

Perspective

Agriculture and food security under a changing climate: An underestimated challenge

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SUMMARY

Pathways to eradicate global hunger while bending the curve of biodiversity loss unanimously suggest changing to less energy-rich diets, closing yield gaps through agroecological principles, adopting modern breeding technologies to foster stress resilience and yields, as well as minimizing harvest losses and food waste. Against the background of a brief history of global agriculture, we review the available evidence on how the global food system might look given a global temperature increase by 3°. We show that a moderate gain in the area suitable for agriculture is confronted with substantial yield losses through strains on crop physiology, multitrophic interactions, and more frequent extreme events. Self-amplifying feedback are unresolved and might lead to further losses. In light of these uncertainties, we see that complexity is underestimated and more systemic research is needed. Efficiency gains in agriculture, albeit indispensable, will not be enough to achieve food security under severe climate change.

INTRODUCTION

In 2022, the year when this text started to evolve, almost 8 billion people lived on our planet. Healthy, sufficient, and diverse food could be available for most in our societies as global food production reached an energy equivalent of 5,000 kCal per person per day. However, there is a 4-fold difference in per capita consumption between the richest countries with more than 8,000 kCal per person per day (Australia, Austria, Canada, etc.) and the poorest countries with about 2,000 kCal (Chad, Congo, Niger, etc.).¹ At the same time, there are still about 800 million people in the world who are undernourished. 250 Million children under the age of five are either malnourished or have reduced height growth—or are significantly overnourished (Figure 1). Children in countries of the Global South are particularly affected by malnutrition, where people live on less than US\$ 8 per person per day. The situation has improved in recent decades as child mortality halved between 1990 and 2017 and the number of people living in extreme poverty fell to 736 million in 2015. But further improvements are lacking and extreme poverty increased again slightly between 2013 and 2015 in sub-Saharan Africa.² This makes regional setbacks, such as the 2020 drought in Madagascar, so dramatic, and these will become even more frequent due to climate change. This is the very unsatisfactory current interim status of a development that can be viewed positively by looking at the global average only.

It is well established that food security is not exclusively a question of production volume. Besides stability of production at sufficiently high levels, it is a question of availability, access, distribution, and use. According to UN/WHO figures, there will be around 8.8 to 11.6 billion people living on Earth in the year 2100. They are also expected to have higher incomes and their nutrition will have shifted towards more energy-rich diets, increasing the demand for food by a further 59% to as much as 98% by 2050.³ In the same course of time, climate change will have caused annual mean temperatures to rise and extreme events to increase in frequency and intensity.^{4,5} Climate change will lead to changes in the distribution and availability of water, earlier flowering dates, increasing danger of late frosts due to the faster phenological development, longer growing seasons, more frequent crop failures, increased pest infestations, and much more.⁶ Yield patterns will change, and agricultural yields are likely to decrease rather than increase as 52% of agricultural land is already classified as degraded.^{7,8} Acknowledging that even today global societies are not able to provide everybody with sufficient and healthy food, what will be the situation with a larger, more affluent population under a drastically changing climate? If climate mitigation action is taken too slow or too humble, a plausible assumption could be a global climate that is 2° to 3° warmer and double that on land surfaces.

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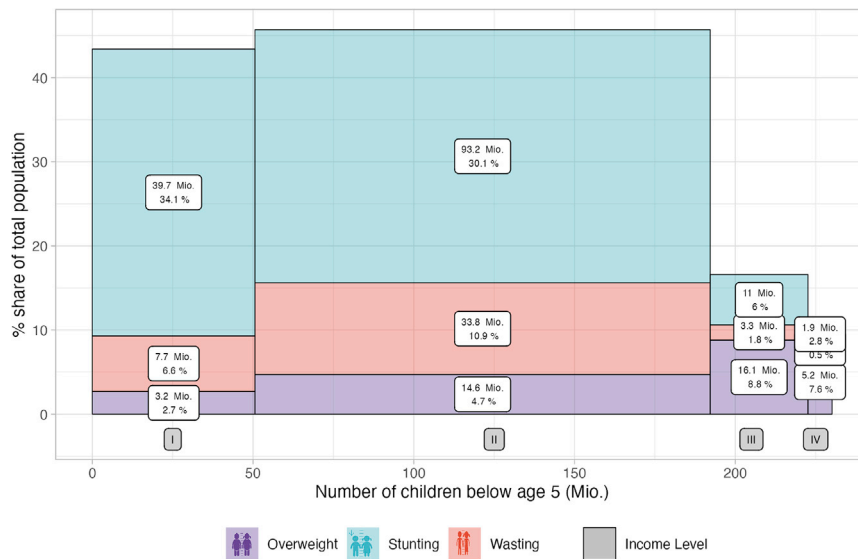


Figure 1. Children suffering from one of the three manifestations of malnutrition by country's income level.

Reduced height growth (stunting), i.e., children below -2 SD median height-for-age (light blue), wasting, i.e., children below -2 SD from median weight-for-height (red) as well as overweight, i.e., children 2 SD above median weight-for-height (purple). Sorted by Income Levels I to IV, from (I) extreme poverty < US-\$ 2 per person per day, (II) US-\$ 2–8, (III) US\$ 3–32 to rich countries (IV) > US-\$ 32), the absolute numbers of children under two years of age and their share in the total population are shown here. Reading aid: 39.7 million children suffer from reduced height in countries with incomes below US-\$ 2. In total, 50 million children in these countries have some form of deficiency, accounting for about 43% of all children under five. Data: UNICEF, WHO.

In this perspective paper our aim is twofold: first, to synthesize the evidence about future agricultural yields under an extreme but likely scenario of a +3° warmer world and, second, to summarize and synthesize the recent history of human societies with respect to agriculture. We will begin with the latter point, which will elucidate the challenges and roadblocks ahead. Our 12,000-year history of continuous optimization of agricultural production under an extremely stable climate now has to adopt within a few decades in the dawn of the Anthropocene.⁹

AGRICULTURE IN THE HOLOCENE: EVOLVING IN A STABLE CLIMATE

With the Neolithic Revolution, *Homo sapiens* began to evolve from a hunter-gatherer to sedentary society. This brought about a large number of changes and has made this species the most successful, or better influential, on the planet. Today, *Homo sapiens* make use of 25% of the net primary production,¹⁰ and the "Earth overshoot day" changed from the end of the year in 1970 to 29th July in 2021. Humans are shaping the process of the Earth's ecosystem as a whole, which supports coining the term "Anthropocene".

The first important innovation 12,000 years ago was the domestication of the first arable crops such as emmer, barley, lentils, and rice, and the first animals were kept by humans⁹ in China, New Guinea, Central America, and of course in the Fertile Crescent (Figure 2A). Already in 2000 BC, about 50% of the total domesticated plants and animals were known and used by humans (Figure 2B). Within the coming 4,000 years, that kind of cultivation spread to almost the entire surface of the earth and displaced other ways of human life. New domesticated plants, such as cotton or maize, came from Central and South America and regions in Africa.

Industrialization enabled mechanized farming and large-scale synthesis of mineral nitrogen fertilizer, and it made fieldwork much easier and less physically demanding and thus enabled the use of larger areas of land. By then, humans had modified almost all the fertile land on the planet in some way. In modern times, from 1950 onwards, the breeding of more efficient varieties through to genetically modified crops, as well as the development and application of sophisticated plant protection compounds, further optimized productivity.

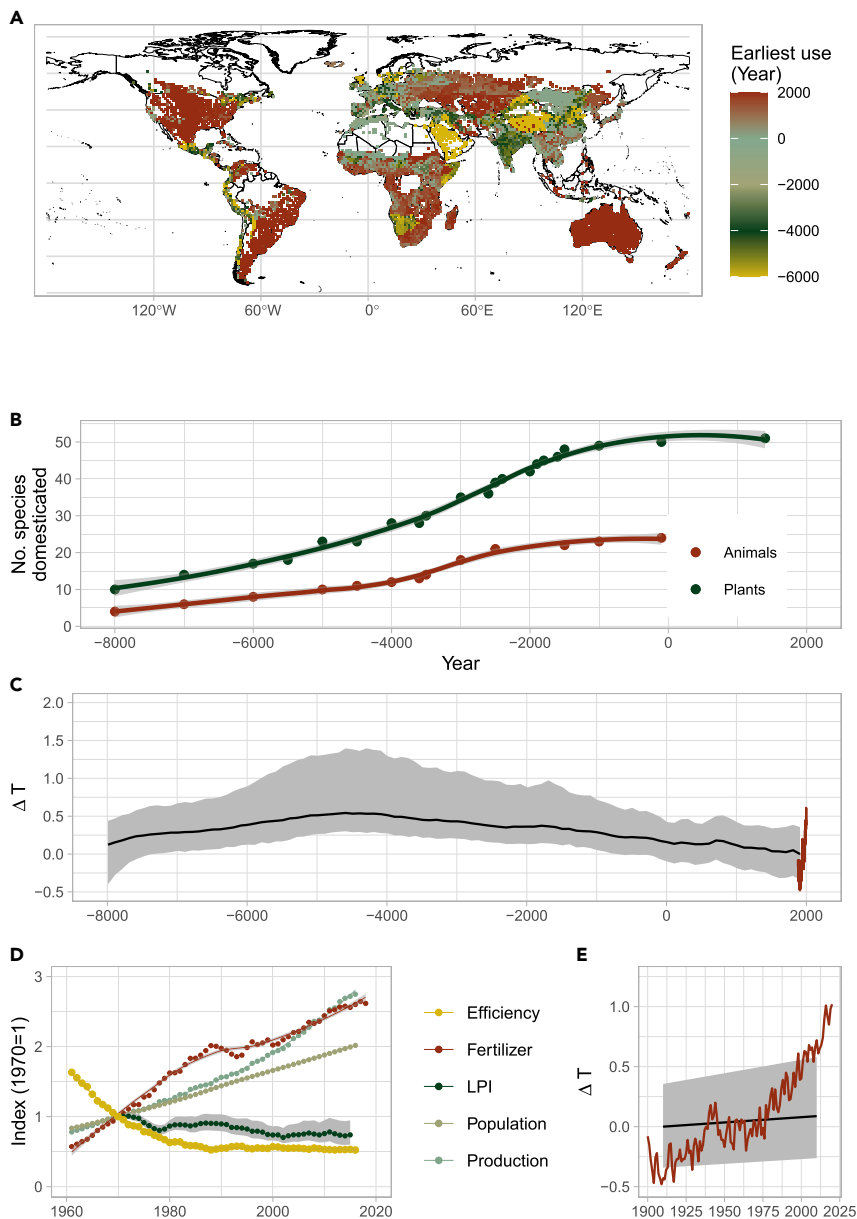


Figure 2. Conditions for agriculture in the Holocene and in modern times

Agriculture developed in the fertile areas of the Near East, China but also Central America and mountainous regions of South America (Inca cultures) (A). Many animal and plant species were quickly domesticated or cultivated (B). During this time, the climate was remarkably stable (C, E). The black line denotes reconstructed temperatures and the uncertainty (gray shading). The red line shows current measurements.¹⁴ While from 1960 onward global agricultural production (green) increased more than 2.8 times, the population grew twice as much (brown), and the amount of mineral and organic N applied worldwide increased more than 2.5 times (red), but the ratio of goods produced per amount of fertilizer used ("efficiency", yellow) has fallen continuously together with the living planet index (LPI, dark green) (D). Data: FAOStat, WHO, refs.^{11–14}

All these innovations that ensure our food supply have developed in a very stable climate. At the same time, a homogenization took place. Since the conquest of the world in the late Middle Ages, an exchange of agricultural cultures has taken place. For the good, easy-to-farm cereal crops from the Near East were introduced throughout the world; potatoes and maize came from America. Annual grasses such as maize, wheat, rice, barley, sorghum, millet, oats, or rye are the main crops cultivated today. On the downside, this homogenization has led in parts to a uniform production system.^{15,16} Introduced alien species have

drastically changed entire ecosystems; the hunting of many species that had no natural enemies until the appearance of humans and many other drivers led to an unprecedented rate of extinction.^{17,18}

AGRICULTURE IN THE ANTHROPOCENE: BOOSTED BY INNOVATION

The application of nitrogen, phosphate, and plant protection products multiplied between 1960 and 1990 (Figure 2D).¹⁹ Since 1960, despite a growing world population, the amount of food produced per capita has increased.^{20,21} This increase has only partly resulted from a growing area for agricultural production, i.e. cropland expansion. This is not to say that the increasing deforestation of tropical rainforests is not driven primarily by the need for agricultural products. However, it does not explain a 2.5-fold increase in production. The decisive factor of why the production of agricultural goods has increased so much is, above all, the higher *intensity* of land use.

For example, during the Green Revolution in the 1960s, varieties were developed that, due to their compact growth, can convert higher amounts of nitrogen fertilizer into yields.²² On agricultural land, therefore, more fertilizer, more pesticides, and sometimes also more water are used to realize this increased yield potential, removing so-called limiting factors following the ideas from Mitscherlich and Liebig in the 19th century,²³ today remembered by the term Liebig's Minimum Principle.²⁴ Based on this, Mitscherlich formulated that there is a marginal yield: The higher yields are, the more likely it is that further increases in yield, e.g., by adding fertilizers, will only be marginal. In parallel, external effects on the environment (e.g., pollution of groundwater and the species community in receiving waters) increase much more. One way to mitigate external effects is to increase the nutrient efficiency of crops through breeding, i.e., more efficient uptake and utilization of the given amount of nutrients. Such strategies benefit from an improved understanding of how the crop functions, as has been realized, for example, for nitrogen uptake of rice.²⁵ Mechanisms of wild plants, which are often highly efficient in uptake of nutrients such as phosphate, can also be transferred to crops.²⁶

On 70% of the terrestrial Earth's surface, there is already some form of anthropogenic activity.^{18,27} The question of how far agricultural production may be further increased through technological developments and ultimately intensification is highly topical but still debated: Answers vary greatly among regions. Where there is a severe undersupply of nutrients, only a small amounts of mineral fertilizer may lead to strong increases in yields, while other regions suffer from a heavy oversupply, e.g., with phosphate.²⁸ In Europe, further substantial increases in yields of currently cultivated crops are difficult to achieve because landscapes are already very intensively cultivated. Is such a maximum of production achievable even globally? By analyzing time series data on the production of renewable as well as nonrenewable (fossil) resources, we can investigate if trends follow a steady continuous, monotonic growth trajectory or are subject to saturation. For many renewable resources, the point of maximum production increase has long been exceeded (Figure 3). Fossil resources, however, continue to show a steady increase. Mankind's hunger for energy seems to be so great that there is no sign of a peak year of production, given the current data. What is more surprising, however, is that the production of both plant and animal products has experienced a year of maximum production increase. Between 1989 and 2008 (median 2006) there was a synchronous slowdown in the increase in production of renewable resources. These results also show that agricultural intensification is an evident pattern of global agriculture. The rate of increase in agricultural land, i.e., expansion, has decreased since 1950. Manure application had its maximum growth shortly after 1970; the increase in the irrigated area had a peak in 1978, increase in mineral N-fertilizer application, in 1993, and increase in potash fertilizer, in 2010, which show how fossil fuel-based agricultural practices spread around the world. This is the global representation of Liebig's principle: first, the most fertile areas were farmed. When fertility of the newly used land gradually decreased, limiting factors (first water, then nutrients) were added. In conclusion, we see humanity reached a maximum yield increase around 2006. Mankind is farming a finite planet; productivity increases start declining as land degradation has reduced productivity on 23% of the global terrestrial area.^{17,18}

However, these growth rates of agricultural production have not been linear in the past but have been episodic with the emergence of innovations such as the Green Revolution. The question is whether there will be sufficient innovations in the near future that will bring about a new maximum in yield increases. The recent quantum leaps in our functional understanding of plants certainly hold out the prospect of such disruptive development.²² New possibilities of genome editing will extremely accelerate the further development of crops as now for the first time precise changes can be made in the genome of adapted

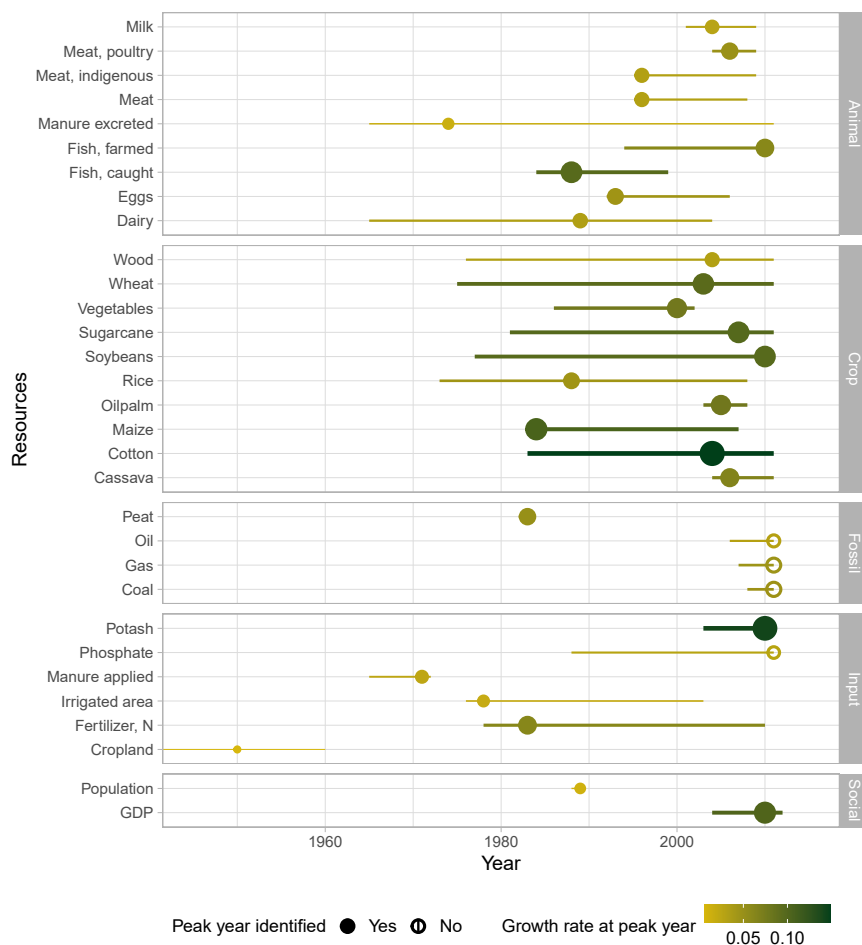


Figure 3. Years of maximum production growth (peak years) of products from animal husbandry, arable farming, fossil materials as well as socioeconomic variables (from top to bottom)

The dot shows the respective year of maximum production growth, the size and color of the dot correspond to the growth rate in that year, and the horizontal bar shows the uncertainties. Bars represent 2.5th and 97.5th percentiles of 5000 bootstrap estimates. An interactive representation can be found at www.ufz.de/global-agriculture (Data: ref ¹³)

genotypes.²⁹ These possibilities go as far as making wild plants usable within a few generations, a kind of domestication in fast motion.³⁰

AGRICULTURE OF TODAY: SPECIALIZED, VULNERABLE, AND ENERGY-INEFFICIENT

What is efficient agricultural production?

The basic idea of agricultural production has been for thousands of years to convert energy from sunlight and CO₂ into biomass using the fertility of soils and perhaps grazing animals. While this has led to energy gains over millennia, now conventional agriculture is subsidized by fossil fuels in the form of fuels, fertilizers, and pesticides.³¹

The efficiency of global agriculture can be assessed by estimating the ratio of output and input, i.e., total yields and fertilizer applied. This indicator of total factor productivity (TFP) allows for assessing the profit or loss of agricultural productivity. In 1960, N application to agricultural fields in form of manure application was of the same magnitude as mineral fertilizer, globally 18.4 and 11.4 Million tonnes (Mio. t). Till 2000, manure application increased to 27.5 Mio. t (+30%), but the application of mineral fertilizer rose to 80 Mio. t, an 8-fold increase. From this recent data, one can depict that the continuous increase in fertilizer applications leads to a declining trend in energy efficiency (Figure 2D). Following that approach, one can estimate how far climate change today affects this efficiency. There is evidence that TFP declined by

21% since 1961 due to anthropogenic climate change.³² This effect is even more drastic for countries in Africa, Latin America, and the Caribbean, where it shows a decline of 26% to 34%.

If we take increasing yields as a necessity, more and more energy, work, and effort have been expended to increase yields. Agricultural production has become more and more energetically unprofitable. Never before have there been so many multiple synthetic substances with corresponding interactions. From a “circular economy” that agriculture was to a larger extent before the beginning of industrialization when legumes were employed to introduce nitrogen into the system, manure was applied to fertilize crops, and food waste and fodder were used to feed animals, we have come to the separation of animal and plant production. Quantities of plant biomass produced are used as feed for meat production because global meat consumption, especially in the richer nations, far exceeds what is recommended for health according to WHO recommendations.³³ But it is small-scale agriculture that continues to provide a major share of food security.³⁴ Although numerous studies have shown that larger farms are more productive in terms of yields per worker, small-scale, sustainable agriculture with polycultures can produce more food per area.³⁵ It is obvious that small-scale, low-energy farming is gaining ground where, for example, pesticides are lacking or cannot be financed, but helping hands are available, such as in China³⁶ or Andhra Pradesh with “zero budget natural farming” in India.³⁷ Subsidies based on the area farmed, as it is still the rule in the European Union or the US, make such forms of assessment completely unfeasible.^{38,39}

Closing yield gaps, adapted varieties, and human nutrition

Identifying yield gaps is one approach to assessing the extent to which yield increases can be achieved and in which regions more could be produced. The literature varies, but in principle, it can be stated that under current climatic conditions a yield increase of 58% is possible globally by closing yield gaps.⁴⁰ Although there are clear potentials to increase yields and close yield gaps and further increases through breeding success, all of this will not be sufficient to feed a larger and more affluent population. For this, breeding successes of 1.7% yield increase on average would be necessary, which is highly questionable.⁴¹ Besides boosting yields, adapting varieties to changing climate is crucial. While at low levels of warming (representative concentration pathway RCP2.6), existing varieties on 85% of currently cultivated land could shift within agroecological zones, to adapt to the conditions of climate change under the RCP8.5 scenario, 39% of global cropland requires new crop varieties that are capable to tolerate extreme conditions to avoid yield loss.⁴² If one also takes into account that trade can lead to the cultivation of completely different crops at some locations, which are then produced much more efficiently, potential yield increases of up to 148% are estimated to be achievable worldwide mostly assuming a more energy-rich way for production, i.e. conventional intensification.⁴³ However, evidence is lacking concerning the consequences for crops not prominently contributing to total calorie production. The provisioning of micronutrients for human nutrition such as magnesium, vitamins A, C, and trace elements supplied by fruits and vegetables, which are dependent on pollination, have not been part of these considerations.

Biodiversity—A threatened production factor

Increasing management intensity seems to be the standard answer to how we are going to feed everyone now and in the future. Increased inputs have made the enormous increases in global agricultural production possible but also led to a massive downward trend for biodiversity (Figure 2D). The Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) identifies land use as the key driver of biodiversity loss.¹⁷ Continuing on a business-as-usual trajectory with a higher land use intensity, the withdrawal of resources, the increasing area under use, and the homogenization and uniformity of use, 500,000 to 1,000,000 species are expected to become extinct by the end of the 21st century.^{17,18} These species are rarely iconic species but are those that underpin a variety of ecological functions such as pollination, biological pest control, super soil fertility, capturing carbon, filtering water, and finally providing fresh and clean air. Agricultural production depends on functioning ecosystems, and this requires sufficient biodiversity, the species diversity inherent in ecosystems. Biodiversity is a crucial production factor: 70% of all crops depend on pollination services provided by insects, birds, or bats. All agricultural production depends on sufficient soil fertility, which in turn is based on the interaction of soil organisms. Birds and insects fight potential pests, i.e., herbivores, and therefore also stabilize yields by providing biological biocontrol services.

Intensification of agricultural production has been the “recipe for success” over the last century and is seen as the lever to close yield gaps. At the same time, there is ample evidence, that conventional intensification leads to a decrease in biodiversity,⁴⁴ and a few studies also investigate the resulting trade-off.^{45,46} This is

indeed critical in farming systems that are rather moderately intensively used. Increasing intensification can lead to yield increases of up to 80% but also a maximum decline in biodiversity of –30%.⁴⁵

Closing yield gaps through intensification thus initially has a positive effect on yields but at the same time has negative effects on biodiversity, which in turn jeopardizes yields and yield stability. This conflict shows that the system is highly sensitive and nonlinear. Therefore, it does not seem to be a good proposal to drive agriculture economically optimized at the load limit, i.e., to maximally clear landscapes and to maximally intensively cultivate them, especially when one considers that climate change will increase disturbances and extremes. One goal must therefore be to achieve resilient crop production at a sufficient level with a reduced input of energy and production factors. Crops that are pathogen resistant and make better use of nutrients can contribute to this.

AGRICULTURE UNDER A FUTURE CLIMATE

Possible futures: A climate that is 3°C warmer

On a business-as-usual trajectory, targets of the Paris Agreement will not be reached, 500,000 to 1,000,000 species will go extinct, and a +2° to +3° warmer world could be our future. With the coupled model inter-comparison projects (CMIP), the climate modeling community presents very stable scenario projections based on more than 100 model runs from approximately 50 research groups. The newest version CMIP6 scenario builds on the previously developed RCP scenarios, which did not provide a fine-grained resolution, especially for the no-mitigation pathway. With CMIP6, for instance, the differences between the rather dramatic scenario RCP8.5, formerly referred to as the "worst-case" scenario, which reaches an increase of +3°C global mean annual temperature around the year 2060 and the RCP6 or RCP4.5 scenarios, where similar conditions will prevail in the year 2100, can be studied in much more detail.⁴⁷ Nonetheless, in our synthesis, we need to refer to the "older" RCP scenarios as our analysis is based on papers, which all use these as references.

What can be expected to happen to today's agroecosystems if the climate will exceed the stable trajectory of the Holocene? How will the available space, available resources such as water, nutrients, and organic carbon, the physiology and growth of arable crops, and the ecology of agricultural landscapes change and the life of farmers be affected?

Environmental conditions of a changing climate: Availability of water, soil fertility, and area

A changing climate will affect multiple environmental conditions relevant to agricultural production. A comprehensive multi-model analysis of various increases in global temperature showed that there is, on global average, an increase in the duration of agricultural droughts by +22% (15%–27%) and in their frequency by +51% (34–63%) under a +3°C scenario. The reference period 1981–2010 already shows an increase of +6.5% and +9.4% for these indicators compared to preindustrial levels. More extreme weather events lead to +25% (13%–38%) increase but also –20% (12–42%) decrease of runoff.⁴⁸

Various studies examine the potential increase in agricultural land under rising temperatures. Model-based calculations show that maize in North America and Europe can be expected to gain +10% to +20% in area, whereas Africa, South America, and Oceania can be expected to lose up to –40%.⁴⁹ A global analysis of the suitability for the cultivation of crops shows a similarly diverse picture and predicts an average land gain of about +3%, with the suitability of the new land being rather moderate.⁵⁰ In particular, potentially new areas are more likely to become available in northern latitudes with shorter day lengths. Increasing temperature considerably leads to soil carbon losses in high-latitude areas, which is a constituent of soil fertility: Global soil carbon stocks in the upper soil horizons are estimated to fall by 30 ± 30 petagrams under one degree of warming.⁵¹

The extent to which an increase in CO₂ concentration has a positive effect on plant growth has been investigated within experiments at many agricultural test stations. An increased CO₂ content in the atmosphere has an undisputed fertilizing effect. In particular, yield increases of +10% (95% confidence interval: 3%–17%), +20% (15%–27%), and +23% (13%–35%) have been observed for C3 crops such as soybean, rice, and wheat, respectively.⁵² However, the assumed CO₂ concentrations with such fertilization effects often correspond to a globally warmer world of far beyond +3°C. Also, these increases can only be achieved if other limiting factors such as water or nitrogen are available.⁵³ Thus, a realistic assessment of a possible CO₂ fertilization effect requires considering corresponding interactions with the availability of nitrogen

and water. A model study assuming a rather drastic climate scenario with a temperature increase of +6° by 2100 (RCP8.5) showed for wheat, soy, and rice that a possible positive CO₂ fertilizer effect is leveled out by negative effects, such as water scarcity, higher ozone levels, or extreme events and is above all geographically distributed in a heterogeneous way.⁵⁴ However, the development of salt-tolerant crops, for example, would make it possible to expand cultivation into previously unusable areas.

Growth of crops under climate change

Increased temperatures lead to faster plant growth, earlier plant maturity, faster accumulation of biomass, and thus yield decrease. The increase of extreme events under rising temperatures further leads to more frequent crop failures. Heat wave frequency could increase by +97% (91%–98%).⁴⁸ Against this background, it is not surprising that climatic changes already observed between 1980 and 2008 resulted in global yield declines of –3.8% and –5.5% for maize and wheat, respectively. These declines were most pronounced in China, Brazil, and Russia.⁵⁵ For wheat, rice, maize, and soybean, which provide two-thirds of the global calorie demand, losses of –3% to –7% per degree temperature increase can be expected, based on the varieties available today.⁵⁶ However, based on model simulations for maize, soybean, and spring wheat, it can also be shown that 7% to 18% of the yield losses could be prevented simply by adjusting the sowing dates of varieties already available today.⁵⁷

Less studied are vegetables, legumes, and fruits. For those, yield increases of about +22% could be expected from CO₂ fertilization effects, but also yield losses of –9% due to increased ozone concentrations, losses of –35% due to water scarcity, and losses of –32% under a +4°C warmer climate could be expected.⁵⁸ In addition, these crops depend on ecosystem functions, e.g., pollination, which is at risk because of temperature-induced shifts in flowering times and insect population dynamics.

In addition to more intensive cultivation of land, the breeding of new varieties naturally also leads to higher yields. For wheat, rice, and maize, breeding-induced yield increases of 1% at the maximum could be observed in the period from 1980 to 2008.⁵⁹ One could optimistically extrapolate such a breeding-related yield increase of 1% and thus arrive at almost 50% higher yields by 2060 (at +3°C under scenario RCP8.5) compared to 2020. However, such a breeding success would only be realistic if it also targets resistance to pests and robustness to drought and higher temperatures (see below).⁴¹ However, the fact that from absolute temperatures of more than 42°C every non-extremophilic organism suffers is a biological constant that cannot be overcome even by the most skillful breeding.

Multitrophic interactions in agricultural landscapes

A warmer climate is in principle favorable for all species whose activity (metabolism) depends on temperature. Of these, ectotherms, organisms that cannot regulate their body temperature themselves, such as insects, will benefit significantly from a warmer climate. In our context, this is particularly relevant for herbivores. Increased temperatures lead to a higher metabolic rate of herbivorous insects, i.e., those who are likely to consume more biomass. Increased temperatures, secondly, lead to increased population dynamics, i.e., more offspring. Based on these basic ecological principles, there is a temperature-induced increase in the activity of pests on rice, maize, and wheat, which can lead to crop losses of –10% to –25% per degree increase in temperature.⁴⁷ Under a 2°C warmer world, wheat yield losses through herbivores of about –18% are predicted for Europe and North America and about –17% for East Asia. Rice would experience losses of about –59% in South and Southeast Asia and of –32% in East Asia. Maize would have the largest decline of about –32% in North America and –23% in Europe.⁴⁷

Like herbivory, plant diseases will benefit from a changing, warmer climate. The decisive factors for the increase in these plant diseases are either introduced species through crop exchange (56%) or the weather (25%).⁶⁰ Specific figures on possible yield losses are not yet available. However, plant diseases will certainly increase under a changing climate.

Socioeconomic aspects of agriculture under a warmer climate

Largely overlooked are impacts on the labor force in two of the most vulnerable regions: sub-Saharan Africa and Southeast Asia. With global warming of +3°C, heat stress in these regions could reduce agricultural labor capacity by –30% to –50%. This would lead to an increase in food prices and requires much higher levels of agricultural employment. The global welfare loss at this level of warming could be as much as US\$136 billion.⁶¹ Extending this to economic output as a whole might lead to losses of –23% in the gross

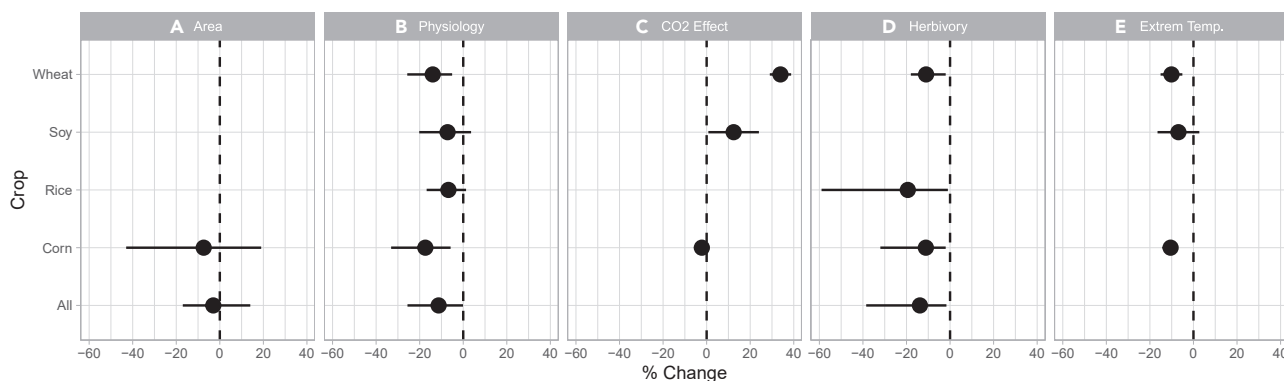


Figure 4. Synthesis of effect sizes given climate change-induced temperature increases

Possible effects of available land area (A), temperature-induced altered physiology (B), CO₂ fertilization effect (C), herbivory (D) and extreme temperatures (E) on yields of different crops. The figures given in the text are in each case mean values of the expected changes under a warmer global climate with a +3°C higher mean temperature. Here these results are shown with the ranges of variation represented by the horizontal lines.

Data: refs.^{47,49,50,56,57,67}

national product.^{62,63} In addition, regional heat centers will make large areas, even densely populated today, no longer farmable or even completely uninhabitable.⁶⁴ Events of food insecurity are hypothesized to imply not only large migration events but also the occurrence of violent uprisings. Although there is a clear link between weather patterns and food production based on 50-year statistics in sub-Saharan Africa, a causal relationship to violent conflict is only weak and inconsistently connected, even in those situations where production shocks are supposed to have devastating social consequences.⁶⁵ Based on data from African states whose population exceeds one million from 1991–2011, it can be shown that these feedback on food insecurity and the likelihood of violence are interactive. State vulnerability moderates the impact of food insecurity on the likelihood of violence and “that a capable governance is a better guarantor of peace than good weather,” the authors conclude.⁶⁶

Syntheses

Climate change-induced land gains up to 2060 are negligible, and CO₂ fertilization effects could bring yield increases but will be offset by losses due to extreme temperatures and extreme weather events. Changing temperatures will cause changes in the population dynamics of herbivores leading to larger crop losses. Future yield losses will be caused by climate extremes, increased herbivory, and more severe plant diseases. High geographic and temporal variability is an underlying pattern (Figure 4).

But the evidence is limited for assessing possible feedback between these different processes. Pollination function might not only get lost due to the decline of the abundance of species but also might disappear due to temporal shifts in development or due to species leaving their geographic ranges. Years of extreme drought have shown that crop failure can jeopardize animal feeding and thus milk and meat production. Knowledge of the ecology of agroecosystems especially the interactions of the multiple drivers under climate change is truly lacking.

PERSPECTIVES AND FUTURE CHALLENGES

Offsetting future yield losses and gains is hardly possible from the available literature as feedbacks are complex. One could expect breeding successes to compensate for yield losses. Conversely, one can expect processes of yield losses to reinforce each other. The general trend, however, is clear and indisputable. A world with a warming of +3°C is confronted with the risk of massive yield losses. Climate impacts will affect agriculture everywhere in the world: richer countries like Australia and China as well as regions where a large part of the population lives on an income less than two US dollars per day.⁶⁴ There, the consequences of climate-induced yield losses will be correspondingly more severe, and the expected increase in days with extreme temperatures may lead to major hunger catastrophes.⁶⁸ Research has to develop regionally differentiated solutions, which not only account for climatic and environmental conditions but also take into account socio-economic conditions.⁶⁹ Conflicts over resources are more likely to intensify. Possible migration to nearby metropolises or other regions will increase.⁷⁰ Not only is climate change putting food provisioning in these regions

at risk but also conflicts between major producers of grain. Expecting a continued increase in yields as it happened between 1960 and 1990 or that global trade will result in a more equitable distribution of available resources is a risky misconception. Supply gaps, which we unfortunately still have today, will tend to increase.

Despite all the uncertainties, the overall balance is frighteningly simple. Based on the facts that already today about twice as much food is produced as is needed, that about 30% of the harvest is lost, that about the same proportion of food is thrown away, and that a large part of the world's population eats a diet that is far too rich in energy, it would in principle be possible, at least at present, to feed a population that would grow to 10 to 11 billion people. The key lever to allow for maneuvering space in adapting the global food system is not to aim at boosting yields by any means but a diet with less meat.³³ This would mean that much less land would be needed for animal feed production and would also significantly reduce greenhouse gas emissions. Secondly, every effort must be made to keep the global food production system stable. It is key to understand that global land use and production of food already today is a common-pool resource problem, which requires strengthening multilateral processes. Stable agricultural production will be achieved by modern breeding technologies to strengthen the resilience of crops against the new climatic conditions but also through more diverse, small-scale land management and the continuous development of crops adapted to changing conditions; agroecosystems and biodiversity can be maintained and yields can be stabilized.^{71,72}

So, the solutions lay less in merely boosting production but in a joint effort to mitigate climate change, as well as to ensure yields under rapidly changing climatic conditions, consisting of five pillars:

1. crop and food losses must be drastically reduced, ideally eliminated;
2. dietary habits must be changed to a more conscious, lower-energy, and healthier lifestyle;
3. yields need to be boosted and stabilized while simultaneously maintaining high biodiversity levels through agroecological principles and diversified crops;
4. production needs to be stabilized against new climatic and environmental conditions through innovative breeding technologies; and
5. trade has to serve to distribute food equitably and compensate for possible climate-related yield losses and must not displace locally adapted farming practices.

Research has to tackle these challenges. Specifically, research needs to consider multiple pillars in parallel and address their "nexus", i.e., the interrelationships between different challenges. Research on self-amplifying feedback between various drivers (crop physiology, trophic interactions, water availability, and frequency of extreme events) is truly lacking as our review showed. This hampers providing any plausible future projections and assessment of trade-offs. Prioritization of which pillar to tackle first is hard to provide. For instance, process-based knowledge on the feedback of biodiversity and yields is lacking and consequently not incorporated into today's capabilities in modeling and integrated assessment for yield gaps.⁷³

The almost obvious but not explicitly mentioned question of how many people can feed themselves healthily and sufficiently under the climatic condition of a 2°C to 3°C warmer world cannot be answered with any degree of certainty. At the end of the day, not the scientific uncertainties of the individual effects compiled here and the unclear effects in their combination make an answer to this question seem speculative: It is above all the uncertainty of how many and which resources we will consume and how and from what we want to live, i.e., how we will decide to live in our societies in the coming years. Our decisions make a forecast uncertain, but this also leaves a bit of room for optimism.

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AUTHOR CONTRIBUTIONS

R.S. conceptualized the idea of the manuscript; S.K. provided knowledge on biodiversity and environmental history, E.P., on plant breeding and crop physiology, and M.V., on climate change impact. All authors contributed to reviewing recent publications, writing, and the improvement of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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