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REVIEW SUMMARY

AGRICULTURE

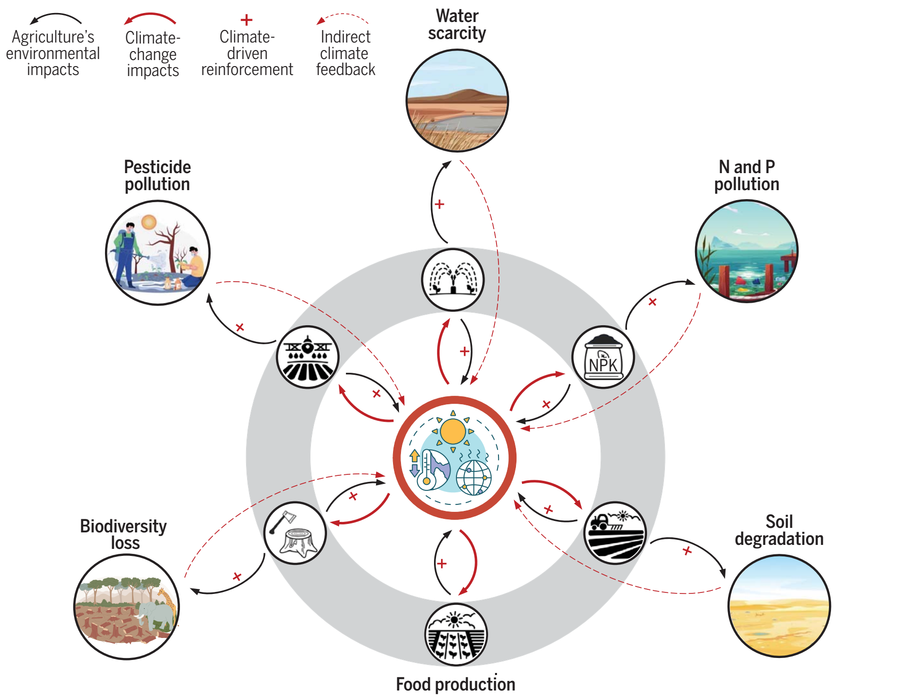
Climate change exacerbates the environmental impacts of agriculture

Yi Yang, David Tilman*, Zhenong Jin*, Pete Smith, Christopher B. Barrett*, Yong-Guan Zhu, Jennifer Burney, Paolo D'Odorico, Peter Fantke, Joe Fargione, Jacques C. Finlay, Maria Cristina Rulli, Lindsey Sloat, Kees Jan van Groenigen, Paul C. West, Lewis Ziska, Anna M. Michalak, the Clim-Ag Team, David B. Lobell*

BACKGROUND: Modern agriculture has large global environmental impacts, from greenhouse gas (GHG) emissions to water and air pollution to biodiversity loss. It is widely expected that agriculture's environmental impacts will escalate because a growing and richer global population will likely demand more agricultural products, including foods, feeds, fibers, and biofuels. Climate change, though less studied in this regard, is a second potential amplifier of agricultural environmental impacts. As climate change intensifies, it not only poses great risks to agricultural productivity, but its deviation from the relatively stable state under which modern agriculture evolved and has long operated also has profound implications for how agriculture interacts with the environment, and vice versa. In this Review, we present a synthesis of how climate change could amplify the environmental impacts of agriculture, from increases in GHG emissions, water use and scarcity, soil erosion, nitrogen and phosphorus pollution, pest outbreaks and pesticide use and pollution, and biodiversity loss. We discuss solutions to the challenges raised by how climate change could affect agricultural sustainability.

ADVANCES: Two major findings emerge from our synthesis. First, climate change will likely exacerbate the already large environmental impacts of agricultural production. It would do so by (i) directly and negatively affecting agricultural productivity; (ii) reducing the efficacy of agrochemicals and increasing their loss to the environment; and (iii) increasing crop pests and soil erosion. Yield reductions and loss of fertile soils would lead to increased land clearing and subsequent species extinctions and GHG emissions, and/or to agrochemical intensification to retain or increase yields. Greater agrochemical inputs mean greater chemical pollution of the environment and greater GHG emissions. Decreased agrochemical efficacy could also lead to compensatory increases in agrochemical use. These climatic impacts can be independent of, hence additive to or multiplicative of, one another, making climate change a potentially important amplifier of agriculture's environmental footprints. Second, agriculture already accounts for almost a quarter of global GHG emissions, and agriculture's response to climate change could create a powerful positive GHG feedback loop through multiple pathways. Climate change could intensify agricultural GHG emissions directly—for example, through increasing CH_4 emissions from rice paddies, N_2O emissions from soil, and CO_2 emissions from land clearing and soil tillage. It could also induce more GHG emissions indirectly—for example, if more agrochemicals are needed to compensate for their reduced efficacy; if drier conditions require more energy- and carbon-intensive irrigation; or if greater losses of nutrients from agricultural fields stimulate more biogenic GHG emissions in aquatic systems. These climate-agriculture feedback effects warrant increased attention.

OUTLOOK: Agricultural reliability and sustainability are of key long-term importance for human and planetary health. The challenges raised by climate change require accelerated adoption of practices and technologies that improve agriculture's environmental sustainability and climate resilience, especially those that can simultaneously deliver multiple benefits, such as diversification and integrated soil fertility management. However, socioeconomic barriers impede adoption of sustainable practices and technologies. Improved context-specific understanding of these barriers is urgently needed, as are innovative policies to overcome them. Greater investments in the discovery, adaptation, and cost reduction of emerging agricultural technologies could help make agriculture more reliable, sustainable, and climate resilient, as could the adoption of novel foods and healthier diets that would require far less land, water, and chemicals per capita than at present. Our synthesis also identifies many unanswered questions. Although the direction of climate impacts is often clear, the relevant magnitudes are not. Quantitative assessments from local to global scales will be needed, especially for the climate-agriculture feedback loop. Other feedback loops, such as the climate-agriculture-biodiversity loop, are also complicated and require mechanistic and quantitative analyses. ■



The major environmental impacts of agricultural systems and potentially exacerbating effects of climate change (dark red circle in the center).

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The list of author affiliations is available in the full article online.
*Corresponding author. Email: tilman@umn.edu (D.T.); jinzn@umn.edu (Z.J.); cbb2@cornell.edu (C.B.B.); dlobell@stanford.edu (D.B.L.)
Cite this article as Y. Yang *et al.*, *Science* **385**, eadn3747 (2024). DOI: 10.1126/science.adn3747

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https://doi.org/10.1126/science.adn3747

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REVIEW

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Climate change exacerbates the environmental impacts of agriculture

Yi Yang[1,2,3], David Tilman[4,5]*, Zhenong Jin[6]*, Pete Smith[7], Christopher B. Barrett[8]*, Yong-Guan Zhu[9,10], Jennifer Burney[11,12], Paolo D'Odorico[13], Peter Fantke[14,15], Joe Fargione[16], Jacques C. Finlay[4,17], Maria Cristina Rulli[18], Lindsey Sloat[19], Kees Jan van Groenigen[20], Paul C. West[21,22], Lewis Ziska[23], Anna M. Michalak[24,25,26], the Clim-Ag Team†, David B. Lobell[27]*

Agriculture's global environmental impacts are widely expected to continue expanding, driven by population and economic growth and dietary changes. This Review highlights climate change as an additional amplifier of agriculture's environmental impacts, by reducing agricultural productivity, reducing the efficacy of agrochemicals, increasing soil erosion, accelerating the growth and expanding the range of crop diseases and pests, and increasing land clearing. We identify multiple pathways through which climate change intensifies agricultural greenhouse gas emissions, creating a potentially powerful climate change–reinforcing feedback loop. The challenges raised by climate change underscore the urgent need to transition to sustainable, climate-resilient agricultural systems. This requires investments that both accelerate adoption of proven solutions that provide multiple benefits, and that discover and scale new beneficial processes and food products.

Agricultural production of crops and livestock covers 40% of Earth's ice-free land surface (*1*) and has experienced substantial growth over recent decades, providing enough food to support an increasing global population. However, it has also contributed greatly to global environmental problems, including climate change, air and water pollution, and biodiversity loss, mainly through the intensive use of fertilizers, animal farming, irrigation, chemical pest control, and land clearing (*1*). Agriculture accounts for 25% of global greenhouse gas (GHG) emissions, 85% of all human blue water consumption, and 80 to 90% of global nitrogen (N) and phosphorus (P) use (*1*). Without major changes in the global trajectory of the agri-food supply chain, agriculture's environmental impacts will continue increasing as global food demand rises because of population growth, economic development, and income-associated dietary changes (*2*). Under current trends, GHG emissions solely from agri-food systems would be sufficient to prevent achievement of the Paris 2°C climate warming limit (*2*), and anticipated cropland expansion poses great threats to biodiversity in many regions of the world (*3*).

There is yet another amplifier of agricultural environmental impacts that is less recognized and appreciated, namely, climate change. Human-driven global climate change is altering the regional distribution of precipitation and temperature at an unprecedented rate, resulting in increases in the frequency and intensity of climate extremes worldwide, including heat waves, droughts, wildfires, and storms. These changes affect both the productivity of agriculture and how agriculture affects the environment. For example, stronger storms can increase nutrient runoff and soil erosion, especially in regions where such problems are already severe (*4*). Warmer temperatures can increase pest populations and expand their ranges, resulting in more intensive and frequent use of pesticides (*5*). However, such examples of climate impacts on agricultural systems have been often studied in different disciplines. A systematic understanding of how climate change affects the wide range of environmental impacts of agriculture is lacking and will be essential for the development of sustainable agriculture under a changing climate.

In this Review, we synthesize knowledge across various research fields to provide a systematic evaluation of how climate affects agriculture's multiple environmental impacts. We elaborate on the mechanisms and examine the potential magnitudes of the impacts, and their geography. We also evaluate climate-driven interactive feedback effects that link these impacts, propose solutions to the challenges raised by climate change, and highlight major unanswered questions for future research. Our Review focuses primarily on the biophysical impacts of climate change on the various aspects of crop and livestock systems, while we also comment on fisheries and forest plantations. We exclude natural forests and other wild environments, which merit attention in future research.

Climate impacts on agricultural production

Improving agricultural productivity and its year-to-year stability will be crucial for long-term global food security and environmental sustainability (*2*). Climate change compounds this challenge. Crop yields are affected by numerous components of Earth's changing climate, including rising temperatures, changing precipitation and cloud patterns, elevated CO_2 levels, and increasing frequency of climatic extremes such as heat waves, floods, and droughts (*6*). The Intergovernmental Panel On Climate Change (IPCC) 6th assessment report found that global climate change impacts on yields were generally negative across most regions and food groups (*7*). Among other mechanisms, higher temperatures can reduce yield by shortening the life cycle of crop growth and increasing water stress (*8*). Zhao *et al.*, for example, found that 1°C of warming was associated with a 3 to 7% decrease in global yields of major staple crops (*9*). Warming during the cold season

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[1]Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing, 400045, PR China. [2]The National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, PR China. [3]The Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, PR China. [4]Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, MN 55108, USA. [5]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA. [6]Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN 55108, USA. [7]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen AB24 3UU, Scotland. [8]CH Dyson School of Applied Economics and Management, JE Brooks School of Public Policy, and Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY 14850, USA. [9]Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China. [10]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China. [11]School of Global Policy and Strategy, University of California, San Diego, La Jolla, CA 92093, USA. [12]Scripps Institution of Oceanography, University of California, San Diego, La Jolla CA 92037 USA. [13]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720, USA. [14]substitute ApS, Graaspurvevej 55, 2400 Copenhagen, Denmark. [15]Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark. [16]The Nature Conservancy, Minneapolis, MN 55415, USA. [17]St. Anthony Falls Laboratory, Dept. of Civil, Environmental, and Geo-Engineering, University of Minnesota, MN 55414, USA. [18]Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy. [19]World Resources Institute, Washington, DC 20002, USA. [20]Department of Geography, University of Exeter, Exeter EX4 4RJ, UK. [21]Department of Applied Economics, University of Minnesota, St. Paul, MN 55108, USA. [22]Project Drawdown, St. Paul, MN 55101, USA. [23]Environmental Health Science, Mailman School of Public Health, Columbia University, New York, NY 10032, USA. [24]Department of Global Ecology, Carnegie Institution for Science, Stanford, California, CA 94305, USA. [25]Department of Earth System Science, and Department of Biology, Stanford University, Stanford, CA 94305, USA. [26]Google Research, Mountain View, CA 94043, USA. [27]Department of Earth System Science and Center on Food Security and the Environment, Stanford University, Stanford, CA 94305, USA.
***Corresponding author. Email: tilman@umn.edu (D.T.); jinzn@umn.edu (Z.J.); cbb2@cornell.edu (C.B.B.); dlobell@stanford.edu (D.B.L.)**
†Clim-Ag Team authors and affiliations are listed at the end of this paper.

may reduce cold stress for crops, but warmer winters may risk inadequate chilling and vernalization, an essential requirement for flowering and fruiting in many temperate horticultural crops (10). Similarly, livestock productivity tends to be negatively affected by warming, with lower feeding and growth rates and higher incidence of disease (6). Many fisheries and aquaculture systems are also negatively affected by warming and related changes; for example, Lotze *et al.* projected a decline of 5% in marine biomass for each 1°C of warming (11).

Changing precipitation has altered the crop production landscape, with projected impacts expected to intensify. Rainfall shortages and droughts have historically harmed food supplies. From 1983 to 2009, about three-fourths of global croplands experienced marked yield losses from one or more droughts (12). Extreme weather conditions and crop failures in 2021 and 2022 caused millions of people in 10 countries of Africa and Central America to be newly faced with acute hunger or starvation (13). Even in industrialized countries, droughts lead to major decreases in crop production, as in the US in 2012 and Australia during 2001–2009 (14, 15). Extreme rainfall and flooding events are also increasing local food insecurity crises (16). Ortiz-Bobea *et al.* estimated that climate change has already reduced agricultural productivity over the past few decades, resulting in a loss equivalent to ~7 years of technology-driven productivity growth (17).

A source of uncertainty is the extent to which rising CO_2 levels might enhance crop photosynthesis and yields and decrease crop water demand. Based on 30 years of free-air CO_2 enrichment (FACE) experiments, C_4 crops (e.g., maize, sorghum, millet) only benefited from higher CO_2 concentrations under drought conditions, but C_3 crops (e.g., rice, wheat, soybean, and most fruit and vegetable crops)—and especially those with high yield potential—generally benefited (18). Roughly 75% of present-day cereal supplies have the C_3 photosynthetic pathway. However, a CO_2 benefit to C_3 crop yields could be offset at least in part by increasing drought, which negatively affects crop productivity independent of temperature (19). Crop models suggest that the combined effects of climate change and increased atmospheric CO_2 could decrease yields, especially for maize in mid-latitude regions such as the US Midwest, Central Asia, and North China, unless irrigation patterns are changed (20, 21).

In addition, air pollutants such as ozone (O_3) and its precursor NO_x—which are co-emitted with GHGs—can be toxic to plants. Widespread exposures to these pollutants decrease yields. In the US, for example, pollutants such as O_3, NO_x, SO_2, and $PM_{2.5}$ (fine particulate matter) are estimated to have caused ~5% yield loss in maize and soybean yields over the past two decades (22). Croplands in China are exposed to high concentrations of NO_x, which, if reduced to the background level, could enhance winter crop yields by ~25% and summer crop yields by ~15% (23).

Climate impacts on water use and scarcity

Crop and livestock production is impossible without adequate water supplies and, of all economic activities, is the dominant user of global water resources. Presently, ~20% of global cropland is irrigated, producing ~40% of global crops and accounting for ~90% of human water use (24). Direct consumption of water by livestock accounts for another 1 to 2% (25). Without irrigation, cereal yields on irrigated lands might decrease ~50%, equivalent to losing ~20% of global cereal production (24). Even if climate change were not a factor, irrigation and fertilization would need to be expanded to meet the increasing demand for agricultural products without clearing land for cultivation (2).

The impact of climate change on precipitation (i.e., its intensity, seasonality, and timing) and on warming, enhanced by land-atmosphere feedbacks (26), is expected to alter both water need and availability for rainfed and irrigated agriculture (27), but water demand by some crops may also be reduced by elevated CO_2 (28). The resultant global reshaping of the regions suitable for production, especially for those crops less benefited by elevated CO_2, is poorly understood but could have profound societal impacts. For such crops, analyses suggest that, with a 1.5°C increase in global mean temperature above preindustrial levels, irrigation may be needed in mid- and high-latitude areas across the US, Canada, Brazil, China, and Russia that are currently suitable for rainfed agriculture (29). The global rainfed cultivated area that is rarely susceptible to water scarcity might shrink from 140 to 60 Mha, and some rainfed lands may become unsuitable for irrigation unless annual water shortages are overcome with new water reservoirs where feasible (29). Moreover, loss of seasonal snowpack in the American Sierra, European Alps, and Asian Himalaya could limit irrigation in those regions (30–32). Demand for water storage would be increased even more in regions that become much hotter and dryer, as projected for parts of South Asia, the Middle East–North Africa (MENA) region, Sub-Saharan Africa, and Central America (33).

A major impact of shifting precipitation patterns is the increasing reliance on groundwater for irrigation (34). Groundwater is the world's largest distributed store of fresh water (except for ice and glaciers) and is more ubiquitous than surface waters. Global groundwater use has increased markedly over the past decades and accounts for ~40% of irrigated cropland (35). However, using groundwater for irrigation poses long-term threats to food security if groundwater recharge is insufficient to offset withdrawals, as is already the case in many regions (34). Climate change could increase the reliance on groundwater by increasing the intensity, duration, and frequency of droughts, further exacerbating regional groundwater depletion. Drought-induced shifts to groundwater have already occurred in many regions worldwide (36). Globally, groundwater pumping has been projected to increase >20% from 2010 to 2050 largely driven by anticipated climate changes (37). In a +3°C global warming scenario, agricultural regions that require irrigation to sustain yields are often projected to have groundwater depletion (Fig. 1).

Influences of precipitation change on agriculture could lead to increasing reliance on groundwater use and result in more energy use and thus more GHG emissions. In cases where water must be brought from other basins, e.g., China's south-to-north water diversion project, the energy and GHG footprint could be even higher per unit of water irrigated (38). Another source of additional GHG emissions is irrigation-oriented reservoirs, the number of which has grown substantially in recent decades and is expected to grow further to help agriculture adapt to climate change (38). In reservoirs, the microbial decomposition of sedimentary organic matter under anaerobic conditions produces substantial methane (CH_4) emissions, which could intensify as more nutrients are washed off farm fields under climate change and fuel algae growth and deposition (39).

Climate impacts on agricultural N_2O and CH_4 emissions

Agriculture is a major source of nitrous oxide (N_2O) and CH_4 emissions, accounting for nearly half of global non-CO_2 GHGs (40). Agricultural N_2O is driven primarily by N fertilizers and manure management, and agricultural CH_4 emissions are primarily from ruminants (cattle, sheep, goats) and flooded rice paddies. Though emissions of these non-CO_2 GHGs are not required to be cut down to net-zero under the Paris climate target, they must be substantially reduced for temperature targets to be achieved (41). As shown below, however, the agricultural emission rates of these potent GHGs are predicted to be intensified by climate change.

Terrestrial biosphere models project that climate change would increase agricultural N_2O emissions (42) because warmer temperatures and increased precipitation create soil conditions that favor N_2O production (43). Fertile but poorly drained soils, such as those in more than half of the US Corn Belt, may be highly susceptible to this (44). Increased drought events can reduce N_2O emissions from pastures (45), but drying and subsequent rewetting may stimulate N_2O emissions (46). Elevated atmospheric CO_2 generally increases soil N_2O emissions from cropland and fertilized grassland, but these CO_2 effects are highly

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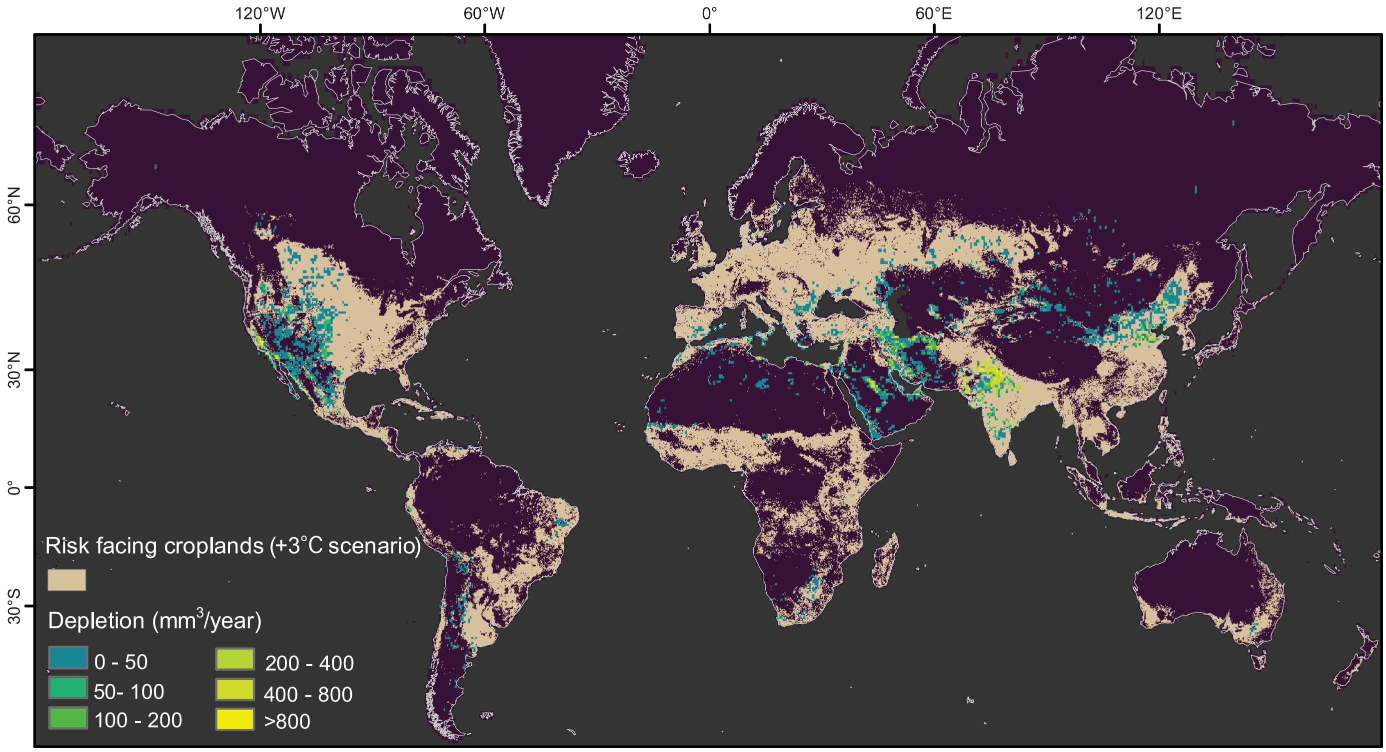

Fig. 1. Areas expected to be affected by green water scarcity in a 3°C global climate warming scenario. Affected areas are shown in ivory yellow [data from (*29*)], and current rates of groundwater depletion are in blue to green yellow (*152*).

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variable (*47*, *48*), making global-scale predictions unclear. Winter climate change may play a greater-than-expected role by affecting non–growing season N_2O emissions, which account for 35 to 65% of annual emissions in seasonally frozen croplands in the Northern Hemisphere (*49*). Reduced snow cover and/or soil warming often coincide with more frequent freeze-thaw cycles that boost soil N_2O emissions (*50*). Increased precipitation before soil freeze and at soil thaw, as well as faster snowmelt caused by higher air temperatures, may also promote soil N_2O emissions (*51*).

Similarly, climate change is projected to increase global CH_4 emissions from rice paddies. Rising CO_2 levels promote rice root growth and the release of root exudates, thereby stimulating CH_4-producing microorganisms (*52*). Meta-analyses indicate that future atmospheric CO_2 levels could boost rice paddy CH_4 emissions by ~34 to 43% (*53*), although these increases may diminish over time (*54*) and are smaller in paddies with straw incorporation (*53*). Warming also affects CH_4 emissions from rice paddies, with +1.5°C increasing CH_4 emissions by ~23% because of warming-induced increases in decomposition (*55*).

Climate change impacts on peatlands drained for agriculture require special attention. Peatlands are vital ecosystems that store vast amounts of C and are a main natural source of CH_4. Globally ~10 to 20% of peatlands have been drained for agricultural purposes (*56*). Although peatland drainage reduces CH_4 emissions, it strongly increases CO_2 emissions from organic matter decomposition and N_2O emissions, turning peatlands from providing net climate benefit to being a net source of GHGs (*57*). Warming has been shown to exacerbate these carbon losses, especially with deeper water tables (*58*, *59*), emphasizing the importance of careful water management of agricultural peat soils.

Global warming also seems to have positive effects on livestock CH_4 emissions, but the mechanisms are complicated, and the magnitude of the total effects remains uncertain and unquantified. First, warming can stimulate CH_4 emissions from manure storage (*60*). Second, elevated atmospheric CO_2 and rising temperatures can decrease forage dry matter digestibility, increasing CH_4 through decreased efficiency of ruminant production (*61*). Third, heat stress can reduce milk and meat production (*62*), and if this occurs on a large scale, global milk and meat production would need to expand substantially to meet demand (*2*). A shift away from ruminant meat in global dietary choices could help reduce livestock CH_4 emissions and counter the potential positive climate-CH_4 feedback from this sector.

Climate impacts on soil degradation

Soils contain the largest terrestrial stores of organic carbon (*63*). Cultivated agricultural soils are a major source of CO_2 emissions as their organic matter decomposes, which also reduces soil water holding capacity, increases irrigation need, and lowers soil fertility (*63*). Soil fertility underpins the delivery of all agricultural ecosystem services. Globally, soil loss already necessitates $110 to 200 billion/year of fertilizer to replace nutrients lost to erosion (*64*), with this soil depletion being most rapid in the low-income countries where future food demand will be greatest (*65*).

Climate change is expected to exacerbate soil degradation through several pathways. Soil warming accelerates soil organic matter respiration and thus increases CO_2 emissions (*66*). It can also cause the release of toxic metals, such as arsenic in paddy rice. Cumulative global CO_2 emissions from the top meter of soil in 2100 under 2°C of warming could be as high as 232 ± 52 Pg C (*67*), equivalent to all global CO_2 emissions from 2001 to 2021. In addition, climate change is expected to increase the number of extreme precipitation events, when most soil erosion occurs (*68*). Global erosion rates are projected to increase by 30 to 66% by 2070 (*69*), but with considerable regional variation in forecasted erosion (*70*). Extreme precipitation events wash away both soil and nutrients. Erosional P losses are greatest in regions with intensive farming or frequent heavy rains (*69*). Jang *et al.* estimated that ~30% of N fertilizer input in US maize production has been used to compensate for long-term fertility loss due to soil erosion (*71*). The need for additional fertilizers, whose production is energy and carbon intensive (72), adds to the climate-driven CO_2 losses from soil erosion, elevating the importance of conservation tillage and cover crops (70).

The previously discussed increased prevalence of drought under climate change can also worsen soil degradation, through increased wind-driven soil erosion, reduced crop yields, increased decompositional CO_2 emissions from soils, and increased risk of soil salinization from expanding irrigation. For example, after intense droughts, soils with greater than 2% organic carbon show increased CO_2 release to the atmosphere (73). Droughts affect yields and thereby both reduce carbon inputs to the soil (74) and increase the need for land expansion.

Increasing irrigation in response to climate change exacerbates the impacts of soil salinization (75). High salinity is already estimated to have reduced yields by 8 million tonnes on 1.6 million acres in California alone, resulting in \$3.7 billion of reduced revenue (76). A recent modeling study suggests that dryland areas of Mexico, South America, southern Australia, southwest US, and South Africa are at risk of higher soil salinity under future climate change, whereas in the drylands in the Horn of Africa, the northwest US, Eastern Europe, Turkmenistan, and west Kazakhstan, the risk of soil salinity could decrease (77). Salinization can also be caused by sea level rise, another impact of climate change (78). Sea level rise and the associated saline contamination of soils threaten coastal agriculture and thus could undermine food security. Bangladesh is at particularly high risk, where nearly 200,000 coastal farmers are projected to become affected by salinity intrusion (79).

Climate impacts on N and P pollution

Climate change may aggravate the already great negative environmental impacts of N and P fertilizers. A substantial fraction of N and P fertilizers are released to the environment (e.g., 7 to 19% in runoff and leaching and 13 to 20% volatized as ammonia), contaminating ground- and surface waters, degrading air quality, and reducing biodiversity (80, 81). Cyanobacterial blooms in highly polluted lakes and rivers that make major water supplies unusable are increasingly common owing to synergistic effects of climate change and agricultural pollution (82).

Altered precipitation patterns and rising temperature are changing the form, amount, and timing of N and P loss from agricultural soils and their transport through the landscape (4, 83). Greater variability in precipitation increases fertilizer loss to the environment (84). In the US, changes in heavy precipitation events increased riverine N loads and are projected to increase total aquatic N loads by ~20% by the end of the century (4). Projected hotspots of increased agricultural N loss include China, Southeast Asia, East Africa, and Brazil (Fig. 2). Because P is far less soluble and volatile than N, erosion and runoff account for most agricultural P losses (69). Regions with intensive agriculture and/or extreme climates, including Eastern China, Indonesia, East Africa, Southeast Brazil, Southern Africa, and Bolivia, have the highest P losses (69). Intensified rainfall under future climate could increase global P losses by 55% under Representative Concentration Pathway (RCP) 2.6 and 75% under RCP8.5 by the end of the 21st century (85), aggravating both environmental pollution and global P fertilizer shortages (69).

Warming could increase atmospheric emission from broadcasted fertilizers of health-harming ammonia (NH_3) (which forms fine particulate matter, $PM_{2.5}$) and NO_x (which forms ground-level ozone) because volatilization of these chemicals is temperature dependent (86, 87). Over several decades, warming increased atmospheric NH_3 emissions ~10 to 15% in China (88) and Australia (87). For Europe and the US, warming is projected to increase such emissions by ~40 and ~80%, respectively (86, 89). The human health costs of this air pollution can be greater than the value of harvested crops (90).

Other aspects of climatic variability can cause elevated agricultural N and P losses, although their effects are often more region specific and can be considered as secondary. Reported

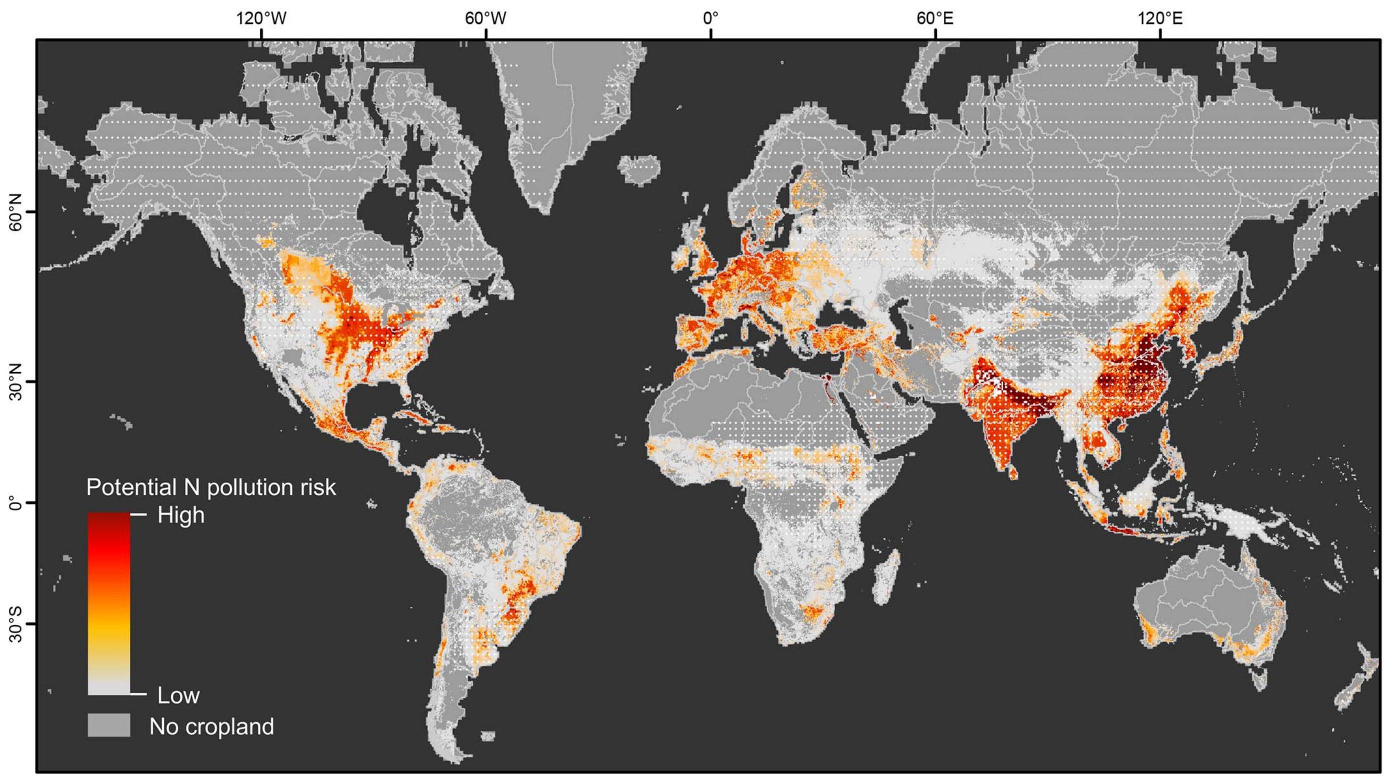

Fig. 2. Global regions likely to experience increases in nitrogen pollution of ground and surface waters due to projected precipitation increases. Regions with excessive N fertilizer application (red to yellow colors) [data from (153)] and increased precipitation (dots) will likely observe greater N losses to the environment. Dots indicate regions where precipitation is projected to increase, according to most (≥80%) global climate models of the Coupled Model Intercomparison Project (CMIP6) [data from (154)].

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mechanisms include summer heat waves (91), more frequent freezing and thawing cycles in arid and cold environments (92), and drought (93). In some situations, climate change may ameliorate N losses, when spring warming or elevated atmospheric CO_2 enhances crop N uptake (94), or decreased precipitation reduces leaching losses.

Increased N and P emissions might also create a climate feedback effect by stimulating GHG emissions from other ecosystems. Rising N and P transport to lentic waters are projected to potentially stimulate aquatic CH_4 emissions by 30 to 90% by the end of the 21st century (39, 95). Although negative feedback has been reported when agricultural fertilizers increase algal abundances and their CO_2 uptake (96), its magnitude is relatively small and insufficient to offset the stronger feedback between eutrophication and lake GHG emission (97). Climate-smart farm management practices, such as cover crops and conservation tillage, can reduce N and P emissions. However, they may have differential effectiveness on N versus P (98). The best management strategy to reconcile C, N, and P stewardship goals is yet to be determined and may be site specific.

Climate impacts on pest pressure and pesticide pollution

Chemical pest control is key for global food production as uncontrolled pests (insects, pathogens, and weeds) cause yield losses of ~17 to 30% (99). Global use of chemical pesticides, dominated by agricultural uses, has increased by 600% from ~0.5 Tg year^{-1} in the 1950s to ~3.5 Tg year^{-1} in 2021 (100). However, only a small amount of most pesticides reaches target pests, whereas the rest is lost to the environment, threatening the health of humans, especially farm workers, and ecosystems (101). Climate change can affect many aspects of pest control—from pest pressure, to pesticide use and related efficacy, persistence, and toxicity—in ways that may increase pesticide use and the associated ecological and human health impacts (Fig. 3).

Climate change is increasing the spatial spread and migration of pest populations, such as subtropical species migrating into temperate zones (102). Warmer temperatures can result in greater pest survival, more pest reproductive cycles during longer growing seasons, and faster evolution of resistance to pesticides and plant defenses. Increased climate variability and extreme weather events may increase the onset, incidence, and severity of pest infestations of crops (103). In China, for example, climate change has increased the occurrence of crop pests and diseases by ~90% since 1970 and could further double to quadruple by the end of the century (104).

The efficacy of pesticides might also decrease because of climate change (105). Higher temperatures and elevated CO_2 levels can increase pesticide metabolic degradation and translocation (106), or cause more rapid evaporative loss of pesticides. These effects of climate change could increase the likelihood of farmers taking additional control measures such as more frequent pesticide application (107). Higher pest resistance may require a larger diversity of pesticides (108), which would increase farmer costs and environmental risks. Increased pesticide use can also result from disruption of optimal application timing because of variable weather, necessitating more frequent pesticide application, as reported for maize farmers in Kenya (109). Based on the positive correlation between insecticide use and temperature in the European Union, Kattwinkel *et al.* projected that insecticide use could increase by ~300 to 2200% from 1990 to 2090 (5). Greater pesticide use increases health harm for farmers, consumers, and nontarget species. It also induces greater energy use and increased carbon emissions in the production, transport, and application of pesticides (110).

In addition, pesticide volatilization rates can increase with temperature and/or soil moisture (111), and leaching and wash-off rates can increase with precipitation, both resulting in lower pesticide efficacy. In drier soils, lower pesticide degradation and mobility rates generally result in increased pesticide persistence (112, 113). On the effect side, the toxicological potency of

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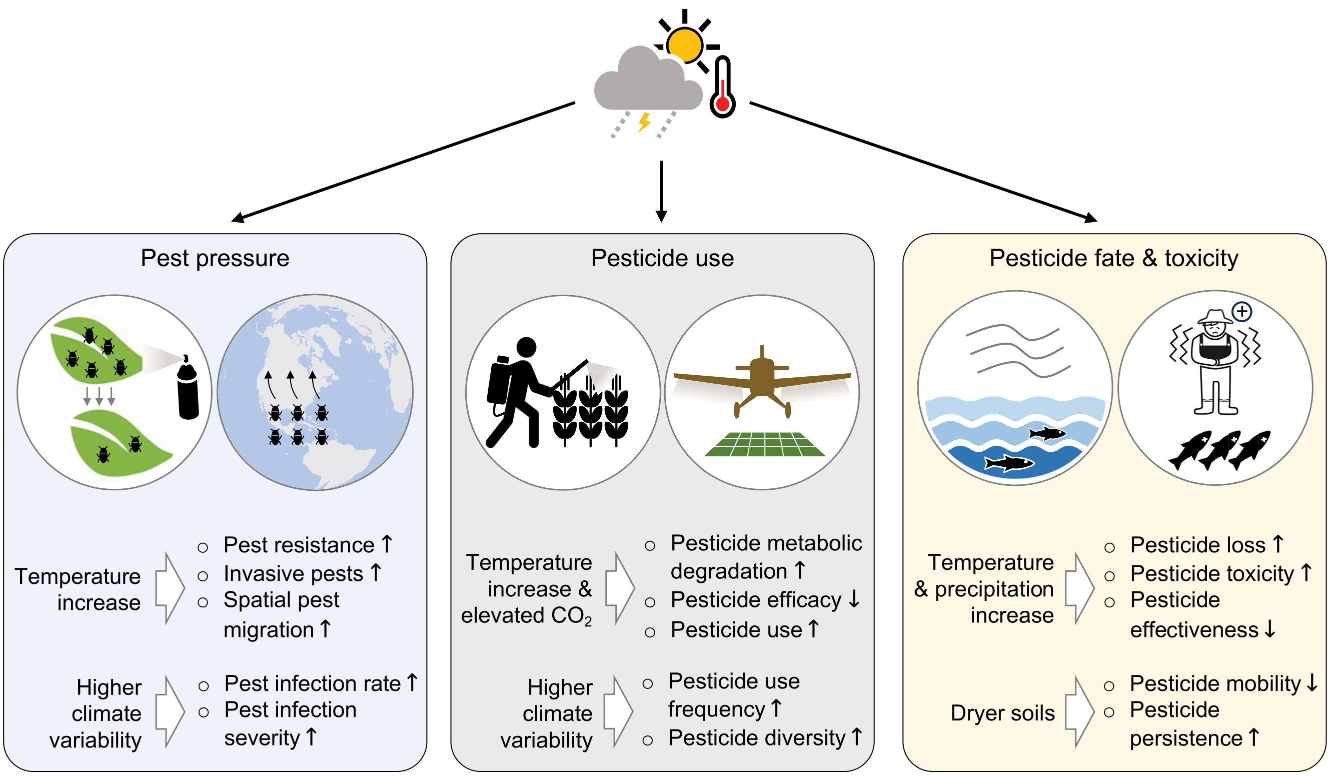

Fig. 3. Impacts of climate change on pest pressure, pesticide use, and pesticide fate and toxicity. How the various aspects of pest pressure and pesticides are affected by climate change is described in the boxes. Up arrows indicate that climate change generally has positive effects and down arrows, negative effects.

pesticides can increase with temperatures for a variety of reasons (114). However, higher environmental pesticide degradation rates (114), more efficient organismal elimination and/or detoxification rates (115), and decreases in nervous system vulnerability (e.g., for pyrethroids (113)) at higher temperatures may decrease pesticides' impacts on ecosystems. Hence, effects of changing climate conditions on the fate and toxicity potency are strongly dependent on pesticide and specific environmental settings.

Although climate impacts on pesticide potency are pesticide- and environment-specific (111, 113, 115), on average climate change seems likely to increase agricultural pest pressure, hence increasing pesticide usage. Its impacts on how pesticides are transported in the environment and affect ecosystem and human health are more complicated, requiring further research to elucidate the mechanisms and quantify the net effects. Overall, there is a critical need to reassess optimal use of pesticides and crop choices to minimize the ecological and human health risks from climate-dependent shifts in pesticide use.

Climate impacts on biodiversity loss through agriculture

Biodiversity provides ecosystem services of great value to society, including services that can increase food security (116), but agricultural land clearing is the single greatest cause of extinction risks worldwide (1). Pressure to clear land would increase under climate change if crop yields and livestock productivity decrease. Even without reduced agricultural production from climate change, global dietary shifts associated with higher incomes and greater global population are expected to cause land clearing that could double the number of vertebrate species threatened with extinction within 50 years (117).

If extreme climate events result in yield losses that drive up global crop prices, farmers would be incentivized to clear lands for production (118), thus threatening biodiversity. An analogous process occurred in the US when promotion of bioethanol from maize reduced maize and soybean supply as food and feed sources, increased their prices, and likely led to the conversion of millions of hectares of native grasslands to cropland domestically (119). Agricultural intensification can also threaten biodiversity, especially for amphibians and insects, through pesticide and nutrient pollution (120).

Farmers are already changing crops in response to regional temperature changes (121). Further climate change might force some farmers to abandon croplands that are no longer viable at the same time climate change makes other lands become suitable for agriculture. Suitability is projected to increase in the northern midlatitudes and decrease in the lower latitudes (20). As a result, climate-driven changes in land suitability could cause increased land clearing and habitat fragmentation, and their threats to biodiversity (122). The direct impacts of climate change on biodiversity could also affect agricultural systems by diminishing the services that diverse ecosystems provide for agricultural systems.

Multiple climate-agriculture feedback effects

The synthesis above suggests that climate change seems likely to exacerbate agriculture's multiple adverse environmental impacts (Fig. 4). Among the environmental problems exacerbated, the climate-agriculture feedback effects are worth emphasizing given the already large global carbon footprint of agriculture [~25% of anthropogenic GHG emissions (1)], how it continues to expand because of increased incomes and global population size (2), and the multiple feedback pathways (Fig. 4). Some feedback effects take place directly on agricultural fields, resulting from intensified emissions of N_2O from fertilizers and CH_4 from flooded rice paddies owing to elevated CO_2 concentrations and/or warming (42, 52). Other feedback effects are less direct, such as from the greater reliance on irrigation water sources that are more energy and/or carbon intensive [e.g., groundwater pumping or water pumped from other basins or newly constructed reservoirs (38)]. There could be additional emissions from greater production of agrochemicals to compensate for their reduced efficacy or increased release to the environment. In particular, the production of N fertilizers is energy and carbon intensive (72), and can be a major contributor to crop carbon footprints (123). Also, under climate change, greater losses of nutrients from farm fields intensify CH_4 emissions from lakes and reservoirs (39). Another

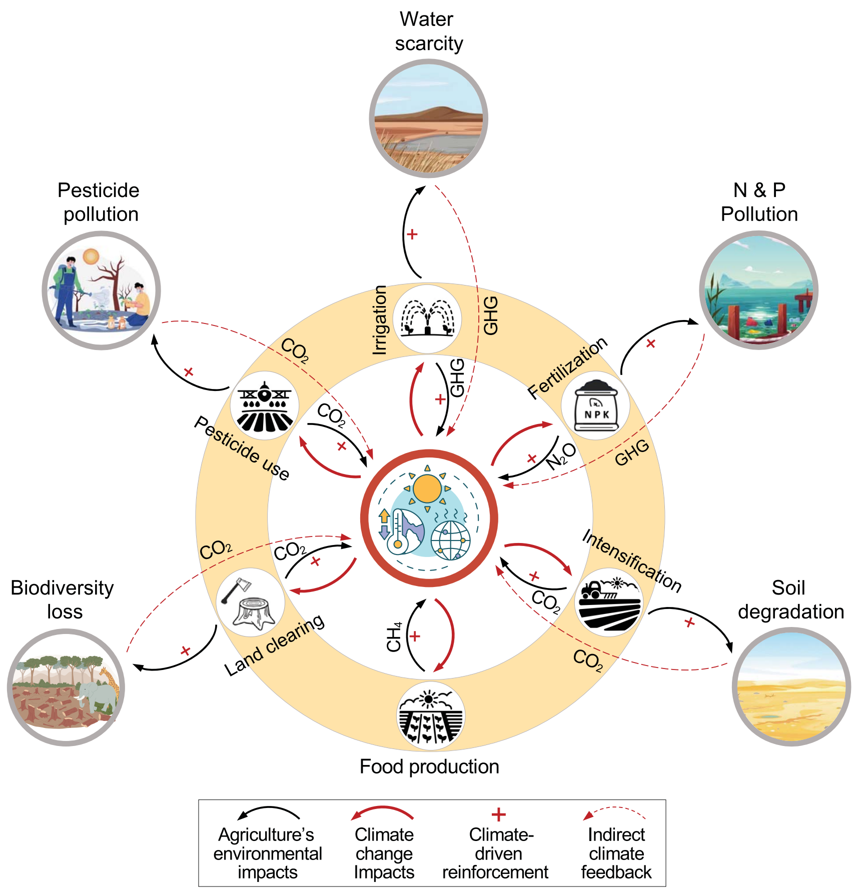

Fig. 4. The major environmental impacts of agricultural systems and potentially exacerbating effects of climate change. The dark red circle in the center represents climate change. The yellow donut represents agricultural systems, and the small circles inside indicate the processes through which it affects the environment (black arrows). Dark red arrows indicate impacts of climate change on agriculture, and plus signs indicate its reinforcing effects on agriculture's environmental problems, including direct feedback to climate change (e.g., intensified CH_4 and N_2O emissions). Dashed arrows indicate indirect climate-change feedback from the different environmental impacts of agriculture (e.g., stimulated CH_4 emissions in lakes from nutrient runoff).

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feedback loop results from climate-driven yield losses (7), which, through global food trade, can lead to land clearing worldwide and associated carbon emissions (118). These feedback effects must be thoroughly evaluated and mitigated if we are to achieve the climate goals of limiting warming to 1.5° to 2°C.

Solutions

The linked food-environmental challenges raised by climate change, global population growth, and economic development necessitate rapid transitions to more sustainable and climate-resilient food systems that ameliorate environmental impacts. We must accelerate wide-scale adoption of the many existing sustainable practices and technologies proven effective at mitigating agriculture's environmental impacts. That requires overcoming related socioeconomic barriers to uptake. We also need greater investments in agricultural research to develop new processes, as well as alternative food products that are tasty, cheap, and easily accessible to facilitate transitions to sustainable and healthy diets.

Many existing agricultural practices and technologies can simultaneously improve agricultural sustainability, productivity, and agricultural systems' resilience to climate change's negative impacts. Chief among these are expanded use of improved cultivars that increase food output per unit of land, water, and chemical input, often through genetic resistance to pests and pathogens; integrated pest management that boosts crop output while minimizing use of toxic chemicals; integrated soil fertility management that combines biological, chemical, and physical measures to sustain soil health; and agricultural diversification that improves yield and yield stability, resource use efficiency, biodiversity, and human well-being (124–126). Context-appropriate combinations of these solutions typically outperform uncoordinated approaches and have the potential to greatly reduce GHG emissions from staple crops (127).

Boosting adoption of known solutions requires identification and targeting of barriers that presently impede uptake. This requires some combination of extension and education activities to boost awareness, subsidization of acquisition costs, taxation of harmful practices, payments for adoption of best practices, and/or insurance against loss while growers learn new methods, or typically combinations of these to make practices available and attractive to producers (128). The pervasive heterogeneity of barriers to uptake makes scaling adoption challenging and demands decentralized processes (128). In some places, policies must secure land and water tenure to promote adoption and safeguard the rights of vulnerable subpopulations (129). In other places, progress requires overcoming obstacles to the use of genetically modified cultivars that reduce pesticide use and boost yields and smallholder farmer profits (130, 131). The expansion of renewable rural energy production could accelerate off-farm production of novel foods or allow energy-efficient controlled environment agriculture (132, 133).

Boosting sustainable food production should be matched by increased efforts to slow and reverse the increasing per capita demand for crops used for feed or fuel, not food, and associated negative health and environmental impacts. Although global food demand per capita has remained fairly constant since the turn of the millennium, livestock feed production per capita has grown steadily, reflecting the dietary transitions associated with per capita income growth (134). The gains from reversing that trajectory would be huge but remain elusive. Diets with less meat and more healthier food are better for both humans and the planet (135). However, healthier diets remain unaffordable for many people (136), and dietary behavioral change interventions have had at best mixed results in small-scale studies, with no evidence of impacts at scale (137, 138). Food choices appear driven more by proximate factors such as convenience, price, and taste than by a food's health or environmental impacts. Shifting diets will require investments to develop, discover, and popularize delicious and convenient foods that are also healthy, environmentally beneficial, and affordable. It also requires policy interventions that induce dietary change at scale through offerings in institutional settings and, to the extent such changes can be made without exacerbating food insecurity and hunger, by reducing subsidies for agricultural products with low health benefits and sustainability. Policies should transcend their historical focus on staple crops and create incentives for diversifying production in response to the growing market demand (139).

Accelerated adoption of proven and new farming practices is essential in regions where intensive agricultural practices currently cause most GHG emissions and water and air pollution, such as the US Midwest, central and north China, and north India (81). But efforts to promote better farming practices and to prevent potential increases in per capita crop demand must also focus on locations where income and population growth will drive most global food demand growth, including many African and Asian countries (140). Because most food is consumed in the country where it was produced (141), solutions based on international trade may prove less impactful than increasing domestic yields and sustainability.

Future research needs

Four key priority questions merit research. First, we must accelerate the discovery, adaptation, and cost reduction of emerging agricultural technologies and practices and of novel and healthy foods and diets. The ~20-fold benefit/cost ratio of investments in international agricultural research suggests that doubling global agri-food research investments would offer major benefits (142). For instance, reallocating about a tenth of high-income country agricultural subsidies could more than double public agri-food research and development investments globally (127).

Many research areas hold particular promise for such investments. Artificial intelligence, machine learning, nanotechnology, remote sensing, and precision agriculture could help growers diagnose and address water, nutrient, and pest issues more effectively through optimal application of irrigation, fertilizers, and pesticides. Integrating more perennial crops might help enhance agriculture's climate resilience, reduce nutrient loss, and increase soil carbon stocks (143). Agrivoltaics and floating solar energy may deliver techno-ecological win-wins (144). Genetic and biotechnological approaches might enable cereals to fix nitrogen or mine phosphorus (145), or increase yields without increasing fertilization (146), or reduce rice CH_4 emissions (147). New genome editing methods exhibit considerable potential to improve the productivity and resilience of globally important staple crops (148). Novel foods offer the potential to reduce the environmental footprint of protein consumption by offering plant-based or cultured alternatives to conventional meat and dairy products (135). These and other promising practices and technologies merit expanded research investment.

Second, climate-agriculture feedback effects merit particular attention given agriculture's large GHG footprint and the multiple mechanisms by which agricultural GHG emissions are amplified by climate change. Global-scale quantitative studies are required to better determine the magnitude, distribution, and greatest drivers of these feedback effects.

Third, how could the complex feedback loops among climate change, agriculture, and biodiversity loss be reduced or eliminated? The direct impacts of climate and habitat fragmentation on biodiversity loss are being evaluated (149), but the indirect impacts through the feedback with agriculture remain largely unknown. If climate change induces agricultural extensification and increased agrichemical leaching, the feedback might negatively affect biodiversity, which itself could adversely influence agricultural production and climate stability (150).

Fourth, what might be the unintended or indirect effects of adoption of known better practices or new foods? For example, how might the adoption of on-farm robots and other technological changes affect N, P, and herbicide applications, crop prices, and dietary shifts? Technologies that advance one objective could adversely affect others (151).

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Science has substantially advanced our understanding of how agriculture affects climate and the environment and has identified viable agri-food system approaches to both mitigate and adapt to climate change. But the pace of climate change demands increased attention to the feedback effects of agri-food systems that could aggravate the closely coupled challenges of feeding an expanding human population, addressing the climate crisis, and conserving biodiversity.

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ACKNOWLEDGMENTS

We thank the reviewers for their constructive comments and suggestions. **Funding:** This research was partly supported by the National Natural Science Foundation of China (52370193) and the US National Science Foundation (DEB-1831944). **Author contributions:** Y.Y. conceptualized the study; Y.Y., D.T., Z.J., C.B.B., D.B.L., P.S., Y-G.Z., J.B., P.D., P.F., J.F., J.C.F., M.C.R., L.S., K.J.G., P.C.W., L.Z., and A.M.M. led the writing effort; and the group authors reviewed and edited the manuscript. All authors made substantial contributions to discussions of the content of the manuscript. **Competing interests:** J.B. is a board member of Aspen Global Change Institute (unpaid); served as an adviser and completed a scoping project for FAIRR on net zero food systems in 2023 (paid, completed); and served a term as science adviser to the DNC Environment and Climate Crisis Committee (ended 2023; unpaid). D.B.L. completed a working paper on mitigation opportunities in agriculture for the Asia Development Bank (ended 2022; paid). All authors declare that they have no competing interests. **Data availability:** Data presented in figures are based on previously published studies that are cited in the Review. **License information:** Copyright © 2024 the authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original US government works. https://www.sciencemag.org/about/science-licenses-journal-article-reuse

The Clim-Ag Team

Michael Clark[28], Jed Colquhoun[29], Teevrat Garg[30], Karen A. Garrett[31], Camilla Geels[32], Rebecca R. Hernandez[33], Mario Herrero[34], William D. Hutchison[35], Meha Jain[36], Jacob M. Jungers[37], Beibei Liu[38], Nathaniel D. Mueller[39], Ariel Ortiz-Bobea[40], Jacob Schewe[41], Jie Song[42], Julie Verheyen[43], Peter Vitousek[44], Yoshihide Wada[45], Longlong Xia[46], Xin Zhang[47], Minghao Zhuang[48]

[28]Department of Biology, and Nuffield Department of Population Health, University of Oxford, Oxford, OX1 2JD, UK. [29]Department of Horticulture, College of Agricultural and Life Science, University of Wisconsin, Madison, WI 53706, USA. [30]School of Global Policy and Strategy, University of California, San Diego, La Jolla, CA 92093, USA. [31]Plant Pathology Department and Global Food Systems Institute, University of Florida, Gainesville, FL 32611, USA. [32]Department of Environmental Science, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark. [33]Wild Energy Center, University of California, Davis, CA 95616, USA. [34]Department of Global Development, College of Agriculture and Life Sciences and Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY 14850, USA. [35]Department of Entomology, University of Minnesota, St. Paul, MN 55108, USA. [36]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109, USA. [37]Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA. [38]State Key Laboratory of Pollution Control and Resource Reuse School of Environment, Nanjing University, Nanjing 210008, PR China. [39]Department of Ecosystem Science and Sustainability and Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80521, USA. [40]Cornell University, SC Johnson College of Business, Ithaca, NY 14853, USA. [41]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam 14473, Germany. [42]Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing, 400045, PR China. [43]Laboratory of Evolutionary Stress Ecology and Ecotoxicology, University of Leuven, Charles Deberiotstraat 32, B-3000 Leuven, Belgium. [44]Department of Earth System Science, Stanford University, Stanford, CA 94305, USA. [45]Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia. [46]Key Laboratory of Soil Environment and Pollution Remediation, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China. [47]Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD 21532, USA. [48]College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions of MOE, China Agricultural University, Beijing 100091, China.

Submitted 7 December 2023; accepted 2 August 2024
10.1126/science.adn3747

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