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CGIAR Research Program on Water, Land and Ecosystems (WLE)

Biodiversity and Agriculture: Rapid Evidence Review

Fabrice A.J. DeClerck, Izabella Koziell, Aman Sidhu, Jonathan Wirths, Tim Benton, Lucas A. Garibaldi, Claire Kremen, Martine Maron, Cristina Rumbaitis del Rio, Michael Clark, Chris Dickens, Natalia Estrada-Carmona, Alexander K. Fremier, Sarah K. Jones, Colin K. Khoury, Rattan Lal, Michael Obersteiner, Roseline Remans, Adrien Rusch, Lisa A. Schulte, Jeremy Simmonds, Lindsay C. Stringer, Christopher Weber, and Leigh Winowiecki.

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Front cover photo: A complex agroforestry mosaic in Kodagu, Western Ghats, India; G. M. Devagiri / World Agroforestry

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Executive summary

Introduction

Agriculture is the largest single source of environmental degradation, responsible for over 30% of global greenhouse gas (GHG) emissions, 70% of freshwater use and 80% of land conversion: it is the single largest driver of biodiversity loss (Foley et al. 2011, 2005; IPBES 2019; Willett et al. 2019). Agriculture also underpins poor human health, contributing to 11 million premature deaths annually. While too many still struggle from acute hunger, a growing number of individuals, including in low and middle-income countries (LMICs), struggle to access healthy foods. Greater consideration for, and integration of, biodiversity in agriculture is a key solution space for improving health, eliminating hunger and achieving nature-positive development objectives.

In November 2020, the Foreign, Commonwealth & Development Office (FCDO) and Climate Change, Agriculture and Food Security (CCAFS) commissioned this rapid evidence review to increase knowledge of the linkages between agricultural practices and biodiversity, within the framework of the UK COP26 Presidency on agricultural innovation. The review documents the best available evidence of agriculture's relationships with biodiversity, drawing on the contributions of leading biodiversity experts, and recommends actions that can be taken to move towards more biodiversity/nature-positive production through the delivery of integrated agricultural solutions on climate, biodiversity, nutrition and livelihoods. Taking a whole-of-food-system approach and bringing together a large body of evidence, the review accounts for aspects not typically captured in a stand-alone primary piece of research, and indicates where there are critical gaps.

What evidence is there?

Healthy diets require dietary diversity, which requires greater crop diversity and agricultural biodiversity supporting production. **Enhancing production of more diverse foods can be a win-win solution for both improved nutrition and biodiversity [*High Agreement, Robust Evidence*]**.

It is possible to produce healthy diets for 10 billion people and halt the loss of biodiversity, securing its contribution to climate regulation and other planetary boundaries, despite significant challenges and trade-offs in several regions of the world, especially in developing economies **[*High Agreement, Medium Evidence*]**.

Agriculture currently occupies 40% of the global land surface. At least 10-20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. **Today, 20% of agricultural lands have insufficient biodiversity to provide those services, an unacceptable risk for food security.**

Agriculture thus needs a multipronged approach. This requires a shift towards regenerative production systems that deliver more diversified diets coupled with strict conservation of intact habitats. Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems. Regenerative agricultural practices can generate additional critical ecosystem services by maintaining biodiversity in agricultural lands. **At scale, these practices offer the potential to sequester 4.3-6.9 Gt CO_2e year^{-1} [*Medium Agreement, Medium Evidence*], create 12-17 M km^2 habitat for biodiversity [*High Agreement, High Evidence*] and increase connectivity for biodiversity [*High Agreement, Limited Evidence*]. There is no evidence that diversified production**

systems compromise food security – many agricultural diversification practices provide multiple complementary benefits [*High Agreement, High Evidence*].

Halting the expansion of agriculture into intact nature is necessary to achieve zero net loss of biodiversity and secure the critical Earth system functions that nature provides. Ecosystems covering half of the global land surface are currently intact, although these are largely within desert, boreal and tundra biomes. Halting extinction loss will require the retention of most remaining intact ecosystems across ice-free areas. **Regulating regional water cycles and achieving the Paris Climate Agreement (including climate mitigation targets) while halting biodiversity loss requires retaining at least 50% intact nature [*Medium Agreement, Robust Evidence*].**

What are the critical research gaps and investment needs?

Global goals, whether the SDGs, the Paris Climate Agreement, or the Convention on Biological Diversity, have repeatedly emphasized the urgent and critical need to halt emissions, and accelerate carbon sequestration opportunities. Investing in context-specific Research and Development (R&D) aligned to global goals, while building local capabilities and capacities is critical. While global models remain helpful in setting pathways and understanding the urgency and ambition needed, they need to be complemented with demand-driven R&D with farmer and pastoralist communities that provides them with flexibility and adaptive capacity without compromising their livelihoods.

In light of the vulnerabilities to climate and environmental change in LMICs, and increases in all forms of malnutrition, including rapid transitions to unhealthy diets, there is a need for a much greater investment in diversified farming systems that meet societal goals, with increased resilience to climate and environmental change. While society still hopes to achieve climate stability, the impacts of climate change and environmental degradation are being manifest, and should be anticipated to persist and worsen for several decades. Farming systems must both be designed to be resilient to anticipate change, while simultaneously contributing to building back better: sinking GHGs, producing foods that contribute to dietary health of local and regional communities, and regenerating environmental goods. Diversified farming systems are a critical strategy for adapting to anticipated change, and mitigating impacts while building back better. Investing in nature positive or circular production systems, which can prevent waste and leakage while supporting reuse, regenerative agroecological systems, complex rotations and mixed farming are no regrets investment options.

Investment in food policy is also urgently needed. All too often, the onus of profitability is placed on farmers and farming systems driving important improvements in efficiency, but at environmental, social, and climate costs which are becoming increasingly evident. Investment in better understanding how food policy, markets and supply chains enable regenerative and diversified systems to be profitable is urgently needed. This includes greater research and investment in market systems and value chains, but also on agricultural tools and technologies that reduce the drudgery of diversified production, and increase labor efficiencies in particular.

In light of the vast environmental footprint of agriculture, the broader food system must be a key part of the solution to the intertwined challenges of biodiversity loss, climate change and human health. Siloed visions of agricultural systems as independent of the natural world and somehow exonerated from environmental responsibilities are no longer compatible with global goals on food and nutritional security, climate security, environmental security and livelihood security. **Thus the first step is for policy makers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This demands thinking about 'food system productivity' rather than agricultural productivity** (Benton and Bailey 2019)**, and requires all sectors of government to break out of their own conceptual silos and institutional structures.**

In considering the relationship between agriculture and biodiversity several key areas for investment emerge:

- Closing the gap between the current composition of crop production and consumption to supply healthy diets at local, regional and global scales in line with SDG2 and SDG3;
- Transitioning to managing agricultural systems as ecological systems (agroecosystems);
- The greater inclusion and recognition of farmers as key actors, with women, youth and indigenous farmers bringing unique knowledge systems and capabilities to bear in food production.

Food security should not be prioritized above other critical goals: nutritional, climate, environmental and livelihood security. Treating these areas solely as inevitable trade-offs fails to recognize important areas of synergy. Making the transition to food production systems that actively take account of and are synergized with biodiversity goals will require significant transitions in the policy landscape. Agriculture needs to be more strongly integrated into global agreements and policies on environment and health. Given that almost 20% of the global dietary energy supply is derived from imported foodstuffs, trade policy also needs to take better account for its impact, creating greater space for diversification of commodities, supporting the conservation of intact ecosystems, and including a consideration of environmental goods and services.

Current agricultural investments and practices generally overlook the important potential for increasing ecosystem services that agroecosystems can provide (Wood et al. 2018). Farmers and farming communities can produce public goods (e.g. climate mitigation, soil water-holding capacity, water quality improvement), but promoting these public good functions has been consistently underexplored and under-resourced, even though they are also necessary for creating sustainable and resilient production systems. Recognizing that farmers and farmlands can produce these benefits in addition to quality food presents an opportunity for revitalizing rural communities by repurposing public funds for public goods and services. Diversification strategies can be applied in a range of contexts and would benefit from investment in technologies, tools, markets and incentives that increase and improve employment opportunities, reduce drudgery of food production and provide greater autonomy to producers**.**

During the next decade, priority approaches to diversify production systems should target:

- Urgent investments in undervalued crops and cropping systems, notably underproduced crops that underpin dietary health, and indigenous cropping and knowledge systems;
- Greater investment in tools, technologies and enabling environments that amplify and/or complement biodiversity's contribution to agriculture rather than seeking to replace it;
- Repurposing policies, and public and private agriculture funds to support farmers producing public goods, including the production of healthy foods, carbon capture, clean water and habitat for biodiversity.

A coordinated, transformational adjustment of policies, incentives, regulations and other public sector instruments is needed to make healthy and sustainable food affordable and available for all and enable farmers and farming communities to gain greater recognition, reward and payments for actions that produce healthy foods or environmental benefits.

Achieving food, nutrition, climate and environmental goals can occur if a policy framework is developed that takes a whole system perspective. This means valuing not just the amount of production, but production of healthy foods with low or regenerative environmental impacts. **This perspective necessarily incorporates reducing food waste, encouraging good eating habits low on the food chain, and providing access to a diversity of nutritious foods for low-income communities globally [*High Agreement, Robust Evidence*].**

Recommendations

Driven by real leadership and will, such a global agenda for transforming our food systems should be developed, grounded in the best available science and economic analysis, and guided by established universal norms. It should emerge through a global, collaborative effort that drives the following key recommendations:

1. Agriculture needs to be more strongly integrated into global environmental policies and agreements, as well as global health policies.
2. Protection of remaining natural ecosystems from agricultural expansion and other extractive activities needs to be tightened.
3. A transition to managing agricultural systems as ecological systems (agroecosystems) is needed through the systematic adjustment of agricultural, land use and fisheries policies and practices guided by science-based targets and true cost accounting to incentivize regenerative, carbon-sequestering and nature-positive production systems.
4. This should be accompanied with critical investments in performance analysis across multiple dimensions and synergies of production systems: increasing production, diversifying crop composition, above or below ground carbon capture, soil health and measures of the ecological integrity of production systems. Global support and alignment for nature-positive production by scaling a diversity of context-specific diversification practices will increase the resilience of food systems.
5. A coordinated, transformational adjustment of policies, incentives, regulations and other public sector instruments and public funds is needed to make healthy and sustainable food affordable and available for all, and enable farmers and farming communities to gain greater recognition and reward for actions that produce healthy foods as well as biodiversity and climate benefits.
6. Investment is needed to close the production gap of crops contributing to healthy diets, including whole grains adapted to local environments, fruits, nuts, vegetables and seeds to supply healthy diets at local, regional and global scales, in line with SDGs 2 and 3, including urgent investments in undervalued and underproduced crops vital to dietary health and integrating sustainable livestock production into cropping systems.
7. Investment is needed in research to fill knowledge gaps on agricultural systems of LMICs, including on building the capacity of scientists and institutions in the Global South, increasing their capacities to engage with regional food system actors, and increasing the access and participation of LMIC scientists in global science-policy interfaces.
8. Food loss and waste should be halved, using strong incentives, regulations and financial innovation along the entire value chain, creating a truly circular food economy.
9. Policy makers need to make the required policy shifts on both the supply and the demand side. In the Global South, policies are needed to allow greater access to sustainably produced protein-rich foods.
10. Financial markets need to shift investment flows away from unsustainable, unhealthy and socially unjust practices and into investments in tools, innovations, technologies and enabling environments that drive transformative change; food companies should integrate environmental, social and health risks into company disclosures.
11. International trade should be reimagined so that higher-income countries take account of the adverse impacts of their consumption on ecosystems and biodiversity through trade in commodities, goods and services with lower-income countries. Sustainability in trade can be supported through due diligence requirements, tracing mechanisms and border tariffs.
12. People everywhere need access to the knowledge and tools required to demand change from policy makers and business, and to enable better informed, satisfying everyday food choices.

1. Introduction

What food people eat, how and where it is produced, and how much is wasted and lost, has a significant impact on human and planetary health, contributing to 11 million premature deaths and responsible for over 30% of global greenhouse gas (GHG) emissions, 70% of freshwater use and 80% of land conversion driving biodiversity loss. Paradoxically, while agriculture is currently the largest single source of environmental degradation and biodiversity loss, it is also likely to be the biggest victim of this degradation. The conversion of natural ecosystems to croplands and pastures, coupled with the impacts of agricultural pollution, severely threaten vital ecosystem services that underpin agriculture itself (Rockström et al. 2020; see Annex 1).

2021 is a pivotal year for the agricultural community. Major events such as the United Nations Food Systems Summit (UNFSS), the United Nations Framework Convention on Climate Change (UNFCCC) COP26, the United Nations Convention on Biological Diversity (CBD) COP15, and the launch of the United Nations Decade on Ecosystem Restoration offer a real chance to make a step change towards the necessary transformation of our food systems – so they can become more sustainable and equitable and deliver affordable, healthy and nutritious food for all. In November 2020, the Foreign, Commonwealth & Development Office (FCDO) and Climate Change, Agriculture and Food Security (CCAFS) commissioned this rapid evidence review to increase knowledge of the linkages between agricultural practices and biodiversity, within the framework of the UK COP26 Presidency on agricultural innovation (see Annex 2 on the methodology). The goal of the study was to conduct a robust but rapid review of the evidence (and evidence gaps) on biodiversity (nature) positive agricultural systems and practices that are inclusive, climate smart and drive improved nutrition outcomes, making recommendations on priority research, development, investment and policy changes leading to biodiversity and livelihoods gain in low and middle-income countries (LMICs). Ensuring there is a clear pathway for harmonizing the links between biodiversity and agriculture is essential, as evidence is growing that food production also has the potential to become the single largest solution space for human and planetary health (Rockström et al. 2020).

1.1 Biodiversity is inextricably linked with food and agriculture

Covering approximately 40% of the global land surface, agricultural ecosystems (including rangelands) comprise the world's largest terrestrial ecosystem, albeit a highly modified and heterogenous one. Biodiversity in agricultural ecosystems, as in natural ecosystems, is highly threatened, and this has very real consequences for the resilience and sustainability of both the production of food and environmental goods and services. The reduction of biodiversity in agriculture diminishes the ecosystem functions that contribute to local, regional and, when scaled, global processes. To ensure environmental and climate security this decade, a transition is necessary towards treating agricultural lands as ecosystems, and greater investment in research, practices, technologies and incentives that reward the efforts of farmers for the environmental services they produce, as much as for the foods.

Which of the diversity of available foods we eat, and in what quantities, plays a key role in our health. Yet today, nearly half of the world's population struggles to access or afford either enough food, or food that is healthy. Global progress against Sustainable Development Goal (SDG) 2 – Zero Hunger – has stalled over the last few years, with current estimates showing that nearly 9% (690 million) of the world's population goes hungry – up by 10 million people in one year and by nearly 60 million over five years (FAO et al. 2020). Global food supply also falls alarmingly short of providing a low health-risk diet: nearly 2 billion experience hunger and malnutrition; another 2 billion struggle with diseases related to overconsumption. Furthermore, modern food production and consumption can be considered to be undermining the main 'shields' that protect humanity from harm from zoonotic pandemics – healthy ecosystems and healthy diets (Box 1).

Box 1: Biodiversity, food and COVID-19 – Adapted from the open letter to the G20 from the EAT Advisory Board

COVID-19 has revealed a fundamental truth: resilient recovery from the pandemic can only be achieved by radically transforming our food systems. The food we eat drives our vulnerability to the disease. The biggest factor for severe illness with COVID-19, apart from age, is metabolic disease, which in turn is largely driven by unhealthy diets. The way we produce food is a critical driver triggering diseases such as COVID-19: SARS-CoV2 is part of a rising frequency (over the past 20 years) of zoonotic virus spill-overs from wildlife (in this case most likely from bats, via an intermediate host, potentially pangolins) to humans. Deforestation and simplification of landscapes due to expansion of agriculture, combined with risky human behavior through wildlife trade and food markets, appears to have caused the zoonotic outbreak in Wuhan, China, which became a global pandemic through trade and travel in our hyper-connected world. Food is thus at the core, both contributing to the cause of the disease, and its human impacts. As devastating as COVID-19 has been, it has laid bare how utterly unprepared society is for global shocks, including those that are predicted to increase in frequency and severity with environmental change. While COVID-19 has been treated as a public health crisis, its origins lie in human interactions with nature in food systems. Never has the challenge for food systems transformation been more urgent than now. There is growing momentum for a food transition with a focus on health, inclusion and environmental sustainability to deliver on the Paris Agreement and the SDGs. UNFSS 2021 is an example of this momentum, together with deepening dialogue on the need to establish an international scientific panel on food. However, considerable knowledge gaps remain (some of which have been identified and addressed, for instance by the Food System Economics Commission and the Commission for Sustainable Agricultural Intensification) on what the transition should look like and how to achieve it, which is stifling action.

All the evidence we have today shows that if we want to achieve a resilient recovery from the COVID-19 crisis, avoid future pandemics and stand a chance of delivering on the SDGs and the Paris Agreement, we have to focus on biodiversity and food.

Producing healthy diets sustainably is dependent on biodiversity. Decades of research demonstrate that 'sharing space' for biodiversity on agricultural lands is logical and cost-effective for many reasons. The most notable example is our increasing dependence on pollinators to produce the foods that underpin more healthy diets. Other examples of agriculture's dependence on biodiversity include: its role in pest and disease regulation, building resilience to shocks through crop and intraspecies diversity, protection of the water cycle and maintenance of soil health. However, investments in the kinds of agricultural practices that will build on and enhance biodiversity benefits are severely lacking, including in modernizing and time-saving technologies that can increase biodiversity's contribution to production.

Finally, the global-scale challenge of stabilizing global climate, regulating regional water cycles and halting the extinction crisis are all dependent on ensuring that sufficient intact nature is retained across all biomes. Avoiding any further loss of intact nature is vital, particularly by halting ongoing conversion of land to agriculture, as called for by the CBD. Achieving these goals requires active contributions from agriculture, starting with the recognition that environmental and climate security are as non-transgressible as food and nutritional security.

Collectively, ***agroecology****, as an ecological science, focuses on enhancing the contribution of biodiversity in food and agriculture to the provisioning of ecosystem services to and from agriculture with the aim of* ***regenerating*** *these services. Diversified, agroecological or regenerative agricultural practices overlap and include a range of management options that can be applied from field to landscape level. Regeneration is useful from the point of view of suggesting a measurable baseline condition that can be improved. This is the shared meaning of 'nature positive'. (See Annex 3 for a glossary of key terms used in this review).*

1.2 Reconfigure biodiversity in agriculture to meet food, nutrition, climate and water security targets

Over the last decade, multiple global reviews, commissions and academic papers have argued for more sustainable and healthy food, farming and agriculture. Promoting biodiversity in diets, in farms and fields, and in intact nature, makes essential contributions to these goals. International policy frameworks that support this change include the Paris Agreement (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), the CBD and the SDGs.

In response, bold biodiversity targets to halt the loss of area and intactness of nature and securing nature's contributions to people are being set by the CBD in 2021. Achieving these targets is a prerequisite for food, nutrition, climate and water security, in addition to halting the ongoing extinction crisis. According to the Global Biodiversity Outlook 5, we have failed to meet the 2020 Aichi Biodiversity targets (CBD 2020; Díaz et al. 2020). This failure points to the need for an urgent rethink and transformation of the relationships between food, agriculture and biodiversity (Leclère et al. 2020; Rockström et al. 2020) if we are to succeed in reaching the 2030 targets.

1.3 Shifting from crop productivity to systemic productivity

While food production has increased over recent decades, this trend masks an underlying decline in ecosystem services that underpin production (Brauman et al. 2020), including pest and disease regulation, pollination and soil fertility. Similarly, this rise in productivity masks an alarming decline in dietary health, across the income status of countries. The focus on crop productivity has fueled a false dichotomy between conservation and production that, if it persists, may have critical consequences for environmental and climate stability. This approach will ultimately also have negative effects on future food production and distribution. Transforming the objective outcomes of agriculture to encompass environmental and human health objectives is a first, and necessary, step in realigning food across multiple global goals. This requires refocusing food from yields per unit input to the food system's overall productivity and efficiency, or the number of people that can be fed healthy diets sustainably per unit input (Remans et al. 2014; DeFries et al. 2015; Benton and Bailey 2019).

1.4 Critical actions to reconcile agriculture and biodiversity

There is considerable evidence available about *what* needs to change in the food and agriculture system to enable, nutritional, climate, environment and livelihood security, and that innovative solutions can emerge when these goals are considered equally non-transgressible. There is similarly substantial biophysical evidence that food and agriculture can provide healthy diets while contributing to environmental restoration and regeneration. But there is still insufficient evidence indicating and understanding *how* to make the necessary social, political, economic and agronomic transformations urgently. Much of the challenge lies in the siloed nature of policy and innovation, as well as entrenched political economies of food. Recognizing the role that agriculture plays within the Earth system, as an ecosystem; considering the dietary health impacts of food; and recognizing and utilizing the dependencies of agriculture on biodiversity for agroecosystem services, suggests the need for agricultural systems that are radically different from those we have today.

In this review, we have attempted to provide the best available evidence of agriculture's relationships with biodiversity. This spans many dimensions of agriculture and biodiversity, including:

- The diversity of food in our diets, calling on production systems to increase that diversity as a contribution to public health. Evidence indicates that there is ample scope to increase the diversity of foods produced in order to improve dietary health, with concomitant benefits for agricultural biodiversity;
- The dependency of food production for healthy diets on in-field and on-farm biodiversity, focusing on five core contributions: i) genetic diversity of seeds and breeds, ii) soil fertility, iii) water, iv) pollination, and v) pest control, and the risks of technologies and practices that replace, rather than amplify, these contributions;
- The role that in-field, on-farm and around-farm biodiversity plays in securing non-food related ecosystem services from agriculture, notably climate mitigation, regulation of local and regional water fluxes, and water quality;
- Halting the expansion of agriculture into intact nature to achieve zero net loss of biodiversity and secure the critical Earth system functions that nature provides.

This review is part of a series that covers agroecology as well as finance and innovations that showcase the complementary solutions that exist and should be leveraged, or need to be developed, to unlock solutions that further support biodiversity-based approaches.

We have not covered livelihood security here, although we find no evidence that better integration of biodiversity in agriculture reduces the opportunities to create more meaningful and remunerative livelihoods in agriculture. There is recent and growing evidence, however, that small and medium fields and farms are better able to integrate biodiversity without compromising yield (Ricciardi et al. 2021).

We present five critical challenges to agriculture in relation to biodiversity that, borrowing from the Science Based Targets Network, suggests that this interaction can be conceived as an **AR^{3}T** 'mitigation hierarchy' with targets aligned with the forthcoming CBD Kunming objectives (Figure 1):

- **Avoid** continued land expansion into intact nature to secure nature's essential contribution to climate mitigation, aiming for levels of 30% protected and >50% intact;
- **Restore** intact nature where possible, prioritizing those areas that have been degraded, have high climate mitigation or have biodiversity conservation potential in line with no net loss as of 2020, restoration in 2030, and full recovery by 2050, contributing to biodiversity conservation, climate mitigation and regional hydrological flow regulation;
- **Reduce** the impacts of agriculture on biodiversity, notably by halting the losses of nutrients, biocides and other pollutants to air, soil and water;
- **Regenerate** the ecosystem services provided by biodiversity in all agricultural lands everywhere retaining a *minimum* 10% of habitat within agriculture;
- **Transform** the food system by creating the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional securities (Rockström et al. 2009; Steffen et al. 2015; Willett et al. 2019).

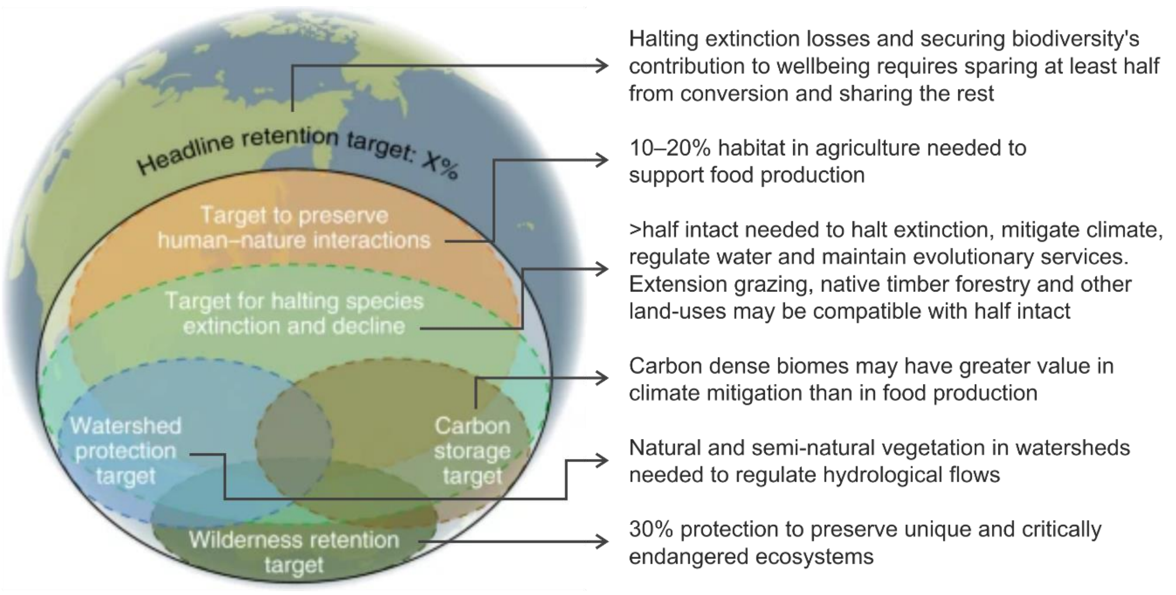

Figure 1: Bold biodiversity targets are required to halt the loss of biodiversity and secure biodiversity's contributions to Earth system and ecosystem processes (Maron et al. 2018). Today, approximately half the Earth's land surface remains intact, making 'half intact' the equivalent of a no net loss target. Combined actions to avoid loss, restore intact nature, reduce impacts of human activities on nature, regenerate ecosystem service production through nature-positive production, and transform agricultural policies and actions are needed to maintain a safe environmental space for humanity (Rockström et al. 2020, 2021). Source: Figure adapted from Maron et al. 2018.

2. Healthy diets require dietary diversity

Take-home messages

- Lack of dietary diversity is a primary cause of diet-related disease and mortality;
- Shifting to increased consumption of fruits, nuts, vegetables and whole grains, and healthy consumption of a diversity of meats, could avert 11 million premature deaths per year;
- Shifting to healthy, plant-rich diets could avert per capita GHG emissions from crop and livestock production by 32% from 2009 to 2050, and lead to a 20% decrease in the land needed to meet consumption demand, in line with the CBD goal of no net loss of nature by 2050;
- Modern plant breeding threatens traditional crop varieties and crop wild relatives but is completely dependent on the genetic diversity they represent.

2.1 Diversity of foods produced and available are insufficient for healthy diets

Nearly 2 billion people globally continue to struggle with hunger and malnutrition. An equally large and rapidly growing number, including in LMICs, are struggling with disease related to overconsumption of unhealthy foods high in sugar, salt and fat and underconsumption of protective foods such as whole grains, fruits, nuts, vegetables and seeds (Garibaldi et al. 2021). Many countries now struggle with this triple burden of malnutrition.

While there is no single solution to these challenges, and many global organizations including the United Nations Children's Fund (UNICEF) and the World Food Programme (WFP) are transitioning from highly targeted to more systemic actions on food security, low dietary diversity is a common thread. Only around 130 internationally significant food plants – including 20 cereal crops, 7 roots and tubers, 28 fruits, 19 vegetables, 11 pulses, 8 nuts, 16 oils, 15 herbs and spices, 2 sugars and 3 stimulants – make up the bulk of peoples' diets around the world. In addition, just 15-20 major domesticated land animals are used in food and agriculture (Scherf and Pilling 2015).

The emphasis on increasing production of a much more limited selection of crops has far-reaching consequences. Even within the smaller group of major crops, varieties can number in the hundreds of thousands for staples such as wheat and rice, and in the thousands for other crops. This varietal and underlying genetic diversity has formed through the interaction of people and crops or livestock breeds over thousands of years (Khoury et al. 2016). Until the beginning of the 20th century, crop and breed diversity existed entirely in agricultural fields and pastures. But the industrialization of cultivation and globalization, including not just agronomic transitions but also the development of seed industries based on professional plant and animal breeding, has drastically reduced the standing diversity in farmers' fields, both of crop species and livestock breeds, and of their varieties. This loss is a trade-off with the short- and long-term gains of quickly adapting to climate change and preserving diversity in fields and in gene banks.

While some portion of historical crop diversity still exists in marginal farming environments and in home gardens, a significant amount now only survives in conservation repositories (so called gene banks or seedbanks). The irony of modern breeding is that it replaces the habitats of traditional farmer crop varieties and crop wild relatives, yet it is absolutely dependent on the ex-situ crop genetic diversity saved in the more than 1,700 gene banks around the world housing over 7 million plant accessions (Singh et al. 2012) (Box 2). It is this diversity in seedbanks, and conserved in situ on farmers' farms, that provides the genetic resources needed to continually develop modern varieties that are resilient to ever-changing production challenges (Castañeda-Álvarez et al. 2016). Greater diversity in and between fields, and greater diversity in community-communal seed banks and seeds companies, are key solutions. Increasing and diversifying access to diversity held in gene banks requires political improvements through the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGFA) and the CBD Nagoya Protocol.

Box 2: Storing seeds for the future

There are crop diversity repositories in almost every country around the world, with back-up repositories such as the Millennium Seedbank Partnership, Wakehurst and the Svalbard Global Seed Vault serving critical preservation roles in times of crisis. Community seed banks, and exchanges between farmers, similarly play an important and active role in the conservation and use of cultivated diversity. Because major crops are cultivated around the world, their genetic diversity is also needed by plant breeders around the world; these repositories serve both national and international needs. They are regulated and facilitated by international agreements governing the exchange of crop and varietal diversity, including the CBD Nagoya Protocol and the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGFA), as well as national policies.

Food diversity is as much about choice as it is about health. There is good evidence showing that while we produce enough food to meet the caloric needs of today's global population, current production systems fail to provide a healthy diet for all because of underproduction of food diversity (Figure 2). Global analyses of regional trends signal a nearly universal underconsumption of fruits, nuts, vegetables, whole grains, nuts and seeds; regional patterns of over and underconsumption of red and processed meat; and equally variable consumption of legumes (GBD 2017 Diet Collaborators 2019). High-sodium, low-diversity diets are the leading cause of mortality attributed to diet (Figure 3), accounting for an estimated 11 million premature deaths per year (GBD 2017 Diet Collaborators 2019; Willett et al. 2019).

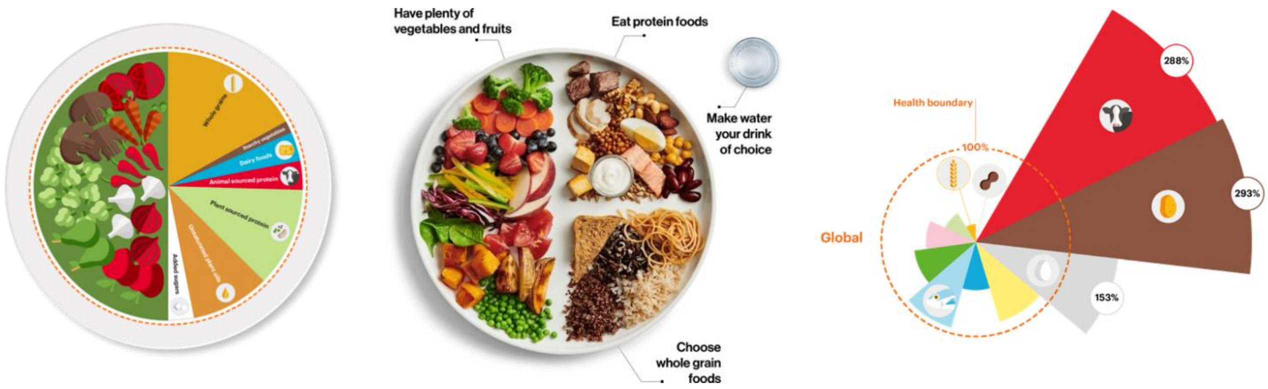

Figure 2: Food-based dietary guidelines are well established for numerous countries and call for increased consumption of a diversity of foods within a range of recommendations. Global consumption is out of sync with food-based consumption recommendations and contributes significantly to health and environmental challenges: (a) EAT-Lancet Planetary Health Diet, (b) Canada's food guide plate (Health Canada 2019), (c) assessment of global consumption compared to 'healthy' consumption by major food group (Willett et al. 2019).

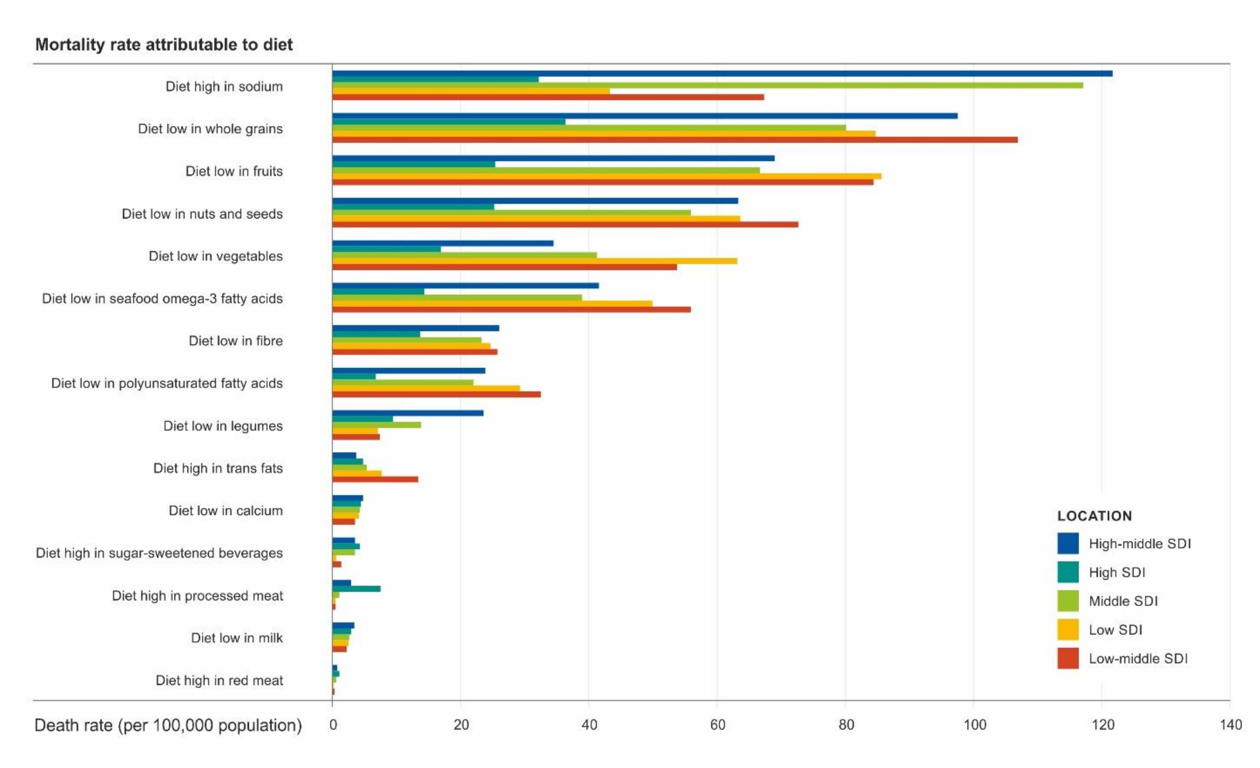

Figure 3: Number of deaths attributable to individual dietary risks by food group and by Social Demographic Index. Source: Global Burden of Disease Collaborative (GBD 2017 Diet Collaborators 2019).

Global production and availability of foods are fundamentally mismatched with recommended healthy consumption patterns (Kc et al. 2018; Willett et al. 2019). Ensuring healthy diets for all by 2050 requires an important shift in what foods are produced and consumed. This would require no significant increase in cereal production coupled with significant increases in vegetables, legumes, fruit, fish, nuts and seeds and a large reduction in red meat production and consumption globally (GBD 2017 Diet Collaborators 2019) – although in some regions, meat consumption could be increased to counter nutritional deficiencies such as iron-deficient anemia (Golden et al. 2011) (Table 1).

2.2 Healthy diets include a wide range of choices

At least five major food groups, and thus at a minimum 4-5 species, are required in a healthy diet, with whole grains, fruits, vegetables, oils and protein (plant or animal) being essential (Table 1). The absence of single food groups drives malnutrition in several global hotspots, requiring emergency assistance or fortification as an intermediate remedy. In both high- and low-income countries, however, increasing dietary diversity, within energy requirements, would have a significant positive impact on health. Thousands more species, breeds and varieties could support human nutrition. Beyond the 130-odd species that dominate global production and consumption, about 120 other food crops that are less well monitored in production, trade and dietary data have regional significance. Beyond these, and practically nonexistent in food system data, are well over 1,000 wild plants known to be used, at least occasionally, as human food (Khoury et al. 2019), and the nutritional value of over 3,200 aquatic animal species used as food has been documented (Golden et al. forthcoming) not including growing interest in edible aquatic plants (algae) (Rajapakse and Kim 2011). Within this range, consumption of each of the food groups (Table 1) and increasing diversity within food groups is the foundation for healthy nutrition (Tilman and Clark 2014).

Table 1: Summary of food groups, recommended per capita daily consumption (Willett et al. 2019), required change in production volume, and approximate diversity of cultivable species.

Food Group	Recommended Per Capita Daily Consumption (g)	Global Production Change (2050)	Diversity of Species/Varieties
Whole Grains	232	0	20 major cultivated species with 850,000 varieties; dozens of minor species; many wild species
Tubers or Starchy Vegetables	0-100	+20%	7 major cultivated species with 25,000 varieties; 12 minor species; various wild species
Vegetables	200-600	+75%	19 major cultivated species; 40 minor species; hundreds of wild species
Fruits	100-300	+50%	28 major cultivated species; 45 minor species; hundreds of wild species
Dairy Foods	0-500	+5%	3 major domesticated species.
Red Meat	0-28	-65%	4 major cultivated species
Poultry	0-58	+2%	6 major cultivated species
Eggs	0-25	-25%	1 major cultivated species
Fish, shellfish and crustaceans	0-100		>3,200 taxa
Legumes	0-100	+75%	11 major cultivated species with 120,000 varieties; 25 minor species; various wild species
Nuts	0-75	+150%	8 major cultivated species; 6 minor species; various wild species
Unsaturated Oils	20-80		16 major cultivated oil crop species; 15 minor species; various wild species
Sugars	0-30		2 major cultivated species; various minor species and wild species

Context will determine whether any single food group is over or under-consumed. Whole-of-plate approaches that ensure that everyone everywhere has access to a diversity of foods, notably across food groups, are key to SDGs 2 and 3. While a healthy diet with balanced consumption across food groups is a universal goal, the diversity of foods within food groups offers people the possibility to match foods across the year to environmental contexts, individual tastes and cultural preferences.

2.3 Demand and supply of healthy diets contributes to climate and environmental outcomes

Crucially, diverse production can bring us closer to planetary health goals. A shift towards healthy diets could reduce per capita emissions from food production between 30% to 50%, while also accounting for a 20% reduction in freshwater consumption and a 20% decrease in the land needed to meet consumption demand (Tilman and Clark 2014; Springmann et al. 2018; Willett et al. 2019). Globally, this would mean no net increase in agricultural lands, in line with the CBD goal of no net loss of nature by 2050, primarily driven by reduced overconsumption of red meat (Tilman and Clark 2014; Clark et al. 2020). The impacts of dietary shifts on biodiversity conservation are greatest in countries with current high per capita meat consumption. Reducing overconsumption in these countries, and avoiding transitions to overconsumption in many LMICs as agricultural systems modernize and dietary habits change, is necessary to achieve biodiversity conservation targets (Tilman et al. 2017). How well the current portfolio of agricultural biodiversity (Table 1, Box 3) will enable humanity to respond to sustainability, resilience and health challenges remains unknown. Trade plays an important role here. We recommend trade policies that complement a countries capacity to produce, and trade regionally appropriate, from an environmental point of view, foods (e.g. ruminant meat from grassland biomes, perennial tree crops from forest biomes).

Climate change will test the capacity of breeding to keep up with production at a pace unforeseen in agricultural history. At the same time, developments in breeding are steadily enabling utilization of an ever-wider pool of crop diversity, including distant crop wild relatives and, via genetic engineering and more recently gene editing, species unrelated to crops, including beyond the plant kingdom. Such advances may help, but the foundation of our ability to nourish ourselves still rests on historical crop diversity, either in farmers' fields, natural and protected areas, or conserved in repositories. This genetic diversity extends far beyond the varieties available to use via laboratories and seed banks. Farmers continue to promote crop genetic diversity by creating locally adapted varieties and engaging in participatory plant breeding programs, but they also play a key role in maintaining mixed tree-crop-livestock systems (Chará et al. 2019), or grassland biomes, that can produce a diversity of products that improve human health and livelihood outcomes (Pickett et al. 2014), while supporting a wide array of public goods including biodiversity conservation (Wood et al. 2018). This is considered in more detail in Section 3.

Box 3: Agricultural biodiversity (written by DeClerck and Remans for the Living Planet Report; Almond et al. 2020)

Agricultural biodiversity, or agrobiodiversity, includes cultivated and uncultivated species that comprise the foods we eat or those that support food production. Cultivated agrobiodiversity encompasses species intentionally planted or reared by farmers. This diversity stems from tens of thousands of years of farmer selection producing edible species suited to many social and environmental contexts.

Non-edible agricultural biodiversity includes a myriad of species, from soil microbiomes to insects, birds and mammals that pollinate crops, regulate pests, absorb excess nutrients from fields and store carbon in soils. These benefits are called agroecosystem services. Production practices such as agroforestry, riparian buffers, wild field margins or conservation tillage help to conserve beneficial biodiversity in fields, and these services are managed and secured for food production.

Because plants are non-mobile, they have evolved numerous chemical adaptations for protection against predators and diseases. For example, they provide sweet rewards to animals that disperse their seeds (e.g. fruits and berries) or provide their own offspring with large energy stores for germination and growth (e.g. seeds and nuts). These adaptations are the source of the diverse nutritional values of plant foods. Consuming a diversity of fresh fruits and vegetables, whole grains, seeds and nuts is an important part of a healthy diet that benefits from this evolutionary history (GBD 2017 Diet Collaborators 2019; Willet et al 2019).

Many underused plant species have excellent nutritional profiles, as well as traits of interest for adapting food production to climate change (e.g. quinoa, millet, sorghum, teff for grains; and zapote, Chaya or chenapodes for fruits and legumes). These qualities are especially important considering the increasing risk that climate change will pose to crop yields and the nutritional content of foods. However, food system simplification drives loss of these plant species and varieties, reducing the options for healthy diets based on the agrobiodiversity of sustainable food systems.

3. Agriculture must share space with biodiversity to meet global environmental goals

Take-home messages

- Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems;
- There is no evidence that diversified production systems compromise food security – in fact, many agricultural diversification practices provide multiple complementary benefits;
- At least 10-20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. Today, 20% of agricultural lands have less than 10% of such natural capital;
- Regenerative agricultural practices have the potential to mitigate emissions by 4.3-6.9 Gt CO_2e $year^{-1}$ globally, and agricultural lands represent 47% of the soil carbon climate mitigation potential;
- Agricultural, field and farm biodiversity can reduce agriculture's dependence on water capture and water quality through soil carbon sequestration, on-farm practices and appropriate crop selection.

3.1 Agriculture depends on biodiversity

All agricultural systems are dependent on biodiversity for crop genetic diversity, pest control, animal-mediated pollination and healthy soils that promote nutrient capture and water delivery for crop growth. However, modern agriculture has frequently sacrificed the long-term safeguarding of these biodiversity-based support services – or ecosystem services – by solely focusing on yield or caloric increases. This has often been achieved by simplifying agroecosystems to single varieties and applying mineral fertilizers and pesticides attuned to their specific needs. Over the short term, this strategy has led to important yield gains for these commodities. Over the long term, however, it has led to degraded agricultural lands, pesticide resistance, loss of soil fertility, pollinator loss and weakened resilience to climate change. Planned integration of biodiversity in agriculture by deploying agroecology and complementary technologies contributes to food and nutritional security and is a primary means through which farmers can respond to challenging conditions.

Diversified agroecological practices offer numerous opportunities at the field, farm and landscape scale, but they are not a panacea. Thoughtful application and integration of novel technologies and practices that complement diversification are required, as well as mitigation of trade-offs such as pest species spilling over from natural or semi-natural habitat (Zhang et al. 2007). Biodiversity in close proximity to agriculture can create new challenges for farmers and farming communities, most dramatically in terms of wildlife encroachment, when wild species such as monkeys, elephants and big cats cause crop damage or the loss of human life.

3.2 Diversification strategies are often regenerative, synergistic and multipurpose

The agricultural practices that support biodiversity's contribution to soil nutrients, water quality and capture, pollination and pest reduction, more often than not, are synergistic (Landis et al. 2000; Kennedy et al. 2013; Scheper et al. 2015; Garbach et al. 2016; Rusch et al. 2017; Garibaldi et al. 2020;

Tamburini et al. 2020). Taken with genetic diversity, these ecosystem functions represent critical inputs into production systems globally. The aim of agroecology and diversification practices is to secure and make use of ecosystem services both to and from agriculture (DeClerck et al. 2016). Within the AR^{3}T framework, the aim of diversification is to *regenerate* the ecosystem functions and services both from, and to agriculture, while *reducing* its negative impacts, notably habitat loss and pollution of soil and water.

3.2.1. Diversification within fields and pastures

Diversification refers to the cultivation of one or more crops on a farm in often mixed systems (i.e. animal-plant). A highly diversified field can have 5-20 crops within it, and many more varieties. They can range from traditional polycultures such as Mexico's 'three sisters' (maize, beans, squash), to soy/maize polycultures, or various forms of diversified agroforests. At this scale, replacing low-diversity annual systems with higher diversity annual or perennial systems has numerous beneficial impacts on ecosystem functions, for example by reducing soil nutrient loss to aquatic environments, and extending the portion of the year that crops are actively being grown, thus reducing nutrient leaching. A very common form of diversification is integrating nitrogen-fixing legumes either as a harvestable or cover crop (Ghosh et al. 2007; Bedoussac et al. 2015; Duchene et al. 2017).

Field-scale farming affects many aspects of water, both in terms of its need and use and its onward flow. Crop types have variable water needs and can thus influence demands on available water resources. Mixing crops with distinct rooting depths or phenologies can increase water use efficiency while maintaining soil cover. Breeding programs can contribute by focusing on traits that consider drought tolerance, or complementarity between crops that could be cultivated in polycultures, or rotations.

At the field or pasture scale, management of soil inputs and disturbance (i.e. tillage/grazing) strongly impacts soil diversity and its contribution to nutrient and water cycling as well as climate mitigation (Lal 2020). Management techniques to promote carbon sequestration and improve drought resilience include organic residue management, mulching and reduced or no-tillage (Amelung et al. 2020). Excessive use of biocides, nutrient inputs and tillage in turn favor soil ecosystems with very high carbon loss and little long-term storage potential (Palm et al. 2014). Preliminary aspatial assessments for the targeting of site-specific interventions indicate that the collective annual increase of soil carbon is possible (Minasny et al. 2017). A simple methodology to measure soil carbon and carbon change would be game-changing in its capacity to guide, and reward, farmer actions to increase soil carbon capture.

High-diversity cropping systems can also increase natural enemies of pests by over 44%, increase pest mortality by 54% and reduce crop damage by 23% (Letourneau et al. 2011). In-field diversification provides habitat, alternative hosts, pollen and nectar as well as overwintering or nesting sites essential to diverse communities of pollinators, predators and parasitoids (Landis et al. 2000; Lichtenberg et al. 2017). Farming practices such as conservation tillage (Tamburini et al. 2020) and organic farming (Muneret et al. 2018) can be beneficial to pest control services, although both encapsulate a range of practices and do not have well-demonstrated capacity to close yield gaps (Corbeels et al. 2020).

Well-managed livestock operations incorporate plant diversity within their pastures and fields, and closely manage manure as a form of fertilizer. Many of the crops or portions of crops that provide benefits in terms of regenerating soil, cycling nutrients and providing pest control within extended rotations of crops cannot be directly consumed by humans, but can provide forage for livestock. Integrating livestock provides further on-farm benefits in terms of carbon management, and this can be incorporated not only with traditional grazed pastures but also with agroforestry or silvopastoral systems that enhance biodiversity (Murgueitio et al. 2011; Poux and Aubert 2018). Livestock integration provides an important source of protein and selected nutrients (e.g. iron) to combat malnutrition for smallholder farmers in LMICs.

3.2.2. Diversification between fields and pastures

Natural elements such as grassed waterways, riparian buffers, prairie strips, hedgerows, live fences and wetlands incorporated around field and pasture margins are highly effective at capturing excess nutrients. To reduce erosion and regulate water, between-field habitat infrastructure can be complemented with engineering features such as terraces, water and sediment control basins, bioreactors and saturated buffers to control nutrient loss. These features also support pollination (M'Gonigle et al. 2015; Scheper et al. 2015; Ponisio et al. 2016; Kremen et al. 2019; Nicholson et al. 2020) and pest regulation (Shelton and Badenes-Perez 2006; Cook et al. 2007; Letourneau et al. 2011; Tschumi et al. 2015) by providing habitat for pollinating and pest-regulating organisms, can serve as barriers to pest movement (Avelino et al. 2012), or can draw pests out of crop fields (Cook et al. 2007; Pickett et al. 2014); a recent synthesis indicated that the planting of annual flower strips on field borders increases pest control by 16% (Albrecht et al. 2020). Between-field habitat can have added value when it is comprised of multi-use species that provide fodder, fuel or food, and can be designed to reduce wind or evaporative stress in crops while creating corridors for wild biodiversity. These corridors are particularly important considering that species movement across landscapes is a key adaptation measure for wild biodiversity in the face of climate change.

3.2.3. Landscape diversification

Even where the most extensive monocultures are practiced, landscape diversification, combined with habitat structures between fields, can have significant positive impacts on many services provided by agricultural biodiversity, notably hydrological, pest regulation (Chaplin-Kramer et al. 2011; Avelino et al. 2012; Veres et al. 2013; Holland et al. 2017) and pollination services (Garibaldi et al. 2011; Kennedy et al. 2013; Dainese et al. 2019). In contrast, landscape simplification – extensive fields of the same crop with few intervening habitat structures – often lead to increased risk of pest infestation (Rusch et al. 2016). Diverse mosaics in agricultural land that include multiple farms and also integrate natural areas are required to capture and potentially convert, store or sequester nutrients lost to the environment.

Smaller to intermediate field sizes, still common in many LMICs, contribute significantly to enhancing the level of biological pest control in agricultural landscapes, particularly when farmers are cultivating different crops (Martin et al. 2019; Aguilera et al. 2020). A synthesis at the European scale revealed that increasing average edge density in agricultural landscapes (i.e. decreasing average field sizes and increasing field shape complexity) increases pest control by 40% (Martin et al. 2019). Policies, or markets that either support increases in field or farm sizes, and/or concentrate the production of a single crop in a landscape, may increase efficiency but drive loss of between-field cropping diversity and increase risks. Impacts of farm size on poverty reduction and sustainability is a renewed area of research interest, with a focus on environmental and socio-economic implications, including the quantity and quality of employment that can be generated from diversified farming systems (Harris and Orr 2014; Harris 2019).

In many regions of the world, managing the flow of nutrients within and from agricultural landscapes also requires paying attention to the flow of water, and thus watershed management. Agricultural lands are generally nested within water catchments, with irrigation of fields dependent on well-functioning ecosystems in the upper regions or in neighboring water supply catchments. Intact ecosystems encourage infiltration of water to recharge soil and groundwater and regulate run-off into the streams that feed the farms, with less flooding in the wet season and more sustained water in the dry season.

3.2.4 Agricultural landscapes need at least 10-20% of diversified habitats to retain ecological integrity

Proposed targets for nature retention within agricultural landscapes (Willett et al. 2019; Garibaldi et al. 2020) are beginning to be reflected in agricultural policy (Díaz et al. 2020). A conservation target for agricultural ecosystems to retain at least 10-20% of habitat per km^2 has been proposed to maintain ecological integrity in production landscapes (Maron et al. 2018; Willett et al. 2019; Garibaldi et al. 2020; DeClerck et al. forthcoming). The rationale for this target is that the services provided by biodiversity to agriculture are locally produced. Nitrogen fixation by legumes impacts soil fertility at the plant scale (0-10 cm), and pollination and pest control are provided by habitats at a wider scale (0-300 m), occasionally further for honeybees (3,000 m) (Tscharntke et al. 2005, 2007; Fremier et al. 2013; Willett et al. 2019; Garibaldi et al. 2020). Similarly, interception of sediment and nutrients lost from agriculture by buffers is most effective within tens of meters (Fremier et al. 2013. While specific impacts are highly contextual and difficult to predict, the evidence is clear: in the absence of proximate habitat (<500 m), ecosystem services to agriculture are not provided. Alarmingly, 18-44% of global agricultural lands fail to meet this threshold (Figure 4; DeClerck et al. forthcoming). We provide a detailed evidence review of these services in Annex 1.

While the proposed thresholds to safeguard key services are universal, a diversity of context-specific interventions at field and landscape scale are possible, as previously described. Such regenerative activities and infrastructures in agriculture can also enhance the effectiveness of protected areas by offering corridors and stepping-stones connecting wild populations across landscapes that might otherwise form barriers or sinks (Fremier et al. 2015; DeFries and Nagendra 2017; Kremen and Merenlender 2018; Estrada-Carmona et al. 2019. Landscape-scale coordination and complementary actions retaining habitat patches, and removing barriers, increase the impacts on conservation outcomes.

Increasing the number of crops produced between farms within a landscape is emerging as a similarly effective high-level target adaptable to a diversity of production practices and systems. Incentives, or rules that would maintain 5-10 crops per 1-10 km^2, are garnering interest as a high-level indicator in the ecological community, although proposed thresholds are yet to be developed. The contributions of between-farm diversity are of particular interest because they are compatible with farm-scale specialization, and support landscape-scale diversification. Actions that reduce the impacts of agriculture on biodiversity, notably the over-use of biocides, are also required. The beneficial impacts of increasing habitat for service-providing biodiversity are easily lost to the systematic, rather than prescriptive, use of biocides. The *regenerate* and *reduce* actions of the conservation hierarchy are complementary.

Both the retention of habitat within agriculture, and the diversity of cropping systems per unit area, have been proposed as indicators to the CBD, and to UNFSS (Díaz et al. 2020). The appeal of these targets is that they allow for alignment and the setting of both global and national goals, while leaving ample scope for farming communities to identify the most locally appropriate practices contributing to these targets.

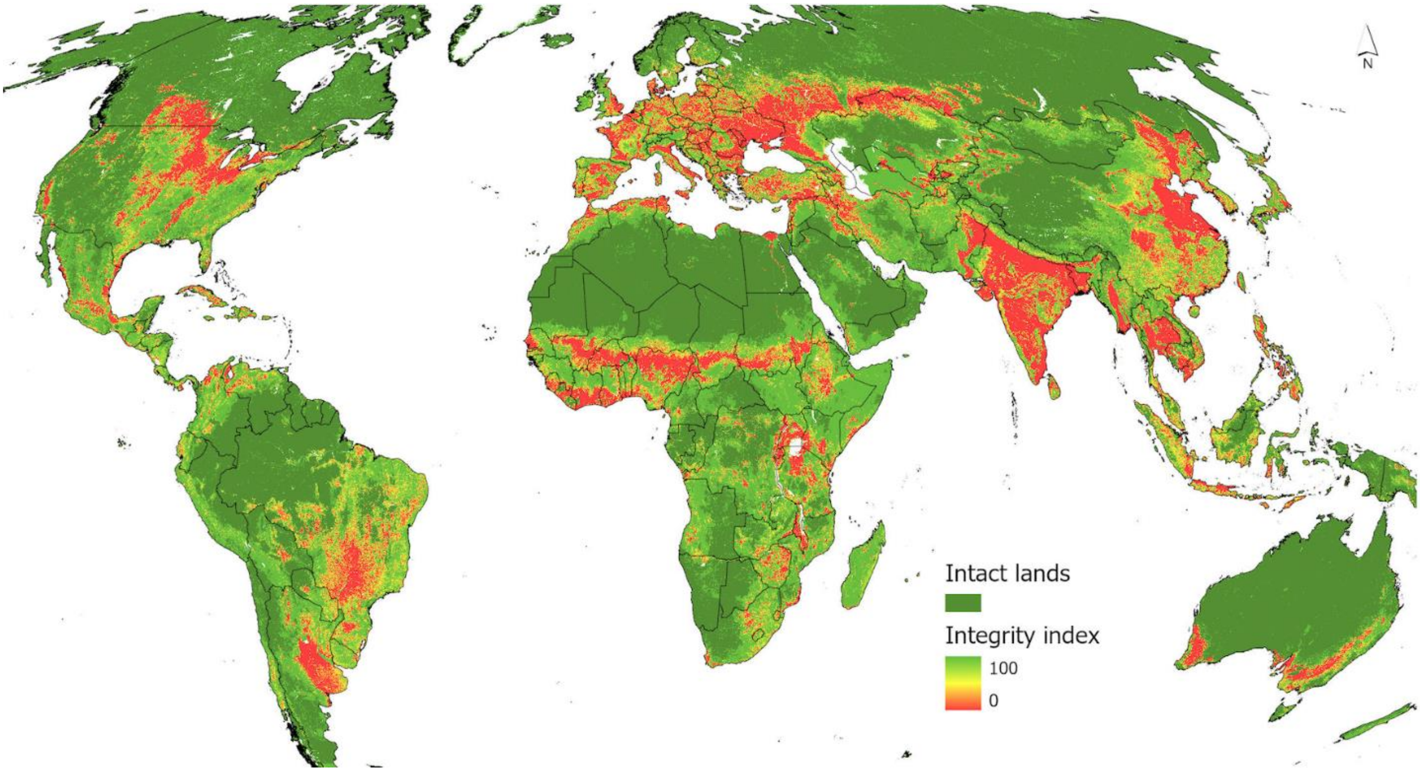

Figure 4: Global distribution of biodiversity intactness (dark green) and ecological integrity. Regions in red are below proposed thresholds for biodiversity in agriculture. Nearly half the terrestrial landmass is currently classified as 'intact'. Halting conversion of remaining 'intact' lands would be consistent with current negotiations for a 'no net loss' target in the CBD. Many agricultural lands have lost integrity (red), where remaining habitat quantity is insufficient to ensure biodiversity's contributions to food production.

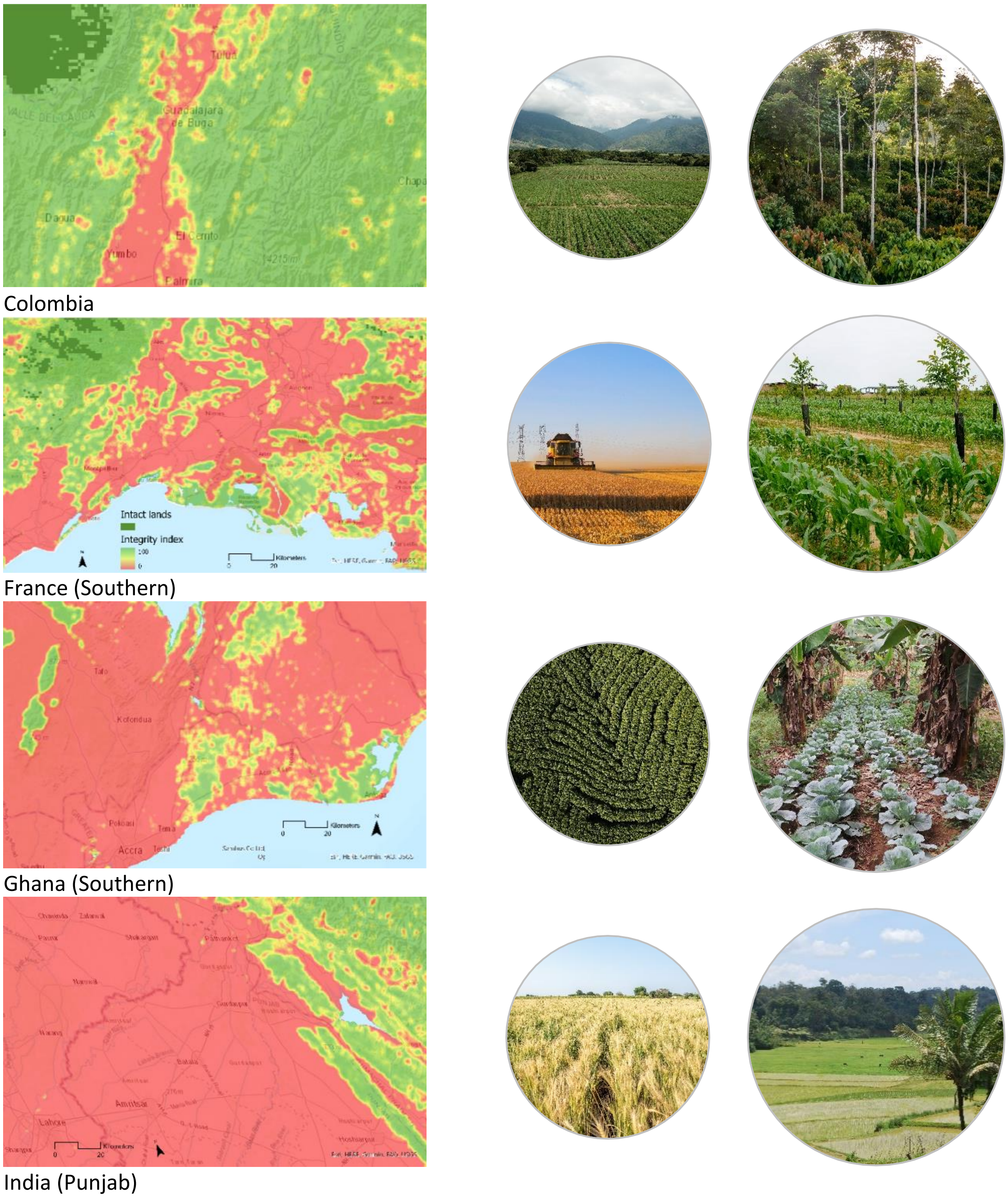

Figure 4 (continued): Country distribution of biodiversity intactness (dark green) and ecological integrity, with regions in red below proposed thresholds for biodiversity in agriculture. The photographs show examples of agricultural landscapes without integrity (left), and with integrity (right), where ecosystem services are potentially being regenerated. These are just single snapshots; there is a significant under-investment in the diversity of context-specific interventions available for regenerating biodiversity's ecosystem services in agriculture while meeting food security targets. Source (maps): Data from DeClerck et al. forthcoming. Photos (left to right, top to bottom): Jose F. Donneys / Shutterstock; GATO /Shutterstock; CSLD / Shutterstock; Philippe Montigny / Shutterstock; Albert Smith Junior / Shutterstock; Dr. Kofi Boa / Conflict & Development at Texas A&M; Tukaram.Karve / Shutterstock; G. M. Devagiri / World Agroforestry.

4. Agriculture must spare space for biodiversity to meet global environmental goals

Take-home messages

- Halting the expansion of agriculture into intact ecosystems is necessary to halt the loss of biodiversity and mitigate climate change and is likely to contribute significantly to stabilizing hydrological cycles;
- Half of the global land surface is currently intact, with strong biases towards desert, boreal and tundra biomes. Halting extinction loss will require the retention of most remaining intact ecosystems across ice-free areas and is compatible with CBD goals of 'no net loss';
- Restoring 15% of converted lands in priority areas could avoid 60% of expected extinctions and help provide vital ecosystem services, such as sequestering 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution.

Human impacts on the environment have now reached planetary proportions, with biosphere-level impacts. Most attention is on the climate and extinction crises, which have driven the establishment of the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and associated global treaties. Biodiversity, natural resources and food are interwoven with human development in the SDGs. Anthropocene impacts through agriculture on hydrological cycles are less well understood, though basin-level disruption of water flows, major river fragmentation, changes to aquatic ecosystems and freshwater and marine pollution are well documented. Reducing and reversing the impact of agricultural systems on biodiversity requires a system-wide transformation of agriculture and food production (Tilman et al. 2017; Williams, D.R. et al. 2020).

A sustainable future should therefore be grounded in improving environmental quality and placing strong limits to biodiversity loss. There is growing interest in how much intact nature is needed to halt biodiversity loss, mitigate climate and secure regional hydrological cycles. At least 79% of Earth's remaining natural and semi-natural (terrestrial) ecosystems need to be retained simply to meet existing international goals for biodiversity conservation, carbon storage, soil conservation and freshwater regulation (Simmonds et al. forthcoming). This equates to keeping half of the planet intact – about the proportion that remains intact today. We can afford to lose very little more: so much land has been converted to agriculture that we are globally either at, or nearing land conversion limits (Ceballos et al. 2020). Within the AR^{3}T framework presented in Section 1, actions to ensure that intact habitats and their biodiversity can contribute to Earth system processes while also halting the ongoing biodiversity extinction crisis require *avoiding* further loss of, and *restoring*, intact nature.

4.1 Halting the loss of intact ecosystems

Agricultural expansion is a leading stressor to biodiversity. It threatens 34% of all terrestrial vertebrates, including >70% of endangered mammals and >80% of endangered birds (IUCN Species Survival Commission 2001). Recent analyses project that nearly 90% of terrestrial vertebrates will lose some habitat to agricultural expansion in the next few decades (Williams, D.R. et al. 2020).

Central to the aim of halting and ultimately reversing biodiversity declines is the retention of intact ecosystems. Preventing the loss or conversion of intact areas, and where necessary enhancing their condition, requires setting limits to loss. How much intact land is needed to preserve functioning populations of all species is difficult to quantify precisely. Local contexts are important in determining extinction risk, and are important tools for setting conservation priorities. There is no 'one size fits all' solution (Maron et al. 2018; Allan et al. 2019). However, there is broad consensus that retaining intact habitat, and connectivity between habitats, is necessary to halt loss. This is often referred to as 'land sparing'. There is also broad consensus that the effect of loss of habitat on the loss of species is non-linear, with accelerating species loss when habitat declines to cover less than 10-30% across the landscape.

Biological intactness is not incompatible with human use, and should not be confused with 'protection', which is a description of legal rather than biological status. While protected areas will continue to play a key role in safeguarding biodiversity, and maintaining the ecosystem services nature provides, keeping biodiversity 'in place' outside of protected areas is crucial. Relatively intact and ecologically functioning systems can and do support a multitude of human uses, including productive and extractive uses. In fact, many such ecosystems rely upon human intervention, and represent the product of millennia of sustainable traditional management. Extensive grazing in grassland and savannah biomes, or sustainable harvest of natural forests, are demonstrable activities that retain intactness while supporting livelihoods. Identifying the particular range of nature-based benefits that each priority avoidance area supports can provide a guide to the human uses that are compatible with its ongoing provision of those benefits.

Interventions should therefore aim *not* to exclude human activities entirely from the areas we need to retain, particularly where local people depend on the natural resource base for their livelihoods. Spatial planning plays a key role here. Proposed agricultural expansion can be managed to minimize impacts on biodiversity, for example in the intact savannas of Colombia (Williams, B.A. et al. 2020) and northern Australia (Morán-Ordóñez et al. 2017). Additionally, land use policies (e.g. vegetation management laws; clearing and logging moratoria), decision-making tools (e.g. environmental impact assessments), and private sector levers (e.g. certification schemes; sustainability commitments including supply chains) can contribute to the retention of vegetation in the landscapes where we co-occur with nature.

Planetary boundaries scientists, who define boundaries for Earth system processes that constitute a 'safe operating space for humanity', have proposed a Biodiversity Intactness Index (BII) (Scholes and Biggs 2005) value greater than 90 (the current estimated level) but do not state how much area at or above this level is required (Steffen et al. 2015). There is a growing call for the retention of at least half of the global land surface (BII>90) in order to halt extinction loss at 80% of known biodiversity (Newbold et al. 2016; Dinerstein et al. 2017; Maron et al. 2018; Willett et al. 2019; Rockström et al. 2020). Other estimates, using species-based approaches, find that 44% might be sufficient to protect the most important sites for terrestrial biodiversity (64 million km^2) (Allan et al. 2019). While the specificity of this boundary is vigorously debated, most ecologists agree that as the intact area of ecosystems dips below 50%, there is growing risk of population decline and extinction risk. Retaining at least half of the terrestrial realm, in each of 782 defined ecoregions, would thus be necessary to halt extinction loss, and has been signaled as a biodiversity boundary for food systems (Willett et al. 2019). Retaining intact regions in ice-free areas requires >67 M km^2; achieving half intactness for all ecoregions would require additional restoration on 23.9 M km^2.

The 17% protected area target (Aichi Target 11) under the CBD's 2010-2020 Strategic Plan, while supporting conservation of unique species, populations or ecosystems, is insufficient to halt extinction loss. This has prompted calls for new post-2020 CBD targets[1] to provide formal, area-based protection of 30% of Earth by 2030 (Roberts et al. 2020). The current proposed target is to protect and conserve, through a well-connected and effective system of protected areas and other effective area-based conservation measures, at least 30% of the planet by 2030, with a focus on areas particularly

[1] To be decided in Kunming, China in October 2021 as part of the CBD COP15.

important for biodiversity. Observing that currently half of the terrestrial realm is considered intact, the CBD has adopted the boundary measure in its ongoing negotiations for a ‘no net loss of nature’ target. Ensemble models have demonstrated that no net loss is possible to achieve but requires aligned actions across biodiversity conservation, food production and food consumption (Leclère et al. 2020).

Biodiversity intactness is not distributed evenly across the globe; it is strongly skewed towards boreal, tundra and arid biomes (Figure 4). Many parts of the world have an intactness deficit, if 50% intactness is considered the target. Estimates of how much restoration is needed range between 19 and 24 million km^2, with the lower value targeting high conservation value areas (Allan et al. 2019; Strassburg et al. 2020), and the higher value targeting half-intact ecoregions, across all ecoregions (DeClerck et al. forthcoming). In 552 ecoregions globally (69%), less than 10% of the area remains intact and may be too far gone for meaningful restoration of intactness or may conflict with food and nutrition security. In these locations, integrating biodiversity into production, as discussed in Section 3, will be a more viable option.

4.2 Mitigating climate change

While reducing fossil fuel burning and halting land conversion are critical strategies to reduce GHG emissions, biodiversity, through photosynthesis, is the only known technology to transfer GHG from the atmosphere to the biosphere. The retention and restoration of natural ecosystems, notably carbon-dense forest and wetland ecosystems, are key actions in this regard. It has been proposed that 75% of forest biomes be conserved globally because of their specific contribution to climate mitigation (Steffen et al. 2015). This forest conservation boundary is further disaggregated into boreal, temperate and tropical forest biomes, of which 85%, 50% and 85% of original extent should be conserved. Temperate and tropical forest biomes are currently below this threshold, although temperate forest areas are increasing due to agricultural abandonment, whereas tropical forest areas are decreasing due to agricultural expansion. Boreal forest biomes remain above this threshold for the moment (Dinerstein et al. 2017; Ramankutty et al. 2018).

A more detailed analysis of the climate mitigation potential of nature-based solutions suggests that these can provide approximately 30% of the mitigation potential needed to achieve Paris Agreement targets for 2030 (Griscom et al. 2017). The majority of this potential (66%) comes from forest conservation and forest restoration. The potential of reforestation to contribute to climate mitigation (i.e. 2.7-17.9 Pg CO_2e y^{-1}) depends on several assumptions (Griscom et al. 2017). Maximum potential, for example, assumes that grasslands and pastures in forest biomes will be restored (reforested). This assumption is similar to that articulated in the previous subsection, that at least half of each ecoregion be restored to maximize conservation potential. Achieving climate mitigation potential would require combined conservation and restoration actions over 85% of the biomes’ area. The extent to which such restoration activities are compatible with extractive activities remains little explored, although there is growing academic interest in whether tree-based cropping systems (e.g. diversified plantations, agroforests, orchards) present options for achieving climate mitigation while meeting food, fiber or wood production targets (Mbow et al. 2014; Griscom et al. 2017; Chapman, M. et al. 2020).

Multiple studies have attempted to target critical areas for conservation and restoration. All of these show broadly consistent trends. Models that prioritize protecting as many species as possible tend to value biodiverse tropical areas; models that prioritize unique species assemblages tend to favor smaller ecosystems faced with conversion threats, such as the Mediterranean system. When climate mitigation potential and biodiversity conservation are jointly considered, tropical latitudes and biomes are typically prioritized. A recent study applying a multicriteria optimization approach identified priority areas for restoration and found that restoring 15% of converted lands could avoid 60% of expected extinctions while sequestering 299 Gt CO_2e: 30% of the total atmospheric CO_2 increase since the Industrial Revolution (Strassburg et al. 2020). Most global models provide important information regarding potential. Local and national spatial planning are essential to materialize this potential while navigating synergies and trade-offs, and ensuring socially just transitions.

4.3 Regulating hydrological cycles

Large tracts of intact nature are key to maintaining regional hydrological patterns (McAlpine et al. 2009; Chapman, S. et al. 2020), including flood pulse flow regulation (Bradshaw et al. 2007) and distribution of rainfall patterns that are critical to agriculture. However, the relationship between water fluxes (storage, evapotranspiration, precipitation and run-off) of extensive intact areas is complex. Intact nature may or may not produce greater volumes of water than converted lands, as losses to storage and evapotranspiration can be greater than in simplified systems such as agricultural ecosystems. However, most evidence does indicate that heavily vegetated ecosystems (e.g. forests, grasslands) provide better flow regulation – while natural ecosystems reduce run-off, they may have greater losses to evapotranspiration.

Better understood is that extensive agricultural conversion, notably when it changes the permanence, density and extent of vegetation cover, has important impacts on water-holding capacity, evapotranspiration rates, run-off and environmental flows. Studies suggest that about 40% of irrigation water currently drawn from surface water bodies is at the expense of environmental flows (Jägermeyr 2020) (Figure 5) and roughly 20% of irrigation water depletes groundwater bodies (Döll et al. 2012; Wada et al. 2012, 2016), indicating that 50-60% of current global irrigation practice is unsustainable (Rosa et al. 2018, 2019). From a global food production perspective reallocating these water volumes to the ecosystem would only impinge upon about 5% of global caloric production. There are regions where the production difference would be dramatic because agriculture is based on unsustainable water supplies (Jägermeyr 2020).

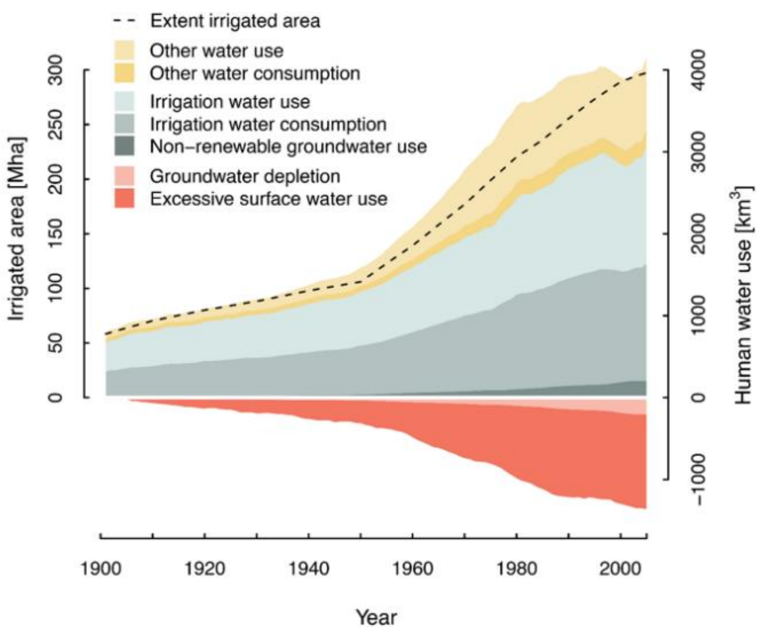

Figure 5: Increasing use of water by agriculture over time, with unsustainable water use highlighted as negative volumes. Source: Jägermeyr 2020.

There is some evidence that forested land surfaces regulate regional precipitation patterns and excessive deforestation has increased the severity and duration of drought in important agricultural regions (McAlpine et al. 2009; Chapman, S. et al. 2020). Compelling anecdotal evidence also suggests that deforestation in the northern Amazon is a contributor to the recurring droughts in the southeastern Amazon, Brazil's breadbasket (Fearsinde 2015; Nazareno and Laurance 2015). On the other hand, extensive intact ecosystems do make important water-based contributions to agriculture. Well-known examples are the Sierra Nevada mountains of California, and the Himalayan ecosystems and their provisioning of irrigation water to downstream agricultural ecosystems. However, numerous models, including from important re-greening efforts in China and the Sahel, show that the impacts of greening on regional precipitation is complicated, difficult to predict and disparate, and merits significant further research (Sen et al. 2004; Giannini et al. 2008; Dardel et al. 2014; Ouedraogo et al. 2014).

The amount, distribution and quality of intact nature necessary to retain hydrological flows remains largely unknown and the subject of important research. Simmonds et al. (forthcoming) made an approximation of the extent of terrestrial ecosystems that would need to be retained in order to contribute to freshwater quality regulation via in situ and catchment-level processes. By combining data on vegetated wetlands and intact natural ecosystems within river basins collectively responsible for 95% of global freshwater discharge (approximately 75,000 individual basins), they found that approximately 14% of remaining intact vegetated ecosystems have to be retained to limit further compromise to freshwater quantity. This does not include ecosystems additionally required to regulate regional and global water cycles, which would further extend these retention priorities to most forested areas globally. Nor does it include the areas that require restoration to repair already-damaged catchments – though earlier global assessments have concluded that limiting threats on land would be more effective for both humans and aquatic biodiversity than costly remediation of rivers (Vörösmarty et al. 2010).

4.4 Restoring ecosystems

Restoration activities can achieve multiple outcomes including climate mitigation, regulation of hydrological flows, and even food security. While a growing number of research articles recommend options for restoration, and evaluate contributions to climate, biodiversity and food security, local and regional implementation of such strategies, including trade-offs over multiple spatial and temporal scales and between different social groups remains little studied (Mehrabi et al. 2018; Leclère et al. 2020; Strassburg et al. 2020). Restoration, in contrast to regeneration, must include improvements in biodiversity intactness (Scholes and Biggs 2005; Newbold et al. 2016) measured by changes in species richness and population abundance. Defined as such, restoration can be interpreted as driving a net reduction in land available for food production, with the exception of wild harvest systems, and potentially extensive grazing systems. In contrast to the assessment of priorities for conservation of remaining natural habitats, a global analysis of priority areas for restoration has not yet been conducted and the interplay between multiple restoration objectives and biomes remains unknown. Many prioritization exercises for biodiversity restoration focus on those areas that are species rich, or unique. There is some merit to these approaches. However, all ecoregions are unique assemblages of species, whether diverse or not, and many ecosystem benefits of intact nature are regional, notably hydrological services.

5. Conclusions and recommendations: Food and agriculture are a core solution to food, environmental and climate security

While the evidence on when and how biodiversity contributes to global goals is highly context specific, this review finds that agriculture has the potential to reconcile global goals that have often been considered contradictory: food and nutritional security versus environmental and climate security. There is strong evidence that realizing this potential requires placing biodiversity at the heart of agriculture policy, investment and innovation, with much greater consideration of the role of agriculture, whether indigenous, conventional, or alternative, as a provider of benefits to biodiversity, rather than just a driver of biodiversity loss. As the ultimate drivers of the food system, people have to be anchored in solutions to upend the system of policies and incentives that are currently stacked against their livelihoods and health.

> We find no evidence of a fundamental incompatibility between producing healthy diets for 10 billion people and halting the loss of biodiversity. There are significant challenges and trade-offs in several regions of the world, however, especially in developing economies. **[*High Agreement, Medium Evidence*]**

This year, there is a chance for the Global North and South to agree on an integrated and interwoven narrative on food systems. This narrative includes biodiversity solutions that work for dietary shifts, together with nature-based solutions. This theme runs through this year's major summits and global meetings, including the CBD CoP15, UNFCCC CoP26 and UNFSS.

> Food, nutrition, climate and environmental goals can be achieved if we develop a policy framework that takes a whole system perspective. This means valuing not just the amount of production, but the production of healthy foods with low environmental impacts. This perspective necessarily incorporates reducing food waste, encouraging good eating habits low on the food chain, and providing access to nutritious foods for low-income communities globally **[*High Agreement, Robust Evidence*]**.

Understanding that there is a menu of solutions, with related opportunities and trade-offs, will help progress towards a future that optimizes sustainable agriculture and prioritizes feeding everyone. Biodiversity strategies are among those solutions and can help us move beyond staple crops and commodities when considering policy, investment and research.

Three elements, as already detailed in this review, can offer a way to bridge conversations between policy makers engaged in the environment, food, agriculture, finance and social protection sectors and have to be considered as part of a holistic solution for food and biodiversity: how can we optimize the opportunities and minimize the trade-offs for ensuring diverse diets for all? How can we maintain shared space where agriculture optimizes ecosystem services and other contributors to regenerative and resilient production systems? And finally, how can we strike the right balance of land sparing, by halting the expansion of agriculture into the intact ecosystems necessary to halt the loss of biodiversity while mitigating climate change and producing enough healthy food?

5.1 Policy implications: the transformation challenge

As has been stated, biodiversity needs to be part of a sustainable agriculture that will feed a projected population of 10 billion with healthy, culturally appropriate and delicious foods by 2050. However, the first step is for policy makers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This leads to thinking about 'food system productivity' rather than agricultural productivity (Benton and Bailey 2019), and requires all sectors of government to break out of their own conceptual silos and institutional structures.

A coordinated, transformational adjustment of policies, incentives, regulations and other public sector instruments is needed to make healthy and sustainable food affordable and available for all and enable farmers and farming communities to gain greater recognition, reward and payments for actions that produce healthy foods or environmental benefits.

For a true transformation of the food system, there is a need to create the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional security (Rockström et al. 2009; Steffen et al. 2015; Willett et al. 2019). Much of the challenge lies in siloed approaches to policy and innovation, entrenched political economies of food, and hypertribalism between sectors both in society and in policy. Several studies have begun to propose nature retention targets in agriculture (Willett et al. 2019; Garibaldi et al. 2020), which are also starting to be reflected in agricultural policy (Díaz et al. 2020), such as the biodiversity boundary for agricultural ecosystems to retain at least 10-20% habitat per km^2 to maintain ecological integrity in production landscapes (Maron et al. 2018; Willett et al. 2019; Garibaldi et al. 2020; DeClerck et al. forthcoming). The rationale for this boundary is that the services provided by biodiversity to agriculture are local.

5.2 Correcting distortions requires reinvestment

Our food system has been distorted by a framework of subsidies (including for research focused on staples), market incentives (including investment in commodity-based transport infrastructure, and marketing/retail incentives for hyper-processed food), and a lack of regulations to curb externalization of costs onto environmental and healthcare systems.

Moving forward, agriculture will require multipronged approaches consisting of a range of techniques, such as strong conservation of intact areas, improved productivity of underperforming agricultural lands and shifts towards healthy diets. Diversification strategies can be applied in a range of contexts and would benefit from investment in technologies, tools, markets and incentives that increase and improve employment opportunities, reduce drudgery in food production and provide greater autonomy to producers.

The heavily subsidized agricultural sectors of many countries in the Global North create trade distortion and foster inequitable trade relationships with developing countries, adversely affecting the economic prospects of farmers in the Global South. This has a strong influence on the foods that are delivered and their price and accessibility, and in encouraging the supply, demand and consumption of foods that may be less conducive to healthy diets and to sustainability in food systems.

In considering the relationship between agriculture and biodiversity several key areas for investment emerge [***High Agreement, Robust Evidence***]:

- Closing the gap between the current composition of crop production and consumption to supply healthy diets at local, regional and global scales in line with SDG2 and SDG3;
- Transitioning to managing agricultural systems as ecological systems (agroecosystems); including greater inclusion of farmers, including women, youth and indigenous farmers, as core actors with unique knowledge systems and capabilities that should be brought more to bear in food production.

During the next decade, priority approaches to diversify production systems should target:

- Urgent investments in undervalued crops and cropping systems, notably underproduced crops that underpin dietary health, and indigenous cropping and knowledge systems;
- Greater investment in tools, technologies and enabling environments that amplify and/or complement biodiversity's contribution to agriculture rather than seeking to replace it;
- Repurposing public funds in agriculture to support farmers producing public goods, including the production of healthy foods, carbon capture, clean water and habitat for biodiversity.

Food security cannot trump other critical goals, notably nutritional, climate, environmental and livelihood security. Treating these as inevitable trade-offs fails to highlight key areas of synergy. Making the transition to food production systems that achieves synergy with biodiversity will require significant transitions in the policy landscape. Agriculture should be more strongly:

- Integrated into global environmental policies, both in recognition of its role as a driver of environmental change, and to leverage its potential contribution to mitigating climate and biodiversity loss;
- Included in global agreements, recognizing its current impacts on climate, degradation and biodiversity, and leveraging its potential contribution to global goals;
- Interwoven into global health policies, as in recent collaborations between the World Health Organization and the Food and Agriculture Organization to define healthy and sustainable diets.

5.3 Developing more dynamic investment and financial opportunities

There is potential to unlock and unblock investment and facilitate better financial flows to encourage farmers to protect and enhance the environment by rewarding them for the provision of ecosystem services, while mitigating the risks to the adoption of sustainable practices. Current agricultural investments and practices generally overlook the important potential for increasing the ecosystem services that agroecosystems can provide (Wood et al. 2018).

Farmers and farming communities can produce public goods (e.g. climate mitigation, soil water-holding capacity, water quality improvement), but promoting these public good functions has been consistently underexplored and under-resourced, even though they are also necessary for creating sustainable and resilient production systems. Recognizing that farmers and farmlands can produce these benefits in addition to quality food presents an opportunity to revitalize rural communities by repurposing public funds for public goods.

While there are many cases where yields increase in response to such farming methods, there is much room for improvement (Ponisio et al. 2016). This requires investments in agronomic and agroecological research to optimize diversified systems for specific crops and regions (Pickett et al. 2014).

5.4 Changing availability through subsidy and research reform

Currently, more than US$620 billion is spent globally each year on agricultural subsidies (e.g. commodity support, services) (OECD 2020). Over the past decade, Organisation for Economic Co-operation and Development (OECD) governments have allocated roughly 26% of their subsidy support to cereal grains, and 14% to fruits and vegetables (Freund and Springmann forthcoming). This value is inverse to the diversity of potential crops within these food categories, inverse to the recommended consumption levels of food groups, and inverse to the projected yield production deficits (Table 1). While the share of sectoral support to fruits and vegetables was much higher in non-OECD countries, at 37%, the other 63% of subsidy support went to cereals, livestock, oilseeds, sugar, production of fiber (wool) and more (Freund and Springmann forthcoming).

Work reviewed in GloPan (2020), the Global Panel on Agriculture and Food Systems for Nutrition, shows that even a relatively modest repurposing of subsidies (e.g. 25%) towards promoting production of nutrient-rich perishable foods, and reduced food loss and nutrient waste (Figure 6), would free up US$150 billion in capital to support the generation of a greater diversity of nutrient-rich foods, while simultaneously lowering the environmental footprint, potentially allowing more nature-positive farming methods, as recommended by the Just Rural Transition and the UNFSS Action Track on nature-positive food production.

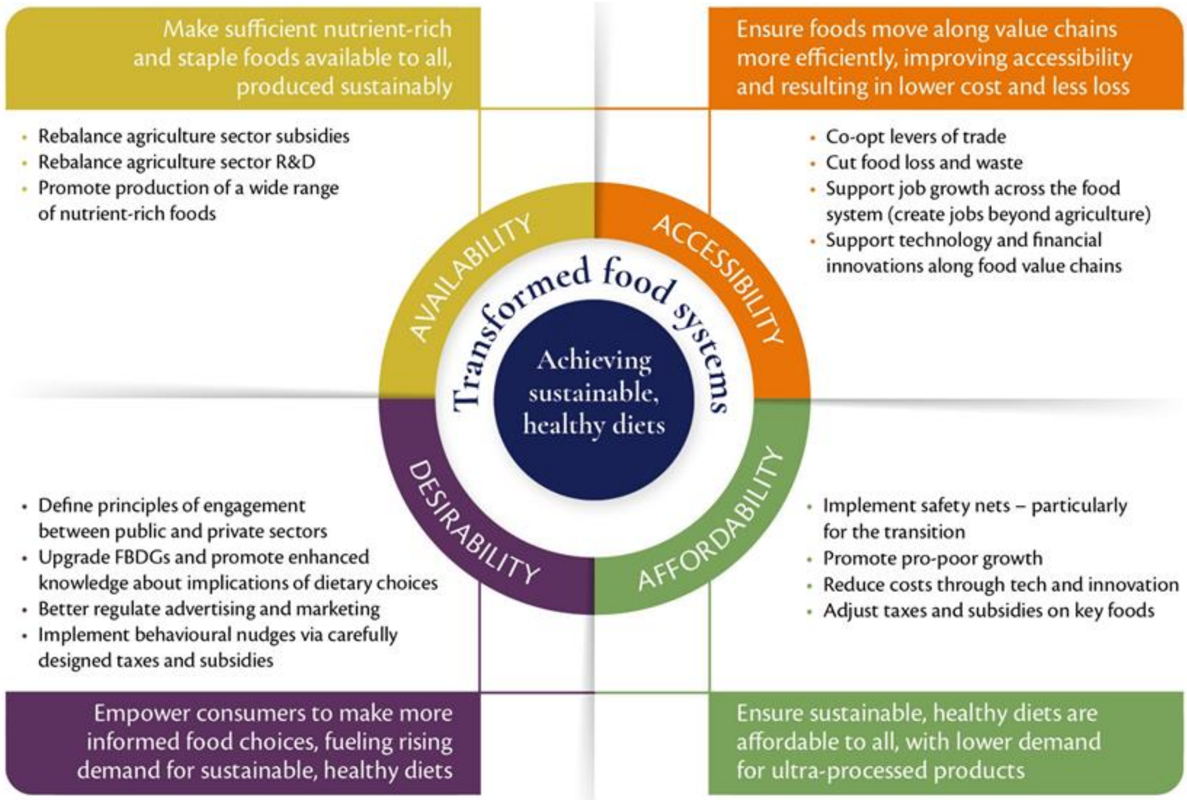

Figure 6: Priority policy actions to transition food systems towards sustainable, healthy diets. Source: GLOPAN 2020 Foresight report: *Future Food Systems: For people, for planet, for prosperity* (Global Panel on Agriculture and Food Systems for Nutrition 2020). FBDGs: Food-based dietary guidelines.

Only 6% of public sector support to the agricultural sector is dedicated to research (Searchinger et al. 2020). This is a small percentage but amounts to a big number globally. However, it is typically targeted to productivity improvements in major commodities. A key research need is for a much greater focus on innovation in diverse farming systems rather than individual crops, for instance through circular agriculture to prevent waste and leakage while supporting reuse, regenerative agroecological systems, complex rotations, mixed farming and so on.

5.5 Making healthy and sustainable diets affordable

Modelling undertaken as part of the GloPan 2020 report (Global Panel on Agriculture and Food Systems for Nutrition 2020) looked at a range of variables influencing the availability and price of more sustainable and nutritious food. This included:

- incorporating externalized costs on the environment and healthcare systems to incentivize more sustainable production;
- cutting food loss and waste by up to 50% from current levels (in line with the SDG target), estimated to reduce the cost of current diets by 14% on average (9-17% across regions);
- growth policies that have positive effects on desired outcomes, including higher rates of poverty reduction, stricter land use regulations, lower barriers to food trade, and a trend towards lower meat consumption in high-income countries.

5.6 Reimagining international trade

With almost 20% of the global dietary energy supply derived from imported foodstuffs, trade policy must better account for its impact by creating greater space for diversification of commodities, supporting the conservation of intact ecosystems, and including trade of environmental goods and services. Trade expansion over recent decades has enabled "higher-income countries to 'off-shore' the adverse impacts of their consumption on ecosystems and biodiversity through trade in commodities, goods and services with lower-income countries" (Dasgupta 2021). International market stability and prices are highly dependent on a few key players (Dasgupta 2021), yet investing well in international trade could bring a range of benefits.

It is crucial to find ways to support sustainability via trade (e.g. 'due diligence' requirements for supply chains such as the Global Reporting Initiative, enhancing traceability through mechanisms such as TRASE, or through border tariffs). A key component of the evolution of the food system's focus on large-scale commodity production is the ability to store, transport and process grains with less loss than with fresh produce.

In recent years, support based on commodity output, which is deemed to have "the strongest potential to distort agricultural production and trade", has started to decline in the OECD area (OECD 2020) .Yet it continues to impact trade relations. Aside from creating trade asymmetries, the total cost of subsidies that degrade nature is estimated to be between US$4-6 trillion per year (Dasgupta 2021).

5.7 Recommendations

Food production plays an outsized role in global environmental and social systems, and we should acknowledge that its impact on human and environmental health needs to be addressed. We need regenerative, carbon- and nature-positive production of healthy and nutritious foods, to be achieved through a systematic adjustment of agricultural and land use policies and practices guided by science-based targets and true cost accounting. This will require:

- enhancing above- and below-ground and aquatic species diversity;
- reducing synthetic inputs coupled with increased use of regenerative agricultural practices;
- enhancing soil and water health;
- maintaining or restoring natural and semi-natural areas;
- protecting and efficiently using water resources and aquatic diversity;

- enhancing habitat diversity;
- delivering multifunctional landscapes.

Driven by real leadership and will, a global agenda for transforming our food systems should be developed, grounded in the best available science and economic analysis, and guided by established universal norms. Global goals, whether the SDGs, the Paris Climate Agreement, or the Convention on Biological Diversity supported by the Science-Policy work of IPCC and IPBES, have repeatedly emphasized the urgent and critical need to halt emissions, and accelerate carbon sequestration opportunities. Ecosystem restoration, and agricultural regeneration are the best bet options for reversing emissions. A diversity of solutions are available but will need to be improved, and enabled in order to make meaningful contributions. Investing in context-specific R&D aligned to global goals, but building local capabilities and capacities to contribute to global goals is critically needed. While global models remain helpful in setting pathways and understanding the urgency and ambition needed, these need to be complemented with demand-driven R&D with farmer and pastoralist communities that provides them with the flexibility and adaptive capacity to respond to global demand, without compromising their livelihoods. This should emerge through a global, collaborative effort that drives the following key recommendations:

1. Agriculture needs to be more strongly integrated into global environmental policies and agreements, as well as global health policies.
2. Protection of remaining natural ecosystems from agricultural expansion and other extractive activities needs to be tightened.
3. A transition to managing agricultural systems as ecological systems (agroecosystems) is needed through the systematic adjustment of agricultural, land use and fisheries policies and practices guided by science-based targets and true cost accounting to incentivize regenerative, carbon-sequestering and nature-positive production systems.
4. This should be accompanied with critical investments in performance analysis across multiple dimensions and synergies of production systems: increasing production, diversifying crop composition, above or below ground carbon capture, soil health and measures of the ecological integrity of production systems. Global support and alignment for nature-positive production by scaling a diversity of context-specific diversification practices will increase the resilience of food systems.
5. A coordinated, transformational adjustment of policies, incentives, regulations and other public sector instruments and public funds is needed to make healthy and sustainable food affordable and available for all, and enable farmers and farming communities to gain greater recognition and reward for actions that produce healthy foods as well as biodiversity and climate benefits.
6. Investment is needed to close the production gap of crops contributing to healthy diets including whole grains adapted to local environments, fruits, nuts, vegetables and seeds to supply healthy diets at local, regional and global scales, in line with SDGs 2 and 3, including urgent investments in undervalued and underproduced crops vital to dietary health and integrating sustainable livestock production into cropping systems.
7. Investment is needed in research to fill knowledge gaps on agricultural systems of LMICs, including on building the capacity of scientists and institutions in the Global South, increasing their capacities to engage with regional food system actors, and increasing the access and participation of LMIC scientists in global science-policy interfaces.
8. Food loss and waste should be halved, using strong incentives, regulations and financial innovation along the entire value chain, creating a truly circular food economy.
9. Policy makers need to make the required policy shifts on both the supply and the demand side. In the Global South, policies are needed to allow greater access to sustainably produced protein-rich foods.

10. Financial markets need to shift investment flows away from unsustainable, unhealthy and socially unjust practices and into investments in tools, innovations, technologies and enabling environments that drive transformative change; food companies should integrate environmental, social and health risks into company disclosures.
11. International trade should be reimagined so that higher-income countries take account of the adverse impacts of their consumption on ecosystems and biodiversity through trade in commodities, goods and services with lower-income countries. Sustainability in trade can be supported through due diligence requirements, tracing mechanisms and border tariffs.
12. People everywhere need access to the knowledge and tools required to demand change from policy makers and business, and to enable better informed, satisfying everyday food choices.

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Annex 1: Agroecosystem services

A1.1 Essential agroecosystem services

A set of well-known principles and practices for farm and landscape management allow the ecosystem services that support agriculture – soil stabilization, nutrient capture and release to crops, water capture and storage, crop pest control and crop pollination (Zhang et al. 2007) – to be established and regenerated. While additional agroecosystem services are described in the literature, the five listed above are the most studied and most critical.

Often, activities that attempt to harness on-farm ecosystem services also produce off-farm goods and services. The synergies between on-farm and off-farm benefits are particularly important in the development of agricultural policies and market reward systems that recognize the active roles of farmers and farming communities in providing public goods (Zhang et al. 2007). These include clean water, habitat for biodiversity, and enhanced carbon capture, while reducing the environmental pollutants that farming often also produces.

A1.2 Soil biodiversity: soil fertility, climate adaptation and mitigation

The need to protect and rebuild soil carbon is widely accepted, but in agricultural production systems, soil carbon losses exceed sequestration rates. These losses are substantial, with a mean estimate to 2 m depth of 133 Pg-carbon, the equivalent of ~63 ppm atmospheric CO_2 (Bradford et al. 2019). Losses vary by type and duration of land use, as well as biophysical conditions such as soil texture, mineralogy, plant species and climate (Sanderman et al. 2017). Adopting regenerative approaches such as conservation agriculture and agroforestry can protect soil carbon and recoup some losses by minimizing soil disturbance and maximizing inputs of carbon into soil via root exudates. While there are important questions remaining as to the feasibility and scale of impact that soil carbon capture might have on climate mitigation, ranging from 1 to nearly 9 Gt CO_2e per year (Table A.1), there is strong evidence that building soil ecosystem health and carbon has a positive impact on plant growth, water storage and resistance to drought, and climate adaptation of farming systems. There is also consistent agreement that increasing soil carbon would offset GHG emissions. Rebuilding soil carbon is a no-regrets option critical for climate adaptation, despite remaining uncertainty as to the plausible scale of impact in climate mitigation (Sanderman et al. 2017).

It has been estimated that 25% of global emissions can be sequestered in soil globally (Lal 2004), though this is difficult to quantify and can be lost quickly if the soil is tilled. Forty percent of this value comes from the protection of existing soil carbon in natural ecosystems, whereas 60% is derived from regenerating depleted stocks through better soil management in agricultural and rangeland. Building up soil carbon offers much more carbon mitigation potential for soils in agriculture and rangelands (47% compared to 9%) (Bossio et al. 2020) relative to natural forests. These data indicate that agricultural and grassland systems play an essential role in climate change mitigation and that taking measures to protect current soil carbon stocks is critical. Increasing soil organic carbon in agricultural soils by 0.4% in the top 1 meter of global agricultural soils would sequester between 1.4-3 Gt CO_2e $year^{-1}$ in emissions (Griscom et al. 2017; Minasny et al. 2017; Bossio et al. 2020) while improving overall soil condition (Lal 2016; Griscom et al. 2017; Minasny et al. 2017; Bossio et al. 2020).

Advances in soil organic carbon monitoring and assessments have enabled quantitative assessments of the impact of regenerative agricultural practices and land restoration in general (Vågen and Winowiecki 2013; Winowiecki et al. 2016). This is a key advance that allows reliable reporting on restoration targets and soil organic carbon accounting.

A1.3 Biodiversity and hydrological services in agriculture

Conversion from natural to agricultural lands has fundamentally altered water cycles at local, regional and global scales, through soil moisture (Rost et al. 2008; Bagley et al. 2012), river flow (Grill et al. 2015, 2019) and vapor transport to the atmosphere. Agriculture impacts both water quantity and water quality through the use of agro-chemicals (e.g. synthesized fertilizers and biocides) (Scanlon et al. 2007). These hydroclimatic influences can feedback to agricultural production through altered precipitation patterns, both locally and through atmospheric teleconnections (Avissar and Werth 2005). Changes in stream quantity and timing are due to irrigation as well as power production, and have had profound impacts on freshwater life, with an estimated 84% decrease in freshwater species abundance since the 1970s.

Table A.1: Mitigation potential of agricultural practices (Source: Griscom et al. 2017)

Practice	Maximum Potential Extent of Implementation	Maximum Mitigation Potential	Range of Mitigation Potential
Soil-based sequestration			
Avoided grassland Conversion	1.7 Mha	116	75-373
Biochar	1,670 TG dm yr^{-1}	1,102	642-1,455
Cropland nutrient management	44 Tg N yr^{-1}	706	399-959
Conservation agriculture	352 Mha	413	310-516
Above-ground sequestration			
Trees in croplands	608 Mha	1,040	469-1,855
Grazing	800 Mha	1,175	272-3,427
Rice cultivation	163 Mha	365	227-319
Total Potential	--	3,817	2,394-8,904

Agricultural field and farm biodiversity can reduce agriculture's dependence on water capture and water quality through soil carbon sequestration and on- and between-farm practices. Diversification practices that improve soil carbon through the retention of vegetative cover and organic matter also improve water retention. Vegetative cover over soils, whether living or residual, has the effect of increasing water infiltration and retention in soil, which can outweigh the potentially negative impact of certain tillage practices (Newbold et al. 2016). Diversified plantings around fields, or in rows across the contours of fields, intercept excess nutrients and soil. As with managing soil carbon, minimizing the disturbance of the soil structure increases infiltration and storage of water in the soil available for crop growth while potentially reducing GHG emissions (Newbold et al. 2016). Combining species with deep and shallow rooting systems, as in many agroforestry systems, both increases the depth at which carbon is stored and leads to improved water use efficiency and storage.

Better use of crop diversity by matching crops to consumptive water needs can significantly reduce water use. Water consumption by crops varies substantially across the globe due to differences in cropping density, crop choice, soil characteristics, irrigation availability and agricultural management as well as climatic drivers of evapotranspiration. Selection of crops adapted to climatic zones could mean much of the caloric yield of these regions is rainfed rather than dependent on irrigation. In arid climates, for example, rainfed farming is dominated by millet and sorghum while irrigation water is used mainly for wheat and rice (Willett et al. 2019). Raising crop water productivity in precipitation-limited regions would increase annual production on rainfed cropland by enough to provide food for an estimated 110 million people, and water consumption on irrigated cropland would be reduced enough to meet the annual domestic water demands of nearly 1.4 billion people (Willett et al. 2019).

A1.4 Pollination

Crop pollination is an excellent example of the connections between biodiversity, crop production, dietary diversity and human health. Three fourths of fruit, vegetable, nut and seed crops previously noted as globally under-consumed are 'pollinator dependent' to a greater or lesser degree (Klein et al. 2007). Some of these crops cannot produce a harvest at all without pollinator visits (e.g. squashes, melons, kiwis, macadamias), or require cross-varietal pollination for a good harvest (e.g. almonds; Brittain et al. 2014) or a better shelf-life (e.g. strawberries; Wietzke et al. 2018). Pollinator-dependent crops contribute the major component of the plant-based global supply of many essential vitamins and micronutrients (Eilers et al. 2011).

Given the existing gap between the need and supply of fruits and vegetables (Mason-D'Croz et al. 2019), pollination is even more critical. Pollinator loss can lead to increases in micronutrient deficiencies, particularly of Vitamin A, a mortality factor (Chaplin-Kramer et al. 2014). In countries where micronutrient production is primarily from pollinator-dependent crops, it has been found that micronutrient deficiency is high in certain regions, suggesting vulnerability to pollinator loss (Chaplin-Kramer et al. 2014). These findings underscore the importance of maintaining pollinator populations and communities, particularly in regions affected by poverty and malnutrition.

Pollination can take place through managed pollinators such as honeybees or through a diverse array of native free-living insects such as other species of bees and flies. Unmanaged insects enhance crop yields even when managed honeybees are present on farm fields (Garibaldi et al. 2013; Chaplin-Kramer et al. 2014). In fact, native pollinators can be more effective than managed honeybees, can interact with honey bees in a way that enhances honey bee effectiveness, or can complement the foraging behavior of honey bees in a way that enhances production, by visiting different locations or by visiting at different times of the day (Klein et al. 2009; Winfree et al. 2018).

Crop yields are enhanced due to both increased richness and total abundance of floral visitors (Dainese et al. 2019). Results from 344 fields in 33 pollinator-dependent crop systems in small and large farms in Africa, Asia and Latin America have found that for smallholder fields (<2 hectares) yield gaps could be closed by a median of 24% through higher flower-visitor density (Garibaldi et al. 2016). Larger fields also experienced yield gaps due to lack of pollination, but increases in yield from enhanced pollinator density only occurred at high flower-visitor richness. Alarms are being raised over the loss of pollinators worldwide, both wild and domesticated (Wagner et al. 2021), driven by agricultural intensification (loss of habitat and pesticide use) and climate change (Garibaldi et al. 2013; Rader et al. 2016; Raven and Wagner 2021).

A1.5 Biological pest control

Crop pests, plant pathogens and weeds collectively affect multiple dimensions of food security, including primary production, stability of production, distribution, quality and nutritive value (Oerke 2006; Savary et al. 2017). Crop losses can be substantial but vary by farming practices, climatic conditions and socio-economic contexts. Recent estimates of actual crop losses due to pests and pathogens for five major crops worldwide (wheat, rice, maize, potatoes and soybean) range from 17% to 30% (Oerke 2006; Savary et al. 2017). Global potential loss due to pests, pathogens and weeds combined vary from 50% in wheat to more than 80% in cotton production (Oerke 2006). The highest potential loss is attributed to weeds (on average 34%), followed by pests (18%) and pathogens (16%) (Oerke 2006). Crop losses are lower in regions that generate food surpluses (e.g. northwest Europe, the United States Midwest, Canada or south Brazil) and higher in food-insecure regions (e.g. sub-

Saharan Africa or the Indo-Gangetic plains) (Savary et al. 2019). Even though pesticides directly limit yield losses due to pests, they also cause increased pest outbreaks because of concomitant impacts on natural enemy communities (Bommarco et al. 2011), evolution of pest resistance to chemical products (Denholm et al. 2002) and emergence of secondary pests (Gross and Rosenheim 2011). Yield losses due to insect pests are projected to increase by 10% to 25% per degree of global mean surface warming, highlighting the urgent need to develop resilient and diversified farming systems better able to cope with pests (Deutsch et al. 2018).

Biological control of pests can be provided by a large range of beneficial organisms including invertebrates (e.g. spiders, wasps, syrphid flies), vertebrates (e.g. bats, birds) and microorganisms (e.g. entomopathogenic fungi). Biological control is directly associated with a diversity of natural enemies (Letourneau et al. 2009; Greenop et al. 2018; Dainese et al. 2019), and maintaining these communities requires the retention of habitat for natural enemies in agricultural lands, diversification of crop production systems and restrictions on the use of broad-spectrum biocides. Fortunately, these strategies can go hand in hand; more diversified cropping systems can reduce the amount of pesticides needed, and thus the cost of these inputs (Davis et al. 2012; Gurr et al. 2016).

A1.6 Crop productivity, sustainability, resilience and adaptive capacity via wild genetic resources

Industrial agricultural systems typically employ crop cultivars bred by plant scientists and distributed via private industry. These varieties are often genetically uniform, and typically display high yield potential under optimal conditions. The trade-off for high yield and conformity to mechanization is increased vulnerability to pests and diseases; low resilience to heat, drought and other abiotic stresses, which are mitigated through frequent turnover of crop varieties (Zhu et al. 2000); and high fertilizer, pesticide and other input requirements. More precise use of nutrients, combined with diversification practices in and around farms, can increase productivity while reducing production costs. The continual development of crop cultivars to keep pace with these challenges is accomplished through the utilization of genetic resources, including crop wild relatives.

Crop wild relatives, the wild progenitors of cultivated plants and related species, provide critically important traits to cultivated crops through plant breeding. Because these wild species have not gone through the bottlenecks of genetic diversity that cultivated crop species have in the course of their domestication, they harbor wild traits that include high resistance to pests and diseases and adaptations to extreme environments (Hajjar and Hodgkin 2007; Dempewolf et al. 2017). As they are close relatives of cultivated crops, their traits can be introduced with relative ease (Tanksley and McCouch 1997), assuming that their diversity is maintained in conservation repositories and available for use (Castañeda-Álvarez et al. 2016). Many crop wild relatives are also collected for direct dietary, medicinal and other cultural uses, and various species represent attractive candidates for development into new crops (Khoury et al. 2020). By maintaining crop diversity in fields and across rotations, farmers can reduce pest and disease outbreaks on crops. Mixing different crops or cultivars together in a field, or using sequences of crops in rotation, can also be designed to improve nitrogen capture, phosphorus delivery and/or the efficiency of nutrient and water use (Isbell et al. 2017). Sequentially rotating different livestock species through fields and orchards can aid both livestock production and pest and disease control. By enhancing natural mechanisms for management of nutrients, pest and diseases, farmers can reduce use of synthetic chemicals and decrease both environmental and human health impacts (Boedeker et al. 2020) that stem from their synthesis and use.

Crop wild relatives occur across the world in a wide range of wild and human-managed habitats, with the richest diversity concentrated in the regions of origin of our most important crops (Khoury et al.

2016), which also generally overlap with global hotspots of biodiversity (Pironon et al. 2020). Because these crops are produced and consumed around the planet, made possible in part by the traits contributed by their wild relatives, the conservation of crop wild relative habitats so that they can continue to evolve in response to climate, pests and other emerging challenges, and their maintenance in conservation repositories where they are widely available for plant breeding, are both essential to the future of productive, sustainable and resilient agriculture.

A1.7 Food security and environmental security are compatible objectives

Assuring food security requires more than high productivity. Sufficient food is currently produced to supply the caloric needs of all humans, yet insufficient diversity is produced to ensure access to a healthy diet. The extent to which diversified cropping systems can contribute to current levels of food production remains an important question, but one that is poorly handled by current modelling efforts.

It is often assumed that chemically intensive, simplified agricultural systems are more productive than diversified systems, but this fails to recognize the range of options available to farmers, including in diversified production systems. Reduced yields from diversified systems are much less common than assumed. In a systematic review of 6,167 original studies, 51% of the yield effects were enhanced in diversified compared to simplified systems, whereas 33% showed no difference and only 16% had reduced yields with diversification (Tamburini et al. 2020). Furthermore the same study, using second-order meta-analysis on a subset of the data (69 meta-analyses, 324 effect sizes, 5,160 original studies), showed that most ecosystem services were significantly improved on more diversified farms, while yields did not differ.

Ecosystem service improvements were found for pollination, pest control, nutrient cycling, water regulation, soil fertility and biodiversity conservation. Only the climate regulation services provided by agriculture did not differ significantly between diversified and less diversified practices. Finally, examining only those meta-analyses that looked simultaneously at the effects of diversification on crop yield and on ecosystem services, the study found that the majority (63%) of effects were positive both for yield and the ecosystem service measured. Thus, this study conclusively demonstrates in three ways that creating more diverse agriculture, through a wide variety of agroecological practices, generally enhances or has a neutral effect on yield, while having a positive effect on one or more ecosystem services. Positive effects were more pronounced when multiple diversification strategies were used together (e.g. field, farm and landscape diversification) (Beillouin et al. 2020).

The question is often framed in terms of *whether* diversified, or regenerative agriculture, can feed the world while staying within environmental limits or regenerating biosphere and ecosystem processes. This may be reframed: *how* can regenerative agriculture be adapted to produce enough nutritious food, be a negative emission technology, and advance the SDGs? Our evidence review finds no evidence that regenerating agriculture and ensuring the production of healthy diets are incompatible. System-based regenerative agriculture reconciles the need to produce adequate and nutritious food with the need to restore ecosystems, making farming a solution to environmental issues rather than a source of degradation. What is missing is research investment in collaborative and co-designed trials with farmers to identify the context-specific bundles of diversification practices to apply, and more importantly, the repurposing of public support to farmers and farms for health, and the sustainability outcomes they generate.

Annex 2: Methodology

In this rapid evidence review, we called on twenty leading biodiversity experts with critical experience in dietary health, agriculture, Earth Systems science and conservation to provide their individual reviews of the evidence on relationships and pathways between agriculture and biodiversity.

A whole-of-food-system approach was adopted that considered diversity in diet and impacts on human health; biodiversity in agriculture and impacts on nature-positive production; and the reduction of agricultural pressures on intact nature. Collectively, these three domains provide a comprehensive consideration of the risk of continued loss of biodiversity in food systems, and by food systems.

Contributing experts were asked to pay particular attention to co-benefits and impacts on key outcomes: (i) climate adaptation, resilience and mitigation; water security; (ii) yields; pest control and pollination; and (iii) dietary health and non-communicable diseases. They were also requested to consider trade-offs or synergies with production, health, environment and economic/livelihood outcomes.

Collectively, we have documented the best available evidence on actions that can be taken to move towards more biodiversity/nature-positive production through the delivery of integrated agricultural solutions on climate, biodiversity, nutrition and livelihoods, addressing challenges and opportunities.

This evidence review acknowledges existing research, and the analysis brings together a large body of evidence, including aspects not typically captured in a stand-alone primary piece of research. The approach and scope of work was developed through regular consultation with the CGIAR Research Programs on Water, Land and Ecosystems and Climate Change, Agriculture and Food Security, and FCDO. Where evidence was limited, the review indicates critical gaps.

Contributing authors, institutional affiliations and contacts are included in Annex 4.

Annex 3: Glossary of key terms

Agricultural biodiversity or **agrobiodiversity** – cultivated and uncultivated species that comprise the foods we eat or those that support food production. Cultivated agrobiodiversity encompasses species intentionally planted or reared by farmers. This diversity draws on tens of thousands of years of farmer selection producing edible species suited to many social and environmental contexts. Non-edible agricultural biodiversity includes a myriad of species, from soil microbiomes to insects, birds and mammals that pollinate crops, regulate pests, absorb excess nutrients from fields and store carbon in soils.

Agricultural diversification – the intentional diversification of food and non-food crops with the intent of improving one or more farm outputs. These are accompanied by a range of diversification practices. Also see *Diversified farming systems*.

Agricultural expansion – the growth in cultivated arable land. It is frequently linked with habitat conversion, typically of native or natural ecosystems including, currently, deforestation. Agricultural expansion, when it encroaches on intact ecosystems, is one of the primary drivers of biodiversity loss. Agricultural expansion is a type of *Land conversion*.

Agricultural landscapes – see *Agroecosystems*.

Agricultural policy – a set of laws regulating agricultural production, including its impact on the environment as well as trade in agricultural goods.

Agricultural practices – the tools and methods used in *Agricultural systems* with the aim or producing a food, fuel, fiber or fodder crop.

Agricultural subsidies – payments or benefits often provided by states to partially offset the cost of agricultural activities, including activities within production, sales and export.

Agricultural systems or **farming systems** – a decision-making unit comprising the farm household, cropping systems and livestock systems, which transforms land, external inputs (seed, pesticides, nutrients, etc.), and labour (including knowledge) into useful products that can be consumed or sold.

Agrochemicals – any chemical substance or mixture of substances used in agriculture, including *Fertilizers* and *Pesticides*.

Agroecology and **agroecological farming** – the study of ecological processes as applied to agricultural production systems. Agroecologists study how biodiversity contributes to the production of food, environmental goods and services, and farmer well-being. Agroecology can also refer to a social movement and a set of principles but in this review is mostly used to refer to the scientific discipline. Agroecological farming practices are those that manipulate biodiversity at the field, farm or landscape scale in order to improve the social, economic, agronomic or environmental outcomes of farming systems while supporting autonomy from external inputs. The field of agroecology is not associated with any one particular method of farming, be it organic, regenerative, integrated, conventional, intensive or extensive. Agroecology is a toolbox comprised of a diversity of tools that can and should be adapted to the context, problem or objective at hand.

Agroecosystems – *Ecosystems* that are converted for agriculture. They comprise polycultures, monocultures and mixed systems, including crop-livestock systems (rice-fish), agroforestry, silvopastoral systems, aquaculture as well as rangelands, pastures and fallow lands. The term emphasizes that agricultural systems, like natural ecosystems, are comprised of communities of species that are subject to ecological interactions including competition, collaboration, predation and herbivory. Agroecology often aims to leverage these processes in support of sustainable food production.

Agroecosystem services – ecosystem services from agricultural biodiversity, including a myriad of species, from soil microbiomes to insects, birds and mammals that pollinate crops, regulate pests, absorb excess nutrients from fields and store carbon in soils. Production practices such as agroforestry, riparian buffers, wild field margins or conservation tillage help to conserve beneficial biodiversity in fields, and these services are managed and secured for food production.

Agroforestry – an agricultural practice whereby woody perennials (trees, shrubs, bamboos, palm trees, woody lianas) are grown on the same land management unit with crops and/or livestock.

Agronomy – the science of crop production and soil management.

Anthropocene – a term increasingly used to define a new planetary era: one in which humans have become the dominant force shaping Earth's bio-geophysical composition and processes.

Aquaculture – the farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants with some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated.

AR^{3}T Framework – the AR^{3}T Action Framework is built on the mitigation hierarchy set out in the International Financial Corporation's (IFC) Performance Standard 6. As currently used, IFC PS6 helps companies plan for and address their impacts on biodiversity at a project level. The AR^{3}T Framework is also built on the conservation hierarchy (from bottom to top: Avoid, Reduce, Restore & Regenerate, and altogether Transform), which expanded the mitigation hierarchy concept to include proactive, positive steps for nature. First and foremost, the aim of the AR^{3}T framework is to regenerate the ecosystem functions and services both from, and to agriculture, while reducing its negative impacts, notably habitat loss and pollution of soil and water.

BII – the Biodiversity Intactness Index (BII) is a high-profile metric of an area's average abundance of wild species relative to that in pre-modern times or in primary vegetation under current climatic conditions. It is one of the nine *Planetary boundaries*.

Biocides – natural or synthetic chemical substances used to kill living organisms.

Biodiversity – biological diversity, or *Biodiversity*, means the diversity of life in all its forms. This includes an organism's genes and its functional characteristics in ecosystems. Biodiversity is a characteristic of ecosystems that makes them more resilient to shocks, safeguarding the basis of human livelihoods.

Biological corridors – areas connecting separated habitats that allow movement to and access by wild species. These spaces make gene flow between isolated populations possible and may ameliorate the negative effects of habitat fragmentation.

Biomes – the highest order classification of biodiversity (e.g. rainforest, tundra). They are defined by broad temperature and precipitation gradients that define their predominant vegetation. Biome scale changes in ecosystem health impact global processes (e.g. loss of forest biomes and climate change). Biomes are comprised of distinct ecoregions, of which more than 700 have been defined by ecologists. Each ecoregion is unique in its composition of biodiversity, irrespective of whether it has many or few species.

Bioreactors – tools or devices for generating products using the synthetic or chemical conversion capacity of a biological system. These can be classical fermenters, cell culture perfusion systems or enzyme bioreactors. For production of proteins or enzymes, recombinant microorganisms such as bacteria, mammalian cells, or insect or plant cells are usually chosen.

Biosphere – the part of Earth occupied by living organisms in which living systems make use of and transform non-living, or abiotic, material, forming one regenerative entity. It is one of the major Earth system components along with the atmosphere, hydrosphere, lithosphere and cryosphere.

Boreal forests – forests growing in high-latitude environments where freezing temperatures occur for 6 to 8 months and in which trees are capable of reaching a minimum height of 5 m and a canopy cover of 10%.

Carbon management – the management of anthropogenic releases of greenhouse gases, such as those associated with the combustion of fossil fuel use, in an effort to mitigate the potential impacts of these emissions on climate systems. In agriculture it particularly considers carbon captured in soils.

Carbon negative, **carbon positive** and **carbon neutral** – because of the positivity of its impact, the term 'carbon positive' is often used as an equivalent to 'carbon negative', meaning that an activity goes beyond achieving net zero carbon emissions ('carbon neutral') by removing additional carbon dioxide from the atmosphere.

Carbon sequestration or **carbon capture** or **carbon storage** – uptake and storage of carbon in a carbon sink, such as the oceans, or a terrestrial sink such as forests or soils, in order to keep it out of the atmosphere. Soils contain the largest dynamic reservoir of carbon on Earth.

CBD – signed by 150 government leaders at the 1992 Rio Earth Summit, the Convention on Biological Diversity (CBD) is dedicated to promoting sustainable development. Conceived as a practical tool for translating the principles of Agenda 21 into reality, the Convention recognizes that biological diversity is about more than plants, animals and microorganisms and their ecosystems – it is about people and our need for food security, medicines, fresh air and water, shelter, and a clean and healthy environment in which to live.

CBD Nagoya Protocol – the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (ABS) to the Convention on Biological Diversity is a supplementary agreement to the Convention on Biological Diversity. It provides a transparent legal framework for the effective implementation of one of the three objectives of the CBD: the fair and equitable sharing of benefits arising out of the utilization of genetic resources. The Nagoya Protocol on ABS was adopted on 29 October 2010 in Nagoya, Japan and entered into force on 12 October 2014. Its objective is the fair and equitable sharing of benefits arising from the utilization of genetic resources, thereby contributing to the conservation and sustainable use of biodiversity.

Climate goals – the Paris Agreement and climate-related Sustainable Development Goals.

Climate adaptation – adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change.

Climate mitigation – anthropogenic interventions to reduce the sources or enhance the sinks of greenhouse gases. In other words, reducing the causes of climate change.

Climate security – access by all, at all times, to an environment where safety is unaffected by climate change, building on the idea that the climate change increases other existing risks. Climate security may imply considerations of national security, international security, human security and ecological security.

Conservation tillage – any of several farming methods that provide for seed germination, plant growth and weed control yet maintain effective groundcover throughout the year and disturb the soil as little as possible. The aim is to reduce soil loss and energy use while maintaining crop yields and quality. No-till is the most restrictive (soil-conserving) form of conservation tillage. Other practices include ridge-till, strip-till and mulch-till.

Crop diversification – the strategy of shifting from less profitable to more profitable crops, changing varieties and cropping systems, increasing exports and competitiveness in both domestic and international markets, protecting the environment, and making conditions favorable for combining agriculture, fishery, forestry and livestock. Crop diversification can be a useful means to increase crop output under different conditions

Crop rotation – a system of cultivation whereby different crops are planted in consecutive growing seasons to maintain *Soil fertility*.

Crop wild relatives – wild plant species that are genetically related to cultivated crops.

Dietary diversity – the number of unique foods, and their proportion, consumed over a given period of time. It is often used as a proxy indicator for *Healthy diets*.

Diversified farming systems – the intentional inclusion of biodiversity at one or multiple spatial (field to landscape) and/or temporal scales (seasons or years) to generate critical ecosystem services to and from agriculture. They represent a form of *Landscape diversification* and can contain, but are not exclusive to *Polycultures*. Also see *Agricultural diversification*.

Earth system and **Earth system processes/functions** – the Earth's interacting physical, chemical and biological processes. The system consists of the land (lithosphere), biodiversity (biosphere), atmosphere, oceans and freshwater systems (hydrosphere) and its frozen component, the poles (cryosphere). It includes the planet's natural cycles — the carbon, water, nitrogen, phosphorus, sulphur and other cycles — and deep Earth processes.

Ecoregions – physical regions that are characterized by their distinct species and communities and are also classified by similar physical characteristics such as climate, meteorological factors, topography, elevation and soil types. There are 782 different ecoregions.

Ecosystems – organizational units of nature consisting of an aggregation of plants, animals (including humans) and microorganisms, along with non-living components of the environment.

Ecosystem services or **ecosystem functions** – the benefits that humans receive from nature. IPBES refers to these as Nature's Contributions to People. They are divided into four categories: *provisioning* (food, water, fibers, timber, medicines), *cultural* (pleasure, emotional sustenance, recuperation), *regulating* (e.g. regulate climate, control floods, assimilate waste, filter pollutants) and *maintaining* (e.g. preserve and regenerate soil, pollinate crops, maintain the hydrological cycle).

Environment – the complex of climatic, soil and biotic factors that act upon an organism or ecological community and ultimately determine its form and survival.

Environmental health – the branch of public health dealing with the control of environmental factors that may affect health, such as the reduction of biological, chemical and physical hazards in the environment.

Environmental regeneration – land renewal through the reclamation of derelict land and environmental improvement. In contrast to *Environmental restoration*, which addresses the restoration of previously damaged or destroyed lands, regeneration aims at adapting to changing conditions and human activity.

Environmental restoration – the intentional management of land and water to return either biodiversity, or environmental variables, back to a proximate prehuman condition. Here we include the return of biodiversity intactness as one of the key objectives of environmental restoration.

Environmental security – access by all people, at all times, to safe external conditions in the form of effective governance, sound management and sustainable use of the natural resources that are vital to human security. Environmental stresses can undermine social and political stability, impede economic development and generate conflict.

Environmental services – See *Ecosystem services*.

Evapotranspiration – the transport of water into the atmosphere from surfaces, including soil (soil evaporation), and from vegetation (transpiration).

Extinction crisis – the current global acceleration of extinction, which is the sixth period of plant and animal mass extinction (over the last 500 million years). Extinction is a phenomenon that occurs naturally; however, it normally happens at a rate of 1 to 5 species every year. Scientists estimate that species are currently lost 1,000-10,000 times faster than that (tens of species every day).

Fertilizers – any organic or inorganic material of natural or synthetic origin that is usually added to soil – but also to foliage or through water in rice systems, fertigation, hydroponics or aquaculture operation – to provide nutrients, including nitrogen, phosphorus and potassium, necessary to sustain plant growth.

Flower strips – a conservation practice specifically geared to the needs of beneficial insects. They can be used as a tool by practitioners wishing to enhance biological pest control in the field.

Food system – a system that embraces all the elements (environment, people, inputs, processes, infrastructure, institutions, markets and trade) and activities that relate to the production, processing, distribution and marketing, preparation and consumption of food and the outputs of these activities, including socio-economic and environmental outcomes.

Food system productivity – see *Systemic productivity*.

Food security – access by all people, at all times, to sufficient food for an active and healthy life. Food security includes at a minimum: the ready availability of nutritionally adequate and safe foods, and an assured ability to acquire acceptable foods in socially acceptable ways.

Flood pulse flow regulation – the management of the lateral exchange of water, nutrients and organisms between a river channel (or a lake) and the connected floodplain. It considers the importance of the hydrology and hydrochemistry of the parent river but focuses on their impact on the organisms and the specific processes in the floodplain.

GHG emissions – discharges of greenhouse gases, such as carbon dioxide, methane, nitrous oxide and various halogenated hydrocarbons into the atmosphere. Combustion of fossil fuels, agricultural activities and industrial processes contribute to the emissions of greenhouse gases, among others.

Global goals – the Sustainable Development Goals, the Paris Agreement and the CBD.

GloPan – The Global Panel on Agriculture and Food Systems for Nutrition (GloPan) works with international, multi-sector stakeholders to help governments in low- and middle-income countries develop evidence-based policies that make high-quality diets safe, affordable and accessible. The Panel is an independent international group of leaders who hold, or have held, high office and show strong personal commitment to improving nutrition. It was formally established in August 2013 at the Nutrition for Growth Summit in London and is funded by the UK Foreign, Commonwealth and Development Office (FCDO).

Grasslands – a land cover class that includes any geographic area dominated by natural herbaceous plants (grasslands, prairies, steppes and savannahs) with a cover of 10% or more, irrespective of different human and/or animal activities (e.g. grazing, selective fire management).

GRI – the Global Reporting Initiative (GRI) is an independent, international organization that seeks to help businesses and other organizations take responsibility for their impacts, by providing them with a common language to communicate those impacts. GRI provides the world's most widely used standards for sustainability reporting – the GRI Standards.

Habitat – the natural environment where an organism, population or community lives, including biotic and abiotic factors.

Habitat conservation or **habitat management** – the preservation, maintenance, protection, restoration and enhancement of habitats for wild species.

Habitat connectivity – the spatial interlinkages between core areas of suitable habitat. It is often focused on the establishment or maintenance of corridors of similar habitat to link core areas, although consideration may be given to the capacity of other habitats to act as conduits for dispersal. *Biological corridors* increase habitat connectivity.

Healthy diets – a diet that is balanced, diverse and contains an appropriate selection of foods eaten over a period of time. A healthy diet ensures that the needs for macronutrients (proteins, fats and carbohydrates including dietary fibers) and essential micronutrients (vitamins, minerals and trace elements) are met, specific to the person's gender, age, physical activity level and physiological state, reducing the risk of developing diet-related diseases.

Hedgerow intercropping or **alley cropping** – a cropping system that involves growing crops in a wide strip, typically 6 meters in width, between lines of closely planted, fast-growing trees or shrubs. These woody species are usually leguminous and are pruned frequently to provide a mulching material and nutrients to the crop in the alley.

Hydrological cycle – water movement from the atmosphere through various stages or processes on the ground (e.g. precipitation, interception, run-off, infiltration, percolation, storage) and then back to the atmosphere by evaporation and transpiration. The water cycle includes the storage and transfer of water through multiple Earth system components including hydrosphere to atmosphere (evaporation), biosphere to atmosphere (transpiration), atmosphere to cryosphere (precipitation of snow and ice), and so on. Climate change is leading to mass disruption of the hydrological cycle through melting of the ice caps; land use change drives mass loss from the biosphere to atmosphere, increasing run-off and evaporation.

Intact nature – the state of an ecosystem's species composition and abundance being unimpaired by post-industrial human activity. BII is a proxy for intact nature, with BII>90 serving as the planetary boundary measure.

IPBES – the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) is an independent intergovernmental body established by states to strengthen the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development. It was established in Panama City in 2012 by 94 governments and is not a United Nations body.

IPCC – the Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. It provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. It was created in 1988 by the World Meteorological Organization and the United Nations Environment Programme with the intention to inform climate policies.

ITPGFA – the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGFA) was adopted by the Thirty-First Session of the Conference of the Food and Agriculture Organization in 2001. Its objectives are the conservation and sustainable use of all plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising out of their use, in harmony with the Convention on Biological Diversity, for sustainable agriculture and food security.

Just Rural Transition – the Just Rural Transition aims to put people at the center of global efforts to transform food and land use systems to meet climate, biodiversity and sustainable development goals. It was launched at the 2019 UN Climate Action Summit.

Land conversion or **land use change** – human activities that change the way land is used. Common examples are *Agricultural expansion* and the growth of cities to include areas previously used for agriculture.

Land degradation – the reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands, resulting from a combination of pressures, including land use and management practices.

Land sharing – sharing space for biodiversity on agricultural lands. Many agricultural diversification practices are examples of land sharing.

Land sparing – halting of the destruction of intact habitats, for example by minimizing *Agricultural expansion*.

Landscape diversification – the creation of fields that contain a variety of food and non-food crops, allowing for high levels of natural habitat and plant diversity and fulfilling various ecosystem services including food production. The term is closely linked to *Polycultures*.

Landscape simplification – the creation of extensive fields of the same crop with few intervening habitat structures at the cost of natural habitat and plant diversity. The term is closely linked to *Monocultures* and is the inverse of *Landscape diversification.*

Livelihood security – access by all people, at all times, to the means necessary for a healthy and dignified livelihood. These resources might consist of individual skills and abilities (human capital); land, savings and equipment (natural, financial and physical capital, respectively); and formal support groups or informal networks that assist in the activities being undertaken (social capital).

Land use regulation or **land use planning** – the systematic assessment of land and water potential, alternative patterns of land use, and other physical, social and economic conditions.

Manure – fertilizer from organic sources such as animal faeces, added to soil to provide the nutrients necessary to sustain plant growth.

Mineralogy – the scientific study of minerals.

Mixed farming – farming practices involving both crop and animal production. A form of diversification.

Monocultures – the cultivation of a single crop in a given area. This practice may initially increase yield efficiency but often drives various risks such as soil degradation, loss of habitat, reductions in water quality and loss of species diversity including loss of between-field cropping diversity and, thereby, decreased pest control.

Mulching – an agricultural practice whereby material (e.g. leaves, bark or compost) is spread around or over a plant to enrich or insulate the soil.

Multifunctional landscapes – see Landscape diversification and Diversified farming systems.

Nature – natural resources such as forests, soil, water and biodiversity in *Ecosystems*. Also see *Intact nature*.

Nature-based solutions – the sustainable management and use of nature for tackling societal challenges, including those in agriculture. Building on and complementing traditional biodiversity conservation and management strategies, nature-based solutions integrate science, policy and practice and create biodiversity benefits through diverse, well-managed ecosystems.

Nature-positive production – a form of food production characterized by a regenerative, biodiversity-positive and non-destructive use of natural resources that builds upon natural and social capital. It is based on biodiversity as the foundation of ecosystem services that humanity depends upon – such as regulating water and climate, supporting nutrient cycling and soil formation; and provisioning food and other raw materials.

Nitrogen – a colorless, odorless unreactive gas that forms about 78% of the Earth's atmosphere. Of all plant nutrients, crops need nitrogen in the greatest quantity. Most of the nitrogen found in soil originated as N_2 gas and nearly all the nitrogen in the atmosphere is N_2 gas. This inert nitrogen cannot be used by the plant until it is converted to ammonium (NH_4 +) or nitrate (NO_3 –) forms. The environmental pollution of rivers, lakes and groundwater through nitrogen fertilizers has long been an issue. Nitrogen as a biochemical flow is one of the nine *Planetary boundaries*. From an Earth Systems perspective, nitrogen pollution is the mass transfer of nitrogen from atmosphere to hydrosphere.

Nitrogen fixation – the process in certain bacteria, fungi and cyanobacteria converting free atmospheric nitrogen to biologically usable (organic) forms of nitrogen, such as ammonia, nitrates and amino compounds. Nitrogen fixation is often achieved through a symbiotic relationship between bacteria and a limited number of plant families, notably legumes.

No-tillage or **zero tillage** – a system of planting crops without tilling the soil (turning it over) with a plow, disk, chisel or other tillage implement.

Nutrient absorption or **nutrient capture** – the uptake and storage of nutrients in soil.

Nutrient leaching – the process of drawing nutrients from soils by the action of percolating liquid.

Nutrient loss – see *Land degradation*.

Nutrition security – access by all people, at all times, to an appropriately nutritious diet coupled with a sanitary environment, including access to safe water and adequate health services and care, in order to ensure a healthy and active life.

OECD – the Organisation for Economic Co-operation and Development (OECD) is an international organization that aims to build better policies for better lives that are characterized by prosperity, equality, opportunity and well-being for all. OECD members are high-income economies with a very high Human Development Index and are regarded as developed countries.

One Health – the concept that the health of animals, the health of people and the viability of ecosystems are linked. It focuses on delivering collaborative, multidisciplinary solutions to complex problems at the animal, human and environmental interface. This approach brings together the strengths of multiple health science professionals including veterinarians, physicians, public health professionals, epidemiologists, ecologists, social scientists, toxicologists and others, working locally, nationally and globally, to attain optimal health for people, domestic animals, wildlife, plants and our environment.

Organic agriculture or **organic farming** – a practice of agricultural production that focuses on production without the use of synthetic inputs and does not allow the use of transgenic organisms. Organic farming aims to sustain the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, while avoiding adverse effects from inputs. According to Organics International (IFOAM), organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. Organic-certified farms are often but not necessarily agroecological.

Organic residue management – management of plant material remaining on the field after harvesting, including leaves, stalks, roots.

Oxbow restoration – the practice of restoring a previously cut-off or destroyed meander bend of the mainstream channel of a river or stream.

Parasitoids – insects that sooner or later kill their hosts, situating their relationship close to predation.

Paris Agreement – a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. Its goal is to limit global warming to well below 2°C, preferably to 1.5° C, compared to pre-industrial levels. The Paris Agreement is a landmark because, for the first time, a binding agreement joins all nations into common cause to undertake ambitious efforts to combat and adapt to climate change.

Pest control or **pest regulation** – all the actions taken to reduce the pest level down to a level where the risk to people, their food and the environment is minimized. It is often mediated by biodiversity and essential for agricultural productivity.

Pesticides and **pesticide resistance** – any substance or mixture of substances intended for preventing, destroying, repelling or mitigating any pest, including *Biocides*. Pesticide resistance is the adaptation of pest species targeted by a pesticide, resulting in decreased susceptibility to the chemicals it contains. Continued use of a single agent, or a group of closely allied agents, increases the probability of pesticide resistance.

Phenology – the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life.

Phosphorus – Phosphorus is abundant in the Earth's crust in the form of phosphates. It is essential to living organisms; organic phosphates are involved in storing energy in cells, and calcium phosphate is a major component of bone. The main commercial use of phosphorus compounds is in fertilizers. As a biochemical flow, it is one of the nine *Planetary boundaries* described as the mass transfer of Phosphorus from a geological stock (geosphere) to water (hydrosphere).

Photosynthesis – the synthesis of carbohydrates from carbon dioxide and water by chlorophyll using light as energy, and producing oxygen.

Planetary boundaries – a set of nine upper limits within which humanity can continue to develop and thrive for generations to come, constituting a safe operating space. The indicators are based on biogeochemistry, and include climate change, biosphere integrity (extinction per million species per year), *BII*, land-system change, freshwater use, biochemical flows (phosphorus, nitrogen), ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and novel entities. Crossing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes.

Planetary health – the health of human civilization and the state of the natural systems on which it depends. As a field, it focuses on interactions between the two.

Pollination and **Pollinators** – the transfer of pollen grains to the plant ovule such that fertilization and seed production can occur. Pollinators are animals that move compatible pollen to a receptive stigma of the same plant species. Three fourths of the world's flowering plants and about 35% of the world's food crops depend on animal pollinators to reproduce.

Polycultures – the rearing or cultivation of two or more types of species in the same physical space at the same time, for food or other purposes.

Prairie strips – a conservation practice that protects soil and water while providing habitat for wildlife on strips of coarse grasses within or along the edges of agricultural fields.

Productivity – the state or quality of being able to produce large amounts of crops or other goods. In modern agriculture this conventionally implies the efficient substitution of natural capital (ecosystems) for labour and produced goods and capital. The contrasting notion of *Systemic productivity* could function as a more sustainable alternative.

Regenerative agriculture – agricultural practices that aim to regenerate ecological processes in agricultural production systems. Attention is currently on 'regenerating' above- and below-ground carbon pools, but regenerative agriculture more broadly refers to the regeneration of ecosystem services on farms, including habitat for wild biodiversity, pollination, pest control and hydrological ecosystem services. Regenerative agriculture often sets specific environmental targets, the achievement of which requires agroecological practices. While there is debate over what agricultural practices are included or excluded, regenerative agriculture lays its focus on achieved outcomes in a specific context.

Riparian buffers – natural landscape features, frequently mandated by law, or supported by conservation payments that, because they lie at the junction of terrestrial and aquatic systems, effectively capture and retain excess nutrients before they enter waterways. The most effective riparian buffers are those that contain a high diversity of plant types (e.g. grasses, shrubs, trees) forming multiple interception barriers. Riparian buffers are particularly interesting for the habitat they create for both aquatic and terrestrial biodiversity, and the safer passage (*Habitat connectivity*) they provide for many species.

Saturated buffers – a buffer that stores water within the soil of the field buffer by diverting drainage water from the control structure (that raises the water table) into shallow perforated drains that run parallel to the ditch. As a result, the water flows through the natural filter of the soil. Research has shown that this practice is effective in controlling nutrient loss and in reducing nitrate transport to downstream water bodies.

Semi-natural habitat – habitat that has been affected directly or indirectly by human activity.

Silvopastoral systems – land use systems that combine the use of forestland or woodland for both wood production and animal production by grazing of the coexisting indigenous forage, or vegetation that is managed like indigenous forage. A form of *Agroforestry*.

Soil carbon – carbon stored in soil in either inorganic or organic form. Soil inorganic carbon consists of mineral forms either from weathering of bedrock or from the reaction of soil minerals with atmospheric carbon dioxide to produce carbonate compounds. Soil organic carbon is present as living or decomposing biological matter. It includes relatively available carbon as fresh plant remains and relatively stable or recalcitrant forms in materials derived from plant remains such as humus and charcoal. Soils contain the largest dynamic reservoir of carbon on Earth.

Soil degradation – the diminishing capacity of the soil to provide ecosystem goods and services as desired by its stakeholders. It is one aspect of *Land degradation*.

Soil fertility – a measure of soil's ability to provide plants with sufficient amount of nutrients and water, and a suitable medium for root development to assure proper plant growth and maturity. The term is closely linked to *Soil health* and *Soil productivity*.

Soil health – the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. In short, it is the capacity of the soil to function.

Soil loss – the removal of soil surface material, mostly caused by erosion. Loss of total soil material can occur through by single soil erosion events including tillage.

Soil management – the strategic planning of all inputs into and outputs from the soil ecosystem so that there is a favorable balance of essential components that constitute the basis of soil's life-support system. Good management of soils assures that mineral elements do not become deficient or toxic to plants, and that appropriate mineral elements enter the food chain.

Soil productivity – the capacity of a soil to produce a certain yield of agricultural crops or other plants using a defined set of management practices.

Spatial planning – the process of analyzing and allocating parts of three-dimensional spaces to specific uses, to achieve ecological, economic and social objectives that are usually specified through the political process.

Streambank stabilization – the prevention of further destruction of streambanks, especially through erosion.

Sustainable Agriculture Intensification – *Agricultural practices* that promote, or at minimum do not cause harm to, the following objectives, consistent with the *Sustainable Development Goals*: increased availability and broad access to affordable, safe and nutritious food (SDG2); improved productivity and efficiency of resource use, with reduced pollution, loss and waste (SDG12); improved natural environment, including climate action and promotion of *One Health* (SDG15, SDG13, SDG3); reduced poverty and increased resilience of livelihoods (SDG1, SDG8); and improved social equity, including reduced gender inequality and social exclusion (SDG10). Rockström *et al.* (2017) define sustainable intensification as adopting practices along the entire value chain of the global food system that meet rising needs for nutritious and healthy food through practices that build social-ecological resilience and enhance natural capital within the safe operating space of the Earth system.

Sustainable agriculture – an integrated system of plant and animal production practices having a site-specific application that will, over the long-term, satisfy human food and fiber needs; enhance environmental quality and the natural resource base upon which the agricultural economy depends; make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance quality of life for farmers and society as a whole.

Sustainable Development Goals – the SDGs are integrated and indivisible goals, defined by the United Nations 2030 Agenda for Sustainable Development, providing a shared blueprint for peace and prosperity for people and the planet, now and in the future. The SDGs are an urgent call for action by all countries – developed and developing – in a global partnership. They were adopted at the 2015 UN Sustainable Development Summit in New York. They recognize that ending poverty and other deprivations should go hand in hand with strategies that improve health and education, reduce inequality and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.

Synthetic inputs – synthetic fertilizers and pesticides, veterinary drugs, genetically modified seeds and breeds, preservatives, additives and irradiation. In contrast to their organic counterparts, their production is based on research in synthetic biology that combines engineering in the formulation, design and building (synthesis) of novel biological structures, functions and systems.

Systemic productivity – this is defined in contrast to conventional notions of *Productivity*, and is measured as the number of people fed healthily and sustainably per unit input. The goal is healthier people and intact ecosystems.

TRASE – a supply chain transparency initiative that aims to transform the understanding of globally traded agricultural commodities. It wants to empower companies, governments and others to address sustainability risks and opportunities by linking supply chain actors to production landscapes across the world.

Tundra – Arctic or subarctic regions where tree growth is limited due to low temperatures, the short growing season and the permanently frozen subsoil. The dominant vegetation consists of grasses, sedges, mosses, lichens, and dwarf shrubs and trees.

UNFCCC – the United Nations Framework Convention on Climate Change (UNFCCC) is an international agreement with near universal membership (197 Parties). It is the parent treaty of the 1997 Kyoto Protocol and the 2015 Paris Agreement. The ultimate objective of all three agreements under the UNFCCC is to stabilize greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system, in a time frame that allows ecosystems to adapt naturally and enables sustainable development.

UNFSS – the United Nations Food Systems Summit (UNFSS) is being held in 2021 as part of the Decade of Action to achieve the Sustainable Development Goals (SDGs) by 2030. The Summit plans to launch bold new actions to deliver progress on all 17 SDGs, each of which relies to some degree on healthier, more sustainable and equitable food systems.

UNCCD – established in 1994, the United Nations Convention to Combat Desertification (UNCCD) is the sole legally binding international agreement linking environment and development to sustainable land management. The Convention addresses specifically the arid, semi-arid and dry sub-humid areas, known as the drylands, where some of the most vulnerable ecosystems and peoples can be found. The new UNCCD 2018-2030 Strategic Framework is the most comprehensive global commitment to achieve Land Degradation Neutrality to build a future that avoids, minimizes and reverses desertification/land degradation and mitigates the effects of drought in affected areas at all levels to achieve a land degradation-neutral world consistent with the 2030 Agenda for Sustainable Development.

Water catchment or **watershed** – a natural division line along the highest points in an area. A catchment area is a hydrological unit. Both terms are typically used interchangeably. Each drop of precipitation that falls into a catchment area eventually ends up in the same river going to the sea if it does not evaporate. Catchment areas are separated from each other by watersheds.

Water cycles – see *Hydrological cycle*.

Water security – the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being and socio-economic development; for ensuring protection against water-borne pollution and water-related disasters; and for preserving ecosystems in a climate of peace and political stability.

Watershed management – the management of all the natural resources of a watershed to protect, maintain or improve its water yields.

Wildlife encroachment – in the context of agriculture, this occurs when wild species such as primates, elephants or big cats cause crop damage or the loss of livestock or human life.

Wild field margins – conservation practices such as *Flower strips* or *Prairie strips* around the margins or edges of fields.

Annex 4: Author teams

Four teams were formed to develop the review, the leadership, core, author and reviewer teams. Meetings were held virtually.

Leadership team: charged with the overall leadership and execution of the project. This team was responsible for communication with FCDO including the drafting of key messages as they emerged. This team has met weekly since the start of the review.		
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Koziell, Izabella	Lead	WLE, Colombo, Sri Lanka
Sidhu, Aman	Project Manager	Independent Consultant
Wirths, Jonathan	Project Support	Independent Consultant

Core team: consisted of the leadership team and five senior experts to determine the focus and direction of the review. They captured the breadth of necessary experts including agronomy, nutrition, biodiversity, (farmer) cost-benefit analysis, policy and meta-analysis/synthesis methods. This group convened in December.	
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Maron, Martine	University of Queensland, Brisbane, Australia
Rumbaitis del Rio, Cristina	World Resources Institute, London, UK
Author team: additional experts who, together with the former groups, were charged with conducting the evidence review. These experts gathered evidence and assisted in identifying key sources of evidence in the published and grey literature. This group have met twice with the core and leadership teams.	
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Jeantet, Florence	One Planet Business for Biodiversity (OP2B)
Loken, Brent	WWF, Global Food Practice
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RESEARCH PROGRAM ON Water, Land and Ecosystems

LED BY: IWMI International Water Management Institute

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CGIAR Research Program on Water, Land and Ecosystems (WLE)

The **CGIAR Research Program on Water, Land and Ecosystems (WLE)** is a global research-for-development program connecting partners to deliver sustainable agriculture solutions that enhance our natural resources – and the lives of people that rely on them. WLE brings together 11 CGIAR centers, the Food and Agriculture Organization of the United Nations (FAO), the RUAF Global Partnership and national, regional and international partners to deliver solutions that change agriculture from a driver of environmental degradation to part of the solution. WLE is led by the International Water Management Institute (IWMI) and partners as part of CGIAR, a global research partnership for a food-secure future.

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