can build trust and accountability in restoration finance.

- **Policy impact research:** Linking farmer-level actions to national/global commitments (GBF, NDCs, Land Degradation Neutrality) with metrics that are transparent and verifiable.

Thailand
(2026)
Ecological
restoration

Malaysia
Indigenous
and local
conservation
efforts

Viet Nam
Agro-
ecological
farming

My Farm Trees in ASEAN countries

Indonesia
(2026)
Kalimantan
ecological
restoration,
agroforestry

Laos
Silvo-
pastoral
systems

Annex 12. Spatial datasets for identifying drivers of biodiversity loss

Emerging spatial data can inform spatial conservation and restoration planning, and the targeting of payments for environmental services.

Global-scale datasets can provide a baseline of land use change, climate variability, and biodiversity patterns. For example, Copernicus Sentinel-2 imagery can be used to monitor land cover changes over time, while NASA's Global Precipitation Measurement (GPM) mission can provide insights into precipitation patterns and water availability, which are critical for agricultural planning and conservation efforts. These global datasets set the stage by providing a baseline that highlights where significant changes or risks may be occurring. **Table A12.1 provides examples of relevant global datasets.**

These can be complemented by **regional/national-scale datasets** that offer more detailed regional information. For instance, national land use and land cover maps can provide information on agricultural land use patterns and protected area coverage, while regional climate models can simulate future climate scenarios.

Local-scale data is essential for capturing the nuances of local landscapes and communities. This may include high-resolution aerial imagery, soil surveys, biodiversity inventories, and socioeconomic data. Weaknesses in local data, such as inconsistencies in land use classifications and the lack of real-time data, highlights the need for localized GIS data. Example spatial datasets for identifying drivers of biodiversity loss to inform targeting of interventions is shown here.

Table A12.1 Spatial datasets for identifying drivers of biodiversity loss for targeting interventions

Integrated Biodiversity Assessment Tool (IBAT)	IBAT provides access to three global biodiversity databases for assessing proximity of an investment site to threatened species and conservation areas (World database of Protected Areas, World database of Key Biodiversity Areas, IUCN Red List of Threaten Species).
WWF Biodiversity/Water risk filter	Corporate and portfolio-level screening tool to help companies and investors prioritize action on what and where it matters the most to address biodiversity risks for enhancing business resilience and contributing to a sustainable future.
Diversity4Restoration	A tool developed to help with decision making on the use of appropriate tree species and seed sources for tree-based restoration or other tree planting activities.
Agrobiodiversity Index (hotspot tool)	Framework for monitoring biodiversity in food systems where this benefits healthy diets, sustainable production, and biodiversity conservation, based on spatial overlay of agrobiodiversity and food system threat layers.
InVEST ecosystem service models	Models designed to estimate the supply, use, and value of ecosystem services, based on land use maps, biophysical and socioeconomic data.
FAO ABC Maps	A geospatial app that holistically assesses the environmental impact of policies, plans, and investments in the agriculture, forestry, and other land use (AFOLU) sector.

Annex 13. Selected indicators for biodiversity monitoring

Selected indicators for biodiversity monitoring based on richness of information provided by indicator on a scale of 1-10 under the Land Health Monitoring Framework (IUCN 2024) is shown below.

Indicator	Richness	
Number of species of earthworms per farm (BioBio)	8	Belowgound diversity
Participatory Earthworm Observatory (ARB idF)	8	
Earthworms protocol (Vigie Nature)	8	
Les indices vers de terre (L'ADEME and EcoBioSoil)	8	
Species diversity (ALL-EMA Switzerland)	6	Aboveground diversity
Species quality (ALL-EMA Switzerland)	6	
Diversity and quality of species and habitats i BPAs (ALL-EMA Switzerland)	5	
Invertebrates protocol (Vigie Nature)	5	
Number of species of wil bees and bumblebees per farm (bioBio)	5	
Bees protocol (Vigie Nature)	5	
Number of species of spiders per farm (BioBio)	4	
Bats protocol (Vigie Nature)	4	
Butterflies protocol (Vigie Nature)	4	
Number of species of vascular plants per farm (BioBio)	4	
Habitat diversity indicators (BioBio)	4	Habitat diversity
Habitat quality (ALL-EMA Switzerland)	4	
Habitat diversity (ALL-EMA Switzerland)	4	
Potential biodiversity index (Biorgest)	4	
Landscape diversity (Biodiversity Performance Tool)	4	
Quality of semi-natual habitat - Management (BOT)	4	
Ecosystem restoration (Landscale)	4	
Quality of semi-natural Habitat - Composition (BPT)	4	
Natural ecosystem protection (Landscale)	4	
Natural ecosystem connectivity (Landscale)	4	

Source: Land Health Monitoring Framework (IUCN 2024)

Annex 14. Case study: Zoning for biodiversity conservation

Integrated terrestrial and marine biodiversity conservation in Mozambique's Primeiras e Segundas Archipelago

Purpose and relation to biodiversity: The Environmental Protection Area of the Primeiras e Segundas Archipelago (APAIPS) was established by the Mozambican government in December 2012 to combine terrestrial and marine biodiversity conservation with sustainable livelihood practices, such as farming and fishing, acknowledging that local communities depend on these ecosystems for their survival.

Zoning: APAIPS creates zones that integrate resource use with conservation for (i) terrestrial and marine natural reserves; (ii) sanctuaries; (iii) communal conservation areas; (iv) tourist investment zones; (v) multiple use zones (marine); and (vi) multiple use zones (terrestrial).

Institutional structure and funding: The initiative is overseen by the National Administration of Conservation Areas (ANAC), which is responsible for managing APAIPS activities with civil society, local communities, and local governments playing key roles in its implementation. APAIPS operates under a public-private funding model, combining government oversight with financial support from civil society organizations, international NGOs, and private donors.

Impact: The initiative has enhanced marine and terrestrial conservation through conservation zoning, no-take zones, farmer field schools, environmental education, and monitoring of illegal activities. No-take zones have been shown to increase fish production, while conservation agriculture, promoted through farmer field schools, has been linked to improved food security. However, the long-term impacts on biodiversity require further assessment.

Success factors and challenges to scaling-up: Success factors include strong community participation, the integration of conservation with development, a public-private funding model, and education and extension efforts. Challenges include financial dependence on donors and enforcement limitations. While the model is context-specific, key elements such as participatory governance and conservation-linked livelihoods can be replicated elsewhere.

Annex 15. Plant genetic resources for food and agriculture case studies

Case study 1: Collaboration between Community Seed Fund and gene banks in China

Motivation: The program started in Guangxi, an economically poor, agroecologically diverse mountainous area and one of the centers of maize genetic diversity in China. The opening of the domestic seed market in 2000 marginalized farmers' systems for saving and exchanging seed of local varieties resulting in a dramatic loss of genetic diversity.

Community Seed Fund Gene Bank Collaboration: In response to the severe loss of plant genetic diversity and the farmers' pressing need for climate resilient crop varieties, farmers and scientists across 19 provinces in China have established innovative solutions to dynamically conserve landraces, breed new varieties and broaden the gene pool for both the formal and farmers' seed systems. Over the course of ten years, 54 farmer-led community seed banks were established across 19 provinces, covering diverse agroecological regions. From a shared gene pool of 234 genetic resources contributed to by both local farmers and breeders, 88 land races have been conserved in situ and in gene banks and 12 new maize varieties bred. These materials were characterized on-farm and in laboratories. Conserved seeds are stored in the gene bank and are regularly regenerated and re-evaluated by breeders. Facilitated by Farmers Seed Network (FSN), the seeds are then redistributed to scale up dissemination to more farmers in other communities.

Benefit Sharing: Given the lack of Access and Benefit Sharing (ABS) legislation in China, a system of access and benefit sharing has been developed through collaboration between FSN (https://www.fsnchina.info), and the gene bank of the Guangxi Maize Research Institute (GMRI). The ABS arrangements provide (i) access to farmers' genetic resources by formal breeders and (ii) farmers with a share in the commercial benefits of their PGRFA and PPB efforts.

Technical Support: Community seed banks have implemented Farmer Field School (FFS) mechanisms, including training for local farmers, community-level field experiments such as Diversity Blocks, Participatory Varietal Selection (PVS) , and Participatory Plant Breeding (PPB).

Impact: Over the course of ten years, 54 farmer led community seed banks were established across 19 provinces, covering diverse agroecological regions. From a shared gene pool of 234 genetic resources contributed to by both local farmers and breeders, 88 land races have been conserved in situ and in gene banks and 12 new maize varieties bred.

Sources: (1) Consultations with Yiching Song and Guanqi Li; (2) Bai, K., Li, G., Song, Y., Yang, Y. Zhang, Z., Vernooy, R. (2024) The conservation of plant genetic resources in China. In Y. Al-Khayri, Jain, S.M., Penna, S. (Eds.) Sustainable utilization and conservation of plant genetic diversity. Springer, Singapore; (3) Song, Y. (1998) "'New' Seed in 'Old' China: impact of CIMMYT collaborative program on maize breeding in south-western China.' PhD thesis, Wageningen Agricultural University: The Netherlands.

Case study 2: Scaling up PGRFA conservation and sustainable use through the collaboration between the farmers community seedbanks and formal gene banks in Zimbabwe[18]

During extended periods of national crisis, when the formal seed systems collapsed and farmers faced seed insecurity and hunger, in 2009 the community seed banks (CSBs) of the Community Technology Development Trust (CTDT)[19] served as the only source of seeds in the driest and economically poor regions of Zimbabwe covering UMP, Tsholotsho, and Chiredzi districts. The community seed banks have been self-governed and self-sustained by local communities; with the dual function of collecting and conserving relevant PGRFA and the bulking and distribution of locally adapted seeds. The success of the PGRFA conservation, sustainable use, and innovation are reflected in: (i) the expansion of the community seed banks from three to 23. These CSBs are fully integrated in farmers' seed systems via more than 1,500 Farmer Field Schools (FFS) serving 45,000 farmers in 11 districts in 2024; (ii) long-standing institutional collaboration between community seed banks and national gene banks on germplasm exchange and conservation; (iii) innovations in plant breeding and seed commercialization between farmers and plant scientists; and (iv) policy engagement for farmer-inclusive seed systems and the incorporation of PGRFA conservation and sustainable use in Zimbabwe's National Biodiversity Strategy and Action Plan (NBSAP).[20] The successes of this approach have resulted in the concept being mainstreamed into the national government's plan of establishing 35,000 FFS.

The following are the pathways for the scaling up and mainstreaming of PGRFA conservation and sustainable use in Zimbabwe:

Participatory diagnosis of farmers' trait preferences and needs combined with technically sound and cost-effective solutions. The diversity of farming systems and ecosystems across the different agro-ecological regions require participatory diagnosis and planning with farmers. For example, CTDT had adapted and further developed the crop diversity wheel[21] to enable farmers to assess their agro-ecosystem and the status of crop diversity in their community. The exercises inform the choice of crops, trait preferences to work with and a list of breeding objectives. CTDT regularly conducts gender segregated diagnostics. This helps ensure that women's varietal trait preferences are part of the program approach.

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[18] Gigi Manicad (World Bank consultant)

[19] CTDT is a registered non-governmental organization founded in 1993 whose main effort is directed toward empowering communities over custodianship of their genetic resources and the protection of these resources through supportive policy and legislative frameworks to enhance conservation and sustainable use. CTDT has emerged as one of the strongest advocates in the region ensuring that farmers have adequate access to genetic resources, receive crop improvements and technological support and participate in the process of formulation of corresponding national and regional policies.

[20] The main instrument for implementing the Convention of Biological Diversity (CBD) at the national level.

[21] https://sdhsprogram.org/assets/2021/08/Illustrated-Field-Guide-Module-2-on-Diagnostic-Stage_revised.pdf

Establish mutually beneficial institutional links between the formal and farmers seed systems for PGRFA management. CTDT has a Memorandum of Understanding with the Ministry of Lands, Agriculture, Fisheries, Water and Rural Development to cooperate and collaborate with the various departments including the National Gene Bank. The elements covered specificity for the Gene Bank include germplasm and passport data collection, capacity building smallholder farmers on conservation and sustainable use of PGR practices for food and agriculture, repatriation and restoration of lost biodiversity, on-farm characterization, data collection, joint variety testing in multi-location sites for climate change adaptation. The other elements are seed physical cleaning, registration, germination testing and packaging of accessions to meet the minimum seed requirements to be safely duplicated at the national gene bank for base collections. CTDT in collaboration with the National Gene bank has cleaned and vacuum sealed nearly 1000 accessions duplicated at three levels (national, SADC region and the Svalbard global seedbank[22])

Continuous innovation through developing improved crop varieties for farmers, combining formal and local farmers' genetic resources and knowledge. Community Seed Banks, gene banks and breeding institutions share germplasm materials required by farmers including advanced and segregating materials from the national crop improvement program to meet the needs and demands of farmers in the context of climate change. This promotes farmer led agriculture research and technology development. In addition, it facilitates agriculture research agenda setting through participatory crop varietal and plant breeding, support on-farm experimentation and farmer capacity building. In this regard, crop diversity offers opportunities for participatory plant breeding, (PPB) and participatory variety selection (PVS). In Zimbabwe, CTDT and partners managed to develop and release two varieties of cowpeas and two varieties of pear millet and one groundnut variety. CTDT has similar arrangements with the CGIAR centers such as ICRISAT and CIMMYT where varied materials for farmer experimentation and action research are accessed.

PGRFA management in times of disaster. In 2019, cyclone Idai destroyed crop fields, granaries, and forests, all of which were important reserves of local seeds. The severe loss of these seed reserves has meant that affected communities have had less food to eat, farm, exchange and sell, impacting people's food and nutrition security and livelihoods – with long term effects. The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and FAO partnered with the national gene bank of Zimbabwe to assess the impact of the cyclones on local seed systems and to restore lost local seeds to affected communities in Zimbabwe (as well as Malawi and Mozambique). The Zimbabwe national gene banks and farmers collaborated to rescue, regenerate and return seed to affected communities. This further strengthened national and regional planning for the protection of local seed systems in the future. Among the main achievements of the project are the inclusion of seed system protection and restoration in national and regional strategies, the rescue of crop varieties that were at risk of becoming lost, and the multiplication and distribution of varieties that respond

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[22] https://www.seedvault.no/

to farmers' needs and preferences, as well as to current and future climate conditions[23].

Enable farmers to participate in the market and expand farmers access to wide range of quality seeds. CTDT has set up the Champion Farmer Seed Enterprise (FSEs) involving 2000 smallholder farmers to be part of the production of certified seed and marketing. This has economically empowered farmers with the technical knowhow, access to good quality seeds of their choice, ability to purchase affordable seeds that is adaptive to their ecological regions and increased productivity. The registration of farmer varieties process ongoing in Zimbabwe would allow Champion Seeds to manage and produce materials adapted to the local conditions and reached out to more farmers in the country.

Policy engagement to mainstream support farmer seed system. CTDT has greatly influenced policy formulation in Zimbabwe especially on issues related to the domestication of the ITPGRFA, highlighting the importance of the recognition and implementation of Farmers' Rights. CTDT has been involved in drafting memorandum of principles for Farmers' Rights legislation in Zimbabwe. CTDT is also engagement in policy reforms to allow the registration of farmer varieties.

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[23] Derived from: International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) Secretariat. 2023. Foundations for rebuilding seed systems post Cyclone Idai – Achievements and insights from project implementation: Malawi, Mozambique and Zimbabwe. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/07b27f6d-0858-41be-b48f-9fb57b5dcc37/content

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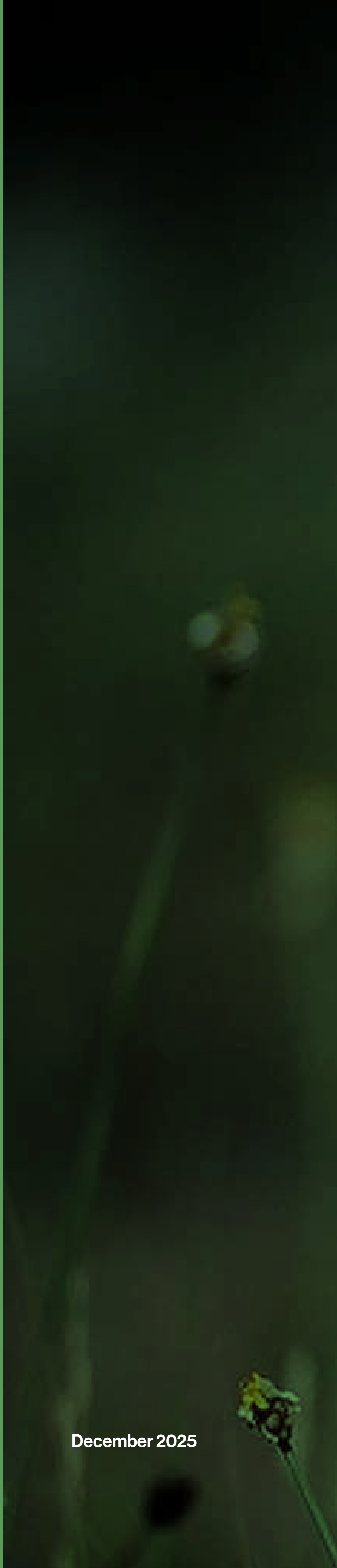

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