A Whole Earth Approach to Nature-Positive Food: Biodiversity and Agriculture

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What Evidence Is There?

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

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

Agriculture currently occupies 40% of the global land surface. At ***least*** 10–20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably, pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. **Today, between 18–33% of agricultural lands have insufficient biodiversity to provide those services, an unacceptable risk for food security.**

Agriculture thus needs a multipronged approach. This requires a shift towards regenerative production systems that deliver more diversified diets, coupled with strict conservation of intact habitats. Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems. Regenerative agricultural practices can generate additional critical ecosystem services by maintaining biodiversity in agricultural lands. **At scale, these practices offer the potential to sequester 4.3–6.9 Gt CO2e year^{-1} year [*Medium Agreement, Medium Evidence*], retain $>$ 30% environmental flows in major water to**

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basins [*High Agreement, Limited Evidence*], create 12–17 M km^2 of habitat for biodiversity [*High Agreement, High Evidence*] and increase connectivity for biodiversity [*High Agreement, Limited Evidence*]. There is no evidence that diversified production systems compromise food security – many agricultural diversification practices provide multiple complementary benefits [*High Agreement, High Evidence*].

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

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

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

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

In light of the vast environmental footprint of agriculture, the broader food system must be a key part of the solution to the intertwined challenges of biodiversity loss, climate change and human health. Siloed visions of agricultural systems being independent of the natural world and somehow exonerated from environmental responsibilities are no longer compatible with global goals on food and nutritional security, climate security, environmental security and livelihood security. **Thus, the first step is for policymakers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This demands thinking about 'food system productivity,' rather than agricultural productivity,[5] and requires all sectors of government to break out of their own conceptual silos and institutional structures.**

In considering the relationship between agriculture and biodiversity, several key areas for investment emerge: (i) closing the gap between the current composition of crop production and consumption to supply healthy diets at the local, regional and global scales in line with SDG2 and SDG3; (ii) transitioning to managing agricultural systems as ecological systems (agroecosystems); (iii) greater inclusion and recognition of farmers as key actors, with women, youths and indigenous farmers bringing unique knowledge systems and capabilities to bear in food production.

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

Current agricultural investments and practices often overlook the important potential for increasing ecosystem services that agroecosystems can provide (Wood et al. 2018), with an estimated 7% of innovation spending explicitly targeting environmental outcomes (CoSAI 2021). Farmers and farming communities can produce public goods (e.g., climate mitigation, soil water-holding capacity, water quality improvement), but promoting these public good functions has been consistently underexplored and under-resourced, even though they are also necessary for creating sustainable and resilient production systems. Recognizing that farmers and farmlands can produce these benefits in addition to quality food presents an opportunity for revitalizing rural communities by repurposing public funds for public goods and services. Diversification strategies can be applied in a range of contexts and would benefit from investment in technologies, tools, markets and incentives that increase and improve employment opportunities, reduce the drudgery of food production and provide greater autonomy to producers**.**

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

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

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

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

1 Introduction

It is widely recognized that a major transformation of food systems is urgently needed if we are to achieve food and nutrition security globally, *while also* meeting global climate, biodiversity and health targets. What foods people eat, how and where it is produced, as well as how much is wasted and lost, have a significant impact on human and planetary health, including 11 million premature deaths, over 30% of global greenhouse gas (GHG) emissions, 70% of freshwater use and 80% of land conversion driving biodiversity loss. Paradoxically, while agriculture is currently the largest single source of environmental degradation and biodiversity loss, it is also likely to be the biggest victim of this degradation – the conversion of natural ecosystems into croplands and pastures, coupled with the impacts of agricultural pollution, severely threaten vital ecosystem services that underpin agriculture itself (Rockström et al. 2020).

Agroecology, *as an ecological science, focuses on the contribution of* ***biodiversity*** *to enhancing the generation of ecosystem services to and from agriculture with the aim of* ***regenerating*** *these services. Diversification, agroecological, or regenerative agricultural practices are overlapping and include a diversity of management options from fields to landscapes (Source: Report Authors).*

FAO and the HLP Report #14 (FAO-HLPE 2019) *on "Agroecological and other innovative approaches" suggests a concise set of 13 agroecological principles related to: recycling; reducing the use of inputs; soil health; animal health and welfare; biodiversity; synergy (managing interactions); economic diversification; co-creation of knowledge (embracing local knowledge and global science); social values and diets; fairness; connectivity; land and natural resource governance; and participation.*

2021 signals a pivotal year for the agricultural community. Major events such as the United Nations Food Systems Summit (UNFSS), the UNFCCC COP26, the UNCBD COP15, and the launch of the UN Decade of Ecosystem Restoration offer a real chance to make a step change towards the necessary transformation of our food systems – so they can become more sustainable and equitable and deliver affordable, healthy and nutritious food for all. Ensuring that there is a clear pathway for addressing biodiversity in all this, as well as highlighting its inextricable links to agriculture, is essential, given growing evidence that food system interventions have the potential to become the single largest solution space for both human and planetary health (Rockström et al. 2020).

1.1 Biodiversity Is Inextricably Linked to Food and Agriculture

Covering approximately 40% of the global land surface, agricultural ecosystems (including rangelands) comprise the world's largest terrestrial ecosystem, albeit a highly modified and heterogenous one. Biodiversity in agricultural ecosystems, as in natural ecosystems, is highly threatened, and this has very real consequences for the resilience and sustainability of both the production of food and environmental goods and services generated on agricultural lands and in water. The reduction of biodiversity in agriculture diminishes the ecosystem functions that contribute to local, regional and, when scaled, global processes. To ensure environmental and climate security by 2030, a transition is necessary toward treating agricultural lands as ecosystems, or as 'agroecosystems,' and greater investment in research, practices, technologies and incentives that reward the efforts of farmers just as much for the environmental services they produce as for the foods they produce.

Which and how much of the diversity of available foods we eat, and in what quantities, plays a key role in human health. Yet today, nearly half of the world's population struggles to access or afford either enough food or food that is healthy. Global progress against SDG2 – Zero Hunger – has stalled over the last few years, with current estimates showing that nearly 9 percent (690 million) of the world's population go hungry – up by 10 million people in 1 year and by nearly 60 million in 5 years (FAO I, UNICEF, WFP, and WHO 2020). Global food supply also falls alarmingly short of providing a low health-risk diet: nearly 2 billion struggle with hunger and malnutrition; another 2 billion struggle with diseases related to overconsumption (Global Panel on Agriculture and Food Systems for Nutrition 2020).

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

Tackling the global-scale challenges of stabilizing global climate, regulating regional water cycles and halting the extinction crisis is dependent on sparing sufficient intact nature from conversion across all biomes. Avoiding any further loss of intact nature is vital, particularly by halting ongoing conversion of land to agriculture, as called for by the Convention on Biological Diversity (CBD) Target 1, "ensuring that all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, *retaining existing intact and wilderness areas.*" Achieving these goals requires active contributions from agriculture, starting with the recognition that environmental and climate security are equally non-transgressible goals, along with food and nutritional security. Increasing the productivity of agricultural lands, shifting to nature-positive practices, reducing food waste and loss, and fostering more sustainable diets are four ways in which food systems contribute to CBD conservation targets.

1.2 Reconfigure Biodiversity in Agriculture to Meet Food, Nutrition, Climate and Water Security Targets

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

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

1.3 Shifting from Crop Productivity to Systemic Productivity

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

1.4 Critical Actions for Reconciling Agriculture and Biodiversity

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

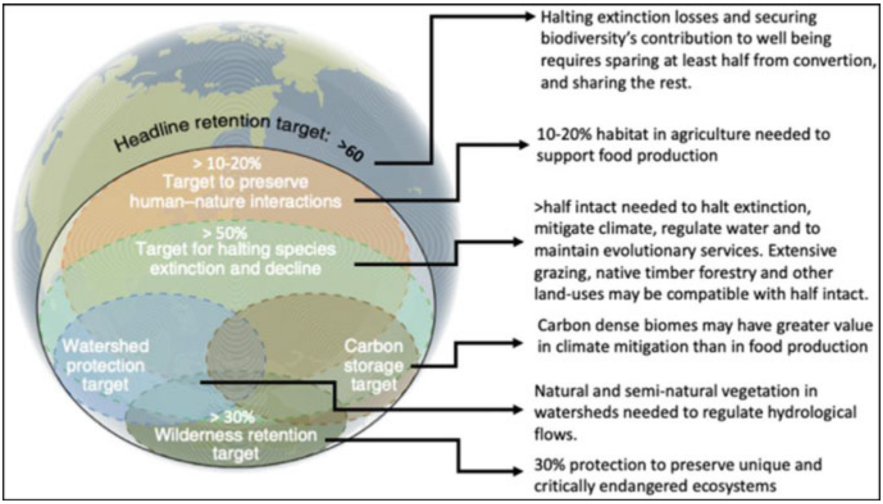
In this review, we have attempted to provide the best available evidence of agriculture's relationships with biodiversity. This spans many dimensions of agriculture and biodiversity, including:

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

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

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

- **Avoid** continued land expansion into intact nature to secure nature's essential contribution to climate mitigation, aiming for 30% protected and > 50 intact.
- **Restore** intact nature where possible, prioritizing those areas that have been degraded, have high climate mitigation or have biodiversity conservation potential in line with no net loss as of 2020, restoration in 2030, and full recovery by 2050, contributing to biodiversity conservation, climate mitigation, and regional hydrological flow regulation.
- **Reduce** the impacts of agriculture on biodiversity, notably by halting the losses of nutrients, biocides, and other pollutants to air, soil and water.
- **Regenerate** the ecosystem services provided by biodiversity in all agricultural lands everywhere, retaining, at *minimum,* 10% habitat per km^2 within agriculture. We note that 20% is a much lower risk boundary.



Halting extinction losses and securing biodiversity's contribution to well being requires sparing at least half from convertion, and sharing the rest.

10-20% habitat in agriculture needed to support food production

>half intact needed to halt extinction, mitigate climate, regulate water and to maintain evolutionary services. Extensive grazing, native timber forestry and other land-uses may be compatible with half intact.

Carbon dense biomes may have greater value in climate mitigation than in food production

Natural and semi-natural vegetation in watersheds needed to regulate hydrological flows.

30% protection to preserve unique and critically endangered ecosystems

Fig. 1 Bold biodiversity targets are required to halt the loss of biodiversity and to secure biodiversity's contributions to Earth system and ecosystem processes (Maron et al. 2018). Several studies (Willett et al. 2019; Maron et al. 2018; Newbold et al. 2016; Dinerstein et al. 2017; DeClerck et al. In Review), using distinct methodologies, find that approximately half the Earth's land surface remains intact, making 'half intact' the equivalent of a no-net-loss target (CBD Goal A, Target 1). We define intactness here as a measure of biodiversity status measured as the relative abundance of originally present species or level of human pressures. Combined actions to avoid loss, restore intact nature, reduce impacts of human activities on nature, regenerate ecosystem service production through nature-positive production, and transform agricultural policies and actions are needed to maintain a safe environmental space for humanity (Rockström et al. 2020, 2021). (Figure adapted from Maron et al. 2018)

- **Transform** the food system by creating the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional securities (Willett et al. 2019; Rockström et al. 2009; Steffen et al. 2015).

2 Healthy Diets Require Dietary Diversity

Take-Home Messages

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

- Modern plant breeding threatens traditional crop varieties and crop wild relatives, but is completely dependent on the genetic diversity that they represent.

2.1 The Diversity of Foods Produced and Available Is Insufficient for Healthy Diets

While there is no single solution to the hunger and dietary health challenges afflicting nearly half the global population, low dietary diversity is a common thread. Only around 130 internationally significant food plants – including 20 cereal crops, 7 roots and tubers, 28 fruits, 19 vegetables, 11 pulses, 8 nuts, 16 oils, 15 herbs and spices, 2 sugars and 3 stimulants – make up the bulk of peoples' diets around the world. In addition, just 15–20 major domesticated land animals are used in food and agriculture (Bélanger and Pilling 2019).

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

Global production and the availability of foods are fundamentally mismatched with recommended healthy consumption patterns (Willett et al. 2019; Kc et al. 2018). Ensuring healthy diets for all by 2050 requires an important shift in what foods are produced and consumed, including no significant increase in cereal production coupled with significant increases in vegetables, legumes, fruit, fish, nuts and seeds and a large reduction in red meat production and consumption globally (Afshin et al. 2019) – although, in some regions, meat consumption could be increased to counter nutritional deficiencies such as iron-deficient anemia (Golden et al. 2011) (Table 1). Increasing the diversity of animal-sourced proteins, notably, of healthier and often less energy intensive fish, shellfish, and poultry proteins, is consistently underexplored in discussions on shifts towards healthy and sustainable diets (see the UNFSS Blue Foods and Livestock Reports).

2.2 Healthy Diets Include a Wide Range of Choices

At least five major food groups, and thus, at minimum, 4–5 species, are required in a healthy diet, with whole grains, fruits, vegetables, oils and protein (plant or animal) being essential (Table 1). The absence of one food group drives critical challenges of

Table 1 Summary of food groups, recommended healthy daily consumption

Food Group	Recommended Per Capita Daily Consumption (g)	Estimated Global Production Change (2050)	Diversity of Species/Varieties
Whole grains	232	0	20 major cultivated species with 850,000 varieties; dozens of minor species; many wild species as well
Tubers or starchy vegetables	0–100	+20%	7 major cultivated species with 25,000 varieties; 12 minor species; various wild species as well
Vegetables	200–600	+75%	19 major cultivated species; 40 minor species; hundreds of wild species as well
Seaweeds	–	–	7 commonly cultivated species, unknown diversity, and contribution to health
Fruits	100–300	+50%	28 major cultivated species; 45 minor species; hundreds of wild species as well
Dairy foods	0–500	+5%	3 major domesticated species.
Red meat	0–28	−65%	4 major cultivated species
Poultry	0–58	+2%	6 major cultivated species
Eggs	0–25	−25%	1 major cultivated species
Fish, shell-fish and crustaceans	0–100		>3200 taxa
Legumes	0–100	+75%	11 major cultivated species with 120,000 varieties; 25 minor species; various wild species as well
Nuts	0–75	+150%	8 major cultivated species; 6 minor species; various wild species as well
Unsaturated oils	20–80		16 major cultivated oil crop species; 15 minor species; various wild species as well
Sugars	0–30		2 major cultivated species; various minor species and wild species as well

Willett et al. (2019) required change in production volume compared to current production to secure low risk diets globally, and approximate diversity of cultivable species.

malnutrition, which are stubbornly persistent in several hotspots requiring emergency assistance or fortification as an intermediate remedy. In both high- and low-income countries, however, increasing dietary diversity, within energetic requirements, would have significant impacts on improved health. Thousands more species, breeds and varieties could support human nutrition. Beyond the 130 odd species that dominate global production and consumption, about 120 other food crops that are less well monitored in production, trade and dietary data have regional significance. Practically nonexistent in food system data are well over 1000 wild plants known to be used, at least occasionally, as human food

(Khoury et al. 2019), and the nutritional value of over 3200 aquatic animal species used as food has been documented, not including growing interest in edible aquatic plants (algae) commonly consumed in Asian diets (Rajapakse and Kim 2011). Seaweeds have largely been unexplored as a more important food source, but present an area of innovation for nutritious food production without land, freshwater, or fertilizer requirements (Bernhardt and O'Connor 2021).

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

2.3 The Demand and Supply of Healthy Diets Contributes to Climate and Environmental Outcomes

Diverse production can bring us closer to planetary health goals. A shift towards healthy diets could reduce per capita emissions from food production between 30% and 50%, while also accounting for a 20% reduction in freshwater consumption and a 20% decrease in the land needed to meet consumption demand (Willett et al. 2019; Clark et al. 2019; Tilman and Clark 2014). Globally, this would mean no net increase in agricultural lands, in line with CBD goals of no net loss of nature by 2050, primarily driven by reduced overconsumption of red meat (Tilman and Clark 2014; Clark et al. 2020).

3 Agriculture Must Share Space with Biodiversity to Meet Global Environmental Goals

Take-Home Messages

- Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems.
- There is no evidence that diversified production systems compromise food security – many agricultural diversification practices provide multiple complementary benefits.
- At least 10–20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably, pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. Today, 18–33% of agricultural lands are below these respective threshold values for biological integrity.

- Regenerative agricultural practices have the potential to mitigate emissions by 4.3–6.9 Gt CO_2e year^{-1} globally, and agricultural lands represent 47% of the soil carbon climate mitigation potential.
- Agricultural, field and farm biodiversity can reduce agriculture's dependence on water capture and water quality through soil carbon sequestration, on-farm practices and appropriate crop selection.
- Crop wild relatives provide critically important traits to cultivated crops through breeding. Many crop wild relatives are also collected for direct dietary, medicinal and other cultural uses, and various species represent attractive candidates for development into new crops.

3.1 Agriculture Depends on Biodiversity

All agricultural systems depend on biodiversity for crop genetic diversity, pest control, animal-mediated pollination and healthy soils that promote nutrient capture and water delivery for crop growth. Diversified agroecological practices offer numerous opportunities at the field, farm and landscape scales, but are not a panacea. Thoughtful application and integration of novel technologies and practices that complement diversification are required, as well as mitigation of trade-offs such as pest species spilling over from natural or semi-natural habitats (Zhang et al. 2007).

3.2 Diversification Strategies Are Often Regenerative, Synergistic and Multipurpose

Agricultural practices that support biodiversity's contribution to soil nutrients, water, pollination and pest reduction, more often than not, are synergistic (Garibaldi et al. 2020; Tamburini et al. 2020; Garbach et al. 2016; Kennedy et al. 2013; Scheper et al. 2015; Landis et al. 2000; Rusch et al. 2017). Taken with genetic diversity, these ecosystem functions represent critical inputs into production systems globally. The aim of agroecology and diversification practices is to secure and make use of ecosystem services both to and from agriculture (DeClerck et al. 2016). Within the AR3T framework, the aim of diversification is to *regenerate* the ecosystem functions and services both from and to agriculture, while *reducing* its negative impacts, notably, habitat loss and pollution of soil and water (DeClerck et al. 2016).

3.2.1 Diversification Within Fields and Pastures

Replacing low diversity annual systems with higher diversity annual or perennial systems has numerous beneficial impacts on ecosystem functions, for example, by reducing soil nutrient loss to aquatic environments, and extending the portion of the year that crops are actively being grown, thus reducing nutrient leaching. Integrating nitrogen-fixing legumes, either as a harvestable or cover crop, is one of the most common forms of diversification (Duchene et al. 2017; Bedoussac et al. 2015; Ghosh et al. 2007). Crop types have variable water needs and can influence demands on available water resources. Management techniques for promoting carbon sequestration and improving drought resilience include organic residue management, mulching and reduced or no-tillage (Amelung et al. 2020). Excessive use of biocides, nutrient inputs and tillage, in turn, favor soil ecosystems with very high carbon loss and little long-term storage potential (Palm et al. 2014). High-diversity cropping systems can also increase natural enemies of pests upwards of 44%, increase pest mortality by 54% and reduce crop damage by 23% (Letourneau et al. 2011; Cook et al. 2007). In-field diversification provides habitat, alternative hosts, pollen and nectar, as well as overwintering or nesting sites essential to diverse communities of pollinators, predators and parasitoids (Landis et al. 2000; Lichtenberg et al. 2017).

3.2.2 Diversification Between Fields and Pastures

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

3.2.3 Landscape Diversification

Even where the most extensive monocultures are practiced, landscape diversification, combined with habitat structures between fields, can have significant positive impacts on many services provided by agricultural biodiversity, notably, hydrological, pest regulation (Avelino et al. 2012; Chaplin-Kramer et al. 2011; Veres et al.

2013; Holland et al. 2017) and pollination services (Kennedy et al. 2013; Dainese et al. 2019; Garibaldi et al. 2011). In contrast, landscape simplification often leads to increased risk of pest infestation (Rusch et al. 2016). Diverse mosaics in agricultural land that include multiple farms and integrate natural areas are required to capture and potentially convert, store or sequester nutrients lost to the environment. Policies, or markets that either support increases in field or farm sizes, and/or concentrate the production of a single crop in a landscape, may increase efficiency, but drive loss of between-field cropping diversity and increase risks.

3.2.4 Agricultural Landscapes Need at Least 10–20% of Diversified Habitats to Retain Ecological Integrity

Proposed targets for nature retention within agricultural landscapes (Willett et al. 2019; Garibaldi et al. 2020) are beginning to be reflected in agricultural policy (Díaz et al. 2020). A conservation target for agricultural ecosystems to retain at least 10–20% of habitat per km^2 has been proposed to maintain ecological integrity in production landscapes (Willett et al. 2019; Maron et al. 2018; DeClerck et al., DeClerck et al. In Review; Garibaldi et al. 2020). The rationale for this target is that the services provided by biodiversity to agriculture are locally produced. Nitrogen fixation by legumes impacts soil fertility at the plant scale (0–10 cm), and pollination and pest control are provided by habitats at a wider scale (0–300 m), occasionally further for honeybees (3000 m) (Willett et al. 2019; DeClerck et al., DeClerck et al. In Review; Garibaldi et al. 2020; Fremier et al. 2013; Tscharntke et al. 2005; Tscharntke et al. 2007). Similarly, interception of sediment and nutrients lost from agriculture by buffers is most effective within tens of meters (Fremier et al. 2013). While specific impacts are highly contextual and difficult to predict, the evidence is clear: in the absence of proximate habitat (<500 m), ecosystem services to agriculture are not provided. Alarmingly, 18–33% of global agricultural lands are below this 10–20% km^2 threshold respectively (Fig. 2; DeClerck et al. In Review).

Both the retention of habitat within agriculture and the diversity of cropping systems per unit area have been proposed as indicators to the CBD and to UNFSS[12]. The attraction of these targets is that they allow for alignment and the setting of both global and national goals while leaving ample scope for farming communities to identify the most locally appropriate practices contributing to their achievement. Additional research will be needed to define what qualifies as “semi-natural” habitat in different regions. Pastures are considered to be semi-natural habitats in European analyses. Agroforests, plantations and orchards may be more appropriate in agricultural systems located in forest biomes. In contrast, winter flooding of rice fields in California have provided critical overwintering habitat for migratory waterfowl and other biodiversity without compromising yield. Investments in local research on the relationships between semi-natural habitats and ecological integrity are needed.

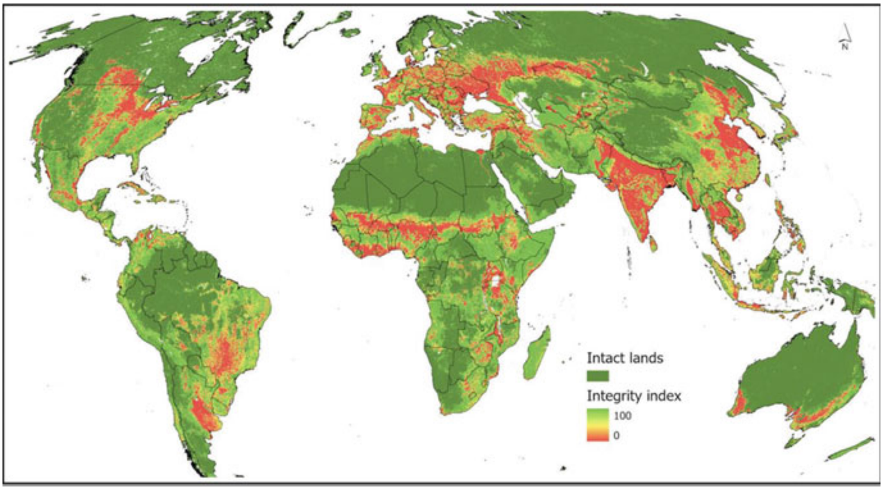


Fig. 2 Global distribution of biodiversity intactness (light green) and ecological integrity. Regions in red are below proposed thresholds for biodiversity in agriculture. (Data from DeClerck et al. In Review. Nearly half the terrestrial landmass is currently classified as "intact." However, many agricultural lands have lost integrity (red), where remaining habitat quantity is insufficient to ensure biodiversity's contributions to food production)

4 Agriculture Must Spare Space for Biodiversity to Meet Global Environmental Goals

Take-Home Messages

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

Reducing and reversing the impact of agricultural systems on biodiversity requires a system-wide transformation of agriculture and food production (Tilman et al. 2017; Williams et al. 2020). A sustainable future must therefore be grounded in improving environmental quality and placing strong limits on biodiversity loss. At least 79% of Earth's remaining natural and semi-natural (terrestrial) ecosystems need to be retained simply to meet existing international goals for biodiversity conservation, carbon storage, soil conservation and freshwater regulation (Simmonds et al. 2021).

This equates to keeping half of the planet intact – about the proportion that remains intact today. We can afford to lose very little more: so much land has been converted to agriculture that we are globally either at or nearing land conversion limits (Ceballos et al. 2020). Actions to ensure that intact habitats and their biodiversity can contribute to Earth system processes while also halting the ongoing biodiversity extinction crisis require both *avoiding* further loss of and *restoring* intact nature.

4.1 Halting the Loss of Intact Ecosystems

Preventing the loss or conversion of intact areas, and, where necessary, enhancing their condition, requires setting limits on loss. How much intact land is needed to preserve functioning populations of all species is difficult to quantify precisely. Local contexts are important in determining extinction risk and are important spaces for setting conservation priorities. There is no 'one size fits all' solution (Maron et al. 2018; Allan et al. 2019). However, there is broad consensus that retaining intact habitat, and connectivity between habitats, is necessary to halt loss.

Biological intactness is not incompatible with human use. Relatively intact and ecologically functioning systems can and do support a multitude of human uses, including productive and extractive uses: many such ecosystems rely upon human intervention, and represent the product of millennia of sustainable traditional management. Extensive grazing in grassland and savannah biomes and the sustainable harvest of natural forests are demonstrable activities that retain intactness while supporting livelihoods. Indigenous areas critically overlap with intact nature, with strong evidence that recognizing Indigenous Peoples' rights to land, benefit sharing, and institutions is essential to meeting local and global conservation goals (Garnett et al. 2018). Identifying the range of nature-based benefits that each priority avoidance area supports can provide a guide to the human uses that are compatible with its ongoing provision of those benefits, so long as retaining biodiversity intactness is an explicit priority in these areas.

Interventions should therefore aim *not* to exclude human activities entirely from the areas we need to retain, particularly where local people depend on the natural resource base for their livelihoods. Proposed agricultural expansion can be managed to minimize impacts on biodiversity through the involvement of local people in decision-making. Land use policies, decision-making tools and private sector levers can contribute to nature retention (Garnett et al. 2018).

There is a growing call for the retention of at least half of the global land surface as intact (BII > 90) in order to halt extinction loss at 80% of known biodiversity (Willett et al. 2019; Rockström et al. 2020; Maron et al. 2018; Newbold et al. 2016; Dinerstein et al. 2017). Other estimates, using species-based approaches, find that 44% might be sufficient to protect the most important sites for terrestrial biodiversity (64 million km^2) (Allan et al. 2019). While the specificity of this boundary is vigorously debated, most ecologists agree that, as the intact area of ecosystems dips below 50%, there is growing risk of population decline and extinction risk.

Retaining at least half of the terrestrial realm, in each of the 782 ecoregions, would thus be necessary to halt extinction loss, and has been signaled as a biodiversity boundary for food systems (Willett et al. 2019). Retaining intact regions in ice-free areas ($>$67 M km^2) and achieving half intactness for all ecoregions would require restoration on 23.9 M km^2. Observing that currently half of the terrestrial realm is considered intact, the CBD has adopted the boundary measure in its ongoing negotiations for a ‘no net loss of nature’ target. Ensemble models have demonstrated that no net loss is possible to achieve, but requires aligned actions across biodiversity conservation, food production and food consumption (Leclère et al. 2020).

Many parts of the world are currently in intactness deficit, considering a 50% intactness target. Estimates of how much restoration is needed range between 19 and 24 million km^2, with the lower value targeting high conservation value areas (Allan et al. 2019; Strassburg et al. 2020), and the higher value targeting half-intact ecoregions, across all ecoregions (DeClerck et al. In Review). In 552 ecoregions globally (69%), less than 10% of the area remains intact and may be too far gone for meaningful restoration of intactness, or may conflict with food and nutrition security. In these locations, integrating biodiversity into production will be a more viable option.

4.2 Mitigating Climate Change

While reducing fossil fuel burning and halting land conversion are critical strategies to reduce GHG emissions, biodiversity, through photosynthesis, is the only known process to transfer GHG from the atmosphere to the biosphere. The retention and restoration of natural ecosystems, notably, carbon-dense forest and wetland ecosystems, are key in this regard. It has been proposed that 75% of forest biomes be conserved globally because of their specific contribution to climate mitigation (Steffen et al. 2015). Temperate and tropical forest biomes are currently below this threshold, although temperate forest areas are increasing due to agricultural abandonment, whereas tropical forest areas are decreasing due to agricultural expansion. Boreal forest biomes remain above this threshold for the moment (Dinerstein et al. 2017; Ramankutty et al. 2018). The potential of reforestation to contribute to climate mitigation (i.e., 2.7–17.9 Pg CO_2e y^{-1}) depends on several assumptions (Griscom et al. 2017).

4.3 Regulating Hydrological Cycles

Large tracts of intact nature are key to maintaining regional hydrological patterns (Chapman et al. 2020; McAlpine et al. 2009), including flood pulse flow regulation (Bradshaw et al. 2007) and distribution of rainfall patterns that are critical to agriculture. However, the relationship between water fluxes (storage, evapotranspiration, precipitation and run-off) of extensive intact areas is complex. Intact nature may or may not produce greater volumes of water than converted lands, as losses to storage and evapotranspiration can be greater than in simplified systems such as agricultural ecosystems. However, most evidence does indicate that heavily vegetated ecosystems (e.g., forests, grasslands) provide better flow regulation – while natural ecosystems reduce run-off, they may have greater losses to evapotranspiration. Studies suggest that about 40% of irrigation water currently drawing from surface water bodies is at the expense of environmental flows (Jägermeyr 2020) and roughly 20% of irrigation water depletes groundwater bodies(Döll et al. 2012; Wada et al. 2012; Wada et al. 2016), indicating that 50–60% of current global irrigation practice is unsustainable (Rosa et al. 2019; Rosa et al. 2018).

4.4 Restoring Ecosystems

A growing number of research articles now point toward options for restoration, and evaluate contributions to climate, biodiversity, and food security, but there remains an important research gap on local and regional implementation of such strategies, including the trade-offs over multiple spatial and temporal scales, as well as between different social groups (Leclère et al. 2020; Strassburg et al. 2020; Mehrabi et al. 2018). Restoration, in contrast to regeneration, must include improvements in biodiversity intactness (Newbold et al. 2016; Scholes and Biggs 2005) measured by changes in species richness and population abundance. Defined as such, restoration can be interpreted as driving a net reduction in land available for food production, with the exception of wild harvest systems, and potentially extensive grazing systems. Restoring 15% of converted lands in priority areas could avoid 60% of expected extinctions while sequestering 299 Gt CO_2e – 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution (Strassburg et al. 2020).

5 Conclusions and Recommendations: Food and Agriculture Must Be the Solution to Food, Environmental and Climate Security

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

Understanding that there is a menu of solutions, with related opportunities and trade-offs, will help in progress toward a future that optimizes sustainable agriculture and prioritizes feeding everyone. Biodiversity strategies are among those solutions and can help us move beyond staple crops and commodities when considering policy, investment and research. Three elements, as already detailed in this review, can offer a way to bridge conversations among policymakers engaged in the environment, food, agriculture, finance and social protection sectors, and must be considered in a holistic solution for food and biodiversity: (1) How can we optimize the opportunities and minimize the trade-offs for ensuring diverse diets for all? (2) How can we maintain shared space where agriculture optimizes ecosystem services, and other contributors to regenerative and resilient production systems? And (3) how can we strike the right balance of land sparing, by halting the expansion of agriculture into the intact ecosystems necessary to halt the loss of biodiversity while mitigating climate change and producing enough healthy food?

5.1 Policy Implications: The Transformation Challenge

Biodiversity needs to be part of a sustainable agriculture that will feed a projected population of 10 billion with healthy, culturally appropriate and delicious foods by 2050. The first step is for policymakers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This leads to thinking about 'food system productivity,' rather than agricultural productivity (Benton and Bailey 2019), and requires all sectors of government to break out of their own conceptual silos and institutional structures. For a true transformation of the food system, there is a need to create the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional security (Willett et al. 2019; Rockström et al. 2009; Steffen et al. 2015).

5.2 Correcting Distortions Requires Reinvestment

Our food system has been distorted by a framework of subsidies (including for research focused on staples), market incentives (including investment in commodity-based transport infrastructure and marketing/retail incentives for hyper-processed food), and a lack of regulations to curb the externalization of costs onto environmental and healthcare systems. The heavily subsidized agricultural sectors of many countries in the Global North result in trade distortion, or in inequitable trade relationships among many developed and developing countries, adversely affecting the economic prospects of farmers in the Global South (OECD, 2016). These have a strong influence on both the foods that are delivered and their price and accessibility, and in encouraging the supply, demand and consumption of foods that may be less conducive to healthy diets and sustainability in food systems.

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

- Closing the gap between the current composition of crop production and consumption to supply healthy diets at the local, regional and global scales in line with SDG2 and SDG3.
- Transitioning to managing agricultural systems as ecological systems (agroecosystems).

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

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

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

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

5.3 Developing more Dynamic Investment and Financial Opportunities

There is potential to unlock and unblock investment and facilitate better financial flows to encourage farmers to protect and enhance the environment by rewarding them for the provision of ecosystem services, while mitigating the risks to the adoption of sustainable practices. Current agricultural investments and practices often overlook the important potential for increasing the ecosystem services that agroecosystems can provide (Wood et al. 2018). The CGIAR Commission on the Sustainable Intensification of Agriculture finds “an uplift in finance could come from reorienting current innovation spending to promote environmental, climate change, inclusivity and nutrition outcomes. A recent study commissioned by CoSAI identified that although around USD 50–70 bn per year is spent on agricultural innovation for the Global South, less than 7% explicitly aims to improve environmental and climate outcomes. And only around half of this also addresses social or nutrition outcomes” (CoSAI. 2021).

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

5.4 Changing Availability Through Subsidy and Research Reform

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

Even a relatively modest repurposing of subsidies (e.g., 25%) toward promoting production of nutrient-rich perishable foods, and reduced food loss and nutrient waste, would amount to US$150 billion in capital to support the generation of a greater diversity of nutrient-rich foods, while simultaneously lowering the environmental footprint, potentially allowing more nature-positive farming methods.

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

5.5 Reimagining International Trade

With almost 20% of the global dietary energy supply derived from imported foodstuffs, trade policy must better integrate its impact by creating greater space for diversification of commodities, supporting the conservation of intact ecosystems, and including trade in environmental goods and services. Trade expansion over recent decades has enabled "higher-income countries to 'off-shore' the adverse impacts of their consumption on ecosystems and biodiversity through trade in commodities, goods and services with lower-income countries" (Dasgupta 2021) International market stability and prices are highly dependent on a few key players (Dasgupta 2021), yet investing well in international trade could bring a range of benefits. It is crucial to find ways to support sustainability via trade (e.g., 'due diligence' requirements for supply chains such as the Global Reporting Initiative (GRI), enhancing traceability through mechanisms such as Trase, or through border tariffs). A key component of the evolution of the food system's focus on large-scale commodity production is the ability to store, transport and process grains with less loss than with fresh produce.

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