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Review article

Broad bidirectional effects of global food production on the environment

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Abstract

As the largest driver of nutrient imbalances, water use and biodiversity loss, and as a major contributor to climate change, global food production poses a threat to the long-term environmental stability of the planet. Excessive use of fertilizers in agriculture causes eutrophication and hypoxia; land use change has led to an unprecedented loss of soil carbon and biodiversity; water use is stressing regions and affecting local crop productivity and food security. These impacts are all exacerbated by increasing demand for resource-intensive foods and international trade that shifts environmental impacts beyond national borders. In this Review, we synthesize the vast literature describing the food system and its bidirectional effects with environmental pressures. We examine the major impacts of the food system on the environment and then explore how these impacts affect cropland production, livestock systems and production from aquatic environments (blue foods). We conclude with a summary of strategies that help to tackle food system pressures and inefficiencies and provide suggestions for future research and policy.

Sections

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Key points

- Global environmental impacts of food production are growing and almost certain to undermine future food production.
- Environmental degradation poses major threats to crop production via extreme weather, soil erosion and related impacts, jeopardizing yields in vulnerable tropical regions such as sub-Saharan Africa.
- Livestock systems are susceptible to increased heat stress and disease owing to climate change.
- Aquatic food production faces threats from ocean warming, acidification and eutrophication, potentially causing marked shifts in global fishing patterns by 2050.
- Integrated supply-side and demand-side transformations of food systems are essential to mitigate environmental impacts and ensure global food security.
- Climate-resilient crop breeding, agroecological practices and food system redesign to achieve circularity will be crucial to mitigate and adapt to environmental change.

Introduction

The advent of the Neolithic agricultural revolution marked the beginning of a period of profound human alteration of the environment for the purposes of food production, driving the selective cultivation of specific crop varieties and animal husbandry over several millennia[1]. Since then, demand for crops and livestock has fuelled continuous agricultural expansion, until a peak in agricultural land use in the early twenty-first century of around 4.8 Gha (according to FAOSTAT). As of 2025, humans use over 1.5 Gha of agricultural cropland and over 3.2 Gha for pastureland, or about 12% and 25% of total land area globally, respectively (according to FAOSTAT). The clearing of forests for agricultural land has triggered major alterations of carbon fluxes from land to the atmosphere, leaving a clear and lasting signal on atmospheric CO_2 levels[2,3]. Although the mid-twentieth century Green Revolution substantially increased agricultural productivity through the development of high-yielding cultivars along with agricultural technologies and high-input farming practices[4], it also brought about a growing dependency on irrigation, fertilizer and pesticide use[4–6] and markedly increased food trade[7,8]. This expansion in global food trade has supported economic growth and improved food access in many import-dependent regions but has also resulted in environmental burden spillovers[7–11] (Box 1). These profound environmental effects are also becoming a threat to the viability of agriculture itself, representing a bidirectional influence between environment and food production.

The environmental impact of food production has altered ecosystems, considerably increased water withdrawals (thus reducing environmental flows) and substantially altered atmospheric chemistry and biogeochemical cycles[2]. Agriculture-induced deforestation contributes considerably to large-scale biodiversity loss[12] and to the ongoing sixth global mass extinction event[13]. The reliance on chemical inputs such as fertilizers drives eutrophication in terrestrial, freshwater and marine ecosystems[14], and the overuse of pesticides has been linked to a substantial loss of aquatic invertebrates[15] and an increase in toxicity for humans[16]. Agriculture contributes to the emission of greenhouse gases, release of antibiotics into the environment and plastic pollution, which are becoming pervasive throughout the world. Nitrogen deposition, in great part because of ammonia emissions from agriculture, adversely impacts biodiversity[17]. The effects of human-induced global environmental change such as a warmer global atmospheric temperature, increased nutrient concentrations in ecosystems and compromised soil health already pose a considerable risk to agriculture. Rising temperatures, increasing frequency of droughts and floods, loss of pollinators[18] and eutrophication threaten crops, livestock, fisheries and global food security[19,20]. This degradation of environmental resilience creates a vicious cycle whereby more inputs are required to maintain high agricultural yields, which in turn further compromises environmental health and food production.

In this Review, we highlight the specific environmental impacts that create perpetual and detrimental feedback loops between food production and environmental integrity, with an emphasis on climate and land use change, biodiversity loss and changes to water demand and quality. We also review key solutions to mitigate and adapt to the environmental pressures from food production systems. Finally, we highlight future research and management priorities that can guide a transformation towards a sustainable global food system.

Environmental impacts of food production

The current food production system is characterized by unsustainable and increasing greenhouse gas emissions, water demand and nutrient losses to the environment[5,7,20–22] (Figs. 1 and 2). Food demand is likely to increase in scale as the global population grows but also change in composition, as a result of growing demand for animal-sourced foods (according to data from FAOSTAT). Below, we outline the research base for various environmental impacts associated with agricultural systems. We do not provide an exhaustive list of all the environmental impacts of the food system from a life-cycle perspective (for example, ref. 23) or on specific biota or environments but rather focus on those that, through feedbacks, threaten food production.

Climate

Greenhouse gas (GHG) emissions for the entire global food supply chain, including waste processing, have reached an estimated 17 Gt carbon dioxide equivalents (CO_2 eq, global warming potential over 100 years (GWP100)) per year[21], representing 25–33% of total net annual anthropogenic GHG emissions. Of food production GHG emissions, livestock and feed production represent around 60%[24]. Land use change, driven largely by agriculture and forestry, has contributed to around 10–15% of total annual anthropogenic CO_2 emissions since the year 2000 (ref. 25).

The fastest-growing portion of agricultural GHG emissions comes from N_2O and CH_4 (ref. 26 and data from FAOSTAT). Bottom-up approaches for estimating food-related methane fluxes suggest that methane emissions from the enteric fermentation of ruminants (112 Tg CH_4 yr^{-1}), landfills and waste (69 Tg CH_4 yr^{-1}) and rice cultivation (32 Tg CH_4 yr^{-1}) combined (212 Tg CH_4 yr^{-1}; 5.3 Pg CO_2 eq yr^{-1}) are greater than those from the fossil fuel sector (120 Tg CH_4 yr^{-1}; 3.0 Pg CO_2 eq yr^{-1}) and are close to the levels of those from natural sources[27] (for example, the 248 Tg CH_4 yr^{-1} from combined wetlands and inland waters; 6.2 Pg CO_2 eq yr^{-1}).

Similarly, the agricultural sector is a major contributor of N_2O emissions, with direct agricultural soil emissions alone equivalent to all other anthropogenic sources combined (around 2.1 Tg N yr^{-1})[28].

Box 1 | Trade in the global food system

Expansion of international agricultural markets has seen specific areas in middle-income and high-income countries with low marginal production costs undergo rapid agricultural and technological development to become the bread baskets of the world. By contrast, many resource-poor or lower-income regions (and farmers) that are unable to afford costly agricultural innovations and inputs (such as high-yielding varieties, fertilizers and pesticides) have become dependent on imports[8,203]. Since 2019, the total volume of exported commodities has hovered around 200 Mt yr^{-1}, which represents roughly 15% of global food production and corresponds to about 20% of global calories produced[204] (data from FAOSTAT). International trade has enabled local carrying capacity limits to be overcome[152] and contributed substantially to a global reduction of hunger. Concomitantly, food trade has created a shift of food production to specific nations with improved efficiencies and opportunity costs, and therefore also the burdens and environmental pressures to these food-producing nations. Exported products are responsible for around 27% of land use GHG emissions, 22% of agricultural land and 17% of global biodiversity loss[10,205], leaving many breadbasket regions, such as Brazil, the USA, Australia and Argentina, to bear the brunt of pollution, land use pressures and ecosystem deterioration.

Increased dependence on food imports leaves importing nations vulnerable to trade disruptions. Both environmental pressures in food-producing nations and import dependence can contribute to food insecurity. With the average diets and production systems of 2015–2019, only about 56% of nations can reach full food production autarky[176], highlighting the importance of coupling international and technological cooperation for the sustainable improvement of yields with dietary shifts towards lower-impact commodities. Although trade has become a fundamental aspect of the global food system, food system alignment with nutritional safeguards, as opposed to economic value, remains an important global policy priority[204].

Here again, livestock have a major role through manure emissions (at 1.7 Tg N yr^{-1}). Total agricultural N_2O emissions (3.9 Tg N yr^{-1}) have reached a third of total natural sources (11.9 Tg N yr^{-1}). In CO_2 eq (GWP100), these N_2O emissions become 0.74 Pg CO_2 eq yr^{-1}, 0.40 Pg CO_2 eq yr^{-1} and 2.3 Pg CO_2 eq yr^{-1} for agriculture, other industries and natural sources, respectively. According to full food supply chain analyses of GHG emissions (ref. 21), an increase of 0.2–0.3 °C since 1990 can be attributed to the food system. Studies projecting food system emissions under a business-as-usual trajectory suggest that the food system alone could breach the 1.5 °C or even the 2.0 °C target of total warming relative to pre-industrial times[29,30].

Soils

Soils are fundamental to terrestrial ecosystems and agricultural productivity, functioning as crucial regulators of biogeochemical processes and ecosystem services[31,32]. Soils have a pivotal role in water filtration and retention, nutrient cycling, carbon sequestration and support of below-ground biodiversity while serving as the primary medium for food and biomass production[33]. Currently, 33% of global soils are moderately to highly degraded owing to unsustainable agricultural practices and other human activities, including erosion, soil organic carbon loss, salinization and alkalinization, acidification, sealing, compaction, excessive irrigation and/or drainage, improper nutrient management, and pollution[34]. Based on 4,285 gross erosion rate estimates from 255 unique locations in 38 countries, almost one-third of soils under conventional agriculture have projected lifespans under 200 years, with 16% projected to last less than 100 years (ref. 35).

Globally, soils store more carbon than the atmosphere and terrestrial vegetation combined, with circa 2,000 Pg C as organic carbon[3,36]. However, agricultural lands are responsible for 54% of global soil erosion[37], and 12 kyr of agricultural activities are responsible for a loss of 133 Pg C from global soils[3]. This erosion is also estimated to result in the loss of 24 Gt of fertile topsoil annually[38].

From a pollution perspective, agriculture has resulted in a large rise in the use of pesticides (herbicides, insecticides and fungicides), which contain active ingredients that are generally harmful to ecosystems. About 3 Tg of pesticides are used yearly in agriculture[39], resulting in 64% of global agricultural lands being at risk of pesticide pollution (with 32% at high risk)[40]. More than 110 kt of antibiotics are applied to livestock globally, mainly in Asia and South America[41], resulting in the accumulation of antibiotic residues, antibiotic-resistant bacteria and antibiotic resistance genes in the soil, affecting the local microbial community structures. This accumulation can lead to a decrease in soil respiration, nitrification and denitrification[42], directly affecting the carbon and nitrogen cycles that maintain a resilient ecological community. Soil pollutants can eventually leach into the groundwater system or reach surface waters via agricultural runoff, degrading water quality.

Soil contamination not only affects plant productivity but also facilitates the transport of pollutants into adjacent water systems, compounding environmental and health risks[43]. Therefore, the degradation of soils compromises the foundation of food systems, accelerating climate change, reducing water quality and diminishing terrestrial biodiversity.

Nutrients and water eutrophication

Nutrient fertilizer production and application in agricultural land and aquaculture ponds have transformed previously unreactive forms of nitrogen in the atmosphere and phosphorus in the Earth's crust into reactive forms within the soil–hydrosphere–atmosphere system. Further, the largely inefficient use of fertilizers in agriculture can create excess nutrients that alter the local nutrient exchange in the mycorrhizal zone and plant–biota interactions[44–46].

Agricultural nitrogen use efficiencies are estimated at only 42% globally, with soy-producing regions (for example, in Brazil and the USA) having considerably higher efficiencies (over 50%) compared with locations where fertilizers are heavily subsidized (for example, in India and China, with efficiencies of under 35%)[47,48]. To satisfy this nitrogen demand, more than 180 Mt N yr^{-1} is currently produced (double that of the natural fixation of nitrogen) via the energy-intensive Haber–Bosch process, which consumes 1–2% of total global energy supply[49]. Excess nitrogen can accumulate in groundwater, leading to legacy effects[50] and runoff into the freshwater–coastal system. Agricultural phosphorus is typically mined from phosphate rock at around 20 Mt P yr^{-1} (ref. 46 and data from FAOSTAT), far surpassing natural weathering (1.5–2 Mt P yr^{-1})[51,52]. Low phosphorus use efficiencies also lead to a large increase in phosphorus accumulation in the soil. Over the twentieth century[52],

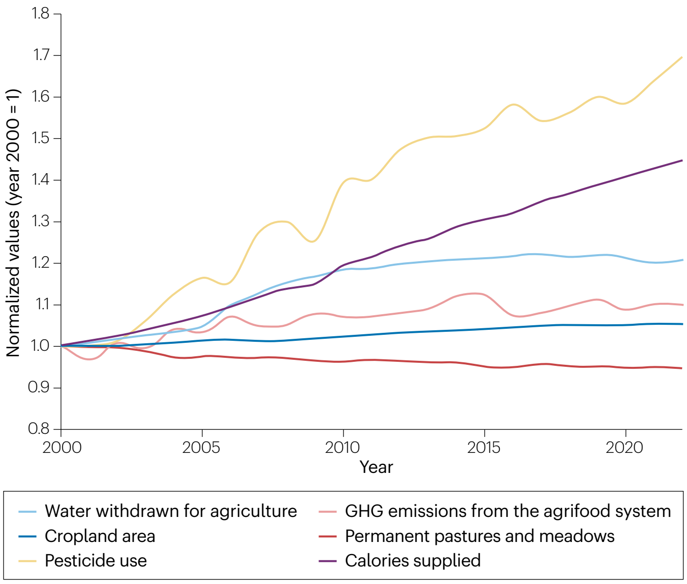

Fig. 1 | Trends in the environmental impacts of food production over the twenty-first century. Normalized (to year 2000 values) changes in global calories supplied (year 2000 = 6.0e15 kcal yr^{-1}), water withdrawn for agricultural use (year 2000 = 2,360 km^3 yr^{-1}), cropland area (year 2000 = 1,490 Mha), permanent grasslands and meadows (year 2000 = 3,380 Mha), pesticide use (year 2000 = 2.2 Mt yr^{-1}) and greenhouse gas (GHG) emissions from the agrifood system (year 2000 = 14.7 Gt CO_2 eq yr^{-1}). Data are from FAOSTAT and AQUASTAT. Since the year 2000, global food supply and most environmental pressures associated with food production have continued to rise.

estimated soil phosphorus stocks doubled (1.9–3.9 Gt P), with current cropland phosphorus stocks estimated at 3.2–4.3 Gt P (ref. 53). Regardless of legacy and accumulation effects, nutrient delivery to surface water grew from 43 to 67 Tg N yr^{-1} and by 5 to 9 Tg P yr^{-1} over the twentieth century[22], and they had reached 73 Tg N yr^{-1} and 10 Tg P yr^{-1} by 2015 (ref. 54).

Excess delivery of nutrients to freshwater and coastal systems leads to increased nutrient retention, concentrations and eutrophication[22]. The oversupply of nutrients can boost primary production, which channels energy away from higher trophic organisms[55]. Eutrophication negatively affects the local ecology, especially in water bodies with large residence times (such as lakes and reservoirs), as the heterotrophic decomposition of primary producers sequesters oxygen from the water column at a faster rate than oxygen replenishment. This process creates a drawdown of dissolved oxygen concentrations. When dissolved oxygen levels drop below a threshold (circa 2 ml O_2 l^{-1}), aerobic organisms struggle to survive (a phenomenon referred to as hypoxia)[55]. An estimated 1.2 million km^2 of waterbodies worldwide are eutrophic, with current trends showing further expansion in the future[56]. Eutrophication is also linked to about 14% of species being threatened with disappearance[57] (that is, based on the potentially disappeared fraction).

Water quality

Beyond nutrient pollution from fertilizers and wastewater, pesticides can leach into surface and groundwater, posing risks to human and ecological health[16]. Pesticide use has grown by two-thirds over the twenty-first century (Fig. 1), and despite most pesticides degrading in soils, 0.73 Gg yr^{-1} of pesticides arrive in surface waters leading to 13,000 km of river length exceeding safety levels, and 0.71 Gg yr^{-1} of pesticides reaching the oceans[39]. Antibiotic use in aquaculture reached over 10 kt in 2017 and could increase up to 13 kt in 2030 (ref. 58), and antibiotic release to the environment can have similar detrimental effects as those observed in soils. Moreover, agricultural runoff is increasingly recognized as a transport pathway for microplastics originating from plastic mulch, irrigation systems and agrochemical packaging[59]. These particles not only degrade water quality but can also carry heavy metals and organic pollutants, exacerbating their toxic effects[60,61]. In addition, pathogens from livestock waste and manure application can contaminate both surface and groundwater, further threatening water safety and public health[62].

Water availability and environmental flows

Water demand for food production considerably impacts the global hydrological cycle, primarily through irrigation practices. Agriculture accounts for roughly 60–70% of freshwater withdrawals, with a 3:1 ratio of surface water to groundwater[63,64]. Irrigated agriculture accounts for 40% of global food production, despite only using 22% of cultivated land (ref. 65 and data from FAOSTAT).

To satisfy this water demand, around half of the world's rivers have been dammed and only a third of the world's longest rivers remain free flowing[66]. Global rates of decreasing groundwater levels outpace the rates of groundwater-level recharge[67]. Over 30% of the studied aquifers are seeing an accelerated decrease of groundwater levels, especially in areas characterized by cultivated drylands. An estimated 30% of irrigated crop production violates environmental flow requirements[68], and around 52% of global irrigation practices are deemed unsustainable, 15% of which is virtually exported in traded food products[69] (Box 1). Excessive abstraction of groundwater for food production is associated with groundwater depletion and degradation, and can also lead to land subsidence and seawater intrusion, threatening food production[7,70]. With more than 40% of water use destined for feed crops, the increasing demand for animal-sourced foods is a key driver of global water transformations[63–65,71,72]. Furthermore, almost 80% of the global population lives in locations with a high risk of water scarcity and/or biodiversity loss[73].

Terrestrial biodiversity

Agricultural land expansion can severely impact terrestrial biodiversity[2]. Permanent encroachment into forestland leading to deforestation accounts for circa 35% of global tree cover loss[74]. Permanent encroachment is the predominant form of agricultural land expansion in southeast Asia (78%) and in Latin America (56%). Temporary encroachment via shifting agriculture (also known as shifting cultivation) is also an important component of global tree cover loss (21%) and is the primary driver of tree cover loss in Africa (92%)[75]. Deforestation is especially concerning in the tropics and in relatively intact landscapes, where over 90% of deforestation is due to agriculture[76]. Species in Borneo, the central Amazon and the Congo Basin are at high risk of extinction under current deforestation rates[77], and habitat loss in the tropics is linked to a loss of 16 million populations per year (equivalent to about 72,000 species)[78]. Biodiversity is also severely affected by the deposition of human-induced ammonia emissions in soils and water bodies[17].

These biodiversity impacts can be long-lasting or time delayed, with legacy effects commonly referred to as extinction debts[79]. Species can decline gradually over time as their habitats continue to degrade.

In response to habitat disturbances such as deforestation, species communities can undergo a process of adjustment over time to reach a new equilibrium, which can delay biodiversity impacts[79]. Population decline is occurring for approximately 32% of vertebrate species, both in range and abundance, and over 40% of selected mammal species lost more than 80% of their geographic range between 1900 and 2015, especially in the tropics[13]. More than three-quarters of agricultural land use is estimated to occur in sites of medium to very high conservation priority[80]. The magnitude and extent of this biodiversity decline threatens ecosystem integrity and resilience and is consistent with the onset of a sixth mass extinction.

Aquatic biodiversity

Eutrophication resulting from agricultural nutrient emissions (and excluding point sources) is predicted to lead to around an 11% decrease in global species richness[57]. Statistical analyses of the impacts of agricultural land use on freshwater biotas underscore that impacts (mainly via nutrient loads) can vary by species: minor negative effects for diatoms, moderate to high negative effects for macrophytes and fish, and high negative effects for invertebrates[81]. The effects of river damming and the use of pesticides, fertilizers and antibiotics can affect species downstream beyond national borders, and lead to the externalization of impacts. In addition, around 17% of global biodiversity loss occurs because of the cultivation of commodity crops that are destined for export[10] (Box 1).

Several practices in aquatic food production, such as (bottom) trawling and dynamite fishing, are detrimental to aquatic systems, especially benthic habitats. Bottom trawling uses heavy nets dragged across the seafloor to capture fish. Around 26% of wild fish catches originate from trawling activities[82], and 15–25% of the global continental shelf seabed undergoes bottom trawling each year. Trawling activities not only lead to a substantial amount of by-catch (over 50% for trawled shrimp) but also up to 41% loss of biota, with recovery times for the benthos ranging between 1.9 and 6.4 years[82]. Owing to sediment disturbance, bottom trawling can also release about 5,600 Mg yr^{-1} of anthropogenic mercury from coastal sediments[83]. Although largely discontinued, dynamite fishing, which involves stunning or killing fish by detonation of explosives underwater, creates rubble fields and resuspended sediments that undermine the physical and biological integrity of coral reef systems, with recovery taking up to five years after cessation of blasting[84].

Impacts of changing environmental conditions on food systems

Food production has a profound impact on the environment[23], and the environmental changes wrought by this and other anthropogenic processes feed back on food systems. An assessment of the cumulative environmental pressure for four indicators associated with food production (greenhouse gas emissions, freshwater consumption, nutrient pollution and habitat disturbance) covering about 99% of 2017 global output showcases the different environmental impacts of food products[85]. The normalized, unitless cumulative-pressure index reflects[85] the overall magnitude of environmental impact from food production, whether driven by the co-occurrence of multiple pressures or by the intensity of individual ones.

Mapping the cumulative environmental pressure of calorie production by different food sources for 2010–2022 highlights how the steepness of the relationship varies for the different food groups (Fig. 3), with blue and animal-sourced foods representing more impactful commodities (gentler slopes) than plant-sourced foods (steeper slopes). Importantly, multiple global assessments indicate that ongoing climate change impacts and environmental degradation are flattening these slopes, by lowering productivity and tightening local biophysical limits, as detailed below for croplands, livestock systems, and fisheries and aquatic production.

Croplands

Changing environmental conditions can have detrimental effects on soils, on water quantity and quality, and ultimately on crop growth. Increased pollution and contamination from nutrient runoff and pesticides can adversely impact soil health, local biodiversity and environmental resilience. This degradation compromises food crop safety and leads to food-borne illnesses and other health risks. These effects lower productivity and flatten the calorie production–environmental impact curve, especially in which water, soil and biodiversity constraints exist (Fig. 3).

Worsening environmental conditions and climate change can affect crops in a complex and, at times, interactive way. For example, increasing CO_2 concentrations can promote crop growth by around 19% in C_3 crops (such as wheat and rice) while also decreasing evapotranspiration and improving water use efficiency[86,87]. However, higher CO_2 levels in C_3 crops create imbalances in the C/N ratios[88] of crop tissues and reduce zinc, iron and nutrient content[89]. By contrast, C_4 crops (such as maize and sorghum) show only modest yield improvements under elevated CO_2 conditions and water limitation (yield improvements of up to 5%), with negligible changes to nutrient content[89].

Elevated atmospheric CO_2 levels also raise canopy temperatures by roughly 0.7 °C, which could intensify heat stress and offset potential

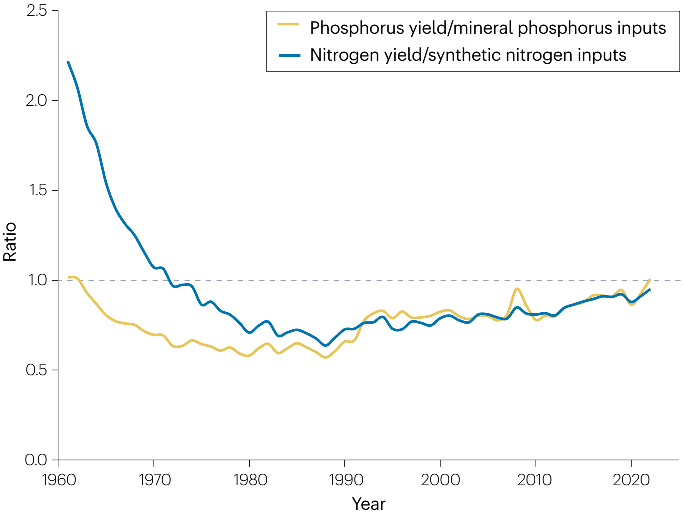

Fig. 2 | Declining agricultural nutrient use efficiency for the past 60 years. The ratios of crop nitrogen yield to synthetic nitrogen inputs and crop phosphorus yield to mineral phosphorus inputs are depicted. These ratios differ from nutrient use efficiencies calculated for soils, which normally also include inputs from (amongst others) deposition, manure, biological fixation (in the case of nitrogen) and weathering. Values below 1 represent years when artificial nutrient inputs exceeded the harvested quantities and thus indicate accumulation of nutrients in the soil–hydrosphere continuum; values above 1 represent years when crop production (or biological fixation, in the case of nitrogen) depletes nutrient levels in the soil. Data are from FAOSTAT. Since the 1980s, nutrient use efficiency has slowly improved but remained below balance in 2020.

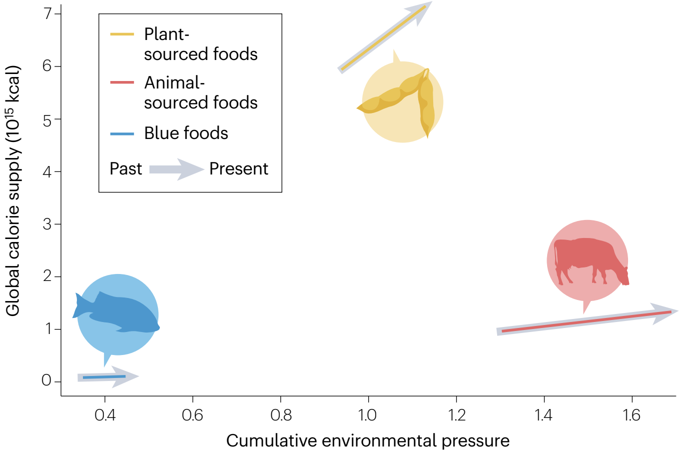

Fig. 3 | Relative cumulative environmental pressure per calorie supplied for different food groups. Global calorie supply is based on FAOSTAT Food Balances (2010–2022). Cumulative environmental pressure includes greenhouse gas (GHG) emissions, blue freshwater use, excess nutrients (nitrogen and phosphorus) and habitat disturbance (environmental coefficients per calorie are from 2017 data[85]). Plant-sourced foods provide large calorie gains with comparatively modest increases in environmental pressure, whereas animal-sourced food add little additional calories while driving large increases in environmental impacts (the plant-sourced slope is about eight times steeper). Blue foods remain low in both calorie contribution and environmental impacts.

yield gains, especially during the plant's reproductive stages[87]. Biochemical processes such as photosynthesis theoretically rise exponentially with increasing tissue temperature up to a thermal optimum. Beyond this point, biochemical reaction rates decline as elevated temperatures lead to enzyme deactivation and denaturation[90]. Higher temperatures also increase the likelihood of heat stress during critical reproductive periods, leading to sterility, lower yields and the risk of complete crop failure[91]. In addition, extreme temperatures can favour the growth and survival of many pests and plant diseases[92,93].

Droughts are predicted to intensify under climate change[94], jeopardizing crop yields and production[95–97]. In Europe, drought and heat waves have intensified over the past five decades, resulting in reduced cereal yields[96]. Annual drought losses in the European Union (EU) and United Kingdom are expected to rise, resulting in economic losses of over €65 billion per year[98]. In addition to intensifying droughts, flooding events are expected to increase in intensity and frequency, with detrimental impacts on crop productivity globally[26,99].

Flooding disrupts a plant's production of secondary metabolites and phytohormones, which are crucial for growth, defence against pathogens and exudate signalling[100]. Flooding also alters the pH and redox conditions of the soil, potentially affecting the general below-ground ecology and ecosystem functioning[101]. These impacts of flooding on soil and plant health can remain even after floodwaters recede, creating legacy effects that are currently understudied[100]. Soil loss via water erosion can also lead to major economic losses from agricultural systems. Modelling scenarios predict an increase in soil erosion rates of between 30% (for Representative Concentration Pathway 2.6, RCP2.6) and 66% (for RCP8.5) by 2070, with the highest rates in tropical areas with abundant agricultural production[102]. By 2070, this soil erosion would incur primary agricultural losses ranging from 102 Mt yr^{-1} for RCP2.6 to 352 Mt yr^{-1} for RCP8.5.

Changing climatic conditions can make some areas unsuitable for specific crops while opening new areas for the cultivation of others. In tropical areas, cultivation of coffee is increasingly moving towards higher altitudes, leading to up to 60% of mostly wild varieties being threatened with extinction[103]. In Mediterranean and temperate regions, harvesting cycles are happening earlier, and some key economic crops can become unsuitable for farming. For example, wine regions in much of the southern parts of the European Mediterranean are likely to become unsuitable for wine production if the 2 °C temperature threshold is exceeded[104]. Furthermore, global caloric production of six staple crops (maize, soybean, rice, wheat, cassava and sorghum) in the year 2100 is predicted to decrease by 5.5×10^{14} kcal yr^{-1} per 1 °C increase in global mean surface temperature under the regional rivalry scenario (shared socioeconomic pathway 3 (SSP3))[105].

Many of these climate impacts will happen in combination and will differ across countries, regions and continents[26,106]. A predicted increase in mean annual temperatures and altered precipitation regimes over the next century pose substantial risks to smallholder farmers and agriculture[95,107,108]. Such changes can disproportionately affect locations where agriculture forms the primary source of livelihood, such as sub-Saharan Africa[26].

Environmental change can also lead to a loss of ecosystem services related to biodiversity. In croplands that experienced unusual temperature increases, insect pollinator abundance has decreased by over 60% compared with undisturbed natural habitats[109]. Under various climate change scenarios (RCP2.6 and RCP6.0), many (small-scale) farmers in tropical to subtropical regions who rely on pollination-dependent crops (for example, cocoa farmers in Africa, mango farmers in India and watermelon farmers in China) face a severe threat of lower production and economic disruptions. This risk can eventually spread globally through trade, affecting major importers and processors of crops such as cocoa and coffee[109]. Declines in bees and various bird species negatively affect crop production, including coffee, soybeans and cocoa[110].

Biodiversity loss has also been linked with soil degradation, which increases dependence on artificial fertilizer inputs[111]. At the farm level, biodiversity loss leads to increased variability in crop yields, reducing the reliability of food production from farms[112]. Resilient agroecosystems also provide ecosystem services and biological pest control[113]. A reduction in species richness can ultimately lead to lower crop production, especially in fields that are not treated with insecticides, which can mask the benefits of biodiversity in providing natural pest control[113].

Livestock systems

Environmental impacts on crops will also indirectly affect livestock systems, as just over one-third of global crop calories are used as livestock feed (according to data from FAOSTAT). For example, poultry and swine rely more on feed than on grazing and, given that maize and soy yields are predicted to decline under most climate scenarios[114], either more cropland area will be needed to provide the same amount of feed for these livestock classes or their global numbers will need to be reduced. Declining crop yields might also necessitate redirecting land use from feed towards food crop production, intensifying the pressures on livestock systems. Reduced forage quality from climate warming could induce a positive climate feedback loop whereby cattle methane emissions increase by about 0.9% per 1 °C and 4.5% per 5 °C rise in temperature[115]. These effects are predicted to lead to fewer calories per unit of environmental pressure as feed shortfalls increase land, water and nutrient inputs per unit of animal-sourced food[26] and a flattening of the calorie production–environmental impact curve (Fig. 3).

Environmental change can also directly impact livestock systems. Heat stress in cattle can lead to a reduction in animal appetite and fertility, an increase in mortality rates and lower yields[116,117]. Climate change also affects the population density and reproduction of insects and vector-borne diseases[118]. Tropical insect populations, such as the *Culicoides* species of biting midge (vectors of diseases and parasites), have migrated to higher latitudes, leading to global outbreaks of the bluetongue virus in Europe and Australia[119]. Climate change can promote the growth of mycotoxin-producing fungi and parasitic diseases such as gastrointestinal nematodes, which can cause acute diseases and impair immune function, increasing the susceptibility of animals to infections[119]. In East Africa specifically, the frequency of dangerous heat stress conditions for livestock, including dairy cattle, beef cattle, sheep, goats, swine and poultry, is projected to increase[120].

Under an RCP8.5 pathway, a high GHG emission and global warming scenario associated with higher climate sensitivity, the percentage of cattle worldwide that are exposed to dangerous heat conditions will increase from the present 7% up to 48% by the year 2100 (ref. 121). In a similar scenario (SSP5-8.5), rising temperatures will severely affect milk and beef production in sub-Saharan Africa, South Asia, Brazil and Central America and result in global losses reaching $9.1 billion for dairy and $31 billion for beef (in 2005 constant $ values)[117]. In pig production systems, increasing temperatures correlate with lower average daily feed intake and lower average daily weight gain[122]. As birds lack sweat glands, poultry are highly susceptible to heat stress, leading to reduced protein digestibility by birds, lower daily feed consumption and a 29% reduction in egg-laying[123].

Fisheries and aquatic production

Warming oceans, eutrophication, salinity changes, pollution and diverted waterways have direct impacts on aquatic life. The extent to which food production impacts aquatic environments, and thereby alters blue food production, has not been fully quantified, but over 90% of blue food production is vulnerable to anthropogenic environmental stresses, affecting food security for 3.2 billion people[124]. Global catch production from freshwater systems (excluding mammals, crocodiles, alligators, caimans and algae) has seen a steady increase, growing from about 7 Mt of live weight in 1990 to around 12 Mt in 2020, driven largely by an increase in production in Asia and Africa[125]. However, global marine catches (excluding mammals, crocodiles, alligators, caimans and algae) have mostly stabilized since the 1990s at around 80–85 Mt of live weight. Most global marine catches have declined, with substantial loss in production from the Atlantic Ocean, Mediterranean Sea and Pacific Ocean (excluding the western central areas). Wild catches have mostly stabilized, owing to large increases in production from China, Vietnam and Indonesia in the Western Central Pacific and from India, Bangladesh and Indonesia in the Indian Ocean. Nevertheless, the share of overfished (unsustainable) fisheries has been growing over the past decades and is 35.5% for the 2020s (ref. 126).

Aquaculture production has increasingly compensated for the stalled wild catch production in the blue food sector and as of 2020 accounts for almost half of blue food production. Nevertheless, little evidence exists for a one-to-one displacement of live catches[127], and aquaculture has its own set of environmental pressures and challenges. For example, economic and environmental sustainability correlate strongly with a frequency of wild catches that maintains healthy populations, but for aquaculture, this correlation is weaker and could further exacerbate environmental pressures, especially in regions such as India and Myanmar[128].

Ocean warming has wide-ranging impacts on tropical seas and the diverse coral reef environments on which many fish species depend. Coral reefs have declined by half since the mid-twentieth century, leading to a decline in catches and ecosystem services[129]. Mass coral bleaching owing to rising temperatures decreases live coral counts but also affects the structural complexity of the habitat. With the abundance of coral reef fish species potentially declining by more than 60%, non-coral biota can also invade reefs, stalling their eventual recuperation[130] and leading to community reshuffling[131]. Ultimately, in a 1.5 to 2 °C warmer world, 4% to 9% (respectively) of freshwater species are projected to have more than half of their present-day geographic range threatened[132]. Furthermore, temperature increases and salinity changes can reduce the density of the surface ocean, and therefore ocean-layer mixing owing to the increased stratification, limiting nutrient upwelling[133]. Although catches from upwelling areas have declined on a global scale, they are highly dependent on the El Niño–Southern Oscillation variability, and production has increased in areas off the West African coast[133].

The adaptability of well-established marine ecosystems can be threatened by changing environmental conditions. Laboratory experiments show that ocean warming and acidification together disproportionately affect mid-trophic levels (primary consumers), leading to an unsustainable situation for many secondary consumers (fishes)[134]. Under both high (720 CO_2 ppmv) and low (360 CO_2 ppmv) climate change scenarios for 2100, low-latitude (equatorial) fishes are increasingly likely to migrate towards higher latitude regions where temperatures become more suitable to their habitat[135]. This potential migration can lead to additional pressures on temperate regions, leading to the deterioration of kelp forests[136], which are already under threat from heat waves[137]. Fish migration will lead to a change in fishing patterns by 2050, with increased open water fishing catches (by 12–18%, mainly in the North Atlantic) expected to compensate for decreased shelf fishing catches (by 4–5%)[135].

Ocean acidification is also likely to have major effects on global marine species, including those used in food production. Global oceanic pH levels have already decreased by over 0.1 units and are on a trajectory to decrease by 0.3 units by the end of the century. Elevated CO_2 levels lead to a decrease in nutrient and fatty acid concentrations in many primary producers, directly affecting the growth and reproduction of their predators (for example, in copepods and oysters[138,139]), and metabolic suppression in gastropods[140]. Overall, warmer and more acidic waters that mix less, together with coral loss, poleward shifts in fish distributions, kelp declines and stressed freshwater species, reduce nutrient supply and growth throughout the food web, resulting in fishing efforts yielding fewer edible calories and a flattening of the calorie production–environmental impact relation (Fig. 3).

Amplified feedback

Climate change alters precipitation and snowmelt patterns, increases temperatures and changes soil moisture and runoff dynamics, affecting water sources useful for food production. Although water availability might increase in some locations, water scarcity can also intensify, leading to an increase in irrigation demand and competition with other water uses. Pollution of the soil and water with nutrients and toxic substances reduces the ability of local ecosystems to sustain diverse and resilient life, reducing the size of fisheries. Biodiversity loss directly affects ecosystem services, including a decrease in the number of pollinators and of traits of wild species that allow for climate and pest tolerance[113]. Climate change is also likely to magnify the environmental impacts of agricultural production, increasing soil erosion and environmental losses of human inputs into agriculture[141]. However, several mitigation and adaptation interventions can be deployed to prevent and reverse the ongoing amplification of these feedback mechanisms (Fig. 4).

Supply-side transformations of global food production

A Great Food Transformation involves both supply-side and demand-side interventions that mitigate current food production pressures and facilitate adaptation to existing environmental changes (Fig. 4). Very broadly, this transformation comprises three pillars: improving production, reducing waste and changing diets to minimize the demand for food with high environmental impacts, especially in high-income regions[30,142]. Whereas reducing food waste and loss and changing diets (such as reductions in the consumption of animal-sourced food) represent highly impactful demand-side interventions with considerable potential to drive food production changes, we focus on supply-side interventions that will reduce the bidirectional effects (feedbacks) between food production and the environment.

Mitigating environmental impacts

Supply-side interventions seek to reduce the resource use and environmental intensity of food production[26]. These interventions rely on a combination of technological advances in crop and livestock breeding and nutrition and improved farming management practices[142]. The most frequently assessed supply-side interventions involve closing crop yield gaps to boost crop yields and increasing livestock productivity through higher yields per animal and improved feed efficiency[142]. These interventions have considerable land-sparing (and forest-sparing) potential, with strong synergies for biodiversity, reduced enteric fermentation and increased carbon sequestration potential[143]. However, increasing crop yields through conventional intensification could entail additional inputs (such as irrigation water and nutrients) and thus needs to be approached carefully to ensure that environmental trade-offs are minimized[5]. Increasing water use and nutrient use efficiency to close yield gaps and minimize agricultural inputs can be achieved via rainwater harvesting, improved irrigation infrastructure and soil conservation practices alongside restoration of degraded soils[144]. Crop migration and irrigation expansion have alleviated environmental shocks to rainfed staples such as maize, wheat and rice, although these approaches face biophysical, political and economic constraints[145].

Farm-level shifts to soil-conserving agricultural systems that enhance soil health are urgently required[146]. These practices include contour cultivation, cover cropping and conservation tillage, and they can extend soil longevity beyond 10,000 years, although their effectiveness depends on local factors such as climate, slope and soil texture[35]. Climate-smart and precision agriculture can promote efficient nutrient and resource use to optimize yields via data-assisted land management tools[147]. Such interventions could avert and potentially reverse climate-induced yield losses at 1–2 °C of global temperature rise while also reducing greenhouse gas emissions and resource use[148,149]. Increasing the share of protein production from new sources (for example, cultured meat, insects, microalgae and mycoprotein) could cut CO_2 eq emissions by 88% and land use by 82% compared with conventional animal-sourced foods[150]. Finally, the distribution of production could be improved by increased trade openness and fairer restructuring of agricultural production to encourage farming in the most efficient locations[151,152].

Adapting to environmental changes

Mitigation can reduce environmental impacts, whereas adaptation facilitates adjustment of agricultural systems to existing and predicted

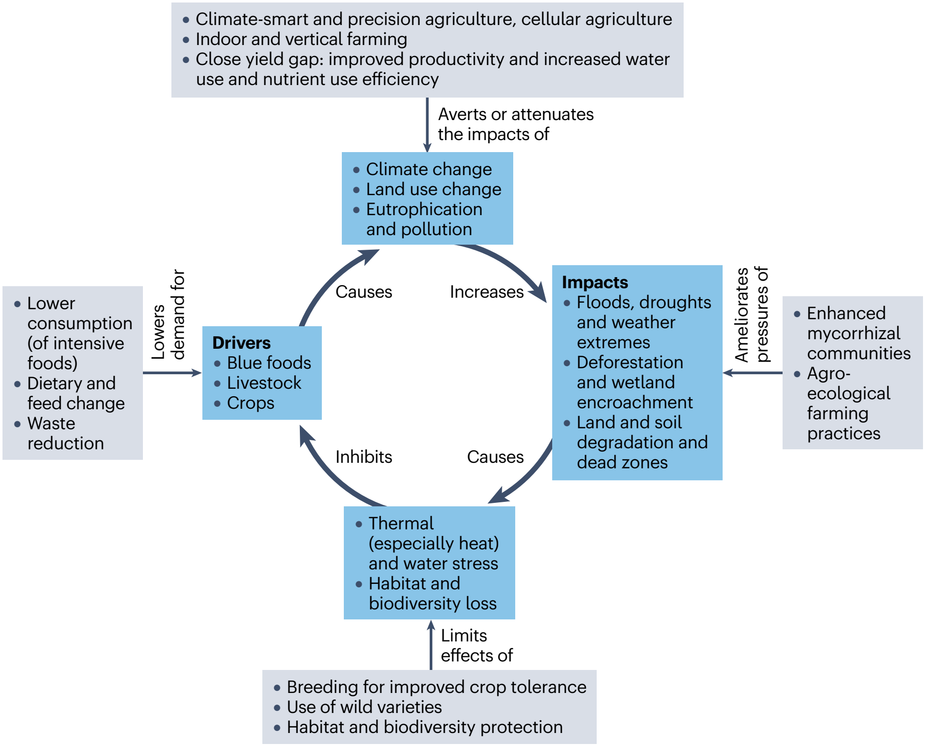

Fig. 4 | Global bidirectional impacts of food production on the environment. Blue boxes show major environmental pressures (climate change, land use change, eutrophication and pollution) and their feedback loops with food production (blue foods, livestock and crops). Grey boxes indicate interventions that can reduce pressures or improve system resilience. Arrows show causal directions: food production drives environmental changes, leading to impacts such as weather extremes and land degradation, which in turn exacerbates stressors such as heat stress, habitat loss and biodiversity loss that limit future food production. Food production thus both drives and is constrained by environmental change, but targeted interventions can shift these feedback loops to stabilize the system and reduce future risks.

Table 1 | Relative environmental impacts of agrifood and animal-food-specific practices

Factor	Agrifood sector contribution to total global impact	Food products with the highest impact	Contribution of animal foods and feed to agrifood sector impacts	Refs.
GHG emissions	25–34%	Beef and lamb, dairy and farmed crustaceans	~60%	21,23,29
Total water consumption	~87%	Beef and lamb, and tree nuts	~42%	71,72
Freshwater withdrawals for irrigation (blue water)	50–70%	Beef and lamb, and tree nuts	40–50%	63,64 (data from AQUASTAT)
Ice-free land surface area	26% for pastures 12% for croplands	Beef and lamb, dairy, and feed	100% of pastures 35% of croplands for feed production	168
Tropical deforestation	>90%	Beef and lamb, soybean, and sugarcane	40–60%	76
Synthetic nitrogen use	77–85%	Fruits and vegetables, and rice	~10–11% fed directly to livestock[a] ~44–47% for feed crops	6,44,48,199 (data from FAOSTAT)
Nitrogen emissions	83–97%	Livestock, cereals, and fruits and vegetables	~35%	47,199
Mineral phosphorus use	80–90%	Wheat, rice and maize	8–9% fed directly to livestock[a] ~2% for grasslands ~27% for feed crops[b]	200,201
Threatened species negatively impacted	53–75%	Beef and lamb, maize, rice, and soybean	20–30%	80,202

[a]Value based on total nutrient production (including for non-agricultural uses). [b]Value based on a proportional allocation of feed and food crops.

environmental changes. For some food types, enclosed food production systems such as greenhouses, vertical farming, cellular agriculture and indoor aquaculture offer potential adaptation pathways by enabling precise control over temperature, nutrients, disease and light, thereby buffering against climatic variability[153]. The development of crop varieties that are tolerant to drought, heat, flooding and salinity represents another crucial strategy for farmers to adapt to environmental changes[154]. Resilience can be enhanced by non-technical supply-side adaptations, including the use of non-native, wild or substitute crop equivalents to improve the climate resilience of staple crops, such as roots, tubers and cereals[108]. To improve nutrient cycling, inoculating soils with (arbuscular) mycorrhizal fungi can improve the uptake of both nitrogen and phosphorus and can re-establish soil communities disrupted by their imposed dependence on synthetic and mineral fertilizers[155]. Furthermore, these fungi can act as important carbon sinks and aid in soil aggregation and health[156].

The breeding and cultivation of climate-resilient crops, including wild relatives of domesticated crops, can further enhance yields through improved biotic and abiotic stress tolerance[157,158]. Complementary strategies such as agroecology promote diversification via polycultures, intercropping, crop rotations, cultivation of perennials, agroforestry and integrated crop–livestock systems, supported by soil management and ecological diversification[159–161]. These agroecological approaches can contribute simultaneously to mitigation and adaptation[162], reduce dependence on chemical inputs and improve environmental and food system health. Effective dissemination of these practices requires farmer participation in field schools[163] and engagement in national and international adaptation decision-making processes and forums[164].

Silvopasture systems involve the integration of trees into pasturelands and can lead to cooling benefits of over 2 °C ha^{-1} per 10 metric tons of woody carbon planted[165]. These systems can provide shade and heat stress protection for animals and are a potential source of roughage, forage and fruit production. Silvopastures also promote carbon fixation to a greater extent than conventional pasturelands. When combined with legumes, silvopastures can also promote biological nitrogen fixation, although legume and grazing practices together with climate and soil conditions can contribute to order-of-magnitude differences in this fixation[166]. Nevertheless, livestock production (including feed) results in greater global environmental impacts (Table 1) owing to the cumulative supply-chain pressures of its per calorie production (Fig. 3) and incurs metabolic losses, with a proportion of the energy and protein (and nitrogen and phosphorus) present in feed lost as heat and excreta. These losses would decrease in production systems that are focussed on food instead of animal feed[167,168]. Although silvopasture and the use of co-products and crop residues that are considered non-edible or non-desirable by humans as feed provide a potential solution for reducing livestock impacts, these approaches would require a substantial reduction in animal numbers[169] and a complete food system redesign that focuses on circularity. In such a system, animals can be nutrient recyclers within the general nutrient needs and capacities of the land[169,170].

Redesigning food systems for circularity following agroecological principles could contribute to them staying within Earth's biophysical limits and transitioning towards sustainability[147,171]. In Europe, circularity principles would reduce land use by 71% and greenhouse gas emissions by 29% per capita while ensuring sufficient production of healthy food[170]. Applying circularity principles together with dietary changes towards the Planetary Health Diet would enable the transition of food systems to the safe operating space within planetary boundaries while fulfilling global nutritional needs. Food losses and waste should then be reduced by 50%, and 90% of the remaining waste should be recycled in the food system as feed or as fertilizer[172]. These improvements highlight the role of circularity as a promising mitigation and adaptation measure (Fig. 4).

Summary and future perspectives

Modern food systems now use over one-third of global land area, drive roughly a quarter to one-third of total anthropogenic GHG emissions and account for most anthropogenic demand for freshwater. Unsustainable fertilizer and pesticide use has led to widespread eutrophication, soil degradation and pollution, compromising ecosystem integrity. Changing environmental conditions are exerting growing pressure on global food systems by constraining productivity and amplifying environmental degradation. Croplands are increasingly affected by soil degradation, pollution, droughts, floods and heat stress, with projected yield declines correlating with increasing projected temperatures. Livestock systems face reduced feed availability, rising heat stress and disease spread, resulting in lower meat and milk yields. Blue food yields are undermined by ocean warming, acidification, eutrophication and coral reef collapse.

Mitigating the numerous environmental pressures outlined here requires supply-side transformations, including precision and climate-smart agriculture, improved water use and nutrient use efficiency, and expansion of new protein sources (Fig. 4). Adaptation strategies such as silvopasture, agroecology, mycorrhizal inoculation and climate-resilient crop breeding can restore ecosystem function, close yield gaps and build resilience. More scientific efforts on enhancing pesticide and antibiotic breakdown, together with improved monitoring and quantification efforts for pesticides and emerging chemicals, can help policymakers to better understand the impacts of agrochemical use and the technological solutions to mitigate these impacts.

To reduce the environmental pressures of food production, supply-side interventions must be adapted to specific geographical contexts and accompanied by demand-side interventions[173]. For example, the primary driver of land use change and forest loss in Latin America is commodity-driven deforestation, whereas in sub-Saharan Africa, it is changes in agricultural production[75]. In Latin America, ideal interventions include consumption changes and more sustainable trade agreements, such as the deforestation regulations of the EU, whereas the most effective interventions for sub-Saharan Africa are limiting increasing demand and closing yield gaps[174]. By combining multiple interventions and food system actors, synergies are maximized[142]. Further studies must evaluate the opportunities and challenges for coordinated demand-side and supply-side strategies to help to mitigate and adapt to food system risks.

Easing food demand pressures is thus also crucial to reducing risks that threaten food production[175]. For example, adopting plant-rich diets can improve national food security[176,177]. Shifts towards plant-based flexitarian diets, such as the Planetary Health (EAT-Lancet) diet[30,178], combined with reducing current levels of food loss and waste by 50% in accordance with the Sustainable Development Goal targets[179], exhibit a very high mitigation potential across all environmental indicators[171,178]. However, demand-side interventions rely on overcoming considerable behavioural feasibility challenges such as culturally ingrained social norms around food consumption choices and would entail the transformation of the broader economic and regulatory environment[180]. To improve understanding of suitable levers, further studies are needed on instruments (taxes, subsidies, regulation and changes to consumption environments)[181] that restrict, eliminate or dissuade consumption of high-impact food products.

More knowledge is needed on the economic and technological feasibility and the cultural acceptability of such interventions to distinguish the roles of different sociodemographic groups and strategies in achieving a sustainable food transition[142]. Improved knowledge can prevent unintended consequences, such as food price hikes and increased food insecurity for lower-income consumers[182]. These efforts require the development of higher resolution data on the food consumption patterns of different socio-demographic groups, which are otherwise hidden by nationally averaged food system modelling[183]. Further research is also needed to understand the loss and damage costs of global environmental change for vulnerable actors in affected food systems[184], given that major breadbasket regions will face climate change risks sooner than previously anticipated[185].

Legislating and developing policy related to the environmental externalities of food systems requires that local land use decisions are linked with their cumulative transboundary consequences, which are transmitted through biophysical and economic connections[186]. Globally defined constructs such as planetary boundaries delineate aggregate biogeochemical limits but do not offer operational guidance at regional to sub-national scales[173]. To address this gap, multi-level governance architectures, in which instruments at different scales are mutually reinforcing for the food system, should be further investigated[187]. Global regimes such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, the Stockholm Convention on Persistent Organic Pollutants and the United Nations Framework Convention on Climate Change (UNFCCC) establish binding obligations that shape national legislation and trade practices. Regional organizations can develop frameworks that translate these obligations into spatially explicit targets, for example, the Baltic Sea Action Plan of the Baltic Marine Environment Protection Commission (Helsinki Commission, HELCOM), the Convention for the Protection of the Marine Environment of the North-East Atlantic of the OSPAR Commission and the Nitrates Directive of the European Commission. National and local authorities can then operationalize these targets through agro-environmental schemes and adaptive land management practices[188].

Decoupling national economies from the agricultural sector can reduce the exposure of countries to environmental change. However, for the food sector, strategies that rely on imports pose a trade-off with national food security[189], increasing susceptibility to trade disruptions. Stockpiling provides an alternative strategy for dealing with environmental pressures, but low-income nations might face critical policy and infrastructure challenges for effective implementation[190]. Diversified food procurement networks have demonstrated greater resilience to environmental shocks than non-diversified systems[191], so they could serve as an alternative to building strategic reserves of staple crops or introducing financial support for vulnerable food producers[192]. The environmental effects of these diverse government actions to increase food security should be investigated further within specific national contexts.

Mitigation and adaptation strategies need to be designed jointly to dampen and even reverse the reinforcing feedbacks between environmental impacts and food production[144,193]. In some cases, mitigation and adaptation efforts are synergistic. Land sparing and rewilding via dietary shifts[11] result in better flood water absorption and management[194] and in the restoration of wetlands and the removal of reactive nitrogen[195], which, in turn, improve the resilience of other food production systems downstream. Another example is adaptation via crop migration[145], in which shifting crop growth locations can be aligned with suitable soil profiles to reduce food production pressures. For example, cultivating crops that are suitable for wet or rewetted peatlands, rather than draining peat for conventional crops, can maintain production while reducing soil carbon emissions and subsidence, acting as both adaptation and mitigation[196]. Conversely, mitigation pursued without adaptation could lead to rebounds. For example, reductions in food waste can be counteracted by an increase in consumption (over 50%)[197], which would also offset a portion of the environmental gains. Similarly, mitigation trade-offs could occur. For example, the use of antimethanogenic feed additives for cattle together with planting trees is a promising strategy for mitigating climate impacts[198], but without efforts to encourage consumers to eat less meat, land use for livestock consumption could increase.

If adaptation is pursued without mitigation, yield gains and stabilized production in the short term (by the use of climate-resilient technologies) can be negated by continued trends towards more resource-intensive consumption patterns[144,193]. Examples of integrated demand-side and supply-side mitigation and adaptation strategies include coupling plant-rich diets with climate-smart agriculture to reduce land and nutrient demand while sustaining yields under rising temperatures; linking agroforestry and sustainable trade agreements to sequester carbon, maintain biodiversity and support farmer livelihoods under climate stress; and combining circular feed systems with downstream food waste reduction to cut GHG emissions and nutrient surpluses while reducing dependence on primary inputs[26]. Furthermore, large-scale uptake of mitigation and adaptation solutions requires adequate financing, socio-cultural acceptance and an enabling regulatory environment in individual countries and globally[193]. Strategies to redress imbalances in power, ownership and autonomy in food systems are also needed to avoid trade-offs between environmental mitigation and social equity[12].

Explicitly considering feedback loops between food production and environmental change in the context of mitigation and adaptation strategies helps to avoid maladaptation. Future research should carefully evaluate the trade-offs of strategies and policy incentives to minimize rebound effects and avoid Jevons Paradox and unintended social costs. Integrated strategies using coupled and spatially explicit modelling approaches (including crop, economic and land use models, global trade and supply chain analysis) can provide systematic intercomparisons to identify in which mitigation and adaptation can be mutually reinforcing rather than counterproductive. Future studies must address the alignment of supply-side mitigation and adaptation innovations with demand-side shifts towards plant-rich diets and reduced food loss and waste. These scientific advances will be crucial to inform a global transformation of food production and finally break the vicious cycle between food production and a compromised environment, thereby ensuring long-term environmental sustainability and food security, and to chart a robust pathway towards long-term food security within planetary limits.

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Author contributions

J.M.M. devised the review with input from M.H. and P.B. J.M.M. and P.B. led the sections on food system impacts on the environment. E.N.N. and H.H.E.v.Z. led the sections on impacts of changing environmental conditions on food systems. O.T. and M.H. led the sections on supply-side transformations of global food production. All authors contributed to writing the article. J.M.M., O.T., M.H., A.J.K. and P.B. performed the final revisions before submission.

Competing interests

The authors declare no competing interests.

Additional information

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