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Food system impacts on biodiversity loss

Three levers for food system transformation in support of nature

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Contents

Summary

- Biodiversity loss is accelerating around the world. The global rate of species extinction today is orders of magnitude higher than the average rate over the past 10 million years.
- The global food system is the primary driver of this trend. Over the past 50 years, the conversion of natural ecosystems for crop production or pasture has been the principal cause of habitat loss, in turn reducing biodiversity.
- Our food system has been shaped over past decades by the 'cheaper food' paradigm. Policies and economic structures have aimed to produce ever more food at ever lower cost. Intensified agricultural production degrades soils and ecosystems, driving down the productive capacity of land and necessitating even more intensive food production to keep pace with demand. Growing global consumption of cheaper calories and resource-intensive foods aggravates these pressures.
- Current food production depends heavily on the use of inputs such as fertilizer, pesticides, energy, land and water, and on unsustainable practices such as monocropping and heavy tilling. This has reduced the variety of landscapes and habitats, threatening or destroying the breeding, feeding and/or nesting of birds, mammals, insects and microbial organisms, and crowding out many native plant species.
- As a major contributor to global greenhouse gas emissions, our food system is also driving climate change, which further degrades habitats and causes species to disperse to new locations. In turn, this brings new species into contact and competition with each other, and creates new opportunities for the emergence of infectious disease.
- Without reform of our food system, biodiversity loss will continue to accelerate. Further destruction of ecosystems and habitats will threaten our ability to sustain human populations. Reform will rely on the use of three principal levers:
  - Firstly, global dietary patterns need to converge around diets based more on plants, owing to the disproportionate impact of animal farming on biodiversity, land use and the environment. Such a shift would also benefit the dietary health of populations around the world, and help reduce the risk of pandemics. Global food waste must be reduced significantly. Together, these measures would reduce pressure on resources including land, through reducing demand.
  - Secondly, more land needs to be protected and set aside for nature. The protection of land from conversion or exploitation is the most effective way of preserving biodiversity, so we need to avoid converting land for

  agriculture. Restoring native ecosystems on spared agricultural land offers the opportunity to increase biodiversity.

  - Thirdly, we need to farm in a more nature-friendly, biodiversity-supporting way, limiting the use of inputs and replacing monoculture with polyculture farming practices.

- These three levers are in part interdependent. Most notably, the protection and setting aside of land for nature and the shift to nature-friendly farming both depend on dietary change, and will become increasingly difficult to achieve if continued growth in food demand exerts ever-growing pressure on land resources.

- The year ahead offers a potentially unique window of opportunity for food system redesign. A series of international summits and conferences will take place in 2021, during which the topic of food systems and biodiversity will be a common thread. Importantly, the UN secretary-general will convene the world's first UN Food Systems Summit (UNFSS) in recognition of the need for a transformation of the food system to improve nutrition security, public health and environmental sustainability.

- In 2021, governments around the world are expected to unlock unprecedented levels of investment to support economic recovery from the COVID-19 pandemic. Efforts to set in motion a 'green recovery' will bring questions of sustainability, equity and societal resilience to the fore, creating new opportunities for joined-up policymaking that affords equal priority to public and planetary health.

- In light of these opportunities, this paper recommends action on three fronts if efforts to establish a biodiversity-supporting food system are to be advanced in 2021:

  - International decision-makers need to recognize the interdependence of supply-side and demand-side action. Dietary change and a reduction in food waste are critical to breaking the system lock-ins that have driven the intensification of agriculture and the continued conversion of native ecosystems to crop production and pasture.

  - Stakeholders leading on the design and delivery of the UNFSS must ensure that it embeds a 'food systems approach' across other key international processes, including UN climate negotiations. The summit should aim to bring together the interdependent policy threads of environmental sustainability, inclusive prosperity, sustainable growth, and improved public health and well-being.

  - International and national decision-makers need to strengthen the coherence between global agreements and national-level action. National dialogues are needed to translate global commitments into action on the ground. At the same time, national accounting frameworks will be key to building understanding of the value of biodiversity, and to supporting biodiversity protection. Global guidelines in policy areas such as responsible investment, dietary change and nature-based climate change mitigation solutions will be needed to guide national-level action plans that can collectively deliver transformative change to the global food system.

01

Introduction

Biodiversity, crucial to human and planetary health, is declining faster than at any time in human history. Agriculture is driving this trend, making food system reform an urgent priority.

Humanity relies on the earth's natural systems to regulate the environment and maintain a habitable planet. The diversity of life – biodiversity[1] – in any given region creates ecosystems of interacting individual organisms, across many species, that collectively contribute to and support key planetary processes. For example, terrestrial and marine ecosystems remove more than half (60 per cent) of carbon emissions from the atmosphere every year,[2] and thus play a crucial role in regulating the earth's surface temperature. Ecosystems help buffer the impacts of adverse weather and provide resilience to climate change. The earth's naturally occurring ecological processes sustain the quality of the air, water and soils that humanity depends on.[3] In addition to providing basic life-enabling conditions, ecosystems are a source of many products vital for survival, including food, fuel, fibre, medicines and shelter. Together, the above processes and goods are known as 'ecosystem services' or 'nature's contributions to people'.

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[1] Biodiversity is defined as follows: 'The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part. This includes variation in genetic, phenotypic, phylogenetic, and functional attributes, as well as changes in abundance and distribution over time and space within and among species, biological communities and ecosystems.' Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (undated), 'Glossary: Biodiversity', https://ipbes.net/glossary/biodiversity (accessed 2 Nov. 2020).

[2] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R. R., Shin, Y. J., Visseren-Hamakers, I. J., Willis, K. J. and Zayas, C. N. (eds), Bonn, Germany: IPBES Secretariat, https://ipbes.net/sites/default/files/2020-02/ipbes_global_assessment_report_summary_for_policymakers_en.pdf (accessed 2 Nov. 2020).

[3] Ibid.

Food production systems require a diverse range of plants, animals, bacteria and fungi, both for the direct supply of food and to sustain the underlying ecosystem processes that make agriculture possible – from water supply to soil fertility enhancement, pollination[4] and natural pest control.

Beyond food, humanity benefits in a myriad of ways from biodiversity in the environment. While the value is difficult to quantify in monetary terms, biodiversity has clear positive impacts on quality of life through both physical and psychological experiences – via nature as an aid to exercise and discovery, for example, or as a source of education and inspiration.[5] Exposure to natural spaces and access to the richness of animal and plant species around us are associated with positive outcomes for well-being and mental health,[6] even in urban settings.[7] One study estimated the annual monetary value of protected areas, in terms of their positive impact on the mental health of visitors to them, to be much greater than the value of protected-area tourism, and far in excess of the combined budgets of global protected-area management agencies.[8] The 'planetary health' concept underlines the intrinsic links between humanity's well-being and the health of the global ecosystem, and the need to ensure the vitality of ecosystems essential for our survival.

1.1 Trends in biodiversity loss

Despite increasing recognition of the crucial role of biodiversity in maintaining human and planetary health, biodiversity is declining faster than at any time in human history, and perhaps as fast as during any mass extinction.[9] Especially over the past 50 years, biodiversity has been severely compromised and altered at an unprecedented rate.[10] The global rate of species extinction is at least tens and possibly hundreds of times higher than the average rate over the past 10 million years.[11] Around a quarter of species in most animal and plant groups are already under threat from extinction, and around 1 million more species face extinction within decades.[12] In total, the extent and condition of natural ecosystems have declined on average by around 50 per cent relative to their earliest estimated states. Since 1970, the population sizes of mammals, birds, fish, amphibians and reptiles

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[4] The contribution of insect pollination alone to crop production has been estimated to be worth as much as €577 billion globally each year. See Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J. and Vanbergen, A. J. (2016), 'Safeguarding pollinators and their values to human well-being', *Nature*, 540: pp. 220–29, doi: 10.1038/nature20588 (accessed 14 Sep. 2020).

[5] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*

[6] White, M. P., Alcock, I., Grellier, J., Wheeler, B. W., Hartig, T., Warber, S. L., Bone, A., Depledge, M. H. and Fleming, L. E. (2019), 'Spending at least 120 minutes a week in nature is associated with good health and wellbeing', *Scientific Reports*, 9(7730), doi: 10.1038/s41598-019-44097-3 (accessed 2 Nov. 2020).

[7] Marselle, M. R., Martens, D., Dallimer, M. and Irvine, K. N. (2019), 'Review of the Mental Health and Well-being Benefits of Biodiversity', *Biodiversity and Health in the Face of Climate Change*, Cham, Switzerland: Springer, doi: 10.1007/978-3-030-02318-8_9 (accessed 2 Nov. 2020); and Dean, J., van Dooren, K. and Weinstein, P. (2011), 'Does biodiversity improve mental health in urban settings?', *Medical Hypotheses*, 76(6): pp. 877–80, doi: 10.1016/j.mehy.2011.02.040 (accessed 2 Nov. 2020).

[8] Buckley, R., Brough, P., Hague, L., Chauvenet, A., Fleming, C., Roche, E., Sofija, E. and Harris, N. (2019), 'Economic value of protected areas via visitor mental health', *Nature Communications*, 10(5005): doi: 10.1038/s41467-019-12631-6 (accessed 2 Nov. 2020).

[9] Ceballos, G., Ehrlich, P. R. and Raven, P. H. (2020), 'Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction', *Proceedings of the National Academy of Sciences*, 117(24): 13596–13602, doi: 10.1073/pnas.1922686117 (accessed 2 Nov. 2020).

[10] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*

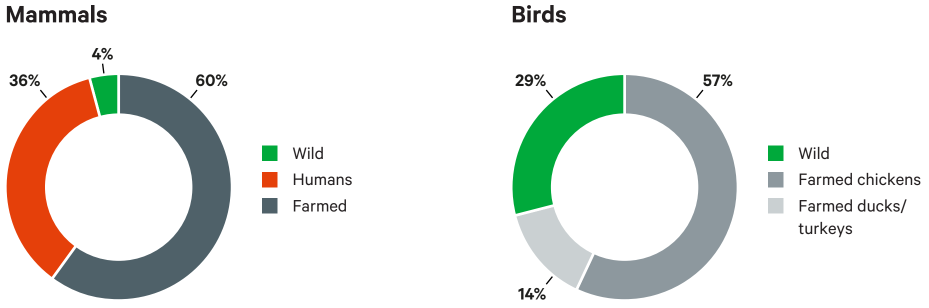
[11] Ibid.

[12] Ibid.

have declined by an estimated average of 68 per cent.[13] Despite the increasingly urgent need to reduce biodiversity loss, recent attempts to arrest the decline have been unsuccessful.[14]

Biodiversity loss applies within agriculture as well as to wildlife: many domesticated plant and animal species that have historically been food sources are becoming less widely consumed. This loss of genetic diversity makes food systems (defined in Box 1, below) less resilient to threats, including pests, pathogens, extreme weather and climate change, thereby threatening global food security.[15]

Figure 1. Distribution of global biomass across all mammals and birds



Source: Bar-On, Y. M., Phillips, R. and Milo, R. (2018), 'The biomass distribution on Earth', *Proceedings of the National Academy of Sciences of the United States of America*, 115(25): pp. 6506–11, doi: 10.1073/pnas.1711842115 (accessed 2 Nov. 2020).

1.2 Food systems as a driver of biodiversity loss

The production of food is the primary cause of biodiversity loss globally. On land, the conversion of land for agriculture and the intensification of agriculture reduce the quality and quantity of habitat available. Food production also has negative impacts on freshwater wildlife[16] (through water extraction and the reduction in water quality resulting from soil and farm chemical run-off). Downstream pollution, especially from fertilizers, also damages marine systems. The wildlife of marine systems is also heavily affected by fishing and in various ways by fish and shellfish farming.

Over the past 50 years, the biggest driver of habitat loss has been the conversion of natural ecosystems for crop production or pasture.[17] The area of land occupied by agriculture has increased by around 5.5 times since 1600 and is still increasing. Currently, cropping and animal husbandry occupy about 50 per cent of the world's habitable land (see Figure 2).[18]

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[13] Almond, R. E. A., Grooten, M. and Petersen, T. (eds) (2020), *Living Planet Report 2020: Bending the curve of biodiversity loss*, Gland, Switzerland: WWF, https://livingplanet.panda.org/en-gb (accessed 2 Nov. 2020).
[14] Convention on Biological Diversity (CBD) (2020), *Global Biodiversity Outlook 5: Humanity at a crossroads*, https://www.cbd.int/gbo5 (accessed 2 Nov. 2020).
[15] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*.
[16] We use the term 'wildlife' to refer to wild – non-domesticated – plants and animals (including fungi and microbes) that contribute to the biodiversity in a place.
[17] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*.
[18] Ritchie, H. and Roser, M. (2019), 'Land Use', Our World in Data, September 2019, https://ourworldindata.org/land-use (accessed 4 Dec. 2020).

The rapid expansion of animal farming has been behind much of this land expansion. Since 1970, the collective weight of wild mammals has declined by 82 per cent, and indicators of vertebrate abundance have shown rapid decline.[19] Instead of wild animals, a small number of farmed animal species (mainly cows and pigs) now dominate global biomass. Together, they account for 60 per cent of all mammal species by mass, compared to 4 per cent for wild mammals and 36 per cent for humans. Farmed chickens now account for 57 per cent of all bird species by mass, whereas wild birds make up 29 per cent of the total (Figure 1).[20] Animal farming now occupies 78 per cent of agricultural land globally (Figure 2).

Converting land to agriculture results in habitat destruction and biodiversity loss because the clearance of natural ecosystems, such as forests, removes the sources of shelter and food that wildlife species depend on to survive and thrive. According to the ‘Red List’ maintained by the International Union for Conservation of Nature (IUCN), agriculture is an identified threat to 24,000 of the 28,000 species so far documented by IUCN as at risk of extinction.[21] In marine ecosystems, fishing is the largest driver of biodiversity loss.

Even the most wildlife-friendly farming systems are less effective at supporting biodiversity than pristine or unmanaged ecosystems are. Although the impacts on wildlife differ from one farming method to another, the intensification of agricultural production has been the most damaging in recent decades in some regions. Intensification is defined as increasing the outputs through using more inputs. Inputs can be pesticides, herbicides, fertilizers, equipment, land (e.g. amalgamating fields or land conversion) or other processes such as allowing grazing farmed animals to degrade the land.[22] Through reductions in the availability and quality of wild food sources, water and habitat, these factors (explored in more depth in the following chapters) limit the ability of wildlife to live in a farmed environment.

Indirectly, the food system also drives biodiversity loss through its contribution to climate change. The global food system is responsible for more greenhouse gas (GHG) emissions than any other aspect of our lives.[23] Climate change affects biodiversity by changing habitat suitability. This causes sensitive species to die out, or prompts them to move to new locations as other species move in. As natural ecosystems lose and gain species in response to climate change, the resilience of whole ecosystems is affected.[24]

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[19] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*

[20] Bar-On, Y. M., Phillips, R. and Milo, R. (2018), ‘The biomass distribution on Earth’, *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, 115(25): pp. 6506–11, doi: 10.1073/pnas.1711842115 (accessed 2 Nov. 2020).

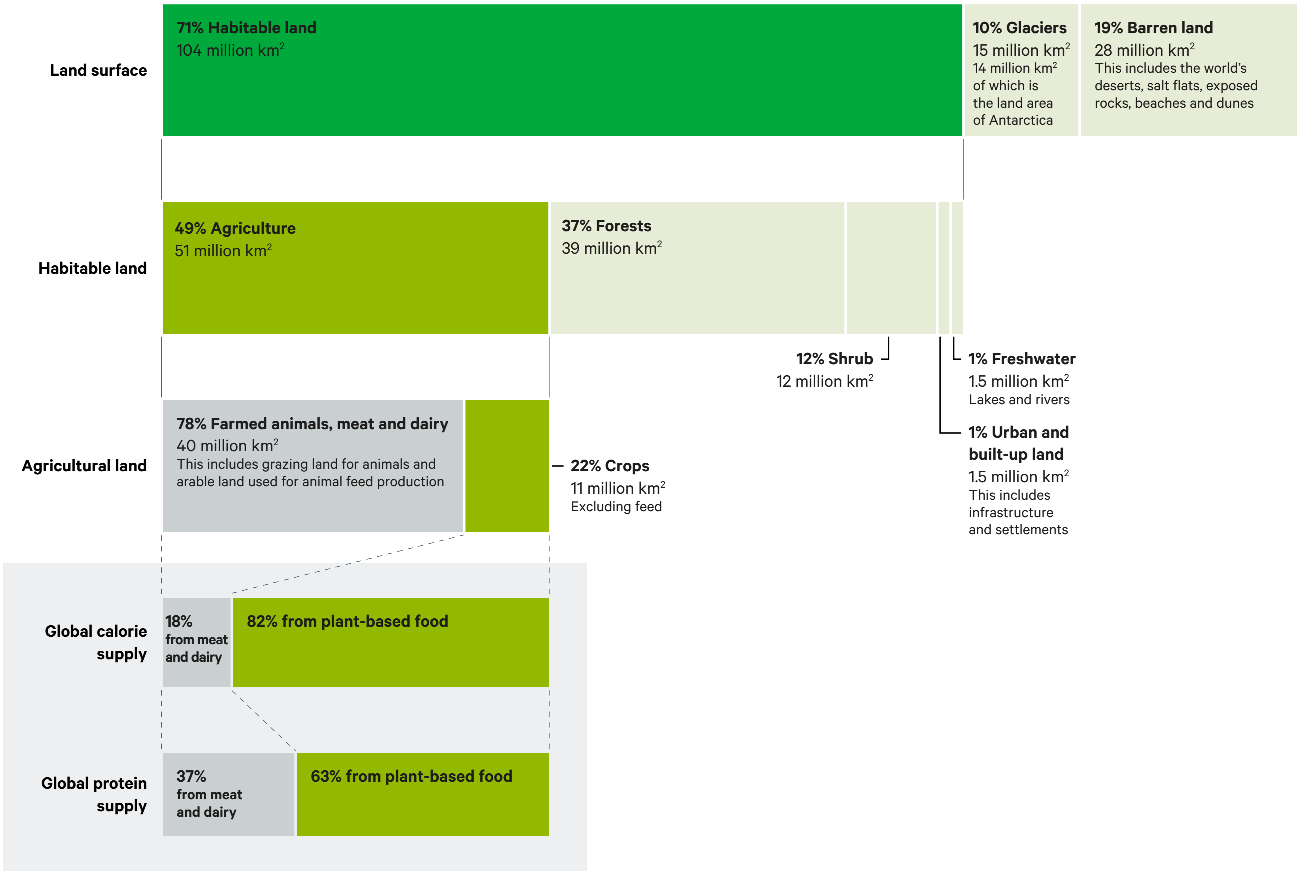
[21] Ritchie, H. and Roser, M. (2019), ‘Environmental impacts of food and agriculture’, Our World in Data, September 2019, https://ourworldindata.org/environmental-impacts-of-food#environmental-impacts-of-food-and-agriculture (accessed 4 Dec. 2020).

[22] Conversely, ‘extensification’ of farming is the opposite of intensification. It is the process of decreasing the use of capital and inputs relative to land area. Due to a decrease in inputs relative to land area, the pressure on the environment may be decreased under extensive farming, and more biodiversity supported. This typically comes at the expense of yields and native ecosystems. The term can be used ambiguously: sometimes the ‘extensification of agriculture’ is about bringing more land into agriculture, even if that land is farmed intensively.

[23] This includes direct emissions from agricultural production, indirect emissions from land-use change, and emissions from transport and energy used along the food supply chain.

[24] Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., Pandolfi, M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J. B., Strugnell, J. M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villaneuva, C., Wernberg, T., Wapstram, E. and Williams, S. E. (2017), ‘Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being’, *Science*, 355(6332): 10.1126/science.aai9214 (accessed 2 Nov. 2020).

Figure 2. Global land 'foodprint'



Source: Ritchie, H. and Roser, M. (2019), 'Land Use', Our World in Data, September 2019, https://ourworldindata.org/land-use (accessed 4 Dec. 2020).

All in all, our food system is the major factor underpinning reductions in the population sizes of wild species of animals and plants, and the erosion of biodiversity, from the local level to the global level.

1.3 Food system-driven biodiversity loss and global health: the case of COVID-19

The impacts of animal farming, and of removing and fragmenting natural habitats, are not limited to biodiversity loss – the wider risks to human health have been brought into sharp focus by the COVID-19 pandemic. COVID-19 is a 'zoonotic' disease, meaning that it originated in non-human animals and passed over to humans. It is the latest in a series of emerging infectious diseases (EIDs) to have reached epidemic or pandemic levels over recent decades; the majority of these EIDs have come from wild or farmed animals.[25] Novel zoonoses are a predictable consequence of new and close contact between species caused by the expansion

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[25] Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L. and Daszak, P. (2008), 'Global trends in emerging infectious disease', *Nature*, 451(7181): pp. 990–93, doi: 10.1038/nature06536 (accessed 2 Nov. 2020).

of agricultural land into natural ecosystems.[26] Coupled with the disruptive impacts of climate change, these forces destabilize ecosystems and give rise to new mixing between wild animals (including predators and prey, as well as their pests, parasites and pathogens), farmed animals and humans, allowing pathogens to move between species in new ways.[27]

For example, pathogens are increasingly jumping the species barrier into humans from wild animals, 'bushmeat'[28] and farmed animals. The impacts of COVID-19 – both those experienced already, and those expected to follow as the pandemic evolves – demonstrate the magnitude, range and severity of the potential fallout from new interrelationships between humans and the food system, and from our intrusion on natural ecosystems. All this demonstrates that the risks to human well-being and natural ecosystems from our current food system are already being realized.[29]

1.4 This research paper

This paper focuses on the global food system and the subsystems (or 'food systems') within it as drivers of biodiversity loss, and on the need and opportunities for food system transformation to protect biodiversity and deliver improvements across the planetary health spectrum, including to human health and well-being. Chapter 2 outlines the multiple ways in which food production drives biodiversity loss, exploring the impacts on land, climate and wildlife at both local and systemic levels. Chapter 3 introduces the concept of three interrelated food system 'levers' that will affect future biodiversity: (1) potential changes in patterns of demand for food; (2) the degree to which we protect and restore natural ecosystems; and (3) actions to increase biodiversity on agricultural land. These can also be framed as three questions: How much and what types of food do we need? How much land do we spare for biodiversity? Can we farm in nature-friendly ways? Chapter 4 considers the implications of the three conceptual levers for broader policy agendas – notably biodiversity conservation, climate change mitigation and improved global nutrition. It looks forward to the rest of 2021 and identifies opportunities to protect biodiversity and restore degraded ecosystems.

A concluding technical annex (Chapter 5) provides more in-depth exploration of the impacts of food production on biodiversity at multiple scales, giving the details that underpin the discussions in Chapters 2 and 3 and offering further information on key avenues for food system transformation.

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[26] IPBES Workshop on Biodiversity and Pandemics.
[27] Brooks, D. R. and Boeger, W. A. (2019), 'Climate change and emerging infectious diseases: Evolutionary complexity in action', *Current Opinion in Systems Biology*, 13: 75–81, doi: 10.1016/j.coisb.2018.11.001 (accessed 2 Nov. 2020).
[28] Defined as meat from wild animals that are killed and taken from their habitats for human consumption.
[29] IPBES Workshop on Biodiversity and Pandemics.

02

How today's food system drives biodiversity loss

The 'cheaper food paradigm' has driven the expansion of agricultural land and intensive farming. Failure to account for the environmental cost of food production has led to habitat destruction and pollution, driving wildlife loss.

The role of our food system as the principal driver of biodiversity loss has been shaped by decades of economic growth that has in part been supported by, and in part incentivizes, increased food production. This trend also reflects a lack of consideration of the true costs of food production. The drive for increased productivity, and failure to account for the impacts of food production on natural ecosystems and human health, have created and sustained vicious circles that make up what we describe as the 'cheaper food' paradigm.

2.1 Vicious circles in our food system

Investment in agricultural productivity, coupled with increased economic competition through the liberalization of trade, has long been considered central to a functioning food system (Box 1). For many, food production is a natural and necessary use of land: people need food, and they depend on the use of land to produce it. Similarly, efforts to reduce food prices are often deemed both desirable and necessary: lower food prices deliver two nominal public goods, in the form of increased access to food (and therefore greater food security, locally and globally) and reduced household expenditure on food (which in turn frees up income for spending on other goods and services, driving consumption, job creation and economic growth).

These key tenets – that we must produce more food and do so at lower cost if we are to support the global population and drive economic growth – have taken primacy over the goals of delivering human and planetary health and well-being, with increasingly problematic side-effects. While it is possible to boost economic growth through productivity improvements, this has typically relied on 'externalizing' the costs of such improvements on to the environment. In other words, the costs of environmental degradation resulting from food production have not been accounted for and included in the cost of food. Financial incentives such as agricultural subsidies are channelled into the food system to increase yields, and the resulting environmental costs – such as pollution through unsustainable production practices – are discounted or ignored by the market.

As mentioned, reducing food prices through increased productivity can stimulate growth in consumer spending, since it increases the amount of disposable income available to buy other goods and services. It also allows consumers to buy more food. Either way, this leads to negative consequences from a planetary health viewpoint: the more disposable income we have, the more we can purchase; the more we can purchase, the more we consume; the more we consume, the more resources we exploit; and the more resources we exploit, the more we drive environmental degradation and disrupt natural ecosystems.

Box 1. Defining a 'food system'

The term '**food system**' encompasses the entirety of the production, transport, manufacturing, retailing, consumption and waste of food. It also includes impacts on nutrition, human health and well-being, and the environment. Food security is a function of variations in the food system in any given location, and is influenced by a range of sociopolitical factors affecting price, availability and access. While there is an overall global food system (encompassing the totality of production and consumption), there are also many subsystems within it. Each location's individual food system is unique, and is defined by that location's mix of food produced locally, nationally, regionally or globally.

For each product consumed there is a **supply chain**, which describes the way food and its ingredients get to consumers. The term **value chain** describes the mechanisms through which the value of a product is increased by transport, processing and packaging along the supply chain. The term 'food system' includes all supply chains (and, implicitly, value chains) as well as their impacts on the environment and people. Food systems inherently incorporate feedback, leading to direct and indirect effects; in turn, this can create feedback loops wherein the system responds in unexpected ways to small changes in the forces acting on it. Food systems are therefore dynamically changing systems; thinking only about supply chains and value chains, for instance, is unhelpful both analytically and for policymaking, as it avoids consideration of wider system dynamics.

All activities within a food system – whether production, processing, retail or cooking – have impacts on the environment. For example, land under agriculture is disturbed from its natural state, which affects soils, water, biodiversity and even local microclimates. Processing, transport and retail require energy, water, infrastructure (e.g. roads) and other inputs – e.g. packaging. Throughout, pollution comes from chemical usage and disposal (e.g. from fertilizers, pesticides, industrial processes and GHG emissions), as well as from the disposal of waste, including plastics and other packaging.

2.2 The 'cheaper food' paradigm

Underpinning the 'cheaper food' paradigm is a two-way relationship between supply and demand. On the one hand, demand can be seen to shape supply: as the so-called 'nutrition transition' around the world has shown, rising incomes tend to prompt greater consumption of resource-intensive foods such as animal products, vegetable oils and processed goods, and relatively lower consumption of staple grains. But demand for food – what we eat, how much we eat, and what we waste – is just as much shaped by its supply and price. The more we produce, the cheaper food becomes, and the more we consume. Demand therefore does not simply determine what food is grown and how. It can also be understood as a function of increased supply of cheaper food, and of the way food is processed, marketed and sold. Understanding this relationship between supply and demand is critical to understanding how the current food system drives biodiversity loss, and to identifying effective levers for moving towards a system that supports biodiversity protection and other components of planetary health.

The 'cheaper food' paradigm drives a set of overlapping and often self-reinforcing mechanisms, in which the ratcheting up of production and liberalization of global markets incentivize economic behaviour that creates negative outcomes for society and the environment.[30] These mechanisms include the following (also see Figure 3):

- A drive towards globally competitive markets incentivizes land use for food production at increasing intensity and scale, because the financial rewards are high. The global production system is based on comparative advantage, and thus specialization, with the result that global calorie production is concentrated around a limited set of commodity crops grown using highly intensive methods in a small number of breadbasket regions.[31]
- Intensive farming has a range of negative consequences for the health and quality of soils, air, water sources and natural ecosystems. Partly, this arises from the use of inputs such as pesticides and nutrients, and partly it

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[30] Benton, T. G and Bailey, R. (2019), 'The paradox of productivity: agricultural productivity promotes food system inefficiency', *Global Sustainability*, 2(e6), doi: 10.1017/sus.2019.3 (accessed 2 Nov. 2020); and McElwee, P., Turnout, E. Chiroleu-Assouline, M., Clapp, J., Isenhour, C., Jackson, T., Kelemen, E., Miller, D. C., Rusch, G., Spangenberg, J. H., Waldron, A., Baumgartner, R. J., Bleys, B., Howard, M., Mungatana, E., Ngo, H., Ring, I. and Ferreira dos Santos, R. (2020), 'Ensuring a Post-COVID Economic Agenda Tackles Global Biodiversity Loss', *One Earth*, ISSN: 2590-3322, Vol: 3, Issue: 4, pp. 448–61, doi: https://doi.org/10.1016/j.oneear.2020.09.011 (accessed 6 Nov. 2020).

[31] Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D. and Zaks, D. P. M. (2011), 'Solutions for a cultivated planet', *Nature*, 478: pp. 337–42, doi: 10.1038/nature10452 (accessed 24 Jun. 2019).

is a function of the prevalence of 'monocultural landscapes' in which there is little opportunity for nature. In turn, the loss of biodiversity and soil fertility leads to a need to intensify agriculture further.

- The concentration and intensification of agriculture have driven down the cost of staples such as grains, which are now sufficiently cheap to be diverted from direct human consumption to farmed animals. This has led to growth in the global herd of farmed animals, with negative consequences for air and water quality and GHG emissions.[32]
- Cheaper calories from staple crops have become increasingly abundant, while more nutritious crops have become more expensive and relatively less available. At the same time, the costs of producing and consuming meat have fallen. These trends have together led to a rapid change in global diets, including an increase in overconsumption of calories and underconsumption of nutrients that has resulted in a global 'double burden' of malnutrition.
- As food prices have fallen, it has become increasingly economically rational to waste food.[33] Waste is now occurring at scale along supply chains, creating additional sources of pollution and resulting in 'leakage' of the finite resources – including land, water and soil – involved in food production. The more prices fall, the more food we demand and the more we waste; and the more food we waste, the more we demand.
- As per capita availability of food, including meat, has increased, GHG emissions from the food system (both direct emissions from food production and farmed animals, and indirect emissions from the conversion of natural ecosystems to cropland and pasture) have risen. The global food system now accounts for around 30 per cent of total anthropogenic emissions and is a key driver of climate change.[34]
- Climate change is reducing crops' yields and nutritional quality across many producing regions,[35] thereby further increasing the pressure to intensify production or convert more land to agriculture.
- As GHG emissions continue to rise, there is an increasing need to sequester carbon in the land as a means of mitigating climate change, including through bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation.[36] However, these strategies increase competition for land, further increasing incentives to intensify farming methods or expand agricultural production into new areas.

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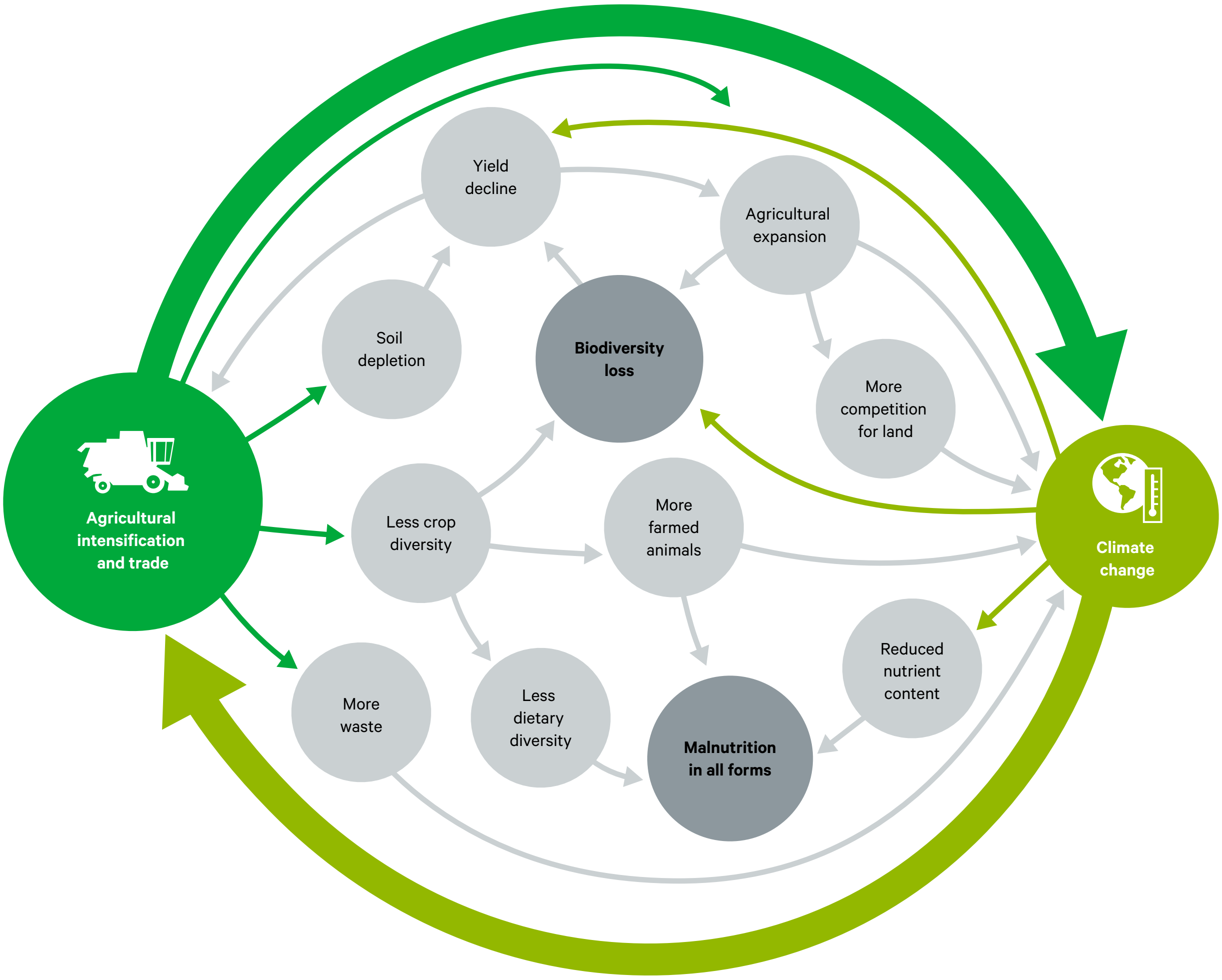
[32] Intergovernmental Panel on Climate Change (IPCC) (2019), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds), https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf (accessed 2 Nov. 2020).
[33] Benton and Bailey (2019), 'The paradox of productivity: agricultural productivity promotes food system inefficiency'.
[34] IPCC (2019), *Climate Change and Land.*
[35] Ibid.
[36] Ibid.

Figure 3. The 'cheaper food' paradigm



Source: Authors' original diagram.

Box 2. The 'cheaper food' paradigm and food and nutrition security

Determining the 'true cost' of food, and the need to reflect this in food prices, is a contentious issue. 'Internalizing' the environmental and social costs of food production through measures such as a carbon tax is seen by many as regressive, threatening to disproportionately harm lower-income households and the poorest communities. Across low-, middle- and high-income countries alike, economic insecurity is closely linked to food insecurity. For this reason, proposals to move away from the 'cheaper food' paradigm could be viewed as counterproductive for food security.

In reality, the relationship between economic insecurity and food insecurity is more complicated. In high-income countries, and increasingly across the developing world, the cheapest foods are often those that are calorie-dense but nutritionally poor.[37] Fresh whole fruits and vegetables tend to be more expensive and less readily available to those living

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[37] Drewnowski, A. (2018), 'Nutrient density: addressing the challenge of obesity', *British Journal of Nutrition*, 120(S1): pp. S8–S14, doi: 10.1017/S0007114517002240 (accessed 20 Sep. 2020); and Benton, T. (2016), 'The many faces of food security', *International Affairs*, 92(6): pp. 1505–15, doi: 10.1111/1468-2346.12755 (accessed 14 Sep. 2020).

in deprived communities, whether in advanced economies or low-income countries.[38] Low prices for calorie-dense, nutritionally poor foods – the supply of which is incentivized by the 'cheaper food' paradigm – encourage low-income households to follow a nutritionally suboptimal diet. The result has been a rapid rise in the incidence of overweight and obesity alongside continued micronutrient deficiency (also known as 'hidden hunger').[39] The twin burdens of malnutrition – undernutrition co-occurring with cheap calories driving obesity – are increasingly an issue for low-income countries as well as high-income ones.[40]

Low food prices are not invariably a negative outcome of the food system; indeed, in regions with high levels of household economic insecurity, including communities where subsistence farming has traditionally been a lifeline but no longer offers a viable livelihood, low food prices are critical to food and nutrition security. It is perfectly possible to imagine food systems that do not 'externalize' costs on to the environment, and where food prices are subsidized directly for the vulnerable. But food systems that ignore the costs to the environment, or the costs to human health and nutrition, merely encourage unhealthy diets lacking in nutrition while undermining the capacity of communities and natural ecosystems to produce sufficient and nutritious food over time. This creates a risk of increased food and nutrition insecurity in the longer term.

Accounting for the true cost of food is thus necessary if incentives in the system are to be realigned to promote environmental and human well-being. Where this results in higher food prices, complementary policies will be needed to mitigate the risk of income-driven food insecurity. These measures could include the payment of a mandatory fair wage, the provision of social safety nets to vulnerable households, and subsidies to support the consumption of healthy and sustainable foods.[41]

2.3 How the 'cheaper food' paradigm drives biodiversity loss

What an understanding of the 'cheaper food' paradigm illustrates is that it is not agriculture *per se*, nor any particular agricultural practice, that drives biodiversity loss; nor is it the inherent need to feed a growing number of people that does so. Instead, a combination of factors (see Figure 4) is responsible: the way in which food is produced and used; the types of food produced; the way in which supply, demand and price interact to drive agriculture; and the privileging of productivity growth over the sustainable use of finite resources. Our current food system is structured to drive demand, leading to biodiversity loss through (1) the continued conversion of natural or semi-natural ecosystems to managed ones, and (2) the use of unsustainable agricultural practices at farm level, landscape level and global level.[42]

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[38] Popkin, B. M. (2019), 'Rural areas drive increases in global obesity', *Nature*, 569: pp. 200–01, doi: 10.1038/d41596-019-01182-x (accessed 14 Sep. 2020); and Malik, V. S., Willett, W. C. and Hu, F. B. (2013), 'Global obesity: trends, risk factors and policy implications', *Nature Reviews Endocrinology*, 9: pp. 13–27, doi: 10.1038/nrendo.2012.199 (accessed 14 Sep. 2020).

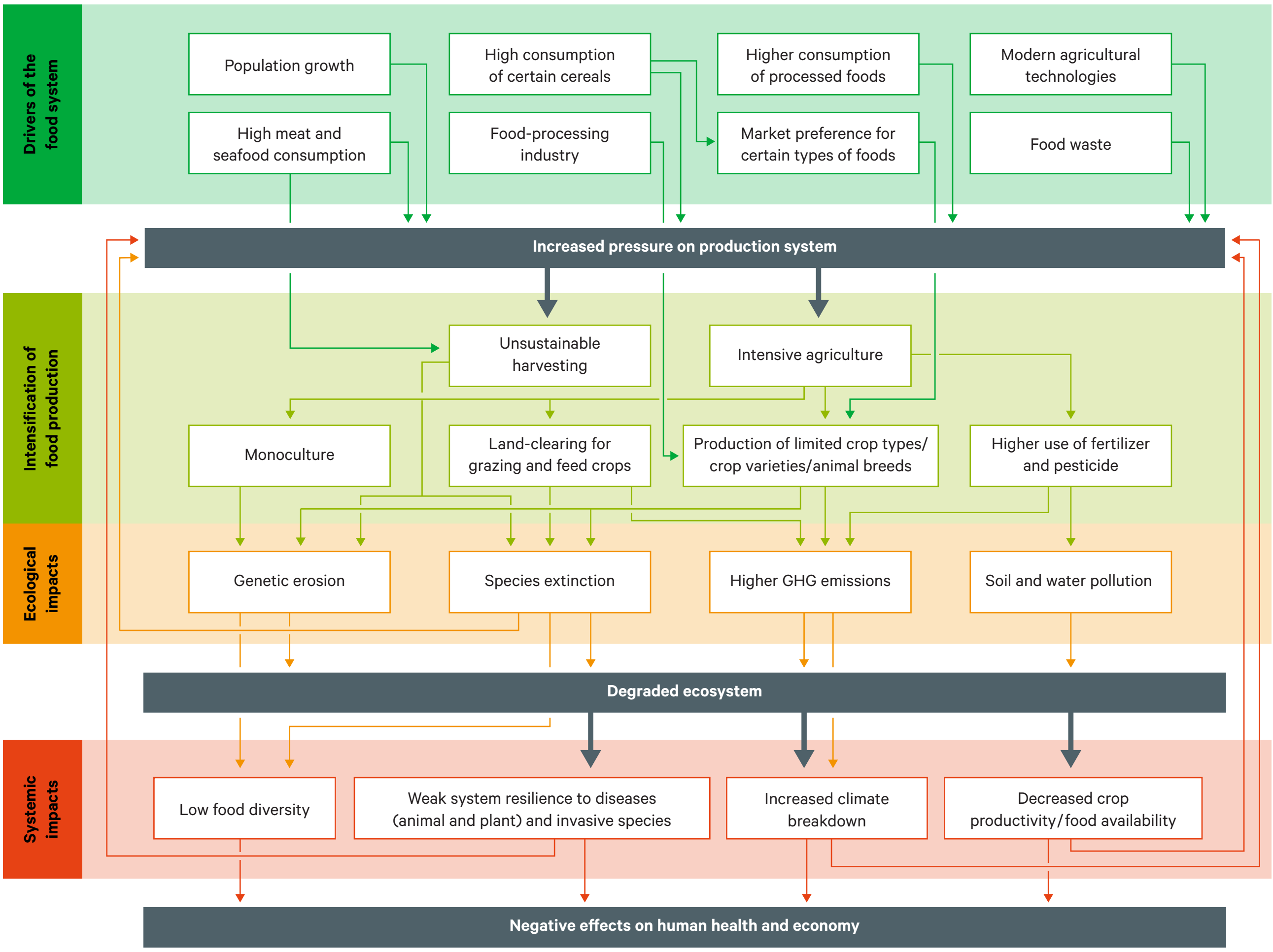
[39] Popkin, B. M. (2017), 'Relationship between shifts in food system dynamics and acceleration of the global nutrition transition', *Nutrition Reviews,* 75(2): pp. 73–82, doi: 10.1093/nutrit/nuw064 (accessed 20 Sep. 2020).

[40] Global Panel on Agriculture and Food Systems for Nutrition (2020), *Future Food Systems: For people, our planet, and prosperity*, https://www.glopan.org/foresight2 (accessed 15 Oct. 2020).

[41] Springmann, M., Mason D-Croz, D., Robinson, S., Wiebe, K., Godfray, C. J., Rayner, M. and Scarborough, P. (2017), 'Mitigation potential and global health impacts from emissions pricing of food commodities', *Nature Climate Change*, 7: pp. 69–74, doi: 10.1038/nclimate3155 (accessed 20 Sep. 2020).

[42] Please see Chapter 5, 'Technical annex', for the detailed evidence which Section 2.3 summarizes.

Figure 4. The food system and its impacts on biodiversity



Source: Authors' original diagram.

2.3.1 Land-use change as a driver of habitat loss

Agriculture is the single largest cause of land-use change and habitat destruction,[43] accounting for 80 per cent of all land-use change globally.[44] As land is converted to crop production for human consumption or farmed animal feed, or to clear land for farmed animals to graze, habitat is lost for wild animals, plants and other organisms such as fungi. The greatest loss of intact ecosystems in recent decades has occurred in the tropics, the world's most biodiverse regions, primarily through the conversion of forests for the production of soy, cattle and palm oil. In just 20 years, from 1980 to 2000, 42 million hectares of tropical forest in Latin America were lost to cattle ranching, while 6 million hectares were lost to palm oil plantations in Southeast Asia.[45]

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[43] Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., Börger, L., Bennett, D. J., Choimes, A., Collen, B., Day, J., De Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M. J., Feldman, A., Garon, M., Harrison, M. L. K., Alhusseini, T., Ingram, D. J., Itescu, Y., Kattge, J., Kemp, V., Kirkpatrick, L., Kleyer, M., Laginha Pinto Correia, D., Martin, C. D., Meiri, S., Novosolov, M., Pan, Y., Phillips, H. R. P., Purves, D. W., Robinson, A., Simpson, J., Tuck, S. L., Weiher, E., White, H. J., Ewers, R. M., Mace, G. M., Scharlemann, J. P. W. and Purvis, A. (2015), 'Global effects of land use on local terrestrial biodiversity', *Nature*, 520(7545): pp. 45–50, doi: 10.1038/nature14324 (accessed 2 Nov. 2020).

[44] Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A. and Shindell, D. (2017), 'Agriculture production as a major driver of the Earth system exceeding planetary boundaries', *Ecology and Society*, 22(4), doi: 10.5751/ES-09595-220408 (accessed 3 Nov. 2020).

[45] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*

In some cases, the lost habitat is the only place where a particular species is adapted to live. In others, the lost habitat may not be a species' exclusive home but is used at certain times of year or at certain stages in the life cycle. Either way, the loss of habitat threatens the population of the species in question. Some species, particularly the largest animals (known as 'megafauna'), range across very large areas; habitat loss that causes fragmentation of home ranges can lead to a decline in species numbers if, for example, the animals must venture into unsuitable habitats or managed landscapes.

Land-use change from natural to managed habitats always creates a cost to biodiversity because crops or farmed animals dominate the space and use up resources, leaving less of both for wildlife. In addition to wildlife loss through competition for resources and habitat destruction, maintaining managed habitats can incur a direct loss of wildlife – for example, in cases where wild animals are killed in favour of protecting farmed animals from predation or disease.

2.3.2 Food production as a driver of biodiversity loss at multiple scales

Food production systems impact on biodiversity at multiple scales:[46] from localized impacts on farms, to landscape-level and regional impacts, to impacts that are felt globally. There is no single 'channel' through which food production and agriculture drive biodiversity loss; instead, there are many and varied ways in which they alter ecosystems, disrupt the usual feeding, breeding or growing patterns of species, and destroy habitat.

In short, the impact of food production on biodiversity arises not from a single fault, but from the nature of the system as a whole (see Figure 4).

2.3.2.1 Impacts at farm and landscape scale

Agriculture by its nature creates monocultures – homogeneous areas covered by a single crop – which replace the heterogeneity of the natural environment. Most agriculture relies on inputs that have spillover effects beyond the farmed area itself. For example, pesticides kill not only identified 'pests' but other insects in the vicinity. Fertilizers pollute air and water across wide areas. Intensive, large-scale animal farming entails the raising of large herds on relatively small areas of land, creating volumes of manure that leak nutrients into soils and water courses at scales that become harmful. Ploughing disturbs the soil, liberating carbon into the atmosphere. It exposes soils to erosion by wind and water, damaging nearby water courses.

Homogenization of farmland undermines biodiversity at farm and landscape level in multiple ways. Many animals require different habitats at different times of the day or year (e.g. nesting habitat that is near foraging habitat). Habitat uniformity across space and time undermines the land's ability to support diverse ecosystems and viable populations of species. As fields are amalgamated, non-cropped areas decrease in size and abundance, and there is less unmanaged habitat to serve as

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[46] There is a significant bias in the availability of the literature towards higher-income-country farming systems. See discussion in Steward, P. R., Shackleford, G., Carvalheiro, L. G., Benton, T. G., Garibaldi, L. A. and Sait, S. M. (2014), 'Pollination and biological control research: are we neglecting two billion smallholders', *Agriculture & Food Security*, 3(5), doi: 10.1186/2048-7010-3-5 (accessed 2 Nov. 2020).

a site for wildlife to shelter, reproduce or forage. Greater use of inputs and increased homogenization reduce biodiversity, both above and below ground; these impacts spill over into rivers, lakes and oceans in multiple ways (see Chapter 5, 'Technical annex'). Greater homogenization at farm and landscape level also increases agricultural vulnerability to crop losses from pests, disease and climate impacts, thereby contributing to greater use of precautionary measures such as chemical pesticides and genetic crop modifications.

The impacts of farming techniques on biodiversity depend on the scale and intensity at which they are practiced. Given that habitat uniformity is a key driver of biodiversity loss,[47] farms with smaller fields are often associated with higher biodiversity. This is especially true for farms where different fields are managed for different crops or farmed animals. Many agro-ecological farming systems – such as organic farming – are inherently more diverse, relying on rotations and mixed farming. Looking at the different types of farms and farming systems, there is often an inverse association between farming yields and biodiversity.[48] Greater yields typically arise from greater intensification: increased planting density, increased use of machinery, increased use of inputs (particularly synthetic ones), and increased specialization. In general, intensification reduces biodiversity. Some innovative agro-ecological approaches aim to maximize yields and minimize the impact on biodiversity. However, in general the yield–biodiversity relationship means that nature-friendly farming systems tend to be lower-yielding than intensive farming systems (a review of the data most available worldwide suggests that organic yields may be, on average, 75 per cent those of conventional intensive systems).[49]

2.3.2.2 Impacts at regional and global scale

The impacts of food production on biodiversity are not limited to farm and landscape scale. Through a number of channels, food production in one location can lead to negative outcomes for biodiversity in faraway locations.[50] These impact channels can be grouped into three categories: physical channels, where pollutants from farms are carried long distances by air or along waterways; biological channels, where impacts on one species or population prompt changes in other species or populations; and market channels, where changes to agricultural practices in one location may, through market dynamics, drive biodiversity-damaging practices in other locations.

Physical impact channels

Synthetic fertilizers and manure are both sources of air pollution in the form of nitrogen oxides (NOx) and ammonium (NH_3). NOx are important GHGs. They contribute to global climate change, and together NOx and NH_3 help create

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[47] Benton, T. G., Vickery, J. A. and Wilson, J. D. (2003), 'Farmland biodiversity: is habitat heterogeneity the key?', *Trends in Ecology & Evolution*, 18(4): pp. 182–88, doi: 10.1016/S0169-5347(03)00011-9 (accessed 2 Nov. 2020).

[48] Gabriel, D., Sait, S. M., Kunin, W. E. and Benton, T. G. (2013), 'Food production vs. biodiversity: comparing organic and conventional agriculture', *Journal of applied ecology*, 50(2): pp. 355–64, doi: 10.1111/1365-2664.12035 (accessed 2 Nov. 2020).

[49] Seufert, V., Ramankutty, N. and Foley, J. A. (2012), 'Comparing the yields of organic and conventional agriculture', *Nature*, 485: pp. 229–32, doi: 10.1038/nature11069 (accessed 2 Nov. 2020).

[50] McCann, K. S., Cazelles, K., MacDougall, A. S., Fussmann, G. F., Bieg, C., Cristescu, M. E., Fryxell, J. M., Gellner, G., Lapointe, B. and Gonzalez, A. (2020), 'Landscape modification and nutrient-driven instability at a distance', doi: https://doi.org/10.1111/ele.13644 (accessed 21 Nov. 2020); and Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E. and Yoo, K. (2011), 'Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere', *Frontiers in Ecology and the Environment*, 9(1): pp. 53–60, doi: 10.1890/100014 (accessed 2 Nov. 2020).

secondary particulate matter (PM), which contributes to poor air quality and smog. Poor air quality may not always directly affect biodiversity, but increased concentrations of nitrogen in the atmosphere can be deposited in rain, causing ecosystem changes as a result of nutrient enrichment, rendering soils more acidic and degrading the environment for many species.[51] Indeed, some analysts have suggested that excess nitrogen deposition is the third-largest global threat to biodiversity after land-use change and climate change.[52]

In periods of rain, excess nutrients and sediment from poorly managed soils can wash into rivers. This run-off can be carried rapidly over long distances, accumulating to levels that yield drastic effects on biodiversity and the stability of distant ecosystems.[53] Overloading waterways with nutrients – a process called 'eutrophication' – leads to the proliferation of algae which cover the water surface and essentially suffocate the aquatic or marine life beneath. Modifications to waterways to support agriculture, such as damming and channelization to aid irrigation, exacerbate these impacts. At the same time, irrigation through the abstraction of water from groundwater flows potentially threatens the viability of aquatic populations that depend on such flows.[54]

While land-use change, primarily for agriculture, has been the principal driver of biodiversity loss since pre-industrial times, climate change is becoming an increasingly important factor.

At the global level, food production contributes significantly to biodiversity loss by driving climate change. When taking into account the emissions associated with (1) agriculture, (2) land-use change for agriculture, and (3) the processing and transporting of food, the food system accounts for roughly 30 per cent of all anthropogenic emissions (Table 1).[55] Animal agriculture contributes disproportionately to this total, accounting for 16.5 per cent of GHGs.[56] It is

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[51] Dise, N. B., Ashmore, M., Belyazid, S., Bleeker, A., Bobbink, R., de Vries, W., Erisman, J. W., Spranger, T., Stevens, C. J. and van den Berg, L. (2011), 'Nitrogen as a threat to European terrestrial biodiversity', in *The European nitrogen assessment: sources, effects and policy perspectives*, Cambridge, UK: Cambridge University Press, doi: 10.1017/CBO9780511976988.023 (accessed 2 Nov. 2020).

[52] Xiankai, L., Jiangming, M. and Shaofeng, D. (2008), 'Effects of nitrogen deposition on forest biodiversity', *Acta Ecologica Sinica*, 28(11): pp. 5532–48, doi: 10.1016/S1872-2032(09)60012-3 (accessed 2 Nov. 2020); and Payne, R. J., Dise, N. B., Field, C. D., Dore, A. J., Caporn, S. J. M. and Stevens, C. J. (2017), 'Nitrogen deposition and plant biodiversity: past, present, and future', *Frontiers in Ecology and the Environment*, 15(8), doi: 10.1002/fee.1528 (accessed 2 Nov. 2020).

[53] Bennett, E. M., Carpenter, S. R. and Caraco, N. F. (2001), 'Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective', *BioScience*, 51(3): pp. 227–34, doi: 10.1641/0006-3568(2001)051[0227:hioepa]2.0.co;2 (accessed 2 Nov. 2020); and Diaz, R. J. and Rosenberg, R. (2008), 'Spreading dead zones and consequences for marine ecosystems', *Science*, 321(5891): pp. 926–29, doi: 10.1126/science.1156401 (accessed 2 Nov. 2020).

[54] Rolls, R. J. and Bond, N. R. (2017), 'Environmental and ecological effects of flow alteration in surface water ecosystems', in Horne, A., Webb, J. A., Stewardson, M. J., Richter, B. and Acreman, M. (2017), *Water for the Environment: From Policy and Science to Implementation and Management*, Academic Press, pp. 65–82, doi: 10.1016/B978-0-12-803907-6.00004-8 (accessed 2 Nov. 2020).

[55] IPCC (2019), *Climate Change and Land.*

[56] Food and Agriculture Organization of the United Nations (FAO) (2018), Global Livestock Environmental Assessment Model, Version 2.0, Revision 5, July 2018.

also the biggest contributor to two of the three major sources of anthropogenic GHG emissions: methane (accounting for 44 per cent of emissions) and nitrous oxide (53 per cent of emissions).[57]

While land-use change, primarily for agriculture, has been the principal driver of biodiversity loss since pre-industrial times, climate change is becoming an increasingly important factor.[58] Rising global temperatures are changing habitat suitability throughout the world, and prompting the movement of suitable habitats for particular species to different regions: towards the poles for many organisms; up elevation gradients in mountainous areas; or towards deeper waters for aquatic species.[59] As the climate changes, and their habitat moves, species either move with it or risk extinction. As a result of species needing to track a changing climate, and owing to the fact that different groups of species move at different rates,[60] climate change is rewiring entire ecosystems.[61] Many species are now found in areas in which they were not previously present – creating new competition and conflict between species – while other species are disappearing. More broadly, climate change is prompting a series of perturbations to weather patterns and landscapes, undermining the functionality of ecosystems on which human societies depend.

Table 1. Average (2007–16) annual emissions of greenhouse gases from the food system

Source	Amount	Units
Total global anthropogenic GHGs	52.0 ± 4.5	$GtCO_2e\ y^{-1}$
Agricultural land-use change	4.9 ± 2.5	$GtCO_2\ y^{-1}$
Methane from ruminant animals and soils	4.0 ± 1.2	$GtCO_2e\ y^{-1}$
Nitrous oxide (fertilizer, manure)	2.2 ± 0.7	$GtCO_2e\ y^{-1}$
Transport, manufacturing, cooking etc.	2.4–4.8	$GtCO_2e\ y^{-1}$
Total global food system GHGs	15.0 (10.6–19.4)	$GtCO_2e\ y^{-1}$
	28.9 (20.4–37.3)	**% contribution to total GHGs**

Source: IPCC (2019), 'Summary for Policymakers', *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds), Data from Table SPM1, https://www.ipcc.ch/srccl/chapter/summary-for-policymakers.

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[57] Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G. (2013), *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities,* Rome: FAO.
[58] Newbold et al. (2015), 'Global effects of land use on local terrestrial biodiversity'; and IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*
[59] Pecl et al. (2017), 'Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being.'
[60] Ibid.
[61] Bartley, T. J., McCann, K. S., Bieg, C., Cazelles, K., Granados, M., Guzzo, M. M., MacDougall, A. S., Tunney, T. D. and McMeans, B. C. (2019), 'Food web rewiring in a changing world', *Nature Ecology and Evolution*, 3(3), 345–54, doi: 10.1038/s41559-018-0772-3 (accessed 2 Nov. 2020).

Biological impact channels

Animal and plant populations are dynamic. Dispersal and migration mean that organisms often move considerable distances over their life cycles. The ecology of one place can therefore influence the ecology of other places through spillover effects due to the movement of individual organisms.

The presence of migratory birds in summer on farmland in the northern hemisphere, for example, can depend on their continued presence in their winter habitat in the southern hemisphere, and vice versa. In this way, damage to a species' summer breeding grounds resulting from the loss of suitable habitat through, for example, overuse of herbicides may lead to population decline – and thus biodiversity loss – in its winter feeding grounds. Farming can also boost the populations of organisms that have negative impacts on local or native organisms, for example through the introduction of crop diseases which then spread away from their introductory sites to harm surrounding wildlife.

Biodiversity impacts may also be transmitted at a genetic level. Genetic pollution (known as 'gene introgression') can occur from crop plants into wild populations, and from non-native fish escaping from aquaculture farms and mating with wild relatives.[62] In both examples, this alters the natural genetic composition of a given location or ecosystem.

Market impact channels

Globalized supply chains in a competitive marketplace have resulted in a system in which the food consumed in a given country is often sourced from a combination of local and overseas production. These market linkages mean that efforts to implement biodiversity-supporting agricultural practices in one location may generate varied impacts elsewhere in the world.

By way of example, if a country decides to conserve its own biodiversity by making its agricultural production more environmentally friendly, the cost of production in that country will typically increase relative to elsewhere (since the inputs and practices on which the 'cheaper food' paradigm depends will likely be reduced or avoided). Higher costs may drive down demand for the food in question produced in that country, but, if total demand stays the same, price signals through international market linkages will incentivize either greater use of inputs or the conversion of additional land somewhere else to compensate, and demand will be filled through trade. This potentially leads to a biodiversity 'saving' in one place, arising through environmentally friendly farming, but a biodiversity 'cost' in another, through intensification or land-use conversion, to meet demand for cheaper food via imports.[63]

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[62] Karlsson, S., Diserud, O. H., Fiske, P., Hindar, K. and Grant, S. (2016), 'Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations', *ICES Journal of Marine Science*, 73(10): pp. 2488–98, doi: 10.1093/icesjms/fsw121 (accessed 2 Nov. 2020).

[63] Dougill, A. J., Howlett, D. J. B., Fraser, E. D. G. and Benton, T. G. (2012), 'The scale for managing production vs the scale required for ecosystem service production', *World Agriculture*, http://www.world-agriculture.net/article/the-scale-for-managing-production-vs-the-scale-required-for-ecosystem-service-production (accessed 2 Nov. 2020).

03

Key levers for food system redesign

Three principal changes are needed for a more biodiversity-supporting food system. Humanity must shift towards more plant-based diets, set aside more land as protected natural habitat, and adopt more sustainable farming methods.

Our food system today is driving both environmental harm and deteriorations in public health. Its current design is also amplifying external risks to society, as COVID-19 has demonstrated. The pandemic has highlighted the high degree of risk concentrated in certain food supply chains, poor labour standards in food-processing plants that have accelerated the spread of the disease among workers, and the limitations of 'just-in-time' business models that have depleted emergency food stores.

Moving to a food system that supports environmental and human health requires fundamentally changing consumption habits and redesigning how food production systems utilize natural resources. Reducing the conflict between humanity's requirement for food and the negative impacts of food production on biodiversity and the environment will not be achieved simply by identifying a single approach to biodiversity-friendly farming. At the same time, building the resilience of the food system to respond to 'black swan' events such as COVID-19 cannot be done through 'tweaks' at the margins alone. Instead, transformative change, including a realignment of the incentives that drive unsustainable practices, is required both to the way we produce food and to what we consume.

The successful redesign of the food system in support of biodiversity and improved public health will depend on three key 'levers': changing our diets; setting aside land for biodiversity; and adapting how we farm.

3.1 Dietary change

The first key lever for food system redesign is to change diets in such a way as to reduce overall demand for food, and thus reduce demand for the use of land that supports its production. Evidence of the potential for dietary change to deliver fundamental shifts in agriculture and land use has been mounting in recent years. Scientists, civil society and policymakers are increasingly recognizing dietary change as a central pillar in food system transformation. A number of high-profile reports have begun to outline pathways through which all actors in the food system – from financers to producers to retailers to consumers – can effect positive behaviour changes in favour of healthier diets from sustainable production systems.[64]

The importance of dietary change to redesign of the food system stems from three key principles. Firstly, on average and at a global level, we produce more food than we need per capita. Globally, as much as a third of the edible parts of food produced for human consumption are lost or wasted, equal to around 1.3 billion tons per year, either on the farm, in transit, through processing, or at the point of retail and consumption.[65] Secondly, the environmental footprint of food – its associated land use, GHG emissions, water use and biodiversity impact – varies significantly from one product to the next. In general, the largest differences occur between animal-sourced and plant-sourced foods, with the latter having smaller footprints; in some cases, substantially smaller (see Figure 7).[66] And thirdly, demand for the most environmentally damaging foods is both high and rising, a trend partly associated with nutrition transitions that are increasing demand for animal products.[67]

Were global dietary patterns to shift to the extent that we did not waste food, overconsume calories or demand excessive amounts of the most environmentally damaging foods, this would very significantly reduce total demand for food – and hence total demand for land and other natural resources.[68] For example, a switch from beef to beans in the diets of the entire US population could free up 692,918 km^2 – equivalent to 42 per cent of US cropland – for other uses

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[64] Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Sibanda, L. M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S. E., Reddy, K. S., Narain, S., Nishtar, S. and Murray, C. J. L. (2019), 'Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems', *The Lancet Commissions*, 393(10170): pp. 447–92, doi: 10.1016/S0140-6736(18)31788-4 (accessed 2 Nov. 2020); Swinburn, B. A., Kraak, V. I., Allender, S., Atkins, V. J., Baker, P. I., Bogard, J. R., Brinsden, H., Calvillo, A., de Schutter, O., Devarajan, R., Ezzati, M., Friel, S., Goenka, S., Hammond, R. A., Hastings, G. et al. (2019), 'The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report', *The Lancet*, 393(10173): pp. 791–846, doi: 10.1016/S0140-6736(18)32822-8 (accessed 2 Apr. 2020); and Food and Land Use Coalition (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use*, The Global Consultation Report of the Food and Land Use Coalition, https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf (accessed 2 Nov. 2020).

[65] Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. and Mcybeck, A. (2011), *Global food losses and food waste: extent, causes and prevention*, Rome: FAO, http://www.fao.org/3/mb060e/mb060e00.htm (accessed 2 Nov. 2020).

[66] Poore, J. and Nemecek, T. (2018), 'Reducing food's environmental impacts through producers and consumers', *Science*, 360(6392): pp. 987–92, doi: 10.1126/scienceaaq0216 (accessed 2 Nov. 2020).

[67] Godfray, H. C. G., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., Pierrehumbert, R. T., Scarborough, P., Springmann, M. and Jebb, S. A. (2018), 'Meat consumption, health, and the environment', *Science,* 361(6399), eaam5324, doi: 10.1126/science.aam5324 (accessed 2 Nov. 2020).

[68] Clark, M. A., Domingo, N. G. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L. and Hill, J. D. (2020), 'Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets', *Science,* 370 (6517), doi: 10.1126/science.aba7357 (accessed 06 Nov 2020).

such as ecosystem restoration or more nature-friendly farming.[69] Such a shift would also contribute substantially to climate goals (in this example, meeting between 42 and 74 per cent of the US GHG reduction goal for 2020).[70] It would likely contribute to a range of other public goods including improved dietary quality and reduced incidence of diet-related disease associated with overconsumption of red and processed meat.[71] Pandemic risk could also be significantly lowered by reducing animal farming.[72] While the convergence of global food consumption around predominantly plant-based diets is the most crucial element in addressing demand, additional measures (such as efforts to reduce waste and overconsumption of calories) are required to bring food system emissions in line with the temperature goals of the Paris Agreement on climate change.[73]

3.2 Setting aside land for biodiversity

The second key lever for creating a more biodiversity-supporting food system is to set aside land specifically for the conservation and proliferation of habitats and wildlife. Biodiversity is highest in areas of unconverted land. Even farming practices that are designed to be wildlife-friendly require some degree of modification of natural habitat. From a purely theoretical perspective, and according to a growing body of academic literature, setting aside land for biodiversity to the exclusion of other uses, including farming, and either protecting or restoring natural habitat would offer the most benefit to biodiversity across a given landscape.[74]

Setting aside land for biodiversity to the exclusion of other uses, including farming, and either protecting or restoring natural habitat would offer the most benefit to biodiversity across a given landscape.

The value of preserving undisturbed habitats and ecosystems – both for the sake of biodiversity and to support natural carbon sequestration and storage – has underpinned many of the global efforts to preserve primary forest cover, particularly in the tropics. When it comes to restoring native ecosystems, the carbon sequestration potential of particular measures varies according to geographical location and the type of underlying native ecosystem being restored.

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[69] Harwatt, H., Sabaté, J., Eshel, G., Soret, S. and Ripple, W. (2017), 'Substituting beans for beef as a contribution toward US climate change targets', *Climatic Change*, 143(1–2), doi: 10.1007/s10584-017-1969-1 (accessed 2 Nov. 2020).
[70] Ibid.
[71] Clark, M. A., Springmann, M., Hill, J. and Tilman, D. (2019), 'Multiple health and environmental impacts of foods', *Proceedings of the National Academy of Sciences of the United States of America*, 116(46), pp: 23357–62, doi: 10.1073/pnas.1906908116 (accessed 2 Nov. 2020).
[72] IPBES Workshop on Biodiversity and Pandemics.
[73] Clark et al. (2020), 'Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets'.
[74] Phalan, B., Onial, M., Balmford, A. and Green, R. E. (2011), 'Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared', *Science*, 333(6047): pp. 1289–91, doi: 10.1126/science.1208742 (accessed 2 Nov. 2020); and Luskin, M. S., Lee, J. S. H., Edwards, D. P., Gibson, L. and Potts, M. D. (2018), 'Study context shapes recommendations of land-sparing and sharing; a quantitative review', *Global Food Security*, 16: pp. 29–35, doi: 10.1016/j.gfs.2017.08.002 (accessed 2 Nov. 2020).

For example, returning all permanent pasture worldwide to its native forest cover would store 72 gigatonnes of carbon (GtC), whereas returning pasture to its native grassland cover would store less than half this amount (34 GtC), even though native grassland covers three times more land area than native forest.[75] The biggest potential for carbon sequestration through such ecosystem restoration efforts is concentrated in high-income and upper-middle-income countries, which account for 70 per cent of the carbon that would be sequestered by restoring land currently occupied by animal agriculture.[76]

The greatest gains for biodiversity will occur when we preserve or restore whole ecosystems. With some exceptions, this will typically require significant areas of land to be left or managed for nature, primarily because the extinction risk for any species grows as its population size shrinks, and because many large animals require a large area of habitat to sustain an adequate population. Human dietary shifts are thus essential in order to preserve existing native ecosystems and restore those that have been removed or degraded.

3.3 Adapting the way we farm the land

The third lever for transforming the food system in support of biodiversity is to adopt more biodiversity-supporting modes of food production. One way to do this is to retain pockets of habitat for wildlife within the agricultural landscape (some of which can be on farms; others can be patches of land 'spared for nature' within the wider farming landscape). The other way is to change farming methods.

There are three key avenues through which the latter can be achieved.[77] Firstly, we can decrease the volume of inputs. Reduced-input farming has already been widely adopted in developed countries through precision agriculture. Precision agriculture involves the use of a range of technologies to target more efficient use of inputs (according to the '4 Rs' principle: the right source, in the right amount, in the right place, at the right time).[78]

Secondly, we can substitute certain inputs or practices for more sustainable alternatives: forgoing chemical and synthetic inputs as much as possible and instead using ecological processes to manage soil fertility (through crop rotations, for example), supporting natural pollination and pest control, and moving to methods such as 'no-till' farming that limit disturbance of natural processes and habitats. And thirdly, we can switch to modes of production that utilize land and other natural resources in fundamentally different ways, for example replacing

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[75] Hayek, M. N., Harwatt, H., Ripple, W. J. and Mueller, N. D. (2020), 'The carbon opportunity cost of animal-sourced food production on land', *Nature Sustainability* (2020), doi: 10.1038/s41893-020-00603-4 (accessed 2 Nov. 2020).

[76] Ibid.

[77] Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Butler Flora, C., Godfray, C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Vara Prasad, P. V., Reganold, J., Rockström, J., Smith, P., Thorne, P. and Wratten, S. (2018), 'Global assessment of agricultural system redesign for sustainable intensification', *Nature Sustainability,* 1: pp. 441–46, doi: 10.1038/s41893-018-0114-0 (accessed 2 Nov. 2020).

[78] Reetz, H. F., Heffer, P. and Bruulsema, T. W. (2015), '4R nutrient stewardship: A global framework for sustainable fertilizer management', in Dreschel, P., Heffer, P., Magen, H., Mikkelsen, R. and Wichelns, D. (eds) (2015), *Managing Water and Fertilizer for Sustainable Agricultural Intensification*, pp. 65–86, Paris: International Fertilizer Industry Association, International Water Management Institute, International Plant Nutrition Institute and International Potash Institute, ISBN: 979-10-92366-02-0.

conventional agriculture with agroforestry, or converting to agro-ecological approaches (see technical annex for further discussion). Since such practices imply breaking out of many of the 'lock-ins' associated with today's system – including land tenure models, the sunk costs of large farm machinery, and the nature of the dominant supply chains – adoption remains limited to date.

Dietary change is a necessary global enabler to allow widespread adoption of nature-friendly farming without increasing the pressure to convert natural land.

There are many specific ways in which agriculture can become more nature-friendly and support biodiversity (including through agro-ecological farming and regenerative farming,[79] of which organic farming is an example). As outlined above, alternative approaches typically require the use of natural processes to support production, rather than a full substitution of synthetic inputs (nitrogen, pesticides) with natural ones to enable specialization at scale. These approaches are typically associated with enhancing diversity: of farm outputs (genetics, agroforestry), land use across space (to improve biodiversity for ecosystem services) and time (e.g. crop rotations).[80] While some approaches may increase agricultural productivity,[81] in general nature-friendly farming is less productive than conventional methods. For example, on a like-for-like comparison, organic farms typically yield 34 per cent less than intensively managed farms.[82] Even if farm-level incomes can be maintained via appealing to premium markets, dietary change is still a necessary global enabler to allow widespread adoption of nature-friendly farming without increasing the pressure to convert natural land.[83]

In essence, these three avenues – gaining efficiency, substituting artificial processes with ecological ones, and redesigning the system – are about maintaining adequate food yields while reducing environmentally damaging inputs. In other words, they are about sustainably intensifying production. While the concept of 'sustainable intensification' is subject to much debate and is often used to describe practices that are far from sustainable, the underlying principle is one that now lies behind approaches such as 'ecological intensification' (see Box 3).

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[79] Burgess, P. J., Harris, J., Graves, A. R. and Deeks, L. K. (2019), *Regenerative Agriculture: Identifying the impact; enabling the potential*, Report for SYSTEMIQ, Bedfordshire, UK: Cranfield University, https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/Regenerative-Agriculture-final.pdf (accessed 3 Nov. 2020).

[80] Seufert, V., Mehrabi, Z., Gabriel, D. and Benton, T. G. (2019), 'Current and Potential Contributions of Organic Agriculture to Diversification of the Food Production System', in Lemaire, G., De Faccio Carvalho, P. C., Kronberg, S. and Recous, S. (eds) (2019), *Agroecosystem Diversity*, pp. 435–52, Academic Press, doi: 10.1016/B978-0-12-811050-8.00028-5 (accessed 3 Nov. 2020).

[81] Zaralis, K. and Padel, S. (2019), 'Effects of High Stocking Grazing Density of Diverse Swards on Forage Production, Animal Performance and Soil Organic Matter: A Case Study', in Theodoridis, A., Ragkos, A. and Salampasis, M. (eds) (2019), *Innovative Approaches and Applications for Sustainable Rural Development,* HAICTA: International Conference on Information and Communication Technologies in Agriculture, Food & Environment 2017, Springer Earth System Sciences, Cham, Switzerland: Springer, doi: 10.1007/978-3-030-02312-6_8 (accessed 3 Nov. 2020).

[82] Seufert, Ramankutty and Foley (2012), 'Comparing the yields of organic and conventional agriculture'.

[83] Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.-H., Smith, P., Klocke, P., Liebe, F., Stolze, M. and Niggli, U. (2017), 'Strategies for feeding the world more sustainably with organic agriculture', *Nature Communications*, 8(1290), doi: 10.1038/s41467-017-01410-w (accessed 3 Nov. 2020).

Box 3. Sustainable and unsustainable intensification

If demand for food exceeds supply, three conceptual options are potentially available for addressing the shortfall: reduce demand, convert new land for agriculture, or grow more from the land already used for agriculture. Growing more from existing land is a definition of intensification. As described above, in many cases intensification has proven unsustainable in recent decades, externalizing production costs on to the environment. In contrast, the concept of *sustainable* intensification – also referred to as 'ecological intensification' – implies that yield gains must not come at the expense of biodiversity, good resource management, animal welfare, or other ecological and ethical criteria.[84]

Conceptually, sustainable intensification can be subdivided into three main strategies:[85] (1) increasing the efficiency of production; (2) substituting certain inputs or practices with more sustainable alternatives; and (3) system redesign.

The term 'sustainable intensification' is contested,[86] owing to the multiple and distinct ways in which it has been interpreted and championed. In essence, however, the concept is about minimizing the area of land used for agriculture and, where the land *is* used for agriculture, managing that land so that as much food as possible can be grown *in a sustainable manner*.

3.4 The need for all three levers

The three levers discussed here – dietary change, the setting aside of land for biodiversity (or the maintenance of natural ecosystems), and changes to farming practices – are not mutually exclusive. Indeed, the feasibility and efficacy of each rely on the simultaneous deployment of at least one, or both, of the other two.

There is a three-way trade-off between demand, the amount of land used for food production, and the method of farming chosen. Rising demand for food, particularly meat and processed foods, will increasingly limit the options for setting aside land for biodiversity. On current trajectories, our food choices will place more and more pressure on the land used for agriculture. This pressure will be relieved either through the conversion of new land for agricultural production or through the use of increasingly input-intensive methods on existing farmland.

A continuation of today's demand patterns will also limit the move to more wildlife-friendly farming practices, which – at least for now – tend to be lower-yielding. Preserving large tracts of land for biodiversity that could otherwise have been used for agriculture necessarily implies either reducing the amount of food produced or increasing yields on the areas farmed. If demand continues

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[84] Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J. and Godfray, H. C. J. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies', *Science*, 341: pp. 33–34.
[85] Pretty et al. (2018), 'Global assessment of agricultural system redesign for sustainable intensification'.
[86] Benton T. G. (2015), 'Sustainable Intensification', in Pritchard, B., Ortiz, R. and Shekar, M. (eds) (2015), *Routledge Handbook of Food and Nutrition Security*, Ch. 6, Abingdon: Routledge; and Garnett et al. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies'.

to rise, boosting yields becomes the imperative; to date, yield increases have been supported by greater use of inputs. Farming systems that allow land to be set aside for biodiversity alongside productive land will limit the viability of that biodiversity if they continue to rely on synthetic inputs such as pesticides and herbicides. Even radically different modes of farming, such as agroforestry or regenerative farming, will drive rising demand for land if they are not accompanied by a significant reduction in overall demand for food.

Even radically different modes of farming, such as agroforestry or regenerative farming, will drive rising demand for land if they are not accompanied by a significant reduction in overall demand for food.

This trilemma is illustrated in Figure 5. Each row presents indicative permutations of land use needed to deliver a given amount of 'food' and 'biodiversity' under one of three different scenarios. The land is either pristine ecosystem (green), intensively managed farmland (red), or land used for nature-friendly farming (yellow). For illustrative purposes, pristine ecosystems produce one unit of 'food' and 10 units of 'biodiversity'; intensive farmland produces 10 units of food and one unit of biodiversity; and nature-friendly farming produces six units of food and five units of biodiversity.

Each scenario illustrates a different balance between demand for food and the requirement for biodiversity. The top row is a baseline scenario indicating no change in what we eat. Conceptually, we can 'choose' different permutations of land use to produce the same amount of biodiversity: from lots of pristine ecosystem and predominantly intensive farming (on the right), to a smaller amount of pristine ecosystem but lots of land under nature-friendly farming (on the left).

The middle row (Scenario 1) is where biodiversity is prioritized, and dietary change has occurred to reduce pressure on land (relative to the baseline scenario).

The bottom row (Scenario 2) is where demand for food has grown, despite the consequences for biodiversity.

In each scenario, maximizing pristine ecosystems requires significant intensive farming, but a world of nature-friendly farming and significant pristine ecosystems can occur only with reduced dietary demand (i.e. in Scenario 1). The demand for food shapes the trade-off between different land uses, forcing a choice between maximizing the 'sparing' of land for nature (which requires intensive use of farmland areas) or the 'sharing' of land (e.g. baseline scenario, left-hand pie chart, which shows relatively little pristine land because lower-yielding nature-friendly farming occupies most of the land area).

Figure 5. Schematic illustrating indicative land-use choices under three scenarios for food demand

This diagram shows how the three land-use options (land spared for natural ecosystems, land farmed in a nature-friendly way, or land farmed intensively) collectively impact on food supply and biodiversity. The top row is the 'baseline'; the middle row is when we decrease both the amount we eat and the proportion of high-impact food like red meat; and the bottom row is when we increase the amount we eat and the proportion of high-impact food. Significant land left for nature and nature-friendly farming requires less demand; more demand leads to fewer options for both land for nature and nature-friendly farming.

🟩 Natural ecosystems
🟨 Nature-friendly farming
🟥 Intensive farming

Source: Authors' original diagram.

04

Recommendations for action in 2021

A series of high-level summits in 2021 will cover food, climate and biodiversity. A key goal will be to embed consideration of the importance of food systems across a wide range of health and sustainability areas.

A year of unique opportunity for food system redesign is in prospect in 2021. A series of major international forums and conferences will take place throughout the year, focusing on biodiversity, food systems, nutrition and climate change. Nature and food systems will be a common thread at each of these events (Box 4). Also, in the face of a global recession due to the COVID-19 pandemic, world leaders will need to address the root causes of that crisis – both as a public health crisis arising from a zoonotic disease, and as an economic and social crisis exacerbated by the interconnected and fragile nature of food systems – and discuss options for economic recovery.

Box 4. Key international events for food system reform and biodiversity in 2021

***February* – Fifth session of the UN Environment Assembly (UNEA-5).** This is the world's highest-level decision-making body on the environment, with a universal membership of all 193 UN member states. The assembly convenes to set priorities for global environmental policies, catalyse intergovernmental action on the environment, and contribute to the implementation of the UN 2030 Agenda for Sustainable Development.

***May* – 15th Conference of the Parties to the Convention on Biological Diversity (CBD COP15).** A new Post-2020 Global Biodiversity Framework will be agreed, following the conclusion of the implementation period for the 2011–20 Aichi Biodiversity Targets.

***September* – Inaugural UN Food Systems Summit (UNFSS).** The summit is being convened in recognition of the urgent need for food system transformations in support of improved nutrition security, public health and environmental sustainability.

***November* – 26th Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC COP26).** This will be an opportunity for delegates to address the findings of the 2019 special report on climate change and land by the Intergovernmental Panel on Climate Change (IPCC). The IPCC report highlighted th central importance of the food system as a driver of climate change, and the urgent need for its reform in order to deliver on the nutrition needs of a growing population while respecting planetary boundaries. Revised country-level climate commitments, known as Nationally Determined Contributions, are expected to be much more ambitious than previously.

***Late 2021 (date TBC)* – 15th Conference of the Parties to the UN Convention to Combat Desertification (UNCCD COP15).** This will provide a further opportunity for international decision-makers to respond to the IPCC's special report on climate change and land, and more specifically to address the report's findings on sustainable land management to prevent further land degradation.

***December* – Third Nutrition for Growth Summit (N4G).** Halfway through the UN's Decade of Action on Nutrition, the summit, hosted in 2021 by Japan, is expected to result in an agreement aimed at mobilizing resources and political commitment to achieving the nutrition targets under Sustainable Development Goal 2 ('zero hunger').[87]

4.1 The implications of COVID-19 for decision-making in 2021

In recent months the statements and policy positioning of many current and former international leaders, including the UN secretary-general,[88] have begun coalescing around two main messages: firstly, that COVID-19 and the impacts of climate change are both examples of environmental disruptions that will increasingly shape our lives; and secondly, that there is an urgent need to invest in 'building back better' so that societies and economies are more resilient to shocks and more sustainable in the long term.

Both this period of reconstruction and the steer of the G7 and G20 leaders on priorities for collective action will be highly influential in the context of food system transformation and biodiversity protection. The sums of money that governments are looking to invest to kickstart their economies are unprecedented, and dwarf those required or allocated to meet environmental or health targets. By way of example, the IMF estimates that $11.7 trillion had been pledged globally

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[87] Wellesley, L., Eis, J., Marijs, C., Vexler, C., Waites, F. and Benton, T. G. (2020), *The Business Case for Investment in Nutrition*, Chatham House Report, London: Royal Institute of International Affairs, https://reader.chathamhouse.org/business-case-investment-nutrition-wellesley-et-al#towards-an-action-agenda-for-business (accessed 21 Aug. 2020).

[88] UN Department of Global Communications (2020), 'Climate Change and COVID-19: UN urges nations to 'recover better'', 22 April 2020, https://www.un.org/en/un-coronavirus-communications-team/un-urges-countries-%E2%80%98build-back-better%E2%80%99 (accessed 3 Nov. 2020).

by September 2020 to support recovery from the COVID-19 crisis.[89] This is 19,500 to 117,000 times the estimated annual cost of halting deforestation in the Amazon,[90] and 28 to 48 times the annual cost of climate change mitigation anticipated for 2030.[91] It is also between 44 and 1,671 times higher than the estimated cost of ending global undernutrition (estimated to range from $7 billion to $265 billion per year through different investment packages, specific targets, measures and policy pathways).[92]

Evidence of increased morbidity and mortality among COVID-19 sufferers who are malnourished is throwing light on the very real societal costs of the current food system and patterns of consumption.

The scale of this proposed spending shifts the political context within which food system transformation will be discussed over the coming months and years. While there is no easy way to tackle the three-way trade-off outlined in the previous chapter, it is clear that shifting demand and breaking out of the 'cheaper food' paradigm will be key to enabling both land-sparing and more agro-ecological farming to enhance biodiversity. To date, there has been considerable resistance to the idea of government intervention in diet. But evidence of increased morbidity and mortality among COVID-19 sufferers who are malnourished – either undernourished or obese – is throwing light on the very real societal costs of the current food system and patterns of consumption. Approximately 3 billion people suffer one or more manifestations of poor nutrition (undernutrition, including deficiencies of vitamins and minerals, and/or overweight or obesity).[93] These problems alone cost the world an estimated $3.5 trillion each year.[94] This creates a strong economic incentive to save money on healthcare by changing the availability and price of nutritionally adequate, health-promoting food, and by moving towards healthcare systems more focused on prevention of disease. Once the costs of unsustainable food systems and the 'cheaper food' paradigm – in terms of water and air quality, climate change mitigation and longer-term agricultural productivity – are recognized, the benefits of food system transformation potentially exceed the costs, and inaction becomes economically irrational.

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[89] IMF (2020), 'Chapter 1 - Fiscal Policies to Address the COVID-19 Pandemic', *Fiscal Monitor: Policies for the Recovery*, October 2020, Washington, DC: IMF, https://www.imf.org/en/Publications/FM/Issues/2020/09/30/october-2020-fiscal-monitor#Chapter%201 (accessed 19 Jan. 2021).
[90] Mongabay (2008), 'How much would it cost to end Amazon deforestation?', 27 January 2008, https://news.mongabay.com/2008/01/how-much-would-it-cost-to-end-amazon-deforestation (accessed 3 Nov. 2020).
[91] Ritchie, H. (2017), 'How much will it cost to mitigate climate change?', Our World in Data, 27 May 2017, https://ourworldindata.org/how-much-will-it-cost-to-mitigate-climate-change (accessed 3 Nov. 2020).
[92] Fan, S. (2018), 'The multibillion dollar question: How much will it cost to end hunger and undernutrition?', ReliefWeb, 14 March 2018, https://reliefweb.int/report/world/multibillion-dollar-question-how-much-will-it-cost-end-hunger-and-undernutrition (accessed 3 Nov. 2020).
[93] International Food Policy Research Institute (IFPRI) (2017), *2016 Global Nutrition Report. From promise to impact: Ending malnutrition by 2030*, https://globalnutritionreport.org/reports/2016-global-nutrition-report (accessed 3 Nov. 2020).
[94] Food and Land Use Coalition (2019), *Growing Better: Ten Critical Transitions to Transform Food and Land Use*.

In addition to unprecedented spending, we are entering a new era in which entrenched policy 'lock-ins' can now be broken open. Governments around the world have taken highly interventionist actions to slow the spread of COVID-19 and mitigate the economic effects of the pandemic. Measures to make societies more sustainable that had been previously dismissed as overly draconian or market-distorting may now be back on the table. In some ways, this shift poses risks to international cooperation to promote positive change in the food system. For example, the use of export restrictions to shore up domestic markets in the early days of the crisis suggests that protectionist and distortive trade measures may become more prevalent, further destabilizing global supply chains. In other ways, the increased political tolerance for interventionist economic policies signals a breaking open of many of the most intractable lock-ins that underpin our food system today. Moves by governments around the world, and across the political spectrum, to channel funds into emergency food supply networks and relief programmes for small-scale farmers and smallholders mark a significant redirection of conventional financial flows in the food system, and of government policy towards intervention in food markets.

4.2 Recommendations

Below, we set out three key recommendations for action to harness the opportunities that the coming months offer, and to drive forwards food system transformation in support of biodiversity. These are: (1) recognizing the interrelationship between demand and supply; (2) adopting a 'food systems approach' to drive action; and (3) strengthening the coherence between global agreements and local actions.

4.2.1 Recognize the interdependencies of demand and supply in designing food system reform

The importance of food production and consumption patterns to today's global challenges – mitigating and adapting to climate change, tackling malnutrition and worsening diet-related public health, and managing natural resources in a way that respects planetary boundaries – is now firmly established. International bodies across a range of policy spheres are increasingly talking about the importance of sustainable food production and healthy diets for their agendas.

Food systems nevertheless continue to be addressed in their component parts more often than as a coherent whole. Negotiations under the auspices of the UN Framework Convention on Climate Change (UNFCCC) address agriculture, forestry and land use as major sources of emissions. The production-based GHG inventory framework – underpinning Nationally Determined Contributions to global mitigation efforts – does not account for the importance of national food consumption and food waste patterns in driving land-use change and emissions overseas. Discussions under the UN Convention on Biological Diversity (UNCBD) and the UN Convention to Combat Desertification (UNCCD) focus on agriculture as a driver of land degradation, ecosystem erosion and biodiversity loss, but do not address the importance of demand-side changes in easing the environmental pressure caused by food production systems. The Nutrition for Growth summits seek to focus government and private sector attention on nutrition interventions at the point of food processing and distribution, and on the biofortification of farmed crops. But the summits largely overlook discussion of structural changes to production methods that would strengthen nutrition security in the longer term, or discussion of dietary changes that would contribute to improved public health and a reduced burden of diet-related disease.

This disjointed approach to food systems – separating demand and supply – needs to change.[95] To change supply-side practices we need to change demand-side markets, and vice versa. Success in setting aside space for biodiversity while adopting nature-friendly farming practices elsewhere will depend on shifting demand and market incentives: all three levers will need to be deployed in concert, and at multiple scales, if food systems are to be transformed in a way that maximizes planetary and human health benefits.

The Post-2020 Global Biodiversity Framework, to be agreed at the 15th Conference of the Parties to the UNCBD (see Box 4, CBD COP15) in 2021, will provide a crucial opportunity to embed a 'food systems approach' into the global action agenda on biodiversity. It is particularly important for the dialogue around the conference to recognize the complexity of drivers behind biodiversity loss, and to ensure that COP15 speaks to multiple sectors rather than to the environmental community alone. As highlighted in a recent study: 'Whereas the mission of the UNFCCC focuses on one main outcome – preventing dangerous climate change, for which one goal and indicator provide a reasonable proxy for the others – CBD's vision and mission have three components that are distinct, complementary, and often trade off with each other: conserving nature, using it sustainably…, and sharing its benefits equitably.'[96] There is an urgent need for systemic thinking to identify leverage points through which interventions will lead to the greatest change, while mitigating the risk of trade-offs, and to seek aligned policies that interact positively across multiple objectives.

4.2.2 Ensure the UN Food Systems Summit embeds a 'food systems approach' across key international policy processes

The UN Food Systems Summit (UNFSS), planned for September 2021, will be the first time that world leaders have come together, along with the business community and civil society, to discuss food systems and how they must change. It is a key opportunity to embed food systems thinking in the international community.

The success of the summit in bringing a food systems approach into mainstream policy thinking will be measurable by the extent to which the UNFSS leads to the adoption of this approach across related policy processes – specifically, those associated with the UNFCCC and UNCBD. While the Intergovernmental Panel on Climate Change (IPCC) took a food systems approach in its recent special report

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[95] United Nations Environment Programme (UNEP) (2019), *Collaborative Framework for Food Systems Transformation. A multi-stakeholder pathway for sustainable food systems*, https://www.oneplanetnetwork.org/sites/default/files/un-e_collaborative_framework_for_food_systems_transformation_final.pdf.
[96] Díaz, S., Zafra-Calvo, N. and Purvis, A. (2020), 'Set ambitious goals for biodiversity and sustainability', *Science*, 370(6515): pp. 411–13, doi: 10.1126/science.abe1530 (accessed 3 Nov. 2020).

on climate change and land,[97] and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is developing a 'nexus' approach to linking food and biodiversity,[98] these approaches need to become fully integrated into UNFCCC and UNCBD political discourse.[99] This may, in turn, require capacity-building and greater coordination within governments, where there is often a view that agriculture is a primary industry within the purview of trade policy, whereas nutrition is a matter for public health policy, and promotion of consumption a lever for economic growth within the finance policy domain.

A central aim of the UNFSS should be to bring together interdependent policy threads, strongly articulating the co-benefits to be reaped through biodiversity-supporting food system reform. From this, the summit should aim to concentrate attention on a set of common goals for food system transformation:

- To preserve the planet, particularly in regard to climate and biodiversity;
- To drive prosperity, through support for more resilient farmer livelihoods and more inclusive and sustainable growth; and
- To increase health and well-being, by promoting the adoption of healthier diets and access to nature worldwide.

In particular, given the importance of demand-side changes to biodiversity conservation,[100] climate change mitigation, and improved public health and nutrition, the UNFSS should signal the urgent need to adjust demand patterns without undermining prosperity growth. Failure on the part of the UNFSS convenors and decision-makers to move beyond a narrow focus on food security and sustainable intensification of food systems would represent a significant missed opportunity and moreover a risk of current food system trends continuing.

4.2.3 Strengthen coherence between global agreements and national-level action

The coming year is crucial for international cooperation on biodiversity protection in particular, and for environmental governance more generally, as well as for food systems and climate change (see Box 4). But the success of commitments and agreements made at the global level in 2021 will also rest on the effectiveness and pace of policy development at the national level.

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[97] IPCC (2019), *Climate Change and Land*; and Rosenzweig, C., Mbow, C., Barioni, L. G., Benton, T. G., Herrero, H., Krishnapillai, M., Liwenga, E. T., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubeillo, F. N., Xu, Y., Mencos Contreras, E. and Portugal-Pereira, J. (2020), 'Climate change responses benefit from a global food system approach', *Nature Food* 1: pp. 94–97, doi: 10.1038/s43016-020-0031-z (accessed 3 Nov. 2020).
[98] IPBES (2019), 'Nexus assessment', https://ipbes.net/nexus (accessed 3 Nov. 2020).
[99] Schulte, I., Bakhtary, H., Siantidis, S., Haupt, F., Fleckenstein, M. and O'Connor, C. (2020), *Enhancing NDCs for food systems. Recommendations for decision-makers,* WWF Germany and WWF Food Practice, https://wwfint.awsassets.panda.org/downloads/wwf_ndc_food_final_low_res.pdf.
[100] Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J. P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., Mace, G. M., Ohashi, H., Popp, A., Purvis, A., Schipper, A. M., Tabeau, A., Valin, H., van Meijl, H., van Zeist, W.-J., Visconti, P., Alkemade, R., Almond, R., Bunting, G., Burgess, N. D., Cornell, S. E., Di Fulvio, F., Ferrier, S., Fritz, S., Fujimori, S., Grooten, M., Harwood, T., Havlík, P., Herrero, M., Hoskins, A. J., Jung, M., Kram, T., Lotze-Campen, H., Matsui, T., Meyer, C., Nel, D., Newbold, T., Schmidt-Traub, G., Stehfest, E., Strassburg, B. B. N., van Vuuren, D. P., Ware, C., Watson, J. E. M., Wu, W. and Young, L. (2020), 'Bending the curve of terrestrial biodiversity needs an integrated strategy', *Nature*, 585: pp. 551–56, doi: 10.1038/s41586-020-2705-y (accessed 3 Nov. 2020).

Three avenues for action in 2021 could together create virtuous circles of reinforcement between global agreements and action at the national level. These should consist of: (a) ongoing national dialogues to mirror international policy processes; (b) the development of global guidelines to inform and support national-level action; and (c) efforts to strengthen national accounting of the impacts of today's food system, and to develop pathways for its transformation. The sections below expand upon each of these areas.

a) National dialogues to mirror global policy processes

To date, national progress on biodiversity conservation and climate change mitigation has been too slow. Moreover, indicators are largely heading in the wrong direction. Similarly, countries around the world remain off course in terms of meeting globally agreed targets on ending malnutrition. If commitments emerging from the various summits in 2021 are to be meaningful and practicable, significant efforts will need to be channelled into national-level dialogues that explicitly address how global commitments – across the domains of climate policy, biodiversity and nutrition – will be translated into national action. In particular, it is crucial that national action focuses on a suite of 'triple-duty interventions' that deliver on biodiversity protection, climate change mitigation, and improved public health and well-being, in order to avoid policy incoherence leading to paralysis of action.

It is crucial that national action focuses on a suite of 'triple-duty interventions' that deliver on biodiversity protection, climate change mitigation, and improved public health and well-being.

National-level governance will be key to delivering land-use strategies that support biodiversity while delivering on other policy agendas, including climate change mitigation and nutrition security. Strong governance will be critical if nature-based solutions (NBS) (see Box 5) in the climate sphere are to be deployed in a way that enables land-sparing for biodiversity or wildlife-friendly agriculture. Financial incentives are likely to be important in some countries, where landowner income is crucial in determining how land is managed. In other countries, effective governance may depend more on shifting landowners' relationship with the land and their perception of its value so that sustainable management is ultimately favoured over shorter-term exploitation. In other countries still, there will be an urgent need to identify and address current incentives that result in land conversion from native ecosystems to farmland or timber plantation, for example, and to replace these with incentives more likely to promote sustainability within the context of a common climate-, health- and biodiversity-maximizing NBS framework. Exploring how existing mechanisms (such as climate finance in the Paris Agreement) could be implemented at the national level to support such an approach to NBS is likely to be an important action point in 2021.

Similarly, concrete action on dietary change will need to be informed by national and cultural contexts. The Food Systems Dialogues series, established in 2018 by a group of five organizations,[101] has provided an entry point for nationally tailored, multi-stakeholder discussions around food system reform that are informed by the latest science and policy thinking at an international level. These dialogues will feed into the UNFSS taking place in September; their continuation and roll-out across all countries among a diverse range of stakeholders will be a critical means of bridging the gap between policymaking at the global and national levels.

b) Global guidelines to inform and support national-level action

While national action to transform food systems in support of biodiversity, climate change mitigation and nutrition security will need to be driven by national-level processes, as outlined above, global guidelines could provide an important basis on which to coordinate action across the global food system and ensure that ambition at the international level is sufficiently high to yield meaningful change.

International decision-makers and advocates have a unique opportunity in 2021 to articulate clear guidance on **principles for ‘system-positive’ investments**[102] that would yield changes to food systems in support of biodiversity conservation and broader environmental and human well-being. Responsible investment will be a core theme running through international forums and conferences in 2021. Growing pressure for a ‘green recovery’ from COVID-19 is focusing attention on the direction of financial flows – both public and private – in support of economic recovery that builds environmental sustainability and societal resilience to future disruptive threats. Green recovery efforts will see mainstream economic policy decisions dovetail with climate and environmental negotiations, opening new doors for international financial actors such as the World Bank and IMF to engage with processes including the UNFSS and UNFCCC and UNCBD summits. As a result, it may be possible to develop common guidelines for responsible investment that drives prosperity while delivering benefits across biodiversity, climate and public health agendas.

A second area where a global framework or guidelines would be helpful would be in informing **investment decisions in nature-based solutions** (NBS, Box 5), particularly if these are to be deployed in a way that mitigates known trade-offs for biodiversity and ecosystems.[103] Organizations such as IUCN have advocated a standardized approach to assessing the strength of a given nature-based solution against a broad set of criteria, covering biodiversity, society and the economy.[104] At the same time, investment actors such as CDP (formerly the Carbon Disclosure Project) have called for NBS to be recognized by decision-makers across policy spheres as a cross-cutting tool that requires coherence and coordination between the areas of climate change, biodiversity and sustainable development if negative

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[101] The EAT Foundation, the Food and Land Use Coalition, the Global Alliance for Improved Nutrition, the World Economic Forum and the World Business Council for Sustainable Development.
[102] Preston, F. and Jain, P. (2020), ‘System Positive’, Generation Investment Management Insights 03, 27 August 2020, https://www.generationim.com/media/1759/gim_insights_report03_download_200827_v2.pdf (accessed 26 Oct. 2020).
[103] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services.*
[104] International Union for Conservation of Nature (IUCN) (undated), ‘Ensuring effective Nature-based Solutions’, Issues Brief, https://www.iucn.org/resources/issues-briefs/ensuring-effective-nature-based-solutions (accessed 3 Nov. 2020).

impacts are to be avoided. Greater coordination and dialogue between the UNCBD, UNFCCC and UNFSS processes on NBS in 2021, and a collective commitment to identifying core principles for effective NBS options, would mark an important first step towards coherent and responsible investment in this space. Core principles should include the potential of NBS to restore functioning ecosystems and remove carbon dioxide (which would be sequestered by restoring vegetation, for example), and a transparent process to prioritize such aspects over commercial interests (for example, timber plantations for logging) (see Box 5).

The third area in which global guidelines could support national-level action would be in **dietary change**, particularly in promoting the adoption of healthy diets consisting of sustainably produced food. With strong and growing scientific evidence of the importance of dietary change as a key route to improving public health, mitigating climate change and keeping within critical planetary boundaries, adopting healthier diets should be high on the agenda of international discussions in 2021. To a significant extent, the design and implementation of dietary guidelines will need to be nationally tailored and culturally informed. However, international bodies that already advise on the principles for a healthy diet and sustainable food systems – particularly the World Health Organization and the UN Food and Agriculture Organization – are in a strong position to endorse principles for healthy and sustainable diets, such as those put forward by the EAT-Lancet Commission[105] and leading academics behind the commission's findings.[106] Similarly, the UNFSS offers an opportune moment for world leaders to commit to a common set of principles for diets that are healthy, accessible and environmentally sustainable, while pledges at the Nutrition for Growth Summit could align explicitly with these principles. Pledges could outline concrete plans for tackling the double burden of malnutrition in a sustainable manner that protects biodiversity in support of long-term food and nutrition security.

Box 5. Making nature-based solutions work for biodiversity

Nature-based solutions (NBS) are increasingly being considered as part of climate change mitigation strategies. NBS are in essence natural or ecosystem processes that tackle pressing issues, such as climate change. In some cases, a number of issues can be addressed simultaneously through a single nature-based solution, such as mangrove forests which filter water, protect against storms, and remove GHGs from the atmosphere. Implementing NBS entails the protection or restoration of ecosystems such as forests or wetlands, to ensure their resilience and maximize their ability to help address pressing issues, while delivering biodiversity and human well-being benefits.

In principle, NBS offer an important means of restoring natural infrastructure and ecosystems, including forests, wetlands and soils, all of which are important carbon 'sinks'. But in practice, they could risk furthering activities that degrade rather than

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[105] Willett et al. (2019), 'Food in the Anthropocene: the EAT-*Lancet* Commission on healthy diets from sustainable food systems'.
[106] Springmann, M., Weibe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M. and Scarborough, P. (2018), 'Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail', *Lancet Planet Health*, 2(10): e451-e461, doi: 10.1016/S2542-5196(18)30206-7 (accessed 26 Oct. 2020).

support biodiversity and ecosystem rehabilitation. For example, the planting of monoculture forests may be prioritized over other approaches that could deliver more carbon sequestration and biodiversity-supporting habitats, such as polyculture planting that incorporates multiple species of tree or agroforestry sites that intercrop trees with food crops.[107]

NBS at scale may compete for land resources with other proposed climate change mitigation measures. For example, climate models in line with the Paris Agreement assume deployment of bioenergy with carbon capture and storage (BECCS) at an enormous scale, equivalent to half of the land currently used for crop production.[108] Were deployment on that scale to go ahead, pressure on the remaining land – for food production, energy production and urban expansion, among other uses – would massively increase.[109] This would in turn limit the amount of space available for NBS, and likely drive further intensification of existing food systems through biodiversity-harming inputs and practices.

Designed in the right way, NBS could make a meaningful contribution to increasing biodiversity. For example, reforestation could be implemented to make full carbon sequestration gains and maximize opportunities for constructing or restoring resilient ecosystems (including native flora and fauna, with connecting corridors to neighbouring ecosystems where relevant). NBS could also be limited to land that does not compromise essential food production (for example, high-grade arable farmland could be excluded from land-sparing). There are also differences in terms of the amount of carbon storage and sequestration potential, and biodiversity levels, an ecosystem can support. For example, 'hotspot' areas include tropical rainforests and tropical peatlands – these types of ecosystems are species-rich, contain unique species and store large amounts of carbon.[110] However, the biggest potential for additional carbon sequestration comes from restoring areas where native ecosystems have been removed to a large extent; examples include temperate forests in Western Europe and East Asia.[111]

c) National accounting of food system impacts on nature and people

Identifying effective interventions for food system reform will depend on both an understanding of the scale of the challenge and an evidence base to inform policy and investments (both public and private). Global commitments to biodiversity conservation – such as that laid out in the zero draft of the Post-2020 Global Biodiversity Framework to ensure 'no net loss by 2030 in the area and integrity of freshwater, marine and terrestrial ecosystems, and increases of at least [20%] by 2050, ensuring ecosystem resilience'[112] – will require translation into national-level

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[107] Yang, A. (2018), 'Interventions: Natural Infrastructure', Hoffmann Centre for Sustainable Resource Economy, Chatham House, 11 June 2018, https://hoffmanncentre.chathamhouse.org/article/natural-infrastructure-for-livelihoods-planetary-and-human-health (accessed 25 Aug. 2020).
[108] Brack, D. and King, R. (2020), *Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage?*, Research Paper, London: Royal Institute of International Affairs, https://www.chathamhouse.org/2020/01/net-zero-and-beyond-what-role-bioenergy-carbon-capture-and-storage-0 (accessed 25 Aug. 2020).
[109] Chatham House (forthcoming), *Land Futures* (working title), London: Royal Institute of International Affairs.
[110] Díaz, Zafra-Calvo and Purvis (2020), 'Set ambitious goals for biodiversity and sustainability.'
[111] Hayek et al. (2020), 'The carbon opportunity cost of animal-sourced food production on land'.
[112] CBD (2020), 'Zero Draft of the Post-2020 Global Biodiversity Framework', 6 January 2020, https://www.cbd.int/doc/c/efb0/1f84/a892b98d2982a829962b6371/wg2020-02-03-en.pdf (accessed 26 Oct. 2020).

targets and action plans if they are to be meaningful. Yet currently neither policy decision-makers nor private financiers have the information needed to determine 'system-positive' actions that could yield effective change in respect of the three levers identified in this paper – diet change, preservation of land for nature, and nature-friendly agriculture – while mitigating unintended trade-offs.

Data on the impacts of national food production and consumption – i.e. the impacts on biodiversity, land use, climate change, and public health and nutrition – are lacking, particularly in relation to biodiversity. Efforts to track national progress towards the Aichi Biodiversity Targets have been stymied by the lack of clear, quantifiable baselines, goals and indicators, and by the absence of a common framework for country reporting.[113] The global GHG inventory framework underpinning national targets under the UNFCCC accounts only for the impacts of domestic agriculture; it fails to capture the embedded GHGs in national food consumption. And national data on dietary diversity, nutrition and diet-related ill-health remain patchy and inconsistent.

Approaches such as the TEEBAgriFood Evaluation Framework[114] offer the means of assessing, *inter alia*, the impacts and the costs of food systems and agricultural practices for biodiversity. But there is not yet a common accounting framework to underpin the UNCBD discussions and guide national-level accounting of remaining biodiversity at a domestic level and the embedded biodiversity impacts of national food consumption patterns. Consumption-based GHG emissions accounting under the UNFCCC would go some way to filling the data gap, as this would require assessing land use and land-use change associated with national food consumption. However, such accounting would still offer only a partial snapshot of the environmental costs of a country's food system. What is needed is a comprehensive framework that allows for the costs – and benefits – of national food production and consumption with respect to GHG emissions, land use, biodiversity, and public health and nutrition to be assessed collectively in a standardized way and reported on consistently.

In the absence of such a common framework, efforts to embed national-level accounting and planning processes through partnerships such as the Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium will be critical to building the knowledge and evidence base to guide effective action. FABLE is working with national knowledge partner networks to develop long-term pathways and strategies that would deliver against three identified pillars of integrated land-use and water-use planning: efficient and resilient agriculture systems; conservation and restoration of biodiversity; and food security and healthy diets. Learnings from such country-level processes should be recognized and integrated into international policy discussions in 2021, particularly by convenors and decision-makers at the UNFSS, and used as a basis for identifying and addressing needs in respect of a common global accounting framework that would link across biodiversity conservation, climate change mitigation and public health agendas.

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[113] OECD (2019), *The Post-2020 Biodiversity Framework: Targets, indicators and measurability implications at global and national level*, http://www.oecd.org/environment/resources/biodiversity/report-the-post-2020-biodiversity-framework-targets-indicators-and-measurability-implications-at-global-and-national-level.pdf (accessed 26 Oct. 2020).

[114] TEEB stands for 'The Economics of Ecosystems and Biodiversity'. TEEB (undated), 'The Evaluation Framework', http://teebweb.org/our-work/agrifood/understanding-teebagrifood/evaluation-framework (accessed 27 Oct. 2020).

05
Technical annex

In this annex, we discuss in depth the principal channels through which food systems impact biodiversity, and review the existing literature. The annex focuses on terrestrial biodiversity, as affected by the terrestrial parts of the food system.[115] We also consider the key approaches outlined in the literature to implementing dietary change, land-sparing for nature, and nature-friendly farming. These are the three levers for food system reform outlined in the main body of the research paper.

5.1 The impacts of today's food system on biodiversity

As discussed in Chapter 2, the global food system today is shaped by a predominant 'cheaper food' paradigm. Under this paradigm, policies and economic incentives have been shaped over decades to deliver two key outcomes: greater quantities of food, and food at lower prices. Key to this paradigm has been the intensification of agriculture.

Since the 1960s, global agricultural output has risen enormously: calorie production rose 2.7-fold between 1961 and 2005.[116] This increase was not achieved through agricultural expansion: over the same period, the area of land used for agriculture increased by only 10 per cent worldwide (see Figure 6).[117] Instead, it was achieved through the intensification of agriculture: producing more food per hectare of land. Intensification has in turn been delivered through multiple practices, including breeding new varieties of crop for increased yield; increasing the density of plants in crops; increasing the confinement or stocking density of farmed animals; farming at greater scales; making more use of mechanization; irrigating the soil; and ramping up the use of inputs such as fertilizer, pesticides, growth promotors, soil-liming, and concentrated nutrition and antimicrobials for farmed animals.

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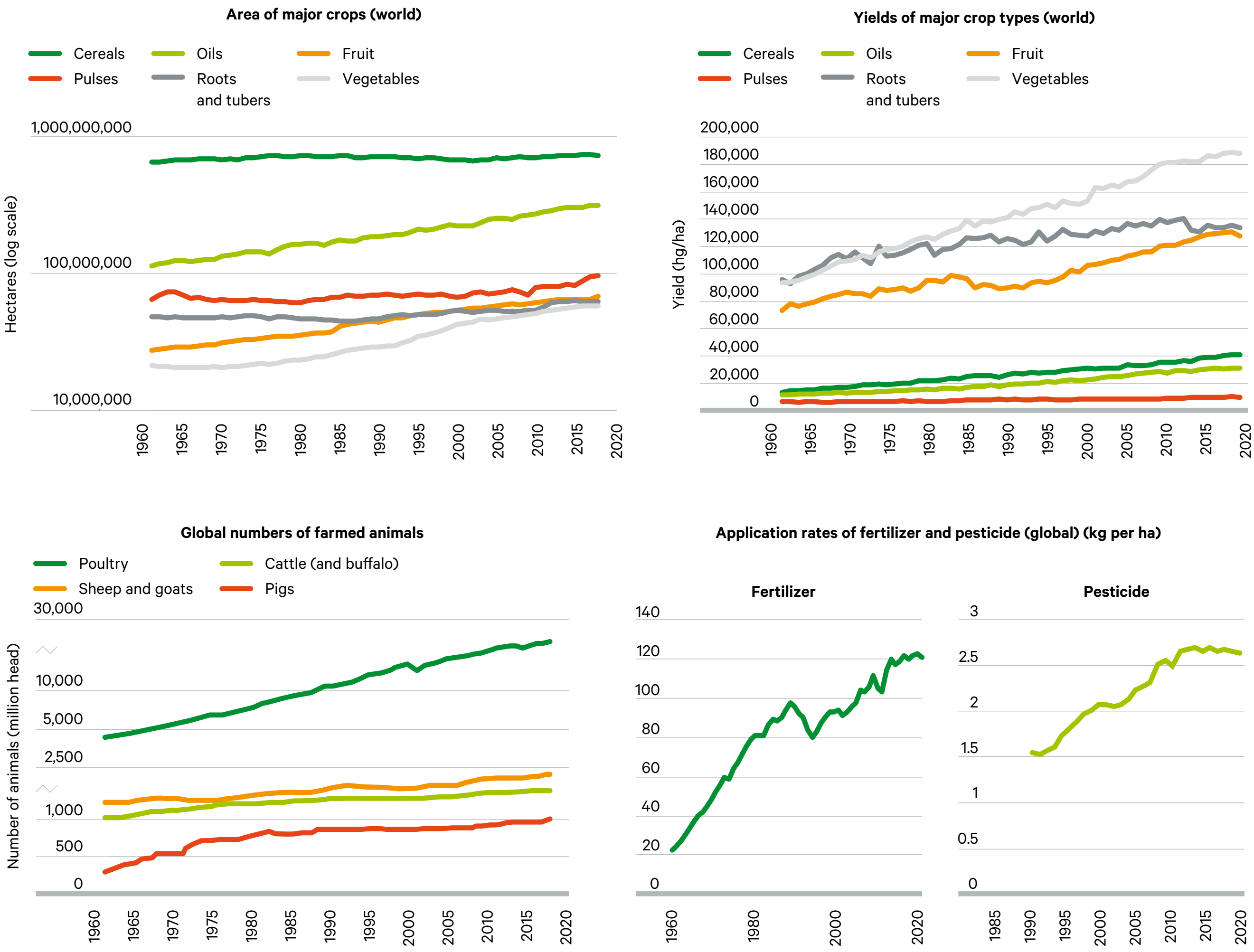
[115] However, we recognize that (a) intensification of capture fisheries impacts both target fish and non-target biodiversity through perturbing habitat and ecosystems, in similar conceptual ways to farming's impact on on-farm biodiversity; and that (b) fish 'farming' or aquaculture leads to significant spillover effects to local ecosystems (e.g. clearing mangrove forest for prawn fisheries; genetic contamination from farmed to wild populations; pollution from farms into the wider aquatic environment).
[116] Table 4.1 in Alexandratos, N. and Bruinsma, J. (2012), *World Agriculture Towards 2030/2050. The 2012 Revision*, ESA Working paper No. 12-03, Rome: FAO, http://www.fao.org/3/a-ap106e.pdf (accessed 3 Nov. 2020).
[117] Ibid.

As can be seen in Figure 6, fertilizer use increased more than fivefold between 1961 and 2018, while pesticide use has almost doubled since 1990.

Figure 6. Trends in world agriculture



Source: Food and Agriculture Organization of the United Nations (2018), FAOSTAT, www.fao.org/faostat/en/#data/OA (accessed 1 Dec. 2020).

Agricultural intensification has supported remarkable yield growth, but has come with significant environmental costs, as outlined in Chapter 2. These costs include huge losses in biodiversity. Globally, the number of species and abundance of organisms found at any given locality are estimated to have declined by about 14 per cent on average over the last 200 years. In sites associated with high land-use intensity, the number of species has declined by nearly three-quarters over the same period.[118] Much of this is directly due to habitat destruction for food production. From 2001 to 2015, 27 per cent of deforestation globally was associated with the expansion of the production of commodities (such as beef, soy and palm oil).[119] In the Amazon, between 1978 and 2020, more than 75 million hectares of rainforest were felled (equivalent to 1.5 times the land area of Spain);

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[118] Newbold et al. (2015), 'Global effects of land use on local terrestrial biodiversity'.
[119] Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. and Hansen, M. C. (2018), 'Classifying drivers of global forest loss', *Science*, 361(6407): pp. 1108–11, doi: https://doi.org/10.1126/science.aau3445 (accessed 6 Nov. 2020).

of this, about three-quarters was for cattle ranching.[120] Habitat and biodiversity losses are occurring not only in forested regions, but across large areas of other types of land that are being degraded through agriculture around the world.

Below, we summarize the existing literature on the impact channels through which food production has driven biodiversity loss.

5.1.1 Impacts at farm scale

5.1.1.1 Homogenization of farmland

The incentives that drive farming productivity are the same as those that create specialization. The advent of herbicides and synthetic fertilizers in the second half of the 20th century reduced the requirement for complex crop rotations that suppress weeds and build fertility. Without rotations, there is no longer a need for separate field parcels. As a result, fields have typically been amalgamated into larger blocks of land for monocultures. Given the ability to manage land at scale with large machinery and equipment, these processes have led to increased homogeneity between fields (with adjoining fields often put to the same use) and over time (with simpler rotations, and large equipment). In effect, large blocks of land have come to be managed in the same way simultaneously.[121]

The fact that fields are typically sown and harvested at similar times means that the landscape is uniform both spatially and temporally. Many animals require different sorts of habitat at different times of the day or year (e.g. nesting habitat that is near foraging habitat), so spatial uniformity is problematic. Take, for example, European skylarks, which are ground-nesting birds that nest on farmland and require short vegetation for an unobstructed view of potential predators. Like many small birds, European skylarks need to rear multiple broods each year to maintain viable populations. Historically, after nesting once, they would have found another field nearby, planted with a different crop at a different time, where vegetation would have been short enough to allow a second brood to be reared. However, today it is likely that all nearby fields would be growing the same crop, planted at the same time, greatly reducing the birds' ability to find a suitable breeding habitat.

As fields are amalgamated, non-cropped field boundaries and unused pockets of land are lost. Habitat that is not managed for production often has a diversity of native plants, and is utilized by animals for resting, reproduction and/or foraging. In studies of UK farmland, field margins are consistently found to house greater biodiversity than field edges or centres – up to three times the numbers of species and individual organisms.[122] Plant biodiversity is greatest outside managed fields in unmanaged, uncropped, ungrazed areas. Non-farmed margins create habitat, supporting animal populations that spread into managed areas as the seasons progress. These populations include important pest-control species such

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[120] Butler, R. A. (2020), 'Amazon destruction', Mongabay, 16 August 2020, https://rainforests.mongabay.com/amazon/amazon_destruction.html (accessed 3 Nov. 2020).
[121] Benton, Vickery and Wilson (2003), 'Farmland biodiversity: is habitat heterogeneity the key?'.
[122] Gabriel, D., Sait, S. M., Hodgson, J. A., Schmutz, U., Kunin, W. E. and Benton, T. G. (2010), 'Scale matters: the impact of organic farming on biodiversity at different spatial scales', *Ecology Letters*, 13(7), doi: 10.1111/j.1461-0248.2010.01481.x (accessed 3 Nov. 2020); and Douglas, D. J. T., Vickery, J. A. and Benton, T. G. (2009), 'Improving the value of field margins as foraging habitat for farmland birds', *Journal of Applied Ecology*, 46(2), doi: 10.1111/j.1365-2664.2009.01613.x (accessed 3 Nov. 2020).

as spiders and ground beetles.[123] The diversity of animals and plants depends on a range of management practices, including sowing dates and pesticide usage.[124] Furthermore, poor management of these marginal areas (e.g. the application of fertilizer and pesticides that seep on to uncropped land) can reduce their value both as habitat for animals and plants and as foraging areas for birds. The yellowhammer, a bird which, in the UK, nests in field margins, prefers to feed its chicks on insects caught in field margins. If this food source is unavailable, it will use unripe grains from crop fields as a substitute; however, such grains have lower nutritional quality, resulting in less robust chicks.[125]

5.1.1.2 Disruption of ecological communities above and below ground

Intensive agricultural practices have adverse effects on above- and below-ground ecological communities. Heavy tillage, monocropping and excessive use of agrochemicals destroy beneficial fungal and bacterial populations that help plants with nutrient availability and disease management.[126] Entire soil microbial communities, which include thousands of beneficial microbes, are being simplified under intensive farming practices. They are losing the diversity they exhibit under organic or less intensive farming practices. This ultimately has negative implications for crop performance and yields.[127] Above-ground biodiversity is also affected by the use of fertilizers and other inputs, such as pesticides. Fertilizer use on managed fields causes excess nutrients to ‘enrich’ natural neighbouring habitats, allowing more competitive grasses to grow and crowd out native, nutrient-limited ecological communities.[128] In terms of other inputs, the use of pesticides (herbicides, insecticides, molluscicides, fungicides etc.) is harmful to non-target organisms both within cropping areas and through leakage into wider landscapes.[129]

Many insect populations have declined drastically in both terrestrial and aquatic ecosystems worldwide due to food production.[130] The largest drivers of insect species decline, in descending order of importance, are as follows: 1) habitat loss, conversion

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[123] Woodcock, B. A., Bullock, J. M., McCracken, M., Chapman, R. E., Ball, S. L., Edwards, M. E., Nowakowski, M. and Pywell, R. F. (2016), ‘Spill-over of pest control and pollination services into arable crops’, *Agriculture, Ecosystems & Environment*, 231: pp. 15–23, doi; 10.1016/j.agee.2016.06.023 (accessed 3 Nov. 2020).

[124] Douglas, D. J. T., Vickery, J. A. and Benton, T. G. (2010), ‘Variation in arthropod abundance in barley under varying sowing regimes’, *Agriculture, Ecosystems & Environment*, doi: 10.1016/j.agee.2009.09.002 (accessed 3 Nov. 2020).

[125] Douglas, Vickery and Benton (2009), ‘Improving the value of field margins as foraging habitat for farmland birds’; and Douglas, D. J. T., Moreby, S. J. and Benton, T. G. (2011), ‘Provisioning with cereal grain depresses the body condition of insectivorous Yellowhammer *Emberiza citrinella* nestlings’, *Bird Study*, 59(1): pp. 105–09, doi: 10.1080/00063657.2011.636797 (accessed 3 Nov. 2020).

[126] Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K. and Hedlund, K. (2015), ‘Intensive agriculture reduces soil biodiversity across Europe’, *Global Change Biology*, 21(2): pp. 973–85, https://doi.org/10.1111/gcb.12752 (accessed 6 Nov. 2020).

[127] Banerjee, S., Walder, F., Büchi, L., Meyer, M., Held, A. Y., Gattinger, A. and van der Heijden, M. G. A. (2019), ‘Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots’, *ISME Journal*, 13(7): pp. 1722–36, https://doi.org/10.1038/s41396-019-0383-2 (accessed 6 Nov. 2020); Nelkner, J., Henke, C., Lin, T. W., Pätzold, W., Hassa, J., Jaenicke, S. and Schlüter, A. (2019), ‘Effect of long-term farming practices on agricultural soil microbiome members represented by metagenomically assembled genomes (MAGs) and their predicted plant-beneficial genes’, *Genes*, 10(6), https://doi.org/10.3390/genes10060424 (accessed 6 Nov. 2020); and Edwards, J., Santos-Medellín, C., Nguyen, B., Kilmer, J., Liechty, Z., Veliz, E. and Sundaresan, V. (2019), ‘Soil domestication by rice cultivation results in plant-soil feedback through shifts in soil microbiota’, *Genome Biology*, 20(1): pp. 1–14, https://doi.org/10.1186/s13059-019-1825-x (accessed 6 Nov. 2020).

[128] Isbell, F., Reich, P. B., Tilman, D., Hobbie, S. E., Polasky, S. and Binder, S. (2013), ‘Nutrient enrichment, biodiversity loss, and consequent declines in ecosystem productivity’, *Proceedings of the National Academy of Sciences of the United States of America,* 110(29): pp. 11911–16, doi: 10.1073/pnas.1310880110 (accessed 3 Nov. 2020).

[129] Milner, A. M. and Boyd, I. L. (2017), ‘Toward pesticidovigilance’, *Science*, 357(6357): pp. 1232–34, doi: 10.1126/science.aan2683 (accessed 3 Nov. 2020).

[130] Seibold, S., Gossner, M. M., Simons, N. K., Blüthgen, N., Müller, J., Ambarlı, D. and Weisser, W. W. (2019), ‘Arthropod decline in grasslands and forests is associated with landscape-level drivers’, *Nature*, 574(7780): pp. 671–74, https://doi.org/10.1038/s41586-019-1684-3 (accessed 6 Nov. 2020); and Sánchez-Bayo, F. and Wyckhuys, K. A. G. (2019), ‘Worldwide decline of the entomofauna: A review of its drivers’, *Biological Conservation*, 232 (September 2018): pp. 8–27, https://doi.org/10.1016/j.biocon.2019.01.020 (accessed 6 Nov. 2020).

to intensive agriculture and urbanization; 2) pollution, mainly from synthetic pesticides and fertilizers; 3) biological factors, including the presence of pathogens and introduced non-native species; and 4) climate change.[131] If current trends continue, it is estimated that 40 per cent of insect species will become extinct within the next few decades, though not all species will be impacted equally. Specialist species are being replaced by pollution-tolerant dietary generalists.[132] Many of these specialist species, which are vulnerable to land modification and pollution, play important functional roles in their ecosystems.[133]

For example, both spiders and ground beetles have been indicated as invertebrate taxa that are particularly affected by agricultural land use. Certain species are more heavily affected than others. However, researchers have found that such groups do not necessarily suffer strict declines in species richness but instead change in composition in response to different land uses.[134] In addition to harming dietary specialists, agricultural land uses have severe impacts on many habitat specialists. Spiders, for example, are important predators in agro-ecosystems, but certain functional types of spiders rely on specific habitats. Among these are aerial web-building spiders, which are particularly dependent on riparian zones and hedgerows as habitat. As more of these areas are developed for food production, the functioning of whole agro-ecosystems may be impaired. That said, even small ‘habitat islands’ within arable croplands can support unique groups of ground-dwelling spiders and carabid beetles that would not be present in regular cropland.[135] The type of habitat in these islands, rather than the islands’ size, mostly determines the diversity of species.[136] This suggests that maintaining habitat heterogeneity – even in small quantities – is crucial for conserving biodiversity and ecosystem functionality in agricultural lands. Hence, habitat complexity on a local scale is important for maintaining specialist predator populations that are important for pest control.[137]

5.1.1.3 Pollution of aquatic ecosystems

Uncropped areas around drains, streams and rivers – riparian zones – also serve as important habitats that integrate communities of plants and animals from aquatic and terrestrial environments. Many terrestrial wildlife species that directly improve food production also rely on riparian zones. Such species include

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[131] Sánchez-Bayo and Wyckhuys (2019), ‘Worldwide decline of the entomofauna: A review of its drivers’.

[132] Ibid.

[133] Dainese, M., Isaac, N. J. B., Powney, G. D., Bommarco, R., Öckinger, E., Kuussaari, M., Pöyry, J., Benton, T. G., Gabriel, D., Hodgson, J. A., Kunin, W. E., Lindborg, R., Sait, S. M. and Marini, L. (2016), ‘Landscape simplification weakens the association between terrestrial producer and consumer diversity in Europe’, *Global Change Biology*, 23(8): pp. 3040–51, doi: 10.1111/gcb.13601 (accessed 3 Nov. 2020).

[134] Cole, L. J., McCracken, D. I., Downie, I. S., Dennis, P., Foster, G. N., Waterhouse, T. and Kennedy, M. P. (2005), ‘Comparing the effects of farming practices on ground beetle (Coleoptera: Carabidae) and spider (Araneae) assemblages of Scottish farmland’, *Biodiversity and Conservation*, 14(2): pp. 441–60, https://doi.org/10.1007/s10531-004-6404-z (accessed 6 Nov. 2020).

[135] Knapp, M. and Řezáč, M. (2015), ‘Even the smallest non-crop habitat islands could be beneficial: Distribution of carabid beetles and spiders in agricultural landscape’, *PLoS ONE*, 10(4): pp. 1–20, https://doi.org/10.1371/journal.pone.0123052 (accessed 6 Nov. 2020); and Thomas, M. B., Wratten, S. D. and Sotherton, N. W. (1992), ‘Creation of “island” habitats in farmland to manipulate populations of beneficial arthropods: predator densities and emigration’, *Journal of Applied Ecology*, 28(3): pp. 906–17, https://doi.org/10.2307/2404216 (accessed 6 Nov. 2020).

[136] Knapp and Řezáč (2015), ‘Even the smallest non-crop habitat islands could be beneficial: Distribution of carabid beetles and spiders in agricultural landscape’.

[137] Chaplin-Kramer, R., O’Rourke, M. E., Blitzer, E. J. and Kremen, C. (2011), ‘A meta-analysis of crop pest and natural enemy response to landscape complexity’, *Ecology Letters*, 14(9): pp. 922–32, https://doi.org/10.1111/j.1461-0248.2011.01642.x (accessed 6 Nov. 2020).

insects that develop in streams, emerge as adults into the air and feed a range of predators, including birds and spiders. In turn these predators, sustained by prey from non-cropped land, can control pests on farmed fields. Importantly, there is a feedback loop between terrestrial and aquatic ecosystems, as the degradation of aquatic ecosystems can negatively impact populations on land and vice versa. For example, the species richness and population density of spiders have been shown to be negatively correlated with pesticide toxicity in streams, which provide habitat for the emerging insects on which the spiders feed.[138]

Riparian zones are also important for reducing nutrient and pesticide run-off and soil erosion into adjacent streams, which can affect water quality and stream communities. At low levels of run-off, these nutrients may promote functioning and stability of communities; however, increasing nutrient flows downstream can rapidly destabilize food webs.[139]

5.1.1.4 Loss of large herbivores through grazing of farmed animals

Incentives to increase agricultural productivity and farm incomes in preference to preserving wildlife habitats are not limited to highly intensive agricultural systems. Land degradation caused by overgrazing from extensively farmed herbivores is particularly acute in some countries, as illustrated in the example in Box 6 on pastoralist/grazer/wildlife conflict in Botswana.

Box 6. Pastoralist/grazer/wildlife conflict in Botswana

Conservation of African wildlife is often dependent on the interaction between conservation areas and adjacent pastoral areas. With human population densities, the size and number of settlements, and grazing pressure of farmed animals in communally managed pastoral areas all increasing, there is the potential for grazing land to become degraded, putting pressure on conservation areas. A study in the Kalahari Desert in 2019 looked at the interactions between farmed animals and wildlife.[140] The study showed that while pastoral activities were largely confined to communally managed grazing areas within about 15 km of the main settlements, the free-ranging farmed animals reduced forage quality and quantity in wet and dry seasons. Large wild herbivores and carnivores avoided the communally managed grazing areas. Medium-sized wild herbivores and carnivores avoided areas of high grazing intensity, but used moderately grazed areas outside the conservation areas. Small wild herbivores, except springbok, foraged across the communally managed grazing areas. These results suggest that, even though pastoral lands near conservation areas are important as seasonal dispersal and breeding grounds for wildlife, intensified pastoral activities (such as increased intensity of farmed animal grazing) and pastoralist-induced risk are restricting the seasonal movements of medium-sized to large wildlife between the conservation areas and the adjacent communal grazing areas.

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[138] Graf, N., Battes, K. P., Cimpean, M., Dittrich, P., Entling, M. H., Link, M. and Schäfer, R. B. (2019), 'Do agricultural pesticides in streams influence riparian spiders?', *Science of the Total Environment*, 660: pp. 126–35, https://doi.org/10.1016/j.scitotenv.2018.12.370 (accessed 6 Nov. 2020).

[139] Huxel, G. R. and McCann, K. (1998), 'Food web stability: The influence of trophic flows across habitats', *American Naturalist*, 152(3): pp. 460–69, https://doi.org/10.1086/286182 (accessed 6 Nov. 2020).

[140] Akanyang, L. (2019), 'Pastoralists, Free-Ranging Livestock and Wildlife Interactions: Adaptation to Land Use Change and Grazing Resources Variability in Kalahari North, Botswana', PhD thesis, University of Leeds, http://etheses.whiterose.ac.uk/24893 (accessed 3 Nov. 2020).

5.1.2 Impacts at landscape scale

The discussion above has focused broadly on what farming does to wildlife at the field and farm scale – through immediate impacts from tillage, grazing, nutrients and other chemical inputs, and farm specialization. Looking at the issue at landscape scale allows analysis of the additional impacts that arise from larger, more uniform agriculture across multiple farms in a given setting. As discussed in the literature, the impact of an intensive farm in a landscape of semi-natural habitat is very different from the impact of the same farm in a landscape of uniform monoculture.[141]

5.1.2.1 Reduced landscape heterogeneity

Agricultural expansion and intensification have simplified once-complex landscapes, causing habitat loss and fragmentation and reducing biodiversity among plants, insects and animals.[142] Decreasing landscape heterogeneity by switching to single crop production over large areas, as well as removing buffers between farms, depletes breeding habitats and important food sources for many different organisms (including birds, butterflies and spiders). Often, the lost or depleted habitats served as refugia for species, providing habitat 'corridors' that facilitated movements across a landscape. The ability to continue to move across landscapes in this way is increasingly important as climate change affects the areas over which species can range – necessitating, generally, a move towards the poles or higher altitudes. Additionally, large-scale intensive farming often removes or reduces numbers of generalist consumer and predator species important for maintaining the stability of ecosystems. Interactions between the remaining components of the simplified food web cause greater variation in species' population sizes, leading to enhanced risks of local extinctions, further reducing the resilience of the overall system. As a result, we can see many other species declining in abundance or being extirpated from heavily farmed areas, and these regions becoming more susceptible to pest outbreaks as a consequence.[143]

5.1.2.2 Disruption of ecosystem services

Food production adversely affects a variety of taxa that play important functional roles in their ecosystems, including providing supporting 'ecosystem services' to agriculture. When agricultural yields increase as a result of more intensive farming, this in turn causes biodiversity losses that negatively affect the land's yield potential (see Chapter 2 and Figure 3). For example, pollinators have suffered drastic declines in regions around the world, with intensive agricultural practices representing a major threat.[144] Fertilizer use, intensive tillage, heavy

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[141] Benton, T. G., Bailey, R., Froggatt, A., King, R., Lee, B. and Wellesley, L. (2018), 'Designing sustainable land use in a 1.5°C world: the complexities of projecting multiple ecosystem services from land', *Current Opinion in Environmental Sustainability*, 31: pp. 88–95, doi: 10.1016/j.cosust.2018.01.011 (accessed 3 Nov. 2020).

[142] Benton, Vickery and Wilson (2003), 'Farmland biodiversity: is habitat heterogeneity the key?'; and Dainese et al. (2016), 'Landscape simplification weakens the association between terrestrial producer and consumer diversity in Europe'.

[143] Ibid.

[144] IPBES (2017), *The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production*, Potts, S. G., Imperatriz-Fonseca, V. L. and Ngo, H. T. (eds) (2017), Bonn: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), doi: 10.5281/zenodo.3402856 (accessed 3 Nov. 2020).

use of pesticides, crop monocultures and high grazing/mowing intensity all dramatically reduce the size and diversity of pollinator communities – there is no single or simple relationship between a single practice and biodiversity decline.[145]

Locally, the species richness of pollinators declines with repeated pesticide application; but, importantly, these patterns are consistent across whole regions.[146] In regions with more intensive pesticide applications, there is far lower species diversity of bumblebees and butterflies.[147] Winged pollinators such as bees are capable of pollinating large areas of land, but actions such as pesticide use on one farm can have implications for entire regions. Moreover, despite many pollinators' wide dispersal abilities, native habitats remain crucial for maintaining pollination on agricultural lands. Additionally, the simplification of habitats on a landscape scale causes mismatches between plant and pollinator functional and phylogenetic associations, suggesting the potential for large-scale changes to ecosystem functionality.[148] Both pesticide use and isolation from natural habitats cause declines in visitation by flying pollinators, although even small patches of native flowers distributed across a landscape have been shown to mediate the effect of isolation, for example in large mango orchards in South Africa.[149]

Monocultures and pesticide use make whole regions more susceptible to pest outbreaks, further diminishing nature's ability to provide a buffer against shocks. As discussed previously, invertebrates such as spiders and beetles, as well as insectivorous bird species, act as important predators for pest control. Declines in these ecological roles are happening due to local land use and modifications, although some research suggests that habitat heterogeneity on a landscape scale is even more important than local action for pest control.[150] Even without crop rotations, habitat complexity across a landscape can significantly improve pest control by predators and parasitoids, and potentially by pollinators as well.[151] This highlights the findings of Knapp and Řezáč.[152] However, it also suggests that on-farm decisions may be insufficient to ensure the maintenance of important ecosystem functions if the whole landscape is not managed properly, given that the spatial scale of pest control depends on the natural predators present in agro-ecosystems and their dispersal abilities as well as their functional traits.[153]

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[145] Ibid.
[146] Brittain, C. A., Vighi, M., Bommarco, R., Settele, J. and Potts, S. G. (2010), 'Impacts of a pesticide on pollinator species richness at different spatial scales', *Basic and Applied Ecology*, 11(2): pp. 106–15, https://doi.org/10.1016/j.baae.2009.11.007 (accessed 6 Nov. 2020).
[147] Ibid.
[148] Dainese et al. (2016), 'Landscape simplification weakens the association between terrestrial producer and consumer diversity in Europe'.
[149] Carvalheiro, L. G., Seymour, C. L., Nicolson, S. W. and Veldtman, R. (2012), 'Creating patches of native flowers facilitates crop pollination in large agricultural fields: Mango as a case study', *Journal of Applied Ecology*, 49(6): pp. 1373–83, https://doi.org/10.1111/j.1365-2664.2012.02217.x (accessed 6 Nov. 2020).
[150] Rusch, A., Bommarco, R., Jonsson, M., Smith, H. G. and Ekbom, B. (2013), 'Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale', *Journal of Applied Ecology*, 50(2): pp. 345–54, https://doi.org/10.1111/1365-2664.12055 (accessed 6 Nov. 2020).
[151] Shackelford, G., Steward, P. R., Benton, T. G., Kunin, W. E., Potts, S. G., Biesmeijer, J. C. and Sait, S. M. (2013), 'Comparison of pollinators and natural enemies: a meta-analysis of landscape and local effects on abundance and richness in crops', *Biological Reviews*, 88(4): pp. 1002–21, doi: 10.1111/brv.12040 (accessed 3 Nov. 2020).
[152] Knapp and Řezáč (2015), 'Even the smallest non-crop habitat islands could be beneficial: Distribution of carabid beetles and spiders in agricultural landscape'.
[153] Chaplin-Kramer et al. (2011), 'A meta-analysis of crop pest and natural enemy response to landscape complexity'.

Farming has been identified as potentially the largest threat to bird populations worldwide.[154] A recent study showed that agriculture in Costa Rica has caused long-term changes to bird communities.[155] Declines in all major guilds were seen, including birds important for pest control, pollination and seed dispersal. Furthermore, these structural shifts led to increases in community similarity and decreases in resilience to climatic events. These results were especially apparent in intensively farmed areas, suggesting that diversified agricultural land uses (i.e. those that maintain some natural land) could lessen the burden of agricultural development on biodiversity.

5.1.2.3 Nutrient pollution at catchment level

Pollution from excess nutrients washing off farmland – known as eutrophication – affects streams and pools adjacent to agricultural lands. The effects can be dispersed downstream into lakes and coastal zones, leading to toxic algal blooms and hypoxic dead zones.[156] As rivers and streams are modified for faster drainage and lower maintenance (i.e. through channelization) and wetlands are developed into productive agricultural land, the natural capacity of ecosystems to deal with excess nutrients and chemicals is being lost. Natural land cover within agricultural catchments is becoming increasingly important as more land is developed and more fertilizers are applied to croplands. There is likely to be a threshold level of natural land cover (e.g. wetlands, woodlots and grasslands) in these catchments that is needed to buffer against increases in dissolved organic carbon and nutrients in streams associated with hydrological patterns (i.e. flood events). As estimated by Fasching et al.,[157] the threshold of natural land cover is likely to be around 30–40 per cent, below which hydrological events can significantly increase nutrient run-off. Pesticides from farmland can also leach into nearby waterways and have negative impacts on aquatic communities both locally and downstream. Various chemicals, especially pesticides, affect the physiology of aquatic animals, increase chances of infections, hamper reproduction, and thus bring changes in the composition of whole ecosystems.[158] Once again, these patterns highlight the importance of native landscape heterogeneity for maintaining ecosystem functioning and resilience.

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[154] Green, R. E., Cornell, S. J., Scharlemann, J. P. W. and Balmford, A. (2005), 'Farming and the fate of wild nature', *Science*, 307(5709): pp. 550–55, https://doi.org/10.1126/science.1106049 (accessed 6 Nov. 2020).

[155] Hendershot, J. N., Smith, J. R., Anderson, C. B., Letten, A. D., Frishkoff, L. O., Zook, J. R. and Daily, G. C. (2020), 'Intensive farming drives long-term shifts in avian community composition', *Nature*, 579(7799): pp. 393–96, https://doi.org/10.1038/s41586-020-2090-6 (accessed 6 Nov. 2020).

[156] Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B. (2001), 'Catastrophic shifts in ecosystems', *Nature*, 413(6856): pp. 591–96, https://doi.org/10.1038/35098000 (accessed 6 Nov. 2020); and Carpenter, S. R. (2005), 'Eutrophication of aquatic ecosystems: Bistability and soil phosphorus', *Proceedings of the National Academy of Sciences of the United States of America*, 102(29): pp. 10002–05, https://doi.org/10.1073/pnas.0503959102 (accessed 6 Nov. 2020).

[157] Fasching, C., Wilson, H. F., D'Amario, S. C. and Xenopoulos, M. A. (2019), 'Natural Land Cover in Agricultural Catchments Alters Flood Effects on DOM Composition and Decreases Nutrient Levels in Streams', *Ecosystems*, 22(7): pp. 1530–45, https://doi.org/10.1007/s10021-019-00354-0 (accessed 6. Nov. 2020).

[158] Schäfer, R. B., van den Brink, P. J. and Liess, M. (2011), 'Impacts of Pesticides on Freshwater Ecosystems', *Ecological Impacts of Toxic Chemicals (Open Access)*, 111–37, https://doi.org/10.2174/978160805121211101010111 (accessed 6 Nov. 2020).

5.1.3 Impacts at regional and global scale

The spatial spread of environmental impacts can occur in many ways: agriculture in one place influences biodiversity in others.[159] The mechanisms can consist of physical effects (e.g. pollution carried by air or water) or biological effects (the enhancement, or depression, of populations in one location creating spillover effects as individuals move). The spread of environmental impacts is also a function of global GHG emissions from agriculture, which change the availability and quality of habitat worldwide. A final route for regional and global impacts is through markets: demand for food in one place can incentivize agricultural intensification or land-use conversion in other distant places.

5.1.3.1 Pollution of rivers and regional-scale impacts

Rivers and streams can be thought of as transport systems that connect ecosystems across a landscape. Nutrients and sediment from agricultural run-off can rapidly be carried long distances, particularly via waterways, and can accumulate and have drastic effects on the biodiversity and stability of distant ecosystems.[160] The prevalence of waterway modifications such as damming and channelization, along with land-use changes for food production, means that nutrient and biological flows between ecosystems are being changed drastically. The magnitude of nutrient flows from urban and agricultural development into ecosystems is increasing. Moreover, the rates at which nutrients are carried between ecosystems are also increasing due to alterations to river and stream morphology.[161]

As well as acting as a transport network for pollutants or sediments, the aquatic environment constitutes a crucial habitat for significant biodiversity, and is sensitive to the amount of water as well as its quality. Irrigation, through abstracting water from groundwater flows, has the potential to reduce such flows to the extent that ecology is affected, in effect interrupting the minimum ‘environmental flow’ necessary to sustain a given ecosystem. Prolonged or frequent examples of low or zero groundwater flows can lead to significantly changed biodiversity.[162] Currently, about 40 per cent of irrigation comes at the expense of environmental flows.[163] Furthermore, water transfer schemes (designed to carry water from a place of excess to a place of need) can significantly alter local aquatic habitats, threatening their inherent biodiversity.[164] Currently, less than one-fifth of the world’s pre-industrial freshwater wetlands remain; this proportion is projected to decline to under one-tenth by mid-century.[165] Climate change, alongside growing demands for fresh

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[159] McCann et al. (2020), ‘Landscape modification and nutrient-driven instability’; and Aufdenkampe et al. (2011), ‘Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere’.
[160] Bennett et al. (2001), ‘Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective’; and Diaz and Rosenberg (2008), ‘Spreading dead zones and consequences for marine ecosystems’.
[161] Raymond, P. A., Oh, N. H., Turner, R. E. and Broussard, W. (2008), ‘Anthropogenically enhanced fluxes of water and carbon from the Mississippi River’, *Nature*, 451(7177): pp. 449–52, https://doi.org/10.1038/nature06505 (accessed 6 Nov. 2020); and Elser, J. and Bennett, E. (2011), ‘A broken biogeochemical cycle’, *Nature*, 478: pp. 29–31, https://doi.org/978-3-540-87644-1 (accessed 6 Nov. 2020).
[162] Rolls and Bond (2017), ‘Environmental and Ecological Effects of Flow Alteration in Surface Water Ecosystems’.
[163] Jägermeyr, J., Pastor, A., Biemans, H. and Gerten, D. (2017), ‘Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation’, *Nature Communications*, 8(15900), doi: 10.1038/ncomms15900 (accessed 3 Nov. 2020).
[164] Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., Winemiller, K. O. and Ripple, W. J. (2020), ‘Scientists’ warning to humanity on the freshwater biodiversity crisis’, *Ambio*, doi: 10.1007/s13280-020-01318-8 (accessed 3 Nov. 2020).
[165] Ibid.

water for direct human use and agriculture,[166] is changing hydrological flows as well as the way in which nutrients are assimilated into ecosystems.[167] This makes it even more important to consider the connectivity between ecosystems and the distant impacts of food production systems.

Nutrients and sediment from agricultural run-off can rapidly be carried long distances, particularly via waterways, and can accumulate and have drastic effects on the biodiversity and stability of distant ecosystems.

The link between agricultural run-off and downstream algal blooms and dead zones around the world is becoming increasingly clear. However, we are beginning to see that food production can have even more distant, and often unexpected, impacts on biodiversity and ecosystem stability.[168] For example, Wang et al.[169] recently found that deforestation and agricultural development in the Amazon River basin appear to be fuelling *Sargassum* seaweed blooms in the tropical Atlantic. The Amazon carries nutrients to the ocean, where currents circulate them, and massive blooms are formed where they accumulate. This results in a massive mat of dense seaweed that is no longer habitable for many species, and that washes ashore throughout the Caribbean and Gulf of Mexico, where it can cause further ecological and environmental problems. At their peak densities, these *Sargassum* blooms have been shown to stretch across the Atlantic, from the Caribbean to West Africa.[170]

5.1.3.2 Air pollution

Both synthetic fertilizers and manure can pollute the air with ammonia and nitrous oxide. Synthetic fertilizers are typically urea or ammonium nitrate. In wet soils, denitrifying bacteria break down nitrates into nitrogen oxides (NOx), leading to emissions of these GHGs. Fertilizers also release ammonium (NH_3), a process termed volatilization. On average, worldwide, 18 per cent of applied N fertilizer (and up to a maximum of 64 per cent) was lost as NH_3 up to 2016.[171] Together, NOx and NH_3 help create secondary particulate matter (PM), which contributes to poor air quality and smog.

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[166] Mekonnen, M. M. and Hoekstra, A. Y. (2016), 'Four billion people facing severe water scarcity', *Science Advances*, 2(2): e1500323, doi: 10.1126/sciadv.1500323 (accessed 3 Nov. 2020).

[167] Pastor, A. V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P. and Ludwig, F. (2019), 'The global nexus of food-trade-water sustaining environmental flows by 2050', *Nature Sustainability*, 2: pp. 499–507, doi: 10.1038/s41893-0287-1 (accessed 3 Nov. 2020); Ho, J. C., Michalak, A. M. and Pahlevan, N. (2019), 'Widespread global increase in intense lake phytoplankton blooms since the 1980s', *Nature*, 574(7780): pp. 667–70, https://doi.org/10.1038/s41586-019-1648-7 (accessed 6 Nov. 2020); and Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B. and Zagorski, M. A. (2013), 'Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions', *Proceedings of the National Academy of Sciences of the United States of America*, 110(16): pp. 6448–52, https://doi.org/10.1073/pnas.1216006110 (accessed 6 Nov. 2020).

[168] McCann et al. (2020), 'Landscape modification and nutrient-driven instability'.

[169] Wang, M., Hu, C., Barnes, B. B., Mitchum, G., Lapointe, B. and Montoya, J. P. (2019), 'The great Atlantic Sargassum belt', *Science*, 364(6448): pp. 83–87, https://doi.org/10.1126/science.aaw7912 (accessed 6 Nov. 2020).

[170] Ibid.

[171] Pan, B., Kee Lam, S., Mosier, A., Luo, Y. and Chen, D. (2016), 'Ammonia volatization from synthetic fertilizers and its mitigation strategies: A global synthesis', *Agriculture, Ecosystems & Environment*, 232: pp. 283–89, doi: 10.1016/j.agee.2016.08.019 (accessed 3 Nov. 2020).

Poor air quality directly affects some biodiversity (for example, lichens are particularly sensitive to NOx), but the increased nitrogen in the atmosphere can also be deposited in rain, leading to nutrient enrichment that has effects similar to the eutrophication of water discussed above (excess nitrogen affects biodiversity through direct toxicity, soil acidification, nutrient imbalances and interspecific competition).[172] Indeed, some authors have suggested that excess nitrogen deposition is the third-largest global threat to biodiversity after land-use change and climate change.[173]

The impact of pesticide drift through the air is not proportionate to the large scale at which nitrogen can be transported around the world. Nonetheless, particularly from aerial applications (by drones and planes), pesticides can drift up to 300 metres from the target.[174] Clearly, this has the potential to affect non-target organisms and, in highly fragmented areas (where habitat patches are small), impact on species viability in a locality.

5.1.3.3 Changes to population processes

Biodiversity is a measure of what lives in a locality, and its genetic composition. However, biodiversity in a given locality can also depend on what is happening elsewhere. Many species migrate seasonally, so the persistence of a population in one place may depend on the conditions in another during a different season. For example, the migratory monarch butterfly (which travels between Mexico and northeast America) is declining in population size. A recent study examined the relative roles of three separate factors in this decline: (1) habitat loss in the monarch butterfly's breeding grounds in northeast America; (2) habitat loss in its overwintering grounds in Mexico; and (3) extreme weather (driven by climate change). The authors concluded that 'recent population declines stem from reduction in milkweed host plants in the United States that arise from increasing adoption of genetically modified crops and land-use change, not from climate change or degradation of forest habitats in Mexico'.[175] In other words, agriculture in one place (in this case, displacing host plants on butterfly breeding grounds in the US) can lead to biodiversity decline in another place through population reduction of a migratory species (in this case, reduced breeding in the US results in fewer butterflies migrating to Mexico).

At the same time, biodiversity loss can arise from agriculture through enhancement of the populations of some species at the expense of others. The coastal Arctic wetlands – hundreds of kilometres away from any agricultural development – serve as breeding grounds for populations of migratory geese and have been completely

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[172] Dise, N. B., Ashmore, M., Belyazid, S., Bleeker, A., Bobbink, R., de Vries, W., Erisman, J. W., Spranger, T., Stevens, C. and van den Berg, L. (2011), 'Nitrogen as a threat to European terrestrial biodiversity', in Sutton, M. A., Howard, C. M., Erisman, J. W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H. and Grizzetti, B. (2011), *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives,* Cambridge: Cambridge University Press, doi: 10.1017/CBO9780511976988.023 (accessed 2 Nov. 2020).
[173] Xiankai, Jiangming and Shaofeng (2008), 'Effects of nitrogen deposition on forest biodiversity'; and Payne et al. (2017), 'Nitrogen deposition and plant biodiversity: past, present, and future'.
[174] Martini, A. T., de Avila, L. A., Camargo, E. R., Helgueira, D. B., Bastiani, M. O. and Loeck, A. E. (2016), 'Pesticide drift from aircraft applications with conical nozzles and electrostatic system', *Ciência Rural*, 46(9), doi: 10.1590/0103-8478cr20151386 (accessed 3 Nov. 2020).
[175] Flockhart, D. T. T., Pichancourt, J.-B., Norris, D. R. and Martin, T. G. (2014), 'Unravelling the annual cycle in a migratory animal: breeding-season habitat loss drives population declines of monarch butterflies', *Journal of Animal Ecology*, 84(1), doi: 10.1111/1365-2656.12253 (accessed 3 Nov. 2020).

transformed in recent decades.[176] Due to increases in agricultural production in the US, where the geese overwinter, breeding populations have increased so much that they have radically altered their fragile breeding habitats: overgrazing and overfertilization have turned salt marshes into hypersaline mudflats, which may be a difficult state to recover from.[177]

Agricultural management can also boost populations of organisms that have negative impacts on local populations, through the introduction of pests and diseases that then spread from their introductory sites. One example is the prickly pear cactus (*Opuntia ficus-indica*), widely used for its fruit[178] and also widely foraged, which is a highly invasive cactus that alters local ecosystems in many areas of the world.[179]

Attempts to control pests, whether plants or animals, through the introduction of predators have sometimes had unintended consequences. For example, in the mid-1930s cane toads were introduced in Australia to suppress a beetle pest of sugar cane. The cane toads have since spread, covering a large area of the country's northeast coastal fringes. Cane toads directly affect local ecology by eating native plants and competing with native animals, and, because they are poisonous, kill their predators indirectly. This contributes to a cascade of impacts across trophic levels: large, anurophagous (toad-eating) snakes (which are apex predators) die, releasing ecological space that allows increases in mammal-eating meso-predatory snakes.[180] Where cane toads are common, native mammals disappear.

It is not just terrestrial agriculture that has been responsible for such problems. Aquaculture also has a significant track record of perturbing biodiversity, through the introduction of alien species (both fish and feed plants) and pests (such as sea lice, which escape from salmon cages and affect the viability of local populations).[181] Iconic examples of escapes/introductions include tilapia and Nile perch, which have subsequently altered ecosystems across the world via changes in competitive interactions. From a biodiversity perspective, perhaps the most impactful change has been the extinction cascade of species 'swarms' of endemic cichlids – perhaps over 500 species died out in Lake Victoria following the introduction of Nile perch.[182]

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[176] Jefferies, R. L., Rockwell, R. F. and Abraham, K. F. (2004), 'Agricultural food subsidies, migratory connectivity and large-scale disturbance in arctic coastal systems: A case study', *Integrative and Comparative Biology*, 44(2): pp. 130–39, https://doi.org/10.1093/icb/44.2.130 (accessed 6 Nov. 2020); and Jefferies, R. L., Rockwell, R. F. and Abraham, K. F. (2004), 'The embarrassment of riches: Agricultural food subsidies, high goose numbers, and loss of Arctic wetlands - A continuing saga', *Environmental Reviews*, 11(4): pp. 193–32, https://doi.org/10.1139/a04-002 (accessed 6 Nov. 2020).

[177] Jefferies, Rockwell and Abraham (2004), 'Agricultural food subsidies, migratory connectivity and large-scale disturbance in arctic coastal systems: A case study'.

[178] Cantwell, M. (1995), 'Post-Harvest Management of Fruits and Vegetable Stems', FAO Plant Production and Protection Paper 132, http://ucce.ucdavis.edu/files/datastore/234-576.pdf (accessed 6 Nov. 2020).

[179] Masocha, M. and Dube, T. (2018), 'Global terrestrial biomes at risk of cacti invasion identified for four species using consensual modelling', *Journal of Arid Environments,* 156 (September 2018): pp. 77–86, https://doi.org/10.1016/j.jaridenv.2018.05.006 (accessed 6 Nov. 2020).

[180] Radford, I. J., Woolley, L., Dickman, C. R., Corey, B., Trembath, D. and Fairman, R. (2019), 'Invasive species-driven trophic cascades: Are cane toads indirectly contributing to small mammal collapses across tropical Australia?', Cold Spring Harbour Laboratory, doi: https://doi.org/10.1101/616771 (accessed 6 Nov. 2020).

[181] Diana, J. S. (2009), 'Aquaculture Production and Biodiversity Conservation', *BioScience,* 59: pp. 27–38, https://doi.org/10.1525/bio.2009.59.1.7 (accessed 6 nov. 2020).

[182] Marshall, B. E. (2018), 'Guilty as charged: Nile perch was the cause of the haplochromine decline in Lake Victoria', *Canadian Journal of Fisheries and Aquatic Sciences,* 75: pp. 1542–59, https://doi.org/10.1139/cjfas-2017-0056 (accessed 6 Nov. 2020).

In aquaculture, another form of biodiversity impact occurs through genetic integration: where escaped farmed animals, with different genetic traits, breed with native 'wild-type' species, thereby potentially undermining the genetic integrity of native animals. In a recent study, significant rates of genetic integration were found, reducing the fitness of wild salmon in many rivers in Norway.[183]

Genetic pollution – gene introgression – can also occur from crop plants into wild populations. A recent study of rice, for example, showed that gene introgression altered the genetic structure of wild relatives of the crops in surrounding populations,[184] creating a challenge wherever crop plants are grown in proximity to wild species with which they can breed. In this case, 'proximity' can mean quite large distances: maize pollen can be detected more than 4 km[185] from the nearest maize fields, so the risks of gene introgression in natural populations are not merely about close exposure between genetically modified and wild plants.

5.1.3.4 Land-use change and teleconnections: market connectivity across space

Another way in which agriculture in one place can affect biodiversity in others is through market linkages, a process called 'teleconnection'. The term is borrowed from climate science, where it is used to indicate when weather in different places is affected by the same underlying climatic cause. Teleconnections in food emerge from globalized supply chains, where food consumed in a given country is often a combination of local and overseas production. Imagine, for example, that a country decides to conserve its own biodiversity by making agricultural production more environmentally friendly. Moves towards wildlife-friendly farming (e.g. agro-ecological or organic farming) typically come with a cost to productivity as farming intensity is scaled down.[186] If total demand for food in the focal country does not change, yet local agricultural production declines because of biodiversity-friendly farming, price signals will incentivize intensification (or 'extensification', i.e. expansion of land use) somewhere else, and demand will be filled through global trade. This potentially leads to a biodiversity saving in one place but a biodiversity cost in another.[187] For example, in 2010 it was calculated that if the EU increased the amount of organic farmland to 20 per cent of all cropland, then overall agricultural yields would decline by an amount that would require more than 10 million hectares of land outside the EU to be used to support food consumption in the EU.[188] This implies a biodiversity cost as agriculture is intensified or as previously unfarmed land is brought into production. The cost

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[183] Karlsson et al. (2016), 'Widespread genetic introgression of escaped farmed Atlantic salmon in wild salmon populations'.
[184] Jin, X., Chen, Y., Liu, P., Li, C., Cai, X., Rong, J. and Rong Lu, B. (2018), 'Introgression from cultivated rice alters genetic structures of wild relative populations: Implications for in situ conservation', *AoB PLANTS* 10, Oxford University Press, https://doi.org/10.1093/aobpla/plx055 (accessed 6 Nov. 2020).
[185] Hofmann, F., Otto, M. and Wosniok, W. (2014), 'Maize pollen deposition in relation to distance from the nearest pollen source under common cultivation - results of 10 years of monitoring (2001 to 2010)', *Environmental Sciences Europe,* 26: pp. 1–14, https://doi.org/10.1186/s12302-014-0024-3 (accessed 6 Nov. 2020).
[186] Gabriel et al. (2013), 'Food production vs. biodiversity: comparing organic and conventional agriculture'.
[187] Benton, T. G., Dougill, A. J., Fraser. E. D. G. and Howlett, D. J. B. (2011), 'The scale for managing production vs the scale required for ecosystem service production', *World Agriculture* 2.1: pp. 14–21.
[188] Von Witzke, H. and Noleppa, S. (2010), 'EU agricultural production and trade: Can more efficiency prevent increasing 'land-grabbing' outside of Europe?', Università Cattolica del Sacro Cuore, Piacenza: OPERA, http://np-net.pbworks.com/f/Von_Witske+(2010)+EU+agri_prod_trade.pdf (accessed 6 Nov. 2020).

could be even higher if production occurs in places with both significantly higher intrinsic biodiversity than the EU and weaker biodiversity governance: the result would be an overall net negative impact on global biodiversity.

5.1.3.5 Climate change's global impacts

The food system is a major source of global GHG emissions, contributing significantly to climate change. In its special report on climate change and land,[189] the Intergovernmental Panel on Climate Change (IPCC) estimated that the food system contributes around 30 per cent of all anthropogenic emissions, when emissions associated with agriculture, land-use change for agriculture, and the processing and transporting of food are all taken into account. This figure is consistent with the most detailed compilation of life-cycle assessments associated with the food system.[190]

While land-use change, mostly driven by agriculture, has been the principal driver of biodiversity loss since pre-industrial times,[191] the 2019 global assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlights the role of climate change as an increasingly important determinant of biodiversity:

> [Climate change has] contributed to widespread impacts in many aspects of biodiversity, including species distribution, phenology, population dynamics, community structure and ecosystem function. According to observational evidence, the effects are accelerating in marine, terrestrial and freshwater ecosystems and are already impacting agriculture, aquaculture, fisheries and nature's contributions to people. The compounding effects of drivers such as climate change, land-/sea-use change, overexploitation of resources, pollution and invasive alien species are likely to exacerbate the negative impacts on nature, as seen in different ecosystems including coral reefs, the Arctic systems and savannas.[192]

Climate change is altering habitat suitability throughout the world. As a first approximation, the area in which a species lives is determined both by the suitability of its physical habitat and by a climatic envelope (which may directly affect an organism's ability to live there by, for example, exposing it to high temperatures; or indirectly affect an organism's ability to live there by affecting its predators, parasites or food). As climate changes, the envelope of suitable climate is expected to move in several ways: (1) towards the poles for many organisms; (2) up an elevation gradient in mountainous areas; or (3) towards deeper waters for aquatic species.[193] Species either move as the climate changes or they risk extinction as the weather changes in their historically suitable habitat. On average, for a variety of species of agricultural pests, the rate of movement over the past 50 years or so has been about 3 km per year.[194]

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[189] IPCC (2019), *Climate Change and Land*.
[190] Poore and Nemecek (2018),'Reducing food's environmental impacts through producers and consumers'.
[191] Newbold et al. (2015), 'Global effects of land use on local terrestrial biodiversity'; and IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*.
[192] Newbold et al. (2015), 'Global effects of land use on local terrestrial biodiversity'; and IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*.
[193] Pecl et al. (2017), 'Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being'.
[194] Bebber, D. P., Ramotowski, M. A. T. and Gurr, S. J. (2013), 'Crop pests and pathogens move polewards in a warming world', *Nature Climate Change,* 3: pp. 985–88, https://doi.org/10.1038/nclimate1990 (accessed 6 Nov. 2020).

As a result of the need for species' movements to track a changing climate, and the fact that different groups of species move at different rates,[195] climate change is rewiring entire ecosystems.[196] The result is increasing introductions and losses of species. At a theoretical level, this amounts to a series of perturbations that decrease a system's resilience. For example, climate change makes aquatic systems more susceptible to nutrient-driven algal blooms and dead zones. It may also alter the phenology of plants/pollinators and change or restructure consumer–resource interactions (e.g. between insects and pollen) that are simultaneously affected by agriculture. Similarly, weather changes associated with climate change affect the linkages between whole ecosystems (for example, between fields, streams and lakes/oceans), with the transfer of nutrients from one place to the next particularly impacted. As highlighted in the IPBES quote above, all these climate change impacts will have compounding effects in conjunction with other major drivers of biodiversity loss associated with agriculture – such as land-use change and intensification of food production – and will thus act as threat multipliers.

5.1.3.6 Interactions with aquatic food production systems

Interconnections within the food system mean that many of the factors we discuss – including supply and demand drivers, pressures on the food system and ecological effects – are intertwined in numerous and complex ways. Actions targeted at one sector or place can have ripple effects on other sectors or places. For example, changes in demand for land-based and water-based food products affect each other: reducing the demand for animal products to improve terrestrial environmental outcomes might increase demand for fish protein, with negative marine environmental outcomes.[197] Blanchard et al.[198] discuss the difficulties of combining marine and terrestrial food production sectors and ecosystems within strategies for meeting the Sustainable Development Goals that are focused on food, biodiversity and climate change. However, they note that an effective formula is needed if progress is to be achieved in sustainably meeting increasing global demand for food and ensuring food security. There is a growing need to recognize the links and interdependencies between fisheries, aquaculture and the agricultural components of the global food system as more food is required and diets change. Similarly, there are feedbacks within this cycle. Some feedbacks may be obvious in terms of the ecological services both required for and degraded by food production, but feedbacks such as climate change may also have important long-term implications. The current food system is contributing significantly to global GHG emissions, and therefore to climate change. At the same time, the resilience of this system to shocks and impacts from climate change is being degraded. Some countries are likely to face increased uncertainties in both fisheries and agriculture due to climate change impacts, so it is important to ensure supply chains equitably distribute food around the world.[199]

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[195] Pecl et al. (2017), 'Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being'.
[196] Bartley et al. (2019), 'Food web rewiring in a changing world'.
[197] Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A. and Blanchard, J. L. (2018), 'Considering land–sea interactions and trade-offs for food and biodiversity', *Global Change Biology,* 24: pp. 580–96, https://doi.org/10.1111/gcb.13873 (accessed 6 Nov. 2020).
[198] Blanchard, J. L., Watson, R. A., Fulton, E. A., Cottrell, R. S., Nash, K. L., Bryndum-Buchholz, A. and Jennings, S. (2017), 'Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture', *Nature Ecology and Evolution*, 1(9): pp. 1240–49, https://doi.org/10.1038/s41559-017-0258-8 (accessed 6 Nov. 2020).
[199] Ibid.

5.2 Options for implementing food system redesign in support of biodiversity

As discussed in the main chapters of this paper, three broad levers exist for altering the relationship between food systems and biodiversity in favour of biodiversity. The first is to reduce the pressure on land by changing patterns in demand for food – including encouraging people to move to more plant-based diets. The second is to set aside land for nature, as unmanaged ecosystems are inherently more biodiverse than managed ecosystems. The third is to adopt more nature-friendly farming systems. The more the first option is taken up in the form of dietary change, the more scope there is for the second and third options.

5.2.1 Demand-side changes to relieve pressure on land

The potential for more sustainable diets to drive changes in agriculture has been highlighted in numerous analyses in the past years.[200] The essence of the argument is that (a) on average we produce more food than we need per capita; that (b) different foods have different environmental footprints; and therefore that (c) if we all ate a diet consisting of the right amount of low-footprint food for a healthy diet (not wasting or overeating), it would significantly reduce total demand for food (notwithstanding the fact that some communities would need to eat more food to lead healthy lives). In theory, if the totality of food demand were reduced, it would significantly reduce the pressures on land, allowing more land to be protected for nature and/or the intensity of farming to be reduced.

In 2011, the UN Food and Agriculture Organization (FAO) published an influential report which stated: 'Roughly one-third of the edible parts of food produced for human consumption gets lost or wasted globally, which is about 1.3 billion tons per year.'[201] Since 2011, considerable effort around the world has been made to improve this statistic. So far, while countries and food systems vary, the figure of 20–30 per cent loss and wastage is taken as a reasonable consensus. A recent academic analysis concluded the following:

> The results suggest that due to cumulative losses, the proportion of global agricultural dry biomass consumed as food is just 6% (9.0% for energy and 7.6% for protein), and 24.8% of harvest biomass (31.9% for energy and 27.8% for protein). The highest rates of loss are associated with livestock production, although the largest absolute losses of biomass occur prior to harvest. Losses of harvested crops were also found to be substantial, with 44.0% of crop dry matter (36.9% of energy and 50.1% of protein) lost prior to human consumption. If human overconsumption, defined as food consumption in excess of nutritional requirements, is included as an additional inefficiency, 48.4% of harvested crops were found to be lost (53.2% of energy and 42.3% of protein). Over-eating was found to be at least as large a contributor to food system losses as consumer food waste.[202]

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[200] EAT-*Lancet* Commission (2019), 'Lancet Commission on Syndemics of Climate change and Obesity'; and IPCC (2019), *Climate Change and Land.*
[201] Gustavsson et al. (2011), *Global food losses and food waste: extent, causes and prevention*, p. 4.
[202] Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D. and Rounsevell, M. D. A. (2017), 'Losses, inefficiencies and waste in the global food system', *Agricultural Systems*, 153, pp. 190–200; and Giner, C. and Brooks, J. (2019), 'Policies for encouraging healthier food choices', *OECD Food, Agriculture and Fisheries Papers, No. 137*, Paris: OECD Publishing, https://doi.org/10.1787/11a42b51-en (accessed 6 Nov. 2020).

Figure 7. Estimated global variation in GHG emissions, land use, terrestrial acidification, eutrophication and scarcity-weighted freshwater withdrawals, within and between 36 major foods

Notes: (A) Protein-rich products. Grains are also shown here, given that they contribute 41 per cent of global protein intake, despite lower protein content. (B) Milks. (C) Starch-rich products. (D) Oils. (E) Vegetables. (F) Fruits. n = farm or regional inventories. Pctl. = percentile. Source: Poore and Nemecek (2018), 'Reducing food's environmental impacts through producers and consumers'.

In other words, reducing food waste, reducing the environmental footprint of diets and reducing overconsumption have, between them, the potential to reduce the pressure on land by a significant amount. Were populations to adopt local dietary guidelines (which are not based on optimizing diets for sustainability in most places), this alone would reduce GHG emissions and other environmental impacts by 29 per cent and 5–9 per cent, respectively.[203] Reducing food loss and waste by 50 per cent could further reduce environmental pressures (in terms of GHG emissions, use of cropland, and use of water, nitrogen and phosphorus) by 16 per cent, taking into account the anticipated increase in food demand by 2050. Reducing food loss and waste by 75 per cent, meanwhile, could yield a 24 per cent decline in environmental pressures. If diets were optimized to minimize their environmental footprint, the pressure on cropland could be reduced by as much as half.[204]

The replacement of animal-sourced products, which now supply 18 per cent of calories consumed by humans,[205] could significantly reduce the pressure on land from agriculture and contribute to environmental sustainability goals.[206] Different agricultural products have different environmental footprints. The most comprehensive study today is by Poore and Nemecek[207] (see Figure 7). As can be seen from the figure, producing 100 g of protein can require an average of 164 m^2 of land for beef, but just 2.2 m^2 of land for tofu: in other words, the land-use footprint for tofu is 1/75 that of beef. Similar variances apply to the carbon footprints of different protein sources, and to their respective pollution footprints (in terms of production contributing to the enrichment and acidification of water courses). Changing patterns of consumption from foods that have large environmental footprints to those that have smaller ones can be a potent way of reducing the land requirements and environmental impacts of food production.[208]

Changing diets and reducing waste have greater potential to reduce environmental footprints and pressure on land than do supply-side interventions.[209] For example, substituting beans for beef in the US diet could free up an area of 692,918 km^2 – equivalent to 42 per cent of US cropland – which could then potentially be used for ecological purposes.[210] Furthermore, one aspect of demand-side change likely to be helpful to biodiversity would be to shift towards healthier diets, rich in fruit

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[203] Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L. and Willett, W. (2018), 'Options for keeping the food system within environmental limits', *Nature*, 562(7728): pp. 519–25, https://doi.org/10.1038/s41586-018-0594-0 (accessed 6 Nov. 2020).
[204] Ibid.
[205] Poore and Nemecek (2018), 'Reducing food's environmental impacts through producers and consumers'.
[206] Aiking, H. (2011), 'Future protein supply', *Trends in Food Science and Technology*, 22(2–3): pp. 112–20, https://doi.org/10.1016/j.tifs.2010.04.005 (accessed 6 Nov. 2020).
[207] Poore and Nemecek (2018), 'Reducing food's environmental impacts through producers and consumers'.
[208] Alexander et al. (2017), 'Losses, inefficiencies and waste in the global food system'.
[209] Bajzelj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E. et al. (2014), 'Importance of food-demand management for climate mitigation', *Nature Climate Change*, 4: pp. 924–29; Bryngelsson, D., Wirsenius, S., Hedenus, F. and Sonesson, U. (2016), 'How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture', *Food Policy,* 59: pp. 152–64; Harwatt et al. (2017), 'Substituting beans for beef as a contribution toward US climate change targets; Hedenus, F., Wirsenius, S. and Johansson, D. J. (2014), 'The importance of reduced meat and dairy consumption for meeting stringent climate change targets', *Climatic Change,* 124: pp. 79–91; Ripple, W. J., Smith, P., Haberl, H., Montzka, S. A., McAlpine, C. and Boucher, D. H. (2014), 'Ruminants, climate change and climate policy', *Nature Climate Change,* 4: pp. 2–5; and Smith, P., Haberl, H., Popp, A., Erb, K.h., Lauk, C., Harper, R., Tubiello, F. N., Siqueira Pinto, A., Jafari, M. and Sohi, S. (2013), 'How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?', *Global Change Biology*, 19(8): pp. 2285–2302, https://doi.org/10.1111/gcb.12160.
[210] Harwatt et al. (2017), 'Substituting beans for beef as a contribution toward US climate change targets'.

and vegetables, and away from ultra-processed diets dependent on calorie-dense crops and animal products. A greater range of crops, coupled with reduced demand for animal products, would potentially allow for more diverse and regenerative farming landscapes to be maintained. Such landscapes would not only reduce nutrient leakage but would also, owing to greater spatial heterogeneity, support greater biodiversity.[211]

Recent years have also seen innovation in the production of alternative proteins, including plant-based meat substitutes, 'clean meat' (animal meat produced via cellular agriculture in laboratories) and insect protein (in the form of processed insect meat). These products are already on the market, and companies and governments are seeking to scale up production and sales.[212] In 2017 China, the biggest consumer of meat, made a $300 million deal to import clean meat from different companies in Israel as a part of a national mission to cut conventional meat consumption by 50 per cent.[213] The global market for alternative protein is expected to grow at a compound annual rate of 9.5 per cent, by value, to $17.9 billion by 2025.[214] As the alternative-meat concept is still in its infancy, further measurement is required to determine its exact implications for human health and environmental sustainability on a larger scale.[215]

5.2.2 Setting aside land for biodiversity

Agriculture requires changing ecosystems from their natural state into a managed state. As a basic approximation, the more the managed state differs from the natural 'unmanaged' state, the more yield can be produced but the less biodiversity-friendly a given farming system becomes. In other words, the more food the system must produce, the less suitable it becomes as habitat for wildlife.[216] Thus, in terms of biodiversity conservation, the biggest gains will be made when whole ecosystems, particularly biodiverse ones such as tropical rainforests, are protected from land conversion (as discussed in the main chapters of this paper).

This argument is summed up by the following logic: broadly speaking, to produce a given amount of food, a large area of land can be used and farmed in a more wildlife-friendly way (but with smaller yields per area), or a smaller area of land can be used and the area farmed more intensively (with larger yields per area). This is the essence of the **'land-sharing'** vs **'land-sparing'**[217] debate, which seeks to understand how best to integrate the needs of wildlife alongside the use of land for agriculture.[218]

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[211] Benton, Vickery and Wilson (2003), 'Farmland biodiversity: is habitat heterogeneity the key?'.
[212] Northfield, R. (2019), 'Is the future meatless? [future food supply]', *Engineering & Technology*, 14(2): pp. 44–45, https://doi.org/10.1049/et.2019.0203 (accessed 6 Nov. 2020).
[213] Ibid.
[214] Meticulous Research (2019), 'Alternative Protein Market by Stage/Type (Insect, Algae, Duckweed, Lab Meat, Pea, Rice, Potato, Corn, Soy, Wheat, Corn, Mycoprotein, Mushrooms)', *Application, and Geography - Global Forecast to 2025,* https://www.meticulousresearch.com/product/alternative-protein-market-4985/?utm_source=globnewswire.com&utm_medium=pressrelease2&utm_campaign=paid (accessed 17 Apr. 2020).
[215] Van der Weele, C., Feindt, P., Jan van der Goot, A., van Mierlo, B. and van Boekel, M. (2019), 'Meat alternatives: an integrative comparison', *Trends in Food Science and Technology*, 88(November 2018): pp. 505–12, https://doi.org/10.1016/j.tifs.2019.04.018 (accessed 6 Nov. 2020).
[216] Gabriel et al. (2013), 'Food production vs. biodiversity: comparing organic and conventional agriculture'.
[217] See Fraanje, W. (2018), 'What is the land sparing-sharing continuum? (Foodsource: building blocks)', Food Climate Research Network, University of Oxford, https://www.foodsource.org.uk/building-blocks/what-land-sparing-sharing-continuum (accessed 6 Nov. 2020).
[218] Green et al. (2005), 'Farming and the fate of wild nature'.

At a given spatial scale (globally, regionally or at a landscape scale), land use can essentially be approached in two distinct ways. On the one hand, land can be **shared** between wildlife and farming, with nature fully integrated within a given area of farmland. Under this arrangement, intensive farming practices (in terms of chemical inputs, scale of operations, etc.) are avoided, and field margins and small areas of uncropped land are left. Such systems are less productive in terms of food output, but more beneficial for on-farm biodiversity. The alternative potential approach – **land-sparing** – is not yet in widespread use as a purposefully designed policy, but theoretically involves separating rather than integrating the two types of land use. In other words, it involves dividing land between intensive agricultural areas (which produce larger yields from smaller areas) and areas spared for biodiversity conservation. Which strategy may be better depends in theory on three factors: (1) how much more beneficial natural ecosystems are for biodiversity relative to nature-friendly farming systems; (2) the degree to which spillover effects can be minimized; and (3) governance of the spared land (including its amount, type, location and protection).

Addressing the first point, a large number of studies have now shown that in principle land-sparing can be more effective for biodiversity conservation.[219] For example, in the UK a study comparing 'land-sharing landscapes' (rich in organic farming) and 'land-sparing landscapes' (intensive farms plus land set aside into wildlife areas) found that, most of the time, the land-sparing landscapes should provide higher agricultural yields and more biodiversity across a larger area.[220] More recently,[221] a broadening of the conceptual approach has indicated that land-sparing is also potentially better for other aspects of sustainability: per unit of production, land-efficient systems generate lower negative externalities (such as GHG emissions).

Addressing the second point on spillover effects, at a relatively small spatial scale (e.g. landscape scale) the proximity of areas of nature reserve (or otherwise spared land) and intensive agricultural areas can be problematic if the intensive agriculture impacts on biodiversity within the spared land (e.g. from pesticide drift or nutrient leakage), or if the area of spared land is too small and too fragmented to allow viable wildlife populations to exist.

The third point is that while the land-sharing versus land-sparing debate is useful because it forces consideration of the spatial issues associated with biodiversity conservation and agricultural land, it is problematic when it comes to governance. Who will determine what land is shared and what is spared?[222] To date, there are

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[219] Phalan, B., Onial, M., Balmford, A. and Green, R. E. (2011), 'Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared', *Science,* 333: pp. 1289–91; Luskin, M. S., Lee, J. S., Edwards, D. P., Gibson, L. and Potts, M. D. (2018), 'Study context shapes recommendations of land-sparing and sharing; a quantitative review', *Global food security*, 16: pp. 29–35.

[220] Hodgson, J. A., Kunin, W. E., Thomas, C. D., Benton, T. G. and Gabriel, D. (2010), 'Comparing organic farming and land sparing: optimizing yield and butterfly populations at a landscape scale', *Ecology Letters* 13, Blackwell Publishing Ltd: pp. 1358–67.

[221] Balmford, A., Amano, T., Bartlett, H., Chadwick, D., Collins, A., Edwards, D., Field, R., Garnsworthy, P., Green, R., Smith, P., Waters, H., Whitmore, A., Broom, D. M., Chara, J., Finch, T., Garnett, E., Gathorne-Hardy, A., Hernandez-Medrano, J., Herrero, M., Hua, F., Latawiec, A., Misselbrook, T., Phalan, B., Simmons, B. I., Takahashi, T., Vause, J., Ermgassen, E. and Eisner, R. (2018), 'The environmental costs and benefits of high-yield farming', *Nature Sustainability* 1(9): pp. 477–85.

[222] Fischer, J., Abson, D. J., Butsic, V., Chappell, M. J., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H. G. and von Wehrden, H. (2014), 'Land sparing versus land sharing: moving forward', *Conservation Letters,* 7(3): pp. 149–57.

no real examples of operational land-sparing strategies. Often the reverse applies: as intensification in an area increases, so do farm profits, incentivizing conversion of unmanaged land into agriculture. To avoid this, land-sparing needs to be strongly regulated, and land set aside requires some degree of statutory protection. At the moment, while protection may often exist on paper, weak enforcement means that protected areas are being exploited in many jurisdictions.[223]

It is key to recognize that land could in effect be spared by shifting to less resource-intensive diets. Hence, land-sparing does not always require an intensification of agricultural land elsewhere to compensate.

Another land management option is the 'integrated landscape approach': a basic framework for integrating multiple land uses within a given area, aimed at maintaining biodiversity, ecosystem services and feedback between the two to ultimately benefit humans. The focus of this approach to date has mostly been on maintaining heterogeneity via mosaic landscapes, habitat corridors and crop variety. Kremen and Merenlender[224] describe numerous initiatives (particularly in Latin America and Africa) that have been initiated by governments (and, in certain cases, by NGOs) and involve multiple stakeholders.

It is key to recognize that land could in effect be spared by shifting to less resource-intensive diets. Hence, land-sparing does not always require an intensification of agricultural land elsewhere to compensate. For example, Hayek et al.[225] demonstrate that a global shift to a plant-based or EAT-Lancet diet would substantially reduce the requirement for pasture and cropland (taking into account human nutritional needs and population growth to 2050); such land could thus be spared for nature.

5.2.3 Adapting the way we farm the land

The discussion above highlights the point that minimizing the impact of food production on biodiversity means minimizing the amount of land used for agriculture and leaving as much land as possible free for nature. However, this creates a further conundrum: if we want to preserve land for nature, we need to grow more on the land we use. Yet this is the very definition of 'intensification'. Can it be done in a way that reduces the damage from intensive farming? This conundrum is at the heart of the concept of **'sustainable intensification'**.

If society demands more food without expanding the land area under agriculture (either because the land is valuable for other uses – for example, the biodiversity and carbon sink properties embedded in tropical forests – or because it is too marginal),

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[223] Chatham House (2020), 'Forest Governance and Legality', https://forestgovernance.chathamhouse.org (accessed 6 Nov. 2020).
[224] Kremen, C. and Merenlender, A. M. (2018), 'Landscapes that work for biodiversity and people', *Science*, 362(6412), https://doi.org/10.1126/science.aau6020 (accessed 6 Nov. 2020).
[225] Hayek et al. (2020), 'The carbon opportunity cost of animal-sourced food production on land'.

then demand will only be met by growing more in the same area. This can be achieved in various ways, but the methods chosen should be sustainable and not have negative impacts on the environment or farm livelihoods. This basic conceptual definition of sustainable intensification[226] has been present in the literature for many years, but the term itself was promoted in a report by the UK's science academy, the Royal Society. The report concludes:

> We must aim for sustainable intensification — the production of more food on a sustainable basis with minimal use of additional land. Here, we define intensive agriculture as being knowledge-, technology-, natural capital- and land-intensive.[227]

In this sense, sustainable intensification can be achieved by using more knowledge, labour, capital and/or inputs (whether synthetic or organic) – in other words, there is a range of ways to boost yields per unit area. Urban food gardens are often higher-yielding than horticultural farms because they are more intensive in terms of labour inputs. Sustainable intensification, therefore, does not necessarily imply that the entire world should adopt Westernized, large-scale, input- and capital-intensive farming systems.[228]

5.2.3.1 Ecological intensification

Sustainable intensification describes a conceptual goal which, at one level, is difficult to disagree with (if intensification is needed, it needs to be sustainable). Other words have been used for essentially the same concept. For example, in 1999 Ken Cassman used the term 'ecological intensification':

> At issue, then, is whether further intensification of cereal production systems can be achieved that satisfy the anticipated increase in food demand while meeting acceptable standards of environmental quality. This goal can be described as an ecological intensification of agriculture.[229]

Other authors use the term 'ecological intensification' more specifically to mean utilizing ecosystem functions to deliver sustainability gains while maintaining yields, productivity gains or resilience.[230] In essence, this means substituting synthetic inputs with enhanced ecological processes (such as soil fertility, pollination and natural pest control). Replacement of inputs may not count as intensification *per se* (i.e. leading to higher yields), but nonetheless it can be seen as a part of the sustainable intensification paradigm in making currently intensive systems more sustainable.[231] In other examples, utilizing ecological processes has the potential to enhance yield growth, perhaps especially in existing, relatively extensive systems in the developing

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[226] Garnett et al. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies'.
[227] Baulcombe, D., Crute, I., Davies, B., Dunwell, J., Gale, M., Jones, J., Pretty, J., Sutherland, W., Toulmin, C. and Green, N. (2009), *Reaping the benefits: science and the sustainable intensification of global agriculture*, London: Royal Society, p. 46.
[228] Tittonell, P. and Giller, K. E. (2013), 'When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture', *Field Crops Research*, 143: pp. 76–90.
[229] Cassman, K. G. (1999), 'Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture', *Proceedings of the National Academy of Sciences of the United States of America*, 96: pp. 5952–59.
[230] Bommarco, R., Kleijn, D. and Potts, S. G. (2013), 'Ecological intensification: harnessing ecosystem services for food security', *Trends in Ecology & Evolution,* 28: pp. 230–38.
[231] Garnett et al. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies'.

world. According to Tittonell, 'Food production can increase and at the same time be sustainable through the ecological intensification of current agriculture, making intensive and smart use of the natural functionalities that ecosystems offer.'[232]

Conceptually, sustainable intensification can be subdivided[233] into three main steps: (1) increasing efficiency, (2) substitution and (3) system redesign. Included in (1) are elements such as precision agriculture: the use of a range of technologies to better target the efficient use of inputs (the right source, in the right amount, in the right place, at the right time – the '4 Rs' principle).[234] This route to sustainable intensification is sometimes called 'doing more for less'. Substitution includes replacing practices that have higher impacts with those that have lower impacts: for example, integrated pest management instead of routine pesticide usage. System redesign includes radical changes to farming practices in ways that can achieve both productivity and environmental goals.

Regenerative farming practices, organic farming, agroforestry, extensive farmed animal systems and mob-grazing all conceptually fit under steps (2) and (3) above. Within the constraints of sustainable management, what approaches can maximize the yields in a given locality?

5.2.3.2 Agro-ecology and regenerative farming

Many agro-ecological and regenerative farming systems – such as organic farming – are inherently more diverse, relying on polycultures and rotations. In general, the yield–biodiversity relationship means that such systems tend to be lower-yielding than intensive farming. Hence, large-scale adoption of such techniques would require other fundamental changes to food systems to reduce overall demand for food (including a reduction in food waste, and shifts to plant-based diets). Organic farming uses fewer synthetic fertilizers and pesticides, restricts the types of synthetic fertilizers and pesticides used, promotes crop rotations, focuses on soil fertility and closed nutrient cycles, and has diversity as an organizing principle.[235] While there are many environmental benefits, organic systems produce lower yields compared to conventional production systems. Therefore, under a scenario in which all food production used organic techniques, the land requirement for agriculture would increase. However, combined with a reduction in food waste and shifts to plant-based diets (allowing a reduction in farmed animals and feed crop production), organic agriculture could contribute to feeding more than 9 billion people in 2050. Not only could this scenario result in sufficient food availability globally, it would offer positive outcomes across a range of environmental indicators, including a reduced requirement for cropland.[236]

Under such a scenario, it would be important to consider how to replace animal-sourced inputs used in organic production, such as manure and fertilizer derived from blood and bones. Stock-free farming techniques require no

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[232] Tittonell, P. A. (2013), 'Farming systems ecology: towards ecological intensification of world agriculture', Wageningen Universiteit, https://research.wur.nl/en/publications/farming-systems-ecology-towards-ecological-intensification-of-wor (accessed 3 Nov. 2020).
[233] Pretty et al. (2018), 'Global assessment of agricultural system redesign for sustainable intensification'.
[234] Reetz, H. F., Heffer, P. and Bruulsema, T. W. (2015), '4R nutrient stewardship: A global framework for sustainable fertilizer management', *Managing Water & Fertilizer for Sustainable Agricultural Intensification,* pp. 65–87.
[235] Seufert et al. (2018), 'Current and potential contributions of organic agriculture to diversification of the food production system'.
[236] Muller et al. (2017), 'Strategies for feeding the world more sustainably with organic agriculture'.

animal-sourced inputs and are likely to be an important part of the food system transformation. Numerous farms around the world rely solely on stock-free inputs. One example is Tolhurst Organic in the UK, which produces around 120 tonnes of vegetables every year on 19 acres of field. The farm's carbon footprint is reportedly 8 tonnes per year, around the same as an average UK household.[237] Tolhurst Organic claims to have increased biodiversity on its farm over the past 20 years, and a range of species is now present that includes water voles, barn owls, polecats, kingfishers and orchids.[238] Green manure, or cover crops, are used to build fertility, improve soil structure, protect against erosion, suppress weeds and attract pollinators.

Agroforestry encompasses a range of methods that combine the cultivation and management of trees with food production. Polycultures of trees are used to produce wood, nuts and fruits – and allow the combination of multiple crops and cropping opportunities throughout the year.[239] For example, 'shadow systems' combine trees with cash crops such as cocoa, with the tree cover beneficial in providing sufficient shade for food crops. Other methods utilize leguminous shrubs to improve fertility and soil structure in between cropping.[240] Agroforestry relies on the interactions among multiple components, in contrast to traditional forestry and agriculture, which focus on individual components. Multifunctional landscapes of this kind also help protect against soil erosion and support the natural recharge of groundwater, thereby limiting further degradation of biodiversity and enhancing the productivity of land in the longer term.[241] Levels of nutrients and organic matter in the soils are found to increase with the adoption of agroforestry in both temperate and tropical regions.[242] And, in supporting ecosystem provisioning such as natural pest control and pollination,[243] agroforestry can lessen the need for chemical inputs to support productivity. Studies of coffee and cacao production in tropical regions suggest that, while species richness is lost in the conversion of natural forest to agroforest, the scale of loss is lower than that associated with conversion to more intensive farming systems such as plantations.[244]

Agroforestry and agro-ecological practices can allow for habitat restoration while diversifying income streams and food supply, in turn increasing the resilience of local communities and habitats, improving nutrition and enhancing biodiversity.[245]

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[237] Tolhurst Organic (2020), 'Our Carbon Footprint', http://www.tolhurstorganic.co.uk/about-us/our-carbon-footprint (accessed 6 Nov. 2020).

[238] Tolhurst Organic (2020), 'Managing Biodiversity on our Farm', http://www.tolhurstorganic.co.uk/about-us/biodiversity (accessed 6 Nov. 2020).

[239] Yang (2018), 'Interventions: Natural Infrastructure'.

[240] Rosenstock, T. S., Dawson, I. K., Aynekulu, E., Chomba, S., Degrande, A., Fornace, K., Jamnadass, R., Kimaro, A., Kindt, R., Lamanna, C., Malesu, M., Mausch, K., McMullin, S., Murage, P., Namoi, N., Njenga, M., Nyoka, I., Valencia, A. M. P., Sola, P., Shepherd, K. and Steward., P. (2019), 'A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa', *One Earth*, 1(3): pp. 330–44, https://doi.org/10.1016/j.oneear.2019.10.017 (accessed 6 Nov. 2020).

[241] Jose, S. (2012), 'Agroforestry for conserving and enhancing biodiversity', *Agroforestry Systems*, 85: pp. 1–8, doi: 10.1007/s10457-012-9517-5 (accessed 20 Aug. 2020).

[242] Torralba, M., Fagerholm, N., Burgess, P. J., Moreno, G. and Plieninger, T. (2016), 'Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis', *Agriculture, Ecosystems & Environment,* 230: pp. 150–61, doi: 10.1016/j.agee.2016.06.002 (accessed 20 Aug. 2020); and Pinho, R. C., Miller, R. P. and Alfaia, S. S. (2012), 'Agroforestry and the improvement of soil fertility: a view from Amazonia', *Applied Environmental and Soil Science*, 2012(1): pp. 1–11, doi: 10.1155/2012/616383 (accessed 20 Aug. 2020).

[243] De Beenhouwer, M., Aerts, R. and Honnay, O. (2013), 'A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry', *Agriculture, Ecosystems & Environment*, 175: pp. 1–7, doi: 10.1016/j.agee.2013.05.003 (accessed 20 Aug. 2020).

[244] Ibid.

[245] Yang (2018), 'Interventions: Natural Infrastructure'.

5.2.3.3 Good governance

As mentioned earlier, the term 'sustainable intensification' is contested.[246] Too often it is interpreted as a licence to adopt 'industrial' intensive farming practices. This does not follow the concept of sustainable intensification:[247] biodiversity is best served by minimizing the area of land used for agriculture; where land *is* used for agriculture, it should be managed in such a way as to deliver the highest possible rate of crop growth (i.e. the intensification) consistent with this *also* being sustainable. This requires stronger governance (e.g. regulatory frameworks, well enforced) and market incentives to ensure that intensification is truly sustainable, and that it does not simply reinforce the 'Jevon's paradox'[248] at the heart of the 'cheaper food' paradigm.[249] Sustainable intensification is most likely to have real impacts in regions where productivity is low as a result of management limitations: in such places, adopting best practice in agro-ecological farming would both enhance yields and benefit the environment. Such areas can mainly be found in Africa, Latin America, Eastern Europe and South Asia. Bringing yields to within 95 per cent of their local potential for 16 important food and feed crops could add 2.3 billion tonnes per year of new global production, a 58 per cent increase,[250] and relieve land-use pressure elsewhere in the system. Similarly, if adaptation and technological efforts focus on the sustainable enhancement of yields in many low- and middle-income nations, there is potential to see significantly lower levels of land clearing, GHG emissions and nitrogen use globally in meeting future food needs.[251] This point is also relevant because many low-GDP countries with the potential to expand their output also often contain or overlap with 'biodiversity hotspots' where the potential negative biodiversity impacts of irresponsible development could be large. But if sustainable enhancement of yields is to work for nature, strong regulation is needed to ensure natural ecosystems are spared and protected, and that any intensification is, indeed, sustainable.[252]

5.2.3.4 Community-based approaches to sustainable farming

An important element of increasing yields sustainably is promoting best practice so that capacity can be built to deliver yields in a sustainable manner. Seventy-two per cent of all farms in the world are smaller than one hectare in size, with such holdings highly dominant in Asia and Africa (mainly South Asia and sub-Saharan Africa).[253] In terms of technology transfer combined with promoting

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[246] Benton (2015), 'Sustainable Intensification', in Pritchard, Ortiz and Shekar (eds) (2015), *Routledge Handbook of Food and Nutrition Security*.

[247] Garnett et al. (2013), 'Sustainable Intensification in Agriculture: Premises and Policies'.

[248] Jevon's paradox describes a situation where efficiency gains are offset or even lost due to a subsequent increase in consumption, driven by the benefits of the efficiency (such as a lower food price delivered through intensifying food production, in turn stimulating an increase in food consumption).

[249] Benton and Bailey (2019), 'The paradox of productivity: agricultural productivity promotes food system inefficiency'.

[250] Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M. and Zaks, D. P. M. (2011), 'Solutions for a cultivated planet', *Nature*, 478(7369): pp. 337–42, https://doi.org/10.1038/nature10452 (accessed 6 Nov. 2020).

[251] Tilman, D., Balzer, C., Hill, J. and Befort, B. L. (2011), 'Global food demand and the sustainable intensification of agriculture', *Proceedings of the National Academy of Sciences of the United States of America*, 108(50): pp. 20260–64, https://doi.org/10.1073/pnas.1116437108 (accessed 6 Nov. 2020).

[252] Shackelford, G. E., Steward, P. R., German, R. N., Sait, S. M. and Benton, T. G. (2014), 'Conservation planning in agricultural landscapes: hotspots of conflict between agriculture and nature', *Biodiversity and Distributions,* 21(3): pp. 357–67, https://doi.org/10.1111/ddi.12291 (accessed 6 Nov. 2020).

[253] Lowder, S. K., Skoet, J. and Raney, T. (2016), 'The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide', *World Development,* 87: pp. 16–29, https://doi.org/10.1016/j.worlddev.2015.10.041 (accessed 6 Nov. 2020).

biodiversity, many approaches are emerging or have already proven successful. Community-based methods such as farmer field schools, community seed banks or community forestry[254] could be customized based on specific socio-economic and environmental settings.[255] However, more investment is needed to enable such innovations to be scaled up. Initiatives such as participatory on-farm research, the promotion of low-impact and healthy diets, and the localization of food systems have been found to engage different actors in food systems, including consumers and grassroots movements.[256] Community-based approaches are increasingly considered models for promoting multifunctional, multi-use, multi-stakeholder forestry to achieve improved forest governance and sustainability.[257]

5.2.3.5 Agro-biodiversity

An important element of biodiversity in agricultural landscapes is the genetic diversity of the produce farmed. This is often encompassed in the term 'agro-biodiversity'. Most of the global genetic diversity in agriculture is associated with low-input farming systems,[258] and this resource is important to low-income societies' food sovereignty as well as to global food sustainability.

Incentivizing more diverse agriculture has many benefits. It potentially allows healthier diets through a greater diversity of fruit and vegetable production. It provides more diverse, heterogeneous landscapes. It leads to potentially more resilient farmer livelihoods and food systems.[259] It also ensures the maintenance of a diverse supply of foods that may be useful in future. On a global basis, about half of the calories consumed come from wheat, rice and maize, yet as many as 300,000 plant species are potentially edible. A recent survey of what is eaten in India suggests about 1,500 species are consumed.[260] Ensuring wild relatives of existing species survive is an important way to preserve potentially useful genetic diversity. This is perhaps most important in terms of adaptation to environmental and climate change (e.g. ensuring that the genetic resources of wild relatives for surviving extreme heat are available for cross-breeding programmes to maintain food supplies as the climate changes). Maintaining a diversity of crops therefore potentially maintains the ability to have a resilient food system in the future.

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[254] Vernooy, R., Sthapit, B., Otieno, G., Shrestha, P. and Gupta, A. (2017), 'The roles of community seed banks in climate change adaption', *Development in Practice*, 27(3): pp. 316–27, https://doi.org/10.1080/09614524.2017.1294653 (accessed 6 Nov. 2020); FAO (2016), *Influencing food environments for healthy diets*, Rome: FAO, http://www.fao.org/3/a-i6484e.pdf (accessed 6 Nov. 2020); and Braun, A., Jiggins, J., Röling, N., van den Berg, H. and Snijders, P. (2006), *A Global Survey and Review of Farmer Field School Experiences*, report prepared for the International Livestock Research Institute (ILRI), 92, https://www.researchgate.net/publication/228343459_A_Global_Survey_and_Review_of_Farmer_Field_School_Experiences (accessed 6 Nov. 2020).
[255] Macmillan, T. and Benton. T. G. (2014), 'Agriculture: Engage farmers in research', *Nature*, 509: pp. 25–27.
[256] IPBES (2019), *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*.
[257] Ibid.
[258] McConnell, D. J. (2003), *The Forest Farms of Kandy: and other gardens of complete design*, Aldershot, Hampshire and Burlington, VT: Ashgate, ISBN: 0754609588.
[259] Abson, D. J., Fraser, E. D. and Benton, T. G. (2013), 'Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture', *Agriculture & food security*, 2(1): p. 2.
[260] Ray, A., Ray, R. and Sreevidya, E. A. (2020), 'How Many Wild Edible Plants Do We Eat—Their Diversity, Use, and Implications for Sustainable Food System: An Exploratory Analysis in India', *Frontiers in Sustainable Food Systems*, 4: p. 56, doi: 10.3389/fsufs (accessed 6 Nov. 2020).

Abbreviations and acronyms

BECCS	bioenergy with carbon capture and storage
CBD COP15	15th Conference of the Parties to the Convention on Biological Diversity
EID	emerging infectious disease
EU	European Union
FABLE	Food, Agriculture, Biodiversity, Land-Use, and Energy Consortium
GDP	gross domestic product
GHG	greenhouse gas
GtC	gigatonnes of carbon
ha	hectare(s)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IFPRI	International Food Policy Research Institute
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
kg	kilogramme(s)
N4G	Nutrition for Growth
NBS	nature-based solutions
NGO	non-governmental organization
NH_3	ammonium
NOx	nitrogen oxides
PM	particulate matter
UN	United Nations
UNCCD COP15	15th Conference of the Parties to the United Nations Convention to Combat Desertification
UNEA-5	5th Session of the United Nations Environment Assembly
UN FAO	Food and Agriculture Organization of the United Nations
UNFCCC COP26	26th Conference of the Parties to the United Nations Framework Convention on Climate Change
UNFSS	United Nations Food Systems Summit

Glossary

Biodiversity
The diversity of life in any given area creates ecosystems of interacting individual organisms, across many species, that collectively contribute to and support many key planetary processes.

'Cheaper food' paradigm
Humanity's drive for increased productivity, and the failure to account for the impacts of food production on natural ecosystems and human health, have created vicious circles that incentivize the production of ever more food at ever lower cost.

Environmental externalities
Environmental externalities refer to the economic concept of uncompensated environmental effects of production and consumption.

Extensive agriculture
This term refers to agricultural production that uses fewer chemical and technology inputs compared to intensive agriculture and is thus more 'nature friendly'. Yields tend to be lower – for example, crop yield per area of land – compared to those delivered using intensive methods, so the same output via extensive methods requires a larger land area.

Food system
Food systems include all elements (environment, people, inputs, processes, infrastructure, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, as well as the outputs of these activities, including their socio-economic and environmental impacts.

Food systems approach
A consideration of all of the elements that comprise a food system, from production through to post-consumer waste. Rather than focusing on one specific element, such as food production, a food system approach simultaneously takes all elements of a food system into account. It recognizes that changing agriculture can arise from intervening directly in agricultural practice, or through the market by changing demand.

Intensive agriculture
This form of agricultural production maximizes productivity per unit area, particularly through the use of chemical (fertilizer, pesticides etc.) and technology inputs, and typically has a high environmental cost per unit area. However, less land is needed to produce a given amount of food than is the case with extensive farming.

Nature-based solutions
Nature-based solutions (NBS) are solutions to climate change, biodiversity decline or other environmental challenges that also offer an important means of restoring natural infrastructure and ecosystems, including forests, wetlands and soils. For example, NBS can include forest regeneration to reduce local flood risks, store carbon and preserve biodiversity.

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The authors are listed in alphabetical order. Tim Benton and Laura Wellesley designed the project. Carling Bieg and Roshan Pudasaini undertook a literature review and contributed to the initial drafting. Tim Benton, Helen Harwatt and Laura Wellesley co-wrote the final version.

Cover image: Farmer standing in his field in the agricultural landscape of Cotabato Province, Mindanao Island, the Philippines.
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