Climate Change, Agriculture, Water, and Food Security:

What We Know and Don’t Know

Report of a workshop conducted at the Massachusetts Institute of Technology

May 8-9, 2018

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Photo: Timothy Griffin, associate professor and chair, Division of Agriculture, Food, and Environment at Tufts University, presenting on GHG emissions from agriculture. ANDI SUTTON, J-WAFS

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EXECUTIVE SUMMARY

On May 8-9, 2018, the MIT Abdul Latif Jameel Water and Food Systems Lab (J-WAFS) held a two-day workshop titled: ***Climate Change, Agriculture, Water, and Food Security: What We Know and Don't Know.*** 46 participants attended, coming mainly from North America and Europe. Their backgrounds spanned agriculture, climate, engineering, and the physical and natural sciences. These experts discussed and debated our current understanding of the complex relationship between climate change and agriculture.

The workshop comprised six sessions:

- Overall Context and Trends
- Greenhouse Gases and Crop Production
- Greenhouse Gas/Soil/Plant Interactions: Measuring, Modeling, Adaptation, and Mitigation
- Implications for Water and Land Resource Management
- Biological Engineering and Crop Genetics for Mitigation and Adaptation
- Tools for Projecting and Managing Climate Risk

Eighteen invited speakers presented; all are regarded as experts in one or more of the session topics.

Throughout the workshop, agriculture was seen to be a complex adaptive system. Agricultural systems include many actors, interacting institutions, and social, environmental, biological, institutional, political, governance, and demographic considerations. Participants expressed the view that most major cropped areas are already experiencing changes in climate and that these changes are likely to continue. In most, but not all cases, climate change makes food production more difficult. Extreme heat, water stress and drought, and other extreme weather events are some of the major climate factors affecting crop productivity. Overall, climate change and water scarcity present real and significant threats to agriculture and the world's food systems. Participants stressed that no single solution will achieve food security or sustainable agriculture under under these threats and the current population growth trajectory.

Research across many disciplines has established much knowledge about the interactions between climate and agriculture. For example, we have evidence of agriculture's impacts on climate change, the relationship between soil carbon and farming practices, and plant responses to atmospheric carbon dioxide concentrations. However, speakers noted many areas with unanswered questions. Among these knowledge gaps are uncertainty in model predictions of climate change and agriculture, an incomplete understanding of plant response to heat, drought, and other stressors introduced or exacerbated by climate change, and quantification of the impact of adaptation strategies that farmers may adopt. Furthermore, global and local variability in climate dynamics and physical processes, as well as varying soil properties, make it difficult to definitively characterize impacts and to find comprehensive solutions. Solutions are often site- and context-specific, and may not be directly transferable to different agro-ecological regions.

In addition to increasing average temperatures and temporal shifts in seasonality, our future climate is also expected to be characterized by increases in the number and intensity of extreme weather events. These events, such as heat waves and droughts or heavy precipitation and floods, have negative impacts on crop yields. This increased variability is likely to be a major challenge to adapting agricultural systems to withstand climate change. Models for crop yield response to future climate change remain highly uncertain, particularly in regard to the impact of extreme events. Such models require improved methodologies that can incorporate uncertainties and associated risk.

The participants agreed that more research is required to better characterize specific challenges and to develop, evaluate, and implement effective strategies. The need for multidisciplinary approaches to improve our understanding, as well as to seek varied solutions, was emphasized.

A number of specific priorities for future research were identified. Although there is overlap, these priorities fall into three general categories: cross-disciplinary research and policy needs; technological advances; and fundamental research questions. Summaries of the recommendations for each area are listed below, with more details provided in the full report.

Cross-disciplinary Research and Policy Needs

- **Convergence Research:** Research should be driven by specific complex problems that involve deep integration across disciplines, a strategy known as "convergence research." This research approach develops new scientific language and common frameworks to facilitate communication across disciplines, developing innovative ways of framing research questions and new approaches to solving vexing research problems.
- **Soil Fertility:** Soil management and fertilizer use affect greenhouse gas emissions, carbon cycling, and crop productivity. Interdisciplinary research on soil fertility management is needed to maintain soil health and improve crop productivity while minimizing greenhouse gas emissions, especially in developing countries.
- **Role of Diet:** Dietary shifts that reduce the consumption of animal protein can reduce the land and water required to produce animal feeds, and also reduce direct greenhouse gas emissions related to animal agriculture. However additional data and improved assessments are needed, as specific resource requirements can vary depending on where and how particular foods are produced and consumed. Policies to incentivize food choice change and strategies

to affect behavioral change need to be further investigated.

Technology Development

- **Geospatial Tools:** Remote sensing technologies and big data analytics are powerful tools to assess physical constraints and other parameters that affect crop yields. Geospatial and analytical tools should be developed and deployed to collect and process very large amounts of data in order to improve crop production in regions experiencing heat and drought stress.
- **Advanced Biotechnology:** Biological sciences are rapidly advancing, especially plant and microbiome genetics and genomics for food crops. Efforts should be made to identify how genetic engineering can improve the resilience of crops to climate change.
- **Carbon Sequestration:** Much more carbon can be sequestered in the soil, depending on weather, soil management, and soil microbiome conditions. Technology is needed to improve site-specific monitoring and measurement of carbon absorbed and emitted by soil.

Fundamental Research Questions

- **Crop Stresses:** As the climate changes, various crop stressors will also change. Better understanding of the cumulative effects of these stresses is needed in order to guide the development of climate resilient cropping systems and climate smart agricultural practices.
- **Crop and Climate Models:** The underlying mechanisms of plant carbon dynamics, including crop response to CO_2 and heat stress, are not well understood. There is also a need for better characterization of the underlying physics in models of precipitation. More research into these areas is important for improving crop and climate models and to better predict crop yields in a changing environment.
- **Deep Uncertainty:** Deep (irreducible) uncertainty in the projections of climate change and crop yield can result in difficulty making even qualitative projections into the future. Advances in data and decision science are needed to improve decision making when there is deep uncertainty in a system. In addition, research into adaptive planning approaches, in the face of uncertain risk, may provide new policy solutions for risk management.

Photo: **(right)** Flooded farm land. ISTOCK

1 OVERVIEW OF THE EXPERT WORKSHOP AND REPORT

A two-day, invitation-only workshop was organized by the MIT Abdul Latif Jameel Water and Food Systems Lab (J-WAFS), with sponsorship from MIT's Office of the Vice President for Research. It brought together a small group of invited academic, industry, and government experts, mainly from North America and Europe. Participants presented and discussed the current state of knowledge about the impacts of agricultural systems and practices on greenhouse gas emissions and climate, and how future climate is likely to affect agriculture. Through these deliberations, uncertainties and open questions were considered, and research needs on the interrelationships between climate change, agriculture, water and food security were identified.

> ***"Future trajectories for the global food system have the potential to exacerbate these emissions, or conversely to provide opportunities to reduce them, and even to sequester carbon."***

Participants were chosen to represent diverse disciplinary backgrounds, and the the small number of attendees allowed time for discussion and deliberations. Both climate's impact on agriculture and agriculture's contributions to climate change were considered, including changes to water availability, changes to food crop productivity, and changes in greenhouse gas (GHG) emissions driven by food production.

Anticipated impacts vary from the very direct—e.g. the impact on plants of an increased concentration of CO_2 in the atmosphere—to the indirect—e.g. the impact of shifting seasons on pest populations and plant susceptibility to disease and pest infestations. Climate change is expected to affect rainfall amounts and intensity, placing significant pressures on water supplies and potentially restricting water availability for agriculture. However, there is much uncertainty around the degree, nature, and local variability of these changes. Heat stress has a deleterious effect on crop productivity, and an increase in extreme temperature events will limit the productive capacity of the commercial plant species on which the population currently depends for food. Climate impacts are geographically specific; solutions for mitigating climate change will vary by region. Similarly, successful strategies to meet the challenge of future food security will have to be informed by an understanding of the prevailing economic, political, social, cultural, jurisdictional, and institutional realities within countries.

The agriculture sector is a substantial contributor to GHG emissions. Future trajectories for the global food system have the potential to exacerbate these emissions, or conversely, to provide opportunities to reduce them, and even to sequester carbon. Better understanding of the role of soil—particularly the soil microbiome—and how agricultural practices affect the carbon cycle may help formulate strategies to reduce the impact of agriculture on climate.

1.1. Scope of the workshop

The workshop addressed a defined and focused set of topics that relate to the expertise and research interests of MIT faculty, researchers, and collaborators as they address the challenges of food security in the context of climate change. These topics included: impacts of climate on agriculture and vice-versa, climate modeling, climate and natural resource policy, big data analytics, engineering of soil-plant systems to adapt to climate change and climatic extremes, and the management of land and water resources. Given the extremely wide range of the subject, the workshop focused food crop production. Bioenergy or fiber crops, forestry, livestock, and fisheries were not covered, although it was recognized that these sectors have their own complex relationships with climate change. Similarly, issues related to biodiversity, food waste, labor, gender in the agriculture sector, agribusiness, human behavior and culture, and geo-political dimensions were acknowledged as important, but were not explicitly addressed in the workshop. Workshop speakers further noted that all elements of the food system—from production to food processing/packaging, supply chains, wholesale and retail markets, and consumption/disposal—must be addressed to ensure future food security in the context of climate change. While discussion focused on crop productivity, the need for research and adaptation goes far beyond questions of what climate change will do to crop yields.

1.2. Workshop objectives

The workshop had three main objectives:

1. Bring together MIT researchers and other international experts to assess the current state of knowledge about the impacts of climate change on agriculture and vice-versa;
2. Identify gaps in knowledge, especially considering the complex interactions between crops, soil, water, greenhouse gas emissions, and environmental stressors; and
3. Define key research questions that can lead to innovative solutions, in terms of both technology and policy development, to reduce the contribution of our current food production systems to climate change, mitigate climate change impacts to food production, and position our food systems for resilience given an uncertain future climate.

1.3. Organization of this report

This report attempts to capture what is known and what is not known about the complex interactions between climate and plant agriculture. Sections 2, 3 and 4 set out the background for the workshop discussions, summarizing the content presented by the invited speakers. Together, these three sections present at a high level our current understanding of the climate/agriculture nexus and the likely future conditions and impacts given current trends and trajectories. Section 2 sets out the current and projected future status of food security across the world. Section 3 explains how the agriculture sector contributes to climate change and environmental degradation, and Section 4 addresses the impact of climate change on agricultural productivity (focusing on crops).

Section 5 contains a distilled summary of workshop discussions on major research areas, knowledge gaps, and technology needs. This section does not cover all aspects of research around climate and agriculture, but reflects the workshop topics and how research may add to knowledge, reduce uncertainty, and help evaluate remediation or adaptation measures.

Finally, Section 6 presents recommendations on research priorities arising from the workshop presentations and deliberations.

2 THE CONTEXT OF CLIMATE, AGRICULTURE, AND FOOD SECURITY

2.1. Overview of food systems and their complexity

Food systems are complex adaptive systems. They are shaped by human activity and decisions across multiple business, governmental, institutional, and individual actors, with complex physical, chemical, and biological interactions and dynamics between multiple components. Understanding food systems thus requires the integration of knowledge and expertise across a diverse range of disciplines.

Individual decisions are made every day by a large number of actors, encompassing farmers at every scale, agribusiness, input suppliers, commodity markets, bankers, corporate product developers, and grocery store managers, as well as truck drivers, chefs, nutritionists, and policy makers, among others. Meanwhile consumers decide what, where, when, and how to buy food, and are key drivers of food supply chains and markets. Collectively, the decisions shape what food is produced, how and where it is grown, and how it is distributed, and thus shape the fate of health, environmental, social, and economic impacts of our agriculture and food systems.

Figure 1 illustrates this complexity, showing the numerous actors, and the interactions between actors and the many institutions involved in farming, food production, input sales, markets, education, research and technology transfer institutions, government regulatory agencies, consumers, health and nutrition, food safety, the value chain, food waste, energy, trade, finance, and banking. The interlinkages between all of the above human systems and the natural systems involved in food production (climate, environment, land, and water) are shown, as is the overarching context of population demographics, economics, politics, governance, society, socio-cultural structures, and security—including food security.

Workshop participants acknowledged the entirety of Figure 1, but focused on very specific segments related primarily to the crop farming system, land, water, climate, soil nutrients and fertilizers, greenhouse gases, crop biotechnology, and food demand management. Therefore, what follows in this report is focused on these specific segments. Additionally, the linkages of those components to climate change and resilience are shown in Figure 1, and were also central to the workshop deliberations.

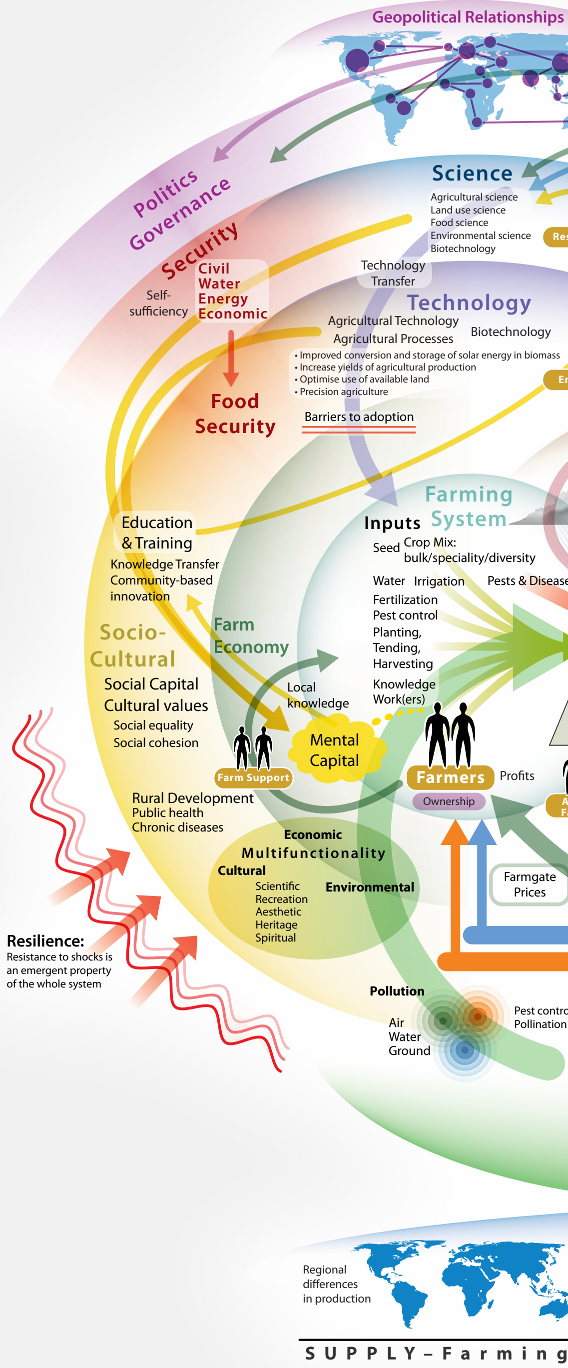
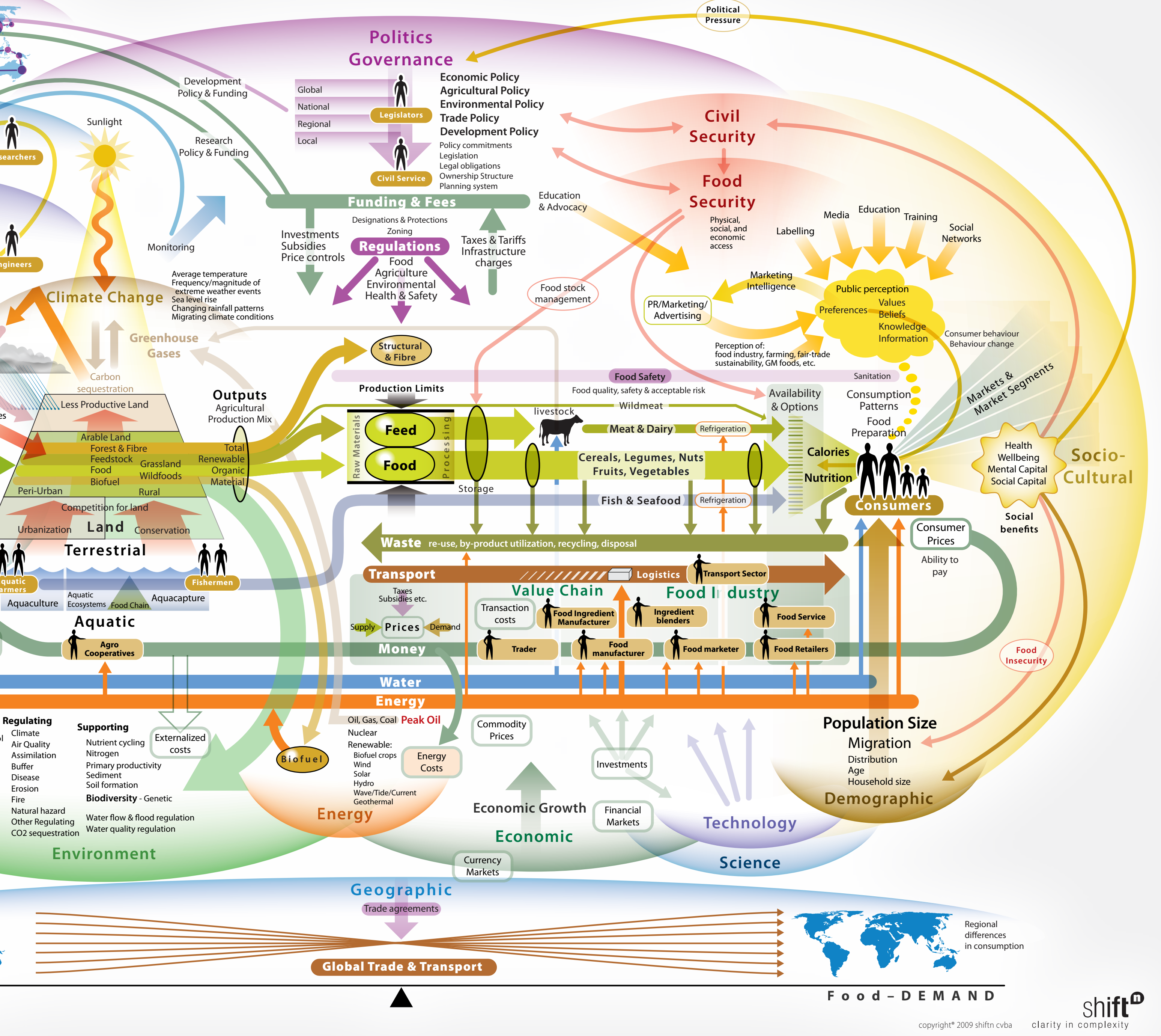


FIGURE 1
Schematic representation of the global food system. (ShiftN, 2009)



2.2. Agriculture and food security in 2018

"Climate is already a significant factor affecting food insecurity."

According to the United Nations Food and Agriculture Organization (FAO) *2018 Report on the State of Food Security and Nutrition in the World* (FAO et al., 2018), nearly 821 million people in the world faced chronic food deprivation in 2017, an increase from 804 million in 2016. The share of undernourished people in the world population, as defined by the "Prevalence of Undernourishment" (PoU) could be as high as 11%. Ongoing armed conflict and political instability, cross-border migration, and adverse climate events in many regions of the world lead to a worsening of food security. In addition to the direct impact of climate change on agricultural productivity, climate change is expected to worsen political instability and human migration in many parts of the world.

Undernourishment remains highest in Africa, at 21%, ranging as high as 31.4% of the population in Eastern Africa. The progress towards improving nutrition has slowed in Asia, while the situation is worsening in South America. This burden of malnutrition is often concentrated among the poor, where poverty and hunger are inextricably linked.

In addition to poverty, climate is already a significant factor affecting food insecurity. The FAO report notes that hunger today is significantly worse in countries where severe drought is compounded by an agricultural system that is highly sensitive to variability in rainfall and temperature, and where a high proportion of the population depends on agriculture for their economic livelihood.

2.3. Future food security given current trends

Exposure to more complex, frequent, and intense weather extremes is expected with climate change, further threatening food and nutrition security. Population growth trends will also exert increasing pressures on food systems, particularly in Africa and Asia. The FAO expects that food production will need to more than double by 2050 to meet the demand of projected world population and economic growth. In addition, income growth in some middle-income countries, and changing dietary preferences towards more meat and processed foods will contribute to demand for increased food production. These changes in dietary patterns are also known to lead to improper nutrition and increased incidence of stroke, obesity, diabetes, and cancer.

Expanding food production to meet future demand will substantially increase demands on water for irrigation, particularly in regions where water availability is already limited. An increase in water scarcity under climate change presents its own challenges, including cross-border water conflicts as well as competing demands for water for agriculture, industry, and residential use. The marginal value of water for agriculture is low compared to other sectors, so where water allocations are market-driven, scarce water resources may be diverted from food production. Continued deforestation in fragile ecosystems will likely occur as land is converted to agriculture in order to grow crops and support livestock.

The FAO 2018 food security report states that if the world is to be free of hunger and malnutrition in accordance with the 2030 UN Sustainable Development Goals, actions to strengthen the resilience and adaptive capacity of food systems must be rapidly implemented in order to adapt to future climate uncertainty.

> ***"If the world is to be free of hunger and malnutrition in accordance with the 2030 UN Sustainable Development Goals, actions to strengthen the resilience and adaptive capacity of food systems must be rapidly implemented in order to adapt."***

Photo: Susan Solomon, Lee and Geraldine Martin Professor of Environmental Studies, Department of Earth, Atmospheric, and Planetary Sciences at MIT, discussing the uncertainty among models that attempt to depict various different climate futures across Africa. ANDI SUTTON, J-WAFS

3 IMPACTS OF AGRICULTURE ON CLIMATE AND THE ENVIRONMENT

Agriculture has a major environmental footprint, including greenhouse gases emissions and deforestation that contribute to global climate change, soil degradation, unsustainable land management, and water pollution from high nutrient loading and various agrochemicals from farms.

Greenhouse gases: Agriculture contributes significantly to global environmental change, as a major emitter of greenhouse gases (see Figure 2), as well as through its substantial impacts on water quality, soil degradation, and deforestation resulting from competition for land resources, especially in developing countries. Various methodologies are used to construct greenhouse gas inventories at national, regional, and local scales. These tend to be model-based, using economic activity data and bottom-up approaches. A fair degree of uncertainty exists in these models, stemming from input uncertainty, model structure uncertainty, and scaling uncertainty. Measurement-based inventories, especially of soil carbon, are generally lacking, but some attempts to validate these models have suggested that the existing inventory methods are reasonably representative. Yet uncertainty at the regional and sub-regional scales is still high.

Based on existing methods, agriculture, forestry and other land uses are estimated to constitute about 24% of 2010 global greenhouse gas emissions (IPCC, 2014), of which agriculture alone contributes 11%. This estimate does not include the removal of carbon dioxide from the atmosphere by ecosystems through sequestration of carbon in biomass, dead organic matter, and soils, which offsets approximately 20% of emissions from the agricultural sector. Greenhouse gas emissions vary significantly across geographic regions and different agro-ecosystems.

Agricultural carbon dioxide emissions result from use of fossil fuels in agricultural production—including fertilizer production—as well as the release of carbon from soil and through decomposition of agricultural residues. Animal agriculture is the primary source of methane emissions, through enteric fermentation in ruminant livestock and decomposition of animal manures. Application of synthetic and organic fertilizer, manure spreading, and burning of agricultural residues are the primary sources of nitrous oxide emissions. Fertilizer production, transportation, and application alone currently account for 2.5% of global greenhouse emissions (IFA, 2016). Land use changes, particularly the conversion of forests to cropland, also account for substantial carbon dioxide emissions, as reflected in Figure 2.

Greenhouse gas emissions in agriculture have remained steady over the past 25 years at approximately 500 MMT carbon dioxide-equivalent, even as agricultural productivity has been steadily rising in recent decades. However, evidence suggests that current anthropogenic changes will increase emissions, with some uncertainty as to the magnitude. For example, agricultural intensification needed to increase food production will likely lead to changes in land use that increase carbon dioxide and nitrogen dioxide emissions. Increased demand for meat is already observed in many developing countries, increasing methane emissions from livestock and driving deforestation for animal feed production. In regions that experience wetter growing conditions, there could be increased greenhouse gas fluxes due to wetter soil conditions.

Water: The agriculture sector is responsible for 70% of global freshwater withdrawals and for over 90% of its consumptive use (FAO, 2012), mostly to irrigate crops. More frequent drought events could lead to water scarcity in agriculture, which in turn will reduce crop yields. Water levels in reservoirs could be reduced over extensive periods, necessitating the implementation of water conservation technologies and drought-proofing measures. A major concern is the depletion of groundwater due to over-pumping of aquifers for irrigation in regions where recharge rates from rainfall are insufficient. Increased groundwater pumping in coastal regions may also contribute to increased groundwater and soil salinity, as decreases in groundwater levels lead to salt water intrusion. Even away from oceans, excessive irrigation can cause soil salinity to rise as dilute dissolved salts in irrigation water can accumulate over time.

On the other hand, in other regions more frequent extreme precipitation events will cause flooding of cropland, soil erosion, and land degradation. In addition, increased rainfall leads to more pollution by agrochemicals through increased runoff into rivers and lakes and percolation into groundwater. Climate change therefore affects both water quantity and water quality.

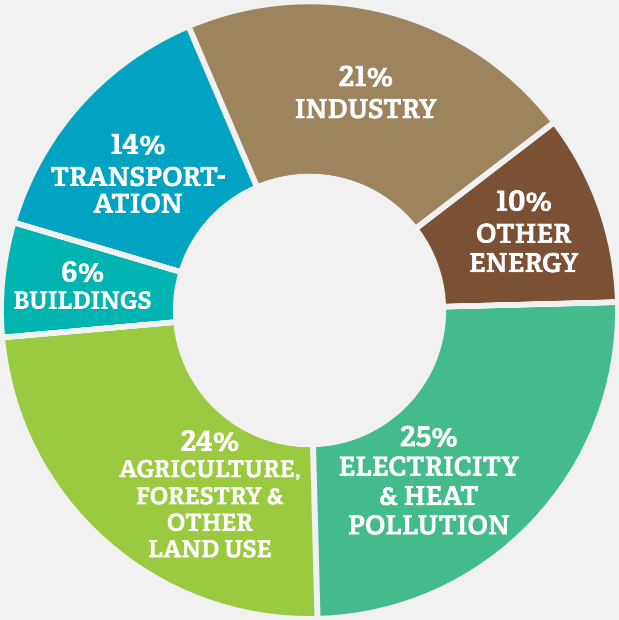


FIGURE 2
Breakdown of emissions of greenhouse gases by sector. (IPCC, 2014)

Land degradation: Some of the major causes of land degradation due to intensive agriculture are: deforestation, soil erosion, soil fertility depletion, land conversion for agriculture supporting uses, soil compaction, mining of soil nutrients, depletion of topsoil and organic matter due to monocropping, excessive tillage, and poor agronomic management. Land degradation from waterlogging and soil salinization due to over-irrigation and poor drainage, described above, are further negative impacts of agriculture.

Land and soil degradation lead to a decrease in crop productivity. At the current pace of land degradation, global food production could be reduced by as much as 12%, and commodity prices might increase in the range of 20-30% over the next 20 years (IFPRI, 2012). Climate change is expected to further intensify the rate of land degradation. Increased heat and drought frequency will escalate desertification, as well as soil salinization in places where farmers turn to marginal water sources for irrigation. Changes in precipitation patterns and amounts could increase soil erosion. Regions with increasing rainfall will see more soil acidification.

Photos: **(above)** William Easterling, assistant director of the Directorate for Geosciences at the National Science Foundation, presents on the importance of convergence research to address the complex and intersecting challenges of climate change's influence on agriculture, water, and food security. ANDI SUTTON, J-WAFS; **(right)** Corn field during drought conditions. ISTOCK

4 IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

Increases in temperature, in particular incidents of extreme heat, will have substantial negative impacts to future crop production and will be a major challenge to adaptation. Changes in patterns and magnitudes of precipitation are also likely to affect rainfed crop productivity and influence the availability of water resources for irrigation.

The IPCC (Intergovernmental Panel on Climate Change) in its 5th Assessment Report (Porter *et al.*, 2014) noted that future yields of major cereals (rice, wheat, maize, soybean) will likely decrease significantly, by at least 25% in tropical and temperate regions. The report further stated with high confidence that global temperature increases of approximately four degrees Celsius or more above late 20th century levels, combined with increasing food demand, could pose large risks to food security, both regionally and globally.

Environmental stresses: Climate change is already occurring in most major cropped areas and is expected to continue. The principal climatic factor for agriculture is extreme heat, which in turn drives water stress. Various studies show that yields of major US crops are adversely affected by exposure

to extremes in cumulative degree-days over a growing season and temperatures above a 30°C threshold (Ortiz-Bobea *et al.*, 2019; Schlenker and Roberts, 2009). Climate change is expected to exacerbate both the degree and incidence of high temperature, thus negatively affecting major crops.

While technological progress continues to raise yields in most areas, in some places crop yields are stagnating or even dropping. Hochman, Gobbett, and Horan (2017) estimated that the water-limited yield potential of Australian wheat has declined by 27% from 1990 to 2015. However, this climate-driven decline is not fully expressed in actual national yields due to an unprecedented rate of technology-driven gains closing the gap between actual and water-limited potential yields. In addition to the effect of heat on crop yield, there is strong evidence that related surface ozone pollution is strongly affecting agricultural productivity. Using an emissions scenario that represents ecologically friendly economic growth, Avnery *et al.* (2011) estimated that ozone-induced global yield reductions by the year 2030 would be 10.6% for wheat, 4.3% for maize, and 12.1% for soybean. Temperature is an important factor in ozone generation.

Since some 80% of total agricultural land is rainfed, changes in precipitation can have significant impact on future crop productivity. Projecting the effects of changes in both temperature and precipitation on soil moisture and evaporation is a major challenge, as is understanding the impact on agriculture.

> ***"Other limiting inputs such as nitrogen prevent crops from fully utilizing the additional carbon dioxide in the atmosphere."***

Photos: (left) Expanding food production to meet future demand will substantially increase demands on water for irrigation, particularly in regions where water availability is already limited. SHUTTERSTOCK
(right) Farmer planting rice in a paddy field during a drought. SHUTTERSTOCK

> ***"The impact of increased atmospheric carbon dioxide on the soil biome is a big unknown, as is the impact on plant productivity of these below-ground factors."***

Effect of carbon dioxide: Increased concentration of carbon dioxide in the atmosphere has the potential to increase crop yield due to the effect of carbon fertilization on the rate of photosynthesis in plants. However in the field, other limiting inputs such as nitrogen prevent crops from fully utilizing the additional carbon dioxide in the atmosphere. Additionally, any increases in plant growth might be offset by negative indirect effects correlated with increased carbon dioxide. For instance, there is no evidence that carbon dioxide and temperature act synergistically on plants, and the temperature increase at which carbon dioxide stimulation is negated is not known. While these physiological responses involving photorespiration and the chemistry of photosynthesis within plant leaves are relatively well documented and understood (see Box 1), yield responses in food crop plants are less well understood mechanistically, because crop yield is the result of a complex system of interacting factors including weather, nutrient availability (White *et al.*, 2015), water availability, and plant phenotypic traits. The impact of increased atmospheric carbon dioxide on agricultural crop yields cannot be extrapolated from, for example, the impact of the same carbon dioxide increases on forest growth rates.

Furthermore, any yield gains due to increased carbon dioxide may come at the cost of decreased nutritional value of crops (Myers *et al.*, 2014), as a result of physiological competition (Bloom *et al.*, 2014, 2012). Key nutrients such as iron and zinc have been observed to fall, as well as protein in crops such as grains. Processes that might contribute to this include reduced uptake of nutrients from absorption of soil moisture

BOX 1
PHYSIOLOGICAL RESPONSE TO CHANGES IN ATMOSPHERIC CO_2

Carbon dioxide is the primary substrate of the photosynthetic enzyme, RuBisCO, and elevated CO_2 increases the enzymatic carboxylation rate when RuBisCO is CO_2 limited (i.e. light saturated). Elevated CO_2 also suppresses photorespiration, a process whereby the RuBisCO enzyme fixes oxygen, causing CO_2 to be released by the plant (Farquhar *et al.*, 1980). Several modes of photosynthesis occur in nature and in crops. For C3 plants (e.g. wheat, rice, potato) both of these RuBisCO-mediated consequences of elevated CO_2 increase the rate of carbon assimilation during photosynthesis and thus the carbon available to the plant (Leakey, 2009). However, C4 plants (e.g. maize, sorghum) have mechanisms that concentrate CO_2 in the leaf which prevent these modes of photosynthesis from benefiting from the above described physiological responses to elevated CO_2 under most conditions (Leakey, 2009).

CO_2 has further physiological impacts on plants' water use. Researchers are investigating whether sensitivity to drought is likely to increase or decrease as CO_2 increases and both plant genetics and management practices change. Some research has shown that high CO_2 levels increase the water efficiency of crops. In response to rising CO_2, plants close their stomatal pores to an optimal degree (Wolf *et al.*, 2016), thereby reducing water use at the leaf scale. However in practice more drought sensitivity has been observed due to planting regimes, choice of seeds, etc.

through roots when plant transpiration decreases, as is the case when carbon dioxide increases. There are significant knowledge gaps in the degree of and causes of decreased crop nutritional value.

Indirect impacts of increased atmospheric carbon dioxide on plants' water use, ambient temperatures, and competition with weed species, further complicate the relationship of carbon dioxide to crop productivity (see Box 2). Furthermore, the impact of increased atmospheric carbon dioxide on the soil biome is a big unknown, as is the impact on plant productivity of these below-ground factors.

Climate variability and adaptation: Major breadbaskets of the world have recently experienced large fluctuations in crop yields. More than 60% of yield variability in mainly non-irrigated regions can be explained by climate variability (Ray *et al.*, 2015). Globally, climate variability accounts for about a third of the observed yield variability. In response to that variability, farmers have already implemented a variety of adaptive measures, representing both incremental changes within the existing system—a form of resilience—and more deliberate structural and systemic changes; ecologists would call the latter true adaptation. Examples of incremental adaptation include shifting planting dates, selecting drought- and heat-tolerant crop varieties, and weather-responsive irrigation scheduling. An example of transformational adaptation is the introduction of mechanization.

Land degradation: Climate change is related to both land use and agricultural land management. Climate change can cause desertification, degradation of soil quality, and increased soil erosion. In addition, there is pressure on land and forests due to demand for land for agriculture. A 2012 report by the International Food Policy Research Institute (IFPRI) estimated a reduction of global food production by as much as 12% if the current pace of land degradation were to continue over the next 20 years.

BOX 2
INDIRECT IMPACTS OF ATMOSPHERIC CO_2

The reduction in water use caused by decreased stomatal conductance can increase canopy temperatures (Leakey, 2009). Crop water use has been shown to influence regional climates (Gerken *et al.*, 2017), and the change in water use and canopy temperature caused by elevated CO_2 may have complex regional biophysical impacts in continental climates where much of the world's food producing regions lie.

Increased CO_2 levels could see more weed growth in cropping systems. The greater genetic variability in weed species compared to cultivated crops favors natural selection for weeds towards a strong carbon dioxide response. Weeds compete with crops for light, water, and nutrients, and thus can significantly affect crop productivity. Climate change is likely to magnify this growing challenge, increasing both the ranges and the distributions of weeds.

5 WORKSHOP DELIBERATIONS

5.1 Climate-smart agriculture and resilient agri-food systems

5.1.1 Sustainable practices

Soil and agronomic management have a significant impact on CO_2 and N_2O emissions. Various practices are understood to reduce these emissions and have a positive effect on both sequestration and mitigation of adverse climate impacts.

Agriculture places significant pressures on the environment, yet it depends on the quality of that environment—fresh water, clean air, a stable climate, and healthy soil—to be productive. Sustainable practices reduce both the environmental and greenhouse gas footprint of agriculture, while improving and maintaining soil fertility, making farms and food production systems economically viable, and producing sufficient food for people. Improved agronomic management offers the most promise to reduce gas emissions from agriculture without compromising productivity, and possibly even enhancing it. Specific strategies which can improve the productivity, resilience, and sustainability of agriculture include: dry planting, conservation agriculture, and mulching to improve soil quality and increase water-holding capacity (Rockström *et al.*, 2010). Integrated soil fertility management, which combines

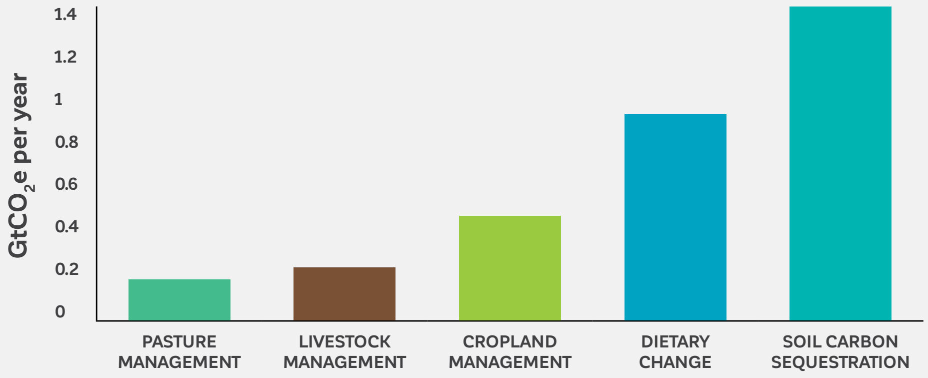


FIGURE 3

Potential for agricultural GHG emission reduction at a carbon tax of \$20/mt CO_2 equivalent. See Box 3 for detail. (Source: Graph courtesy of Mark Rosegrant 2018; Synthesized from Del Grosso and Cavigelli, 2012; Havlík *et al.*, 2014; Smith, 2013; Smith *et al.*, 2007; Springmann *et al.*, 2016; Stehfest *et al.*, 2013; Wollenberg *et al.*, 2016)

the application of chemical fertilizer and organic matter, can maximize the efficiency of nutrients and water use, and improve agricultural productivity.

Given the substantial contribution of agriculture to global GHG emissions, there is a critical need to develop strategies to reduce these emissions, addressing both direct and indirect sources (see Figure 3). Carbon dioxide is one of the most dynamic gases in the atmosphere because of its linkage to respiration, decomposition, and photosynthetic processes. During the growing season, carbon dioxide is taken up by plants through photosynthesis with a net gain of carbon into plant material even though respiration (release of carbon dioxide) is occurring. During the off-season, respiration releases carbon dioxide back to the atmosphere. In combination with plant biomass, soil plays a central role in carbon cycling, and soil management can determine whether soil carbon is retained in the soil or released to the atmosphere. While in theory there is significant soil capacity for carbon uptake, how to accomplish—and measure—soil carbon sequestration is not well understood. The accuracy of measurements and emissions baselines is a challenge; there is a need for better data and measurement techniques—including field measurements and remotely sensed data—complemented by improved understanding of deep soil carbon chemistry and modeling tools to evaluate alternatives.

"Current understanding of the metabolic and physical interactions between soil microbes and plant roots that govern nutrient uptake is limited."

Two primary factors that affect the carbon balance in agricultural systems are the plant species and the tillage systems. Dold *et al.* (2017) found that a corn-soybean rotation in the Midwest of the US was carbon negative, and lost 1.75 Mg of carbon per hectare per year attributed to tillage. Studies increasingly show that sequestration of carbon into soil can best be accomplished through no-till systems that avoid soil disturbance, and the use of cover crops or other cropping systems that increase the amount of time that the soil is covered with vegetation. When cover crops are grown during the off-season, the deposition of atmospheric carbon to soil is increased, while also preventing soil erosion and capturing nitrogen.

Emissions of nitrous oxide—a potent and long-lasting greenhouse gas primarily emitted from agricultural soils—are largely influenced by the rate, timing, and method of nitrogen fertilizer application. Hatfield (2016) provided a review of soil and nitrogen management practices that could reduce nitrous oxide emissions, for example by altering the nitrogen application rate or adding a stabilizer to reduce transformation of soil nitrogen to nitrous oxide. Nitrous oxide emissions from soils are affected by the water content of soil. Parkin and Hatfield (2014) showed that excess nitrogen not used by the crop early in the growing season could be released as nitrous oxide late in the season, especially if excessive rainfall saturates the soil. Therefore, managing soil moisture to reduce saturation, coupled with the adoption of no-till practices to increase retention of soil moisture, is effective in reducing nitrous oxide emissions.

Central to these processes is the role of the soil microbiome and its interactions with plants. Soil microbes play a critical role in nutrient cycling between plants, soil, and the atmosphere. Yet current understanding of the metabolic and physical interactions between soil microbes and plant roots that govern nutrient uptake is limited.

A summary of additional techniques to manage agricultural greenhouse gas emissions is given in Box 3.

BOX 3
MEASURES TO REDUCE GREENHOUSE GAS EMISSIONS

Pasture management: Improved management of grasses and pasture, use of legumes.

Livestock management: Optimized animal feed mixtures and feed additives, improved manure management systems, reproductive efficiency, breeding for reduced methane emissions.

Cropland management: Improved nitrogen use efficiency through precision agriculture, slow release fertilizer, new nitrogen-efficient varieties, improved rice paddy management, water management to reduce runoff.

Demand-side measures: Taxes, education for long-term dietary change, and reduction of food waste.

Soil carbon sequestration: Conservation tillage, integrated soil fertility management, restoring cultivated organic soils and degraded lands, retaining crop residues, growing high residue crops.

5.1.2 Precision agriculture

With advances in drone and satellite technology, robotics, sensors, and information technology, precision agriculture offers promise as a vital strategy for food security and resilient agri-food systems. Continued research in these areas is needed.

Precision agriculture is a management strategy that employs detailed, site-specific information to more efficiently use resources in order to maintain the quality of the environment, while improving the productivity of the food system. Precision farming is facilitated by the application of sensor technologies, information systems, advances in satellite imaging, advanced machinery, and information management to apply appropriate and precise amounts of inputs, such as water and fertilizer, at the optimal time and in response to variations in soil chemistry and soil moisture across a field. The specific objective of precision agriculture is to maximize yield while increasing the efficiency of irrigation and agrichemical use.

By significantly reducing inputs while maximizing yields, precision agriculture supports sustainable land management. It reduces soil quality degradation associated with excessive chemical fertilizer application, and limits groundwater depletion from excessive irrigation. In addition, precision agriculture can facilitate the more efficient use of nitrogen fertilizers and thus reduce greenhouse gas emissions associated with excess application. It is also intended to improve farmers' return on investment and improve the overall economic sustainability of farming by reducing the costs of water, pesticides, and fertilizer. Therefore, precision

Photo: **(above)** ISTOCK

agriculture technologies and business models are receiving substantial attention from agribusiness investors.

Significant research and investment funding are needed to advance precision agriculture to the point of realizing these potential benefits. The effective deployment of precision agriculture technologies will depend on multiple factors, including farm size, farmer sophistication and acceptance of technology, economics, and data accessibility.

5.1.3 Fertilizer use efficiency

Improving the efficiency of fertilizer use will reduce GHG emissions and increase crop productivity. Research is need to develop technologies, policies, and strategies to accomplish this.

Fertilizer use contributes to greenhouse emissions directly (e.g. through nitrous oxide emissions from soil) as well as indirectly (through carbon dioxide emissions from fossil fuels used in the manufacture of ammonia fertilizer) (see Figure 4). Reduced nitrous oxide emissions as well as reduced leaching of nitrogen compounds to groundwater can be achieved through “enhanced efficiency nitrogen fertilizer” (EENF) technologies (Roy, 2018). These include slow and controlled release fertilizers, products formulated with physical barriers applied to the granules or other means to delay the ammonification (urease inhibitors) or nitrification (nitrification inhibitors) of urea. Both inhibitor products are gaining in importance, particularly for cereal crops (Shoji, 2005). For example, controlled sub-surface application of urea, particularly for flooded rice, doubles the nitrogen use efficiency (NUE) compared to conventional practice. Through the use of this technology, Bangladeshi farmers are using 35% less urea yet getting 15% more rice yield. However the availability of a suitable mechanical applicator for the larger granules is a current barrier to widespread adoption of this technology.

Fertilizer products, policies, and use vary considerably across different geographic regions (see Figure 5), highlighting the need to develop location-specific strategies for more efficient fertilizer use. In the United States, which relies primarily on market mechanisms and voluntary approaches, NUE has progressively increased because of: (1) state regulatory programs requiring nutrient management plans; (2) the adoption of the “4Rs” principles (Right nutrient source, Right rate, Right time, and Right place); (3) the availability of EENF products, and (4) outreach efforts by government institutions, the fertilizer industry, and environmental groups.

In Europe, NUE has progressively increased since the 1990s, largely triggered by the European Union Common Agricultural Policy, which reduced crop subsidies and limited the manure application rate on

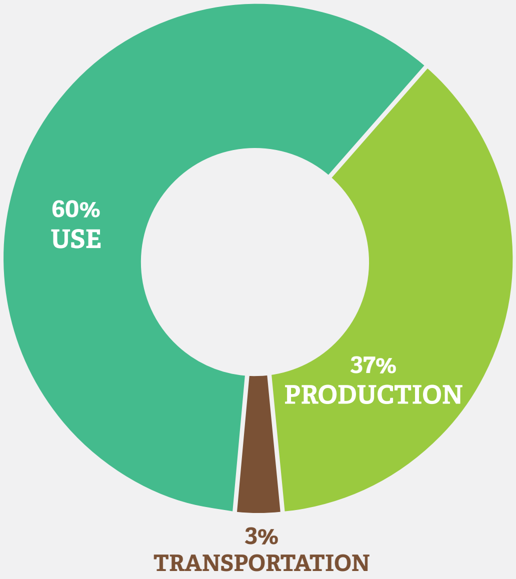


FIGURE 4
Breakdown of fertilizer greenhouse gas emissions from production, transportation, and use. Together, those account for 2.5% of global greenhouse gas emissions. (Roy, workshop presentation)

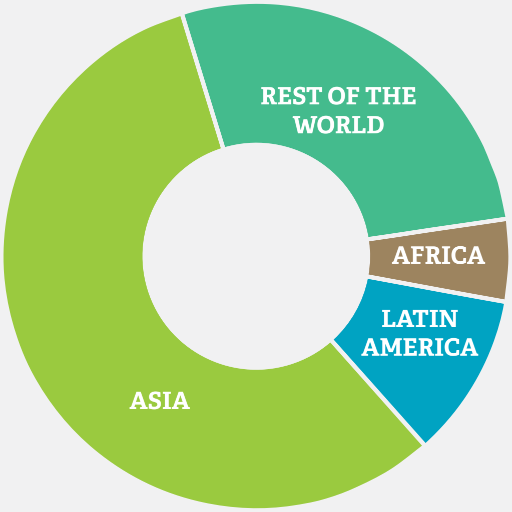


FIGURE 5
Worldwide nitrogen fertilizer use. (Roy, workshop presentation)

agricultural land. In 2016, 30% more crop was produced with half the fertilizer application rate, resulting in an increase of NUE by 20% (IFA, 2016).

China and India, which collectively account for more than 30% of global nitrogen consumption, have a relatively low NUE (ranging between 25% and 30%). In China, the use of nitrogen fertilizer exceeded the recommended amount by 20%-60% in cereals, and even higher in vegetables, whose NUE is around 15%. In India, fertilizers are highly subsidized—nitrogen more so than other nutrients, which results in the overuse of nitrogen-based fertilizer and the ultimate distortion of nutrient (nitrogen-phosphorus-potassium) ratios, all of which results in a low NUE.

Nonetheless, both China and India have taken steps to increase NUE. The Chinese government has capped fertilizer consumption at 2020 levels (*Reuters News Service*, 2015), which should result in increased use of EENF and better management practices. In India, the government required all agricultural urea to be coated with an extract from neem cakes produced from neem trees (Azadipachta indica). This product acts as a nitrification inhibitor and increases NUE by 5 to 7% (Mangat and Narang, 2004).

In contrast to the other continents, fertilizer use in Sub-Saharan Africa is nearly an order of magnitude lower than the world average of 130 kg nutrients per year per hectare, resulting in a significant nutrient loss from soil and land degradation (Roy, 2015).

5.2 Crop Biotechnology

5.2.1 Plant selection and breeding

The full range of plant genotypes may represent an underutilized resource for crop adaptation to rising atmospheric carbon dioxide as well as to future climate scenarios. Research can help the agriculture sector make use of existing genetic and phenotypic variation within crop species as a climate adaptation strategy for food security.

Plants require four essential inputs for growth: light, water, nutrients, and carbon dioxide. Any variation in these resources may have profound effects on plant biology and productivity. However the effects are not uniform across or within different plant species. Rapid or significant changes in any of these resources can exert selection pressures. One essential input has, in fact, already increased dramatically: at over 400 ppm currently, average atmospheric carbon dioxide concentration is higher today than at any point in at least the past 800,000 years, having risen by 40% or more since the mid 1800s. And, depending on anthropogenic emission rates, concentrations may exceed 1000 ppm by the end of the century (IPCC 2014). Increases in carbon dioxide concentration have been shown in numerous studies to affect carbon fixation, with differential responses to plant growth, development, morphology, and reproduction. Plant species that rely solely on the most common pathway of carbon fixation, "C3 photosynthesis" (approximately 95% of all plant species), are most affected by atmospheric carbon dioxide changes (Kimball *et al.*, 2002; Newton and Edwards, 2007).

Such differential responses have obvious implications for agriculture. One potential area for investigation would be whether intra-specific differences in response to rising CO_2 could be used to select for crop lines that could, potentially, convert additional carbon dioxide into seed yield. Numerous studies to date indicate considerable intra-specific variation in seed yield response to projected increases in atmospheric carbon dioxide for numerous crops, including barley (Clausen *et al.*, 2011), cowpea (Ahmed *et al.*, 1993), oat (Johannessen *et al.*, 2005), quinoa (Bunce, 2017), rice (Moya *et al.*, 1998), soybean (Bishop *et al.*, 2015), and wheat (Manderscheid and Weigel, 1997), among others.

These data indicate that sufficient intra-specific variation currently exists for carbon dioxide selection trials (Ziska *et al.*, 2012). However, workshop participants were unaware of any long-term effort to select for crop lines with greater seed responsiveness to recent or projected carbon dioxide levels. In fact, there is no indication that breeders have even selected passively for enhanced carbon dioxide sensitivity (Ziska *et al.*, 2012). There is, however, some evidence that recent increases in carbon dioxide may have already selected for weedy biotypes of rice and oat (Ziska, 2017; Ziska and McClung, 2008).

Many hurdles confront the development of breeding programs geared to the challenges of rising carbon dioxide. Biological traits associated with carbon dioxide responsiveness need to be identified so breeders can select for the most promising crop archetypes. Since increases in carbon dioxide concentration are

> ***"Gene editing offers a new way to rapidly create plants that are drought-resistant, immune to disease, or improved in nutrition and flavor, without the regulatory and public acceptance challenges raised by the introduction of foreign DNA."***

projected to correlate with temperature, precipitation, and other weather and environmental changes, carbon dioxide response and selection strategies need to be understood in the context of projected climatic change, particularly temperature.

> *“Demand management, particularly reduced consumption of meat products, is a policy option that, while politically difficult to implement (see Briggs et al., 2013), would provide co-benefits across a range of global challenges.”*

5.2.2 Genetic editing

Genetic techniques can increase drought and heat resistance and impart other beneficial characteristics—such as better nutrition profiles—to food crop plants.

Genetic diversity is critical to genetic selection for yield gains in plant and animal breeding (Moose and Mumm, 2008), although conventional breeding tends to limit the genetic diversity, particularly in domestic animal production (Flint and Woolliams, 2008).

Two means by which increasing genetic diversity can be obtained are through genetic transformation (Altpeter *et al.*, 2016) and genome editing (Songstad *et al.*, 2017). These are two completely different disciplines. Genetic transformation delivers foreign DNA, which is incorporated into the host genome, whereas genome editing can precisely change one or more nucleotides in native genes to make single nucleotide polymorphisms (SNPs).

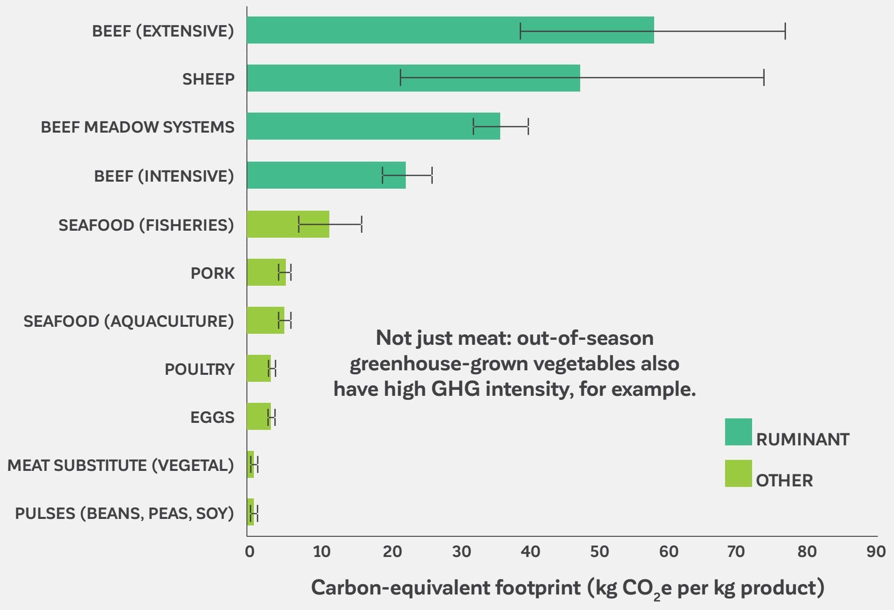
Genetically transformed materials have been commercially available since the 1990s, and the advantages of various traits ranging from yield stability and product safety standpoints have been documented (Edgerton *et al.*, 2012; Glenn *et al.*, 2017). Gene editing offers a new way to rapidly create plants that are drought-resistant, immune to disease, or improved in nutrition and flavor, without the regulatory and public acceptance challenges raised by the introduction of foreign DNA.

5.3 Consumer and societal measures

Consumer preferences and dietary choices help shape the agriculture sector and our food systems and supply chains. Demand management policies can help evolve human diets away from the most GHG-intensive and climate susceptible food crops, and can reduce food waste and its accompanying emissions. There are many dietary choices that simultaneously provide improved nutrition and health benefits, create multiple environmental benefits, and lead to a more sustainable food system.

The greenhouse gas intensity of different foods and crops varies significantly (see Figure 6). A growing body of literature suggests that demand management will be necessary to achieve food security and reduce greenhouse gas emissions, particularly through food waste reduction (Bajželj *et al.*, 2014; FAO, 2011; Kummu *et al.*, 2012), and dietary change (Bajželj *et al.*, 2014; Tilman and Clark, 2014). In particular, current and projected levels of global overconsumption of livestock products cannot be sustained (Herrero *et al.*, 2016; Poore and Nemecek, 2018; Ripple *et al.*, 2013; Tilman and Clark, 2014). Bajželj *et al.* (2014) showed that food security could be achieved, and environmental impacts of agricultural intensification reduced, if there was a shift to healthy diets and a 50% reduction in food waste. More recent studies have shown that demand management will be essential for transitioning to more sustainable agricultural production systems (Muller *et al.*, 2017; Schader *et al.*, 2015).

Demand management, particularly reduced consumption of meat products, is a policy option that, while politically difficult to implement (see Briggs *et al.*, 2013), would provide co-benefits across a range of global challenges. This is supported by a substantial and growing body of academic literature. Livestock production is a very inefficient way of



Not just meat: out-of-season greenhouse-grown vegetables also have high GHG intensity, for example.

FIGURE 6

Greenhouse gas emissions from ruminant meat production are significant. Reductions in global ruminant numbers could make a substantial contribution to climate change mitigation goals and could yield important social and environmental co-benefits. (Based on Ripple *et al.*, 2014)

delivering food to humans since the calories provided by plants have to first pass through a ~10% efficient heterotroph (Smith, 2014). Already, more than 30% of global crop production is currently used to feed livestock, rather than people directly (West *et al.*, 2014). The greenhouse gas footprint of livestock production (as well as the associated degradation of land and water quality) is about 100 times greater than that of plant-based foods (Clark and Tilman, 2017; Poore and Nemecek, 2018). Reducing over-consumption of livestock products would greatly reduce the environmental impact of food production (Bajželj *et al.*, 2014; Poore and Nemecek, 2018; Tilman and Clark, 2014). Studies show that diets need not be strictly vegetarian or vegan to have significant impacts on climate change and food security; a global shift towards healthy diets including reduced animal sources of protein would greatly reduce the adverse environmental impacts of food production (Bajželj *et al.*, 2014; Popp *et al.*, 2010; Smith *et al.*, 2013; Stehfest *et al.*, 2009; Tilman and Clark, 2014; Wirsenius *et al.*, 2010).

Recently, Muller *et al.* (2017) examined how far organic farming could go towards feeding the world. The study showed that organic farming, or other lower impact forms of farming, could make a significant contribution to world food supply, but only if demand for livestock products were dramatically reduced (Muller *et al.*, 2017). The main finding from this and other studies examining dietary change and waste reduction is that tackling demand, particularly the current and projected overconsumption of livestock products, could greatly reduce pressure on land, and create the “headspace” for implementation of more sustainable forms of global agriculture and food production.

5.4 Estimating carbon stocks

Reasonably accurate inventories of carbon stocks and carbon fluxes between the soil and the atmosphere are needed to evaluate the impact of agriculture on the climate system and validate the effectiveness of measures to limit that impact. However, there are substantial challenges to developing robust inventories and metrics, from the farm scale to regional, national, and global scales.

Soils contain the largest amount of carbon in the terrestrial biosphere, estimated at 1500 Pg carbon (to one meter depth); 2300 Pg carbon (to two meters depth) (Batjes, 2014), and play a major role in global carbon fluxes, especially on annual to decadal and century time scales. The carbon dynamics of soils in human-managed ecosystems, e.g., cropland, grazing land, forests, and wetlands, are greatly affected by land use and management practices. Historically, soils have been a major anthropogenic source of CO_2 emissions, as a consequence of conversion of native ecosystems (e.g. forest, prairies, wetlands) to agricultural uses (Sanderman *et al.*, 2017). This has resulted in the loss of 20-50% or more of the carbon contained in the topsoil in these native ecosystems over approximately the past 20 years, mostly to atmospheric CO_2. However, properly managed soils can also function as carbon sinks and hence can play a role in mitigating climate change (IPCC, 2018; Paustian *et al.*, 2016). Consequently, robust inventory methods for soil carbon stock changes are essential for guiding the reduction of CO_2 emissions and sequestration of carbon in soil. Furthermore, soil carbon affects water retention; better information about soil carbon stocks can also inform farming needs under drought conditions.

In contrast to point sources such as stacks on power plants, measuring CO_2 emissions from soil is particularly challenging. Existing inventory methods for anthropogenic soil carbon emissions and removals are driven by “activity data” that represent the human actions giving rise to emissions/removals, and emission or “stock change” factors (standardized emission or sequestration rates related to those actions). For soil carbon, activity data include land use and agronomic practices such as crop types and seasonality, fertilizer, irrigation, and tillage management. Stock change/emission factors are based on simple empirical models, typically derived from long-term field experiments where changes in soil carbon stocks are measured over time (Ogle and Paustian, 2005). An alternative is process-based models that simulate dynamic,

Photo: Keith Paustian, a professor in the Department of Soil and Crop Sciences at Colorado State University, presenting on inventory methods for greenhouse gas emissions. ANDI SUTTON, J-WAFS continuous changes in soil carbon stocks and net CO_2 flux as a function of climate factors and soil characteristics, as well as land use change and agronomic management activities. Common to both approaches is the need for accurate and detailed activity data on land use and management practices and models that link emissions/removals to the activities occurring over time and space (Paustian *et al.*, 2010).

Accurately quantifying soil carbon stock changes (and therefore net CO_2 emissions or removals) is challenging at any scale due to: 1) the multiple environmental conditions (i.e., temperature, moisture, soil physical, and soil chemical attributes) affecting the biotic processes driving soil carbon fluxes, and 2) the high degree of heterogeneity, both temporally and spatially, of these factors across landscapes and regions. The ability to capture the range of responses to these different biotic and abiotic conditions is constrained by the availability of experimental field and soil monitoring observations that are key to both empirical and process-based emission models. Globally, there is a well-known bias between temperate and tropical regions, due to the majority of field experiments and observational networks, as well as researchers, located in temperate countries. Hence uncertainty in the emission factors/models employed is greater in tropical developing countries. Likewise, activity data are more accurate, abundant, and accessible in developed countries that have abundant agricultural statistics and strong extension agencies. Opportunities to strengthen acquisition of detailed activity data exist, particularly in developing countries, through enhanced use of remote sensing (NRC, 2010), and possibly crowd sourcing of management information via mobile apps from the land managers themselves (Paustian, 2013).

5.5 Climate model projections

Computational models have been built to represent climate change under future trajectories of greenhouse gas emissions and concentrations in the atmosphere, as well as crop productivity under different climate scenarios. These models provide valuable information for designing and testing strategies to mitigate, and adapt to, climate change. Yet major advances are still needed to reduce uncertainties, and to bring projections of impacts to the local level.

Global climate models, also known as general circulation models (GCMs) and regional numerical climate models (RCMs), use well understood climate and energy transfer processes to simulate substantial regional changes in temperature and precipitation, with changes in both means and extremes, but with great uncertainties in the patterns of change and year-to-year fluctuation associated with natural variability. Climate models enable different emissions scenarios to be assessed for projected impacts on future climate (see Box 4).

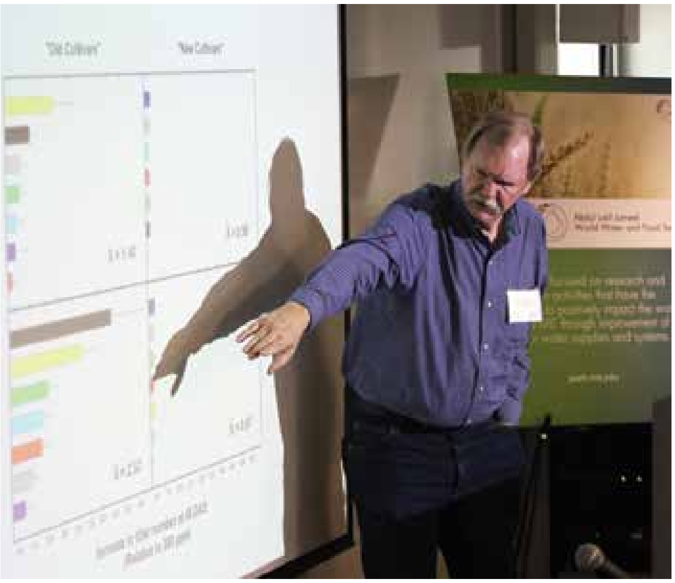
Model simulations typically involve running the models under various “what-if” scenarios, referred to as “representative concentration pathways” (RCPs) (see

Box 4). Because these models look at various possible outcomes for different input scenarios, the simulations based on them are called “projections” rather than “predictions.”

There is a fair amount of confidence in continental and larger scale estimates of future climate change; projections across various distinct and independently developed models exhibit consistent regional warming patterns, with higher temperature increases over land and the polar regions. These models generally reproduce observations of warming and also generally explain the impact of human activity on observed warming. However, large uncertainties exist in projections of global mean climate change, primarily driven by uncertainties in future trajectories of emissions of greenhouse gases and aerosols (mostly related to human-driven factors such as population and economic growth, developments in technology, policy scenarios, etc.), and uncertainties in the global climate system response to changes in external forcing (i.e. climate sensitivity and ocean heat uptake rate).

Variations in the magnitude of projected changes in average temperatures mainly reflect differences in the climate sensitivity and in the level of greenhouse gas emissions for given climate scenarios that are built into the different models. For regional changes in precipitation, however, different climate models project varied magnitudes and patterns of change, largely driven by differences in how physical processes in the atmosphere (i.e. cloud microphysics,

“Weather is “noisy,” so policy makers and farmers alike need to understand not just increases in average temperature or changes in overall precipitation, but how maximum and minimum temperatures might change...”



Photos: (left) Lewis Ziska, research plant physiologist at the Adaptive Cropping Systems Laboratory of the United States Department of Agriculture, presenting on the impact of increased CO_2 on cereal grain nutrition. ANDI SUTTON, J-WAFS; **(right)** Auroop Ganguly, director of the Sustainability and Data Sciences Laboratory at Northeastern University, addressing a comment at the expert workshop. ANDI SUTTON, J-WAFS

“The intent is to build resilient agricultural systems with the capability of recovering from external shocks.”

convection, turbulence) and the land system (i.e. water and energy fluxes) are represented in the model, along with large uncertainties in the representation of the natural variability in the climate system (Deser *et al.*, 2012; Hawkins and Sutton, 2011, 2009; Monier *et al.*, 2015). Better data representing precipitation on a regional scale would help improve models.

In essence, GCMs and RCMs have difficulty providing consistent results because of the inadequate representation in the models of the various processes such as convection and cloud formation involved in precipitation. Additionally, with GCMs, the orographic resolution is quite coarse. An alternative approach is the use of Empirical Downscale Models (EDMs) for climate model simulations. These are built from mapping observed large-scale fields (mainly circulation and humidity) to observed regional-scale precipitation. Examples of such efforts include daily projections in the US Pacific Northwest to monthly time scales in Indonesia, US, Europe, and China (Nicholas and Battisti, 2012; Vimont *et al.*, 2010; Widmann *et al.*, 2003). There are, however, two major caveats to using EDMs: 1) good, long term records of regional precipitation are required, and; 2) they assume the relationship between precipitation and large-scale fields of climate circulation and humidity will be the same in the future as it is today.

Furthermore, weather is “noisy,” so policy makers and farmers alike need to understand not just increases in average temperature or changes in overall precipitation, but how maximum and minimum temperatures might change, and what is likely to happen at particular times of year, for example when crops are planted or pollinated. Adaptation strategies need to provide for these extremes, not just changes in average conditions.

As for crop modeling, the largest uncertainty in model projections is due to uncertainty in regional temperature where crops are grown. Most of the model differences in regional growing season temperature projections are likely due to generic (non-local) challenges in modeling terrestrial processes, clouds being mixed globally by winds, and perhaps aerosol forcing.

The Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rosenzweig *et al.* 2013) is a coordinated international effort using multiple crop models under standard scenarios. Despite this effort, large uncertainties in global change impacts on agriculture remain, including uncertainties discussed elsewhere in this report: the impact of CO_2 fertilization (Müller *et al.*, 2015; Wing *et al.*, 2015), the availability of water for irrigation (Blanc *et al.*, 2017; Elliott *et al.*, 2014), and the role of adaptation (Challinor *et al.*, 2014).

Researchers are also beginning to turn their attention to regional impacts of climate on crop productivity. Dale *et al.* (2017) demonstrated how uncertainties across a range of climate models could influence climate impact assessments for maize production in sub-Saharan Africa. Using 122 climate model projections and three emission scenarios, they found consistency across all model ensembles in projecting widespread yield losses in the Sahel region and southern Africa below the Democratic Republic of the Congo and Tanzania. Subregionally, all model ensembles projected yield increases in the Ethiopian highlands and the southern tip of South Africa. No ensemble projected a substantial median yield change within or surrounding the tropical rainforests of Central and West Africa.

5.6 Risk and uncertainty

Much of the irreducible uncertainty in climate models and in the yield projections of crop models reflects actual risk that is real. It is necessary to develop risk assessment methodologies or frameworks which permit informed decision making, so as to cope with system vulnerability and build resilience in the food system. Improved approaches to communicate risk and uncertainty to decision makers are needed.

Engineering and policy decisions often rely on quantitative estimates of probabilities of occurrence—or qualitative notions of likelihoods—of consequences and vulnerabilities, to develop expected loss assessments and make risk-informed decisions. When uncertainties cannot be treated probabilistically, they have been called "deep" (Lempert *et al.*, 2003) or "severe" (Ben-Haim, 2006). As the prior sections make clear, multiple sources of deep, or irreducible, uncertainty exist in climate projections relevant for agriculture. Even with advances in research, deep uncertainties will remain. According to Walker, *et. al.* (2013), these include model structure uncertainty and unknowable probabilities.

In the context of climate and agriculture, understanding the specific sources and attributes of deep uncertainty, and ways to manage or mitigate it, would be useful. Deep uncertainty in climate models arises in part from variability that is inherent in the natural weather and hydrologic system, as well as with what occurs from built and human-managed systems. Such natural and human-driven variability is difficult to model or forecast, yet has the potential for momentous impacts such as food shortages caused by extreme droughts and floods.

Additional uncertainty in climate models results from attributes of the data and the assumptions that must be made in the models, such as the importance of spatial and temporal extremes (Kao and Ganguly, 2011; Kodra and Ganguly, 2014), especially under non-stationarity (Ganguly *et al.*, 2014; Vandal

BOX 4
REPRESENTATIVE CONCENTRATION PATHWAYS

"What-if" scenarios, or "representative concentration pathways" (RCPs), are used across multiple global climate models, generating a multi-model ensemble (MME). While MMEs have been treated probabilistically, for example by assuming the RCPs come from a distribution, this and other assumptions have been questioned (Kumar *et al.*, 2014).

Each climate model run with a set of RCPs needs to be run for multiple initial conditions to characterize natural variability (Deser *et al.*, 2012; Kirtman *et al.*, 2013; Monier *et al.*, 2015). This relates at least partially to chaos theory in meteorology and to nonlinear dynamical system in general (Strogatz, 2018). The development of statistical probabilities and decision boundaries for multiple initial condition ensembles (MICE) of climate models is an emerging area (Kumar and Ganguly, 2018).

BOX 5
ASSESSMENT OF ADAPTATION ALTERNATIVES BASED ON RISK IDENTIFICATION (ADAPTED FROM ANDERSSON-SKÖLD *ET AL.*, 2015)

1. Identification of climate-related risks.

2. Identification of measures to reduce the climate related risk, considering one risk at a time.

3. Ranking of the effectiveness of the individual alternatives with regard to one climate-related risk at a time.

4. Identification and ranking of other impacts that may compromise the benefit of desired outcomes (i.e. adverse impacts on use of other resources, greenhouse emissions, soil and water impacts, and people's responses to the individual risk management alternatives).

5. Integrated assessment based on the results of the individual rankings with regard to effectiveness, impacts on environment, and people's perceptions.

et al., 2019). (In a system with stationarity, variables may change randomly, but their statistical properties such as mean and variance are stable.) The kind of non-stationarity expected in climate leads to additional uncertainty in decision contexts (Ganguly *et al.*, 2015; Salvi *et al.*, 2016), including for food production (Lobell *et al.*, 2008).

Uncertainties in crop models tend to be structural because the models are unable to properly simulate crop physiological responses to high temperatures. Furthermore, uncertainty is inherent in the coupling of climate, water, and agricultural systems owing to the propagation of errors across these linked systems, cascading failures, and feedback. Ideally, models would enable decision makers to simulate different adaptation or mitigation measures and assess their likely impacts as a way to cope with these risks. However we find that due to gaps in knowledge, existing models are not able to sufficiently reduce uncertainty in the comparison of coping strategy options, especially since it is difficult to find sound data about feedback responses.

Several organizations have come up with methodologies to better assess risk. Generally, risk is defined as the product of the probability of an outcome multiplied by how bad that outcome is (a quantification of damage). Climate adaptation alternatives can be assessed using a process shown in Box 5. This approach is designed to inform decisions to build "resilience frameworks" and to develop early warning programs, insurance products, and other risk-based strategies. The intent is to build resilient agricultural systems with the capability of recovering from external shocks. The overall goal is to reduce the vulnerability of people to food shortages under uncertain climate change risk.

> ***"Experts from several domains of agriculture, climate science, engineering, social science, and policy must integrate their knowledge across these intellectually diverse disciplines, collaboratively framing the research questions, and driving toward deployable outcomes."***

Photo: (right) Rows of corn and soybeans. ISTOCK

6 RECOMMENDATIONS FOR FUTURE RESEARCH

To meet the challenges associated with climate change, water, agriculture, and food security, experts from several domains of agriculture, climate science, engineering, social science, and policy must integrate their knowledge across these intellectually diverse disciplines, collaboratively framing the research questions, and driving toward deployable outcomes. These research teams will need to effectively communicate across disciplines, adopting common frameworks and a new shared vocabulary, to generate new solutions that would otherwise be impossible to attain.

These research programs should be built on a platform of convergence research. The National Science Foundation (NSF) identifies convergence research as having two primary characteristics:

- **Research driven by a specific and compelling problem.** Convergence research is generally inspired by the need to address a specific challenge or opportunity, whether it arises from deep scientific questions or pressing societal needs.
- **Deep integration across disciplines.** As experts from different disciplines pursue common research challenges, their knowledge, theories, methods, data, research communities, and languages become increasingly intermingled or integrated. New frameworks, paradigms, or even disciplines can form sustained interactions across multiple communities.

The overarching recommendations of the workshop are summarized here.

Coordinating and integrating databases:

An overarching and significant challenge in our understanding of agricultural and climate systems is the issue of data. There are numerous "orphan" databases, data of unknown quality, and private data not available to researchers. Better approaches to coordinating and integrating databases across organizations and disciplines are needed.

Investigating crop responses to environmental, biotic, and abiotic stresses:

While there have been various studies on the response of different crops to elevated CO_2, water, and specific pest and disease outbreaks, the integrated effects of environmental, biotic, and abiotic stresses are not understood across the multiple agro-ecologic zones of the world. By studying the integrated or synergistic effects of these various stresses on plants, more climate resilient cropping systems and climate smart agricultural practices can be developed. In addition, for regions where extreme temperatures are projected, crop response to heat stress should be investigated, leading to new breeding programs for heat and drought tolerance. The information derived from these research projects will also inform improvements in existing crop models.

Use of advanced genetics and genomic tools in plant breeding:

Various advances in crop biotechnology are rapidly emerging. It is now possible to undertake the complete genome sequencing of the major food crops. Using this information, together with new genome editing tools, research programs can be established to breed crops that take advantage of elevated carbon dioxide levels and that better withstand heat and drought conditions.

Monitoring of soil carbon stocks and CO_2 emissions:

There is a need to quantify, in a reliable and cost-effective way, soil carbon stock changes and net CO_2 emission or uptake by soils. Such monitoring programs will have the additional benefit of evaluating the effectiveness of policies and practices that seek to limit greenhouse gas emissions from agriculture. Carbon emissions/sinks need to be monitored—from farm level to national scale to global scale at geo-referenced benchmark sites—and all data must be consolidated and harmonized. New approaches should be developed for collecting and curating agronomic management activity data via globally

Photo: Agriculture places significant pressures on water resources. In the many parts of the world experiencing water scarcity, agriculture competes with domestic and commercial uses of water. ISTOCK available remote sensing data of land cover, crop type, tillage systems, residue management, irrigation, and flooding. Incentives should be created to crowd source data from land users.

Improving soil fertility management:

The very intensive use of nitrogen fertilizers results in a significant nutrient flux out of soil and leads to land degradation. Research is required on inexpensive sensor technologies to rapidly record and monitor soil nutrient status in order to make fertilizer application more efficient, and on low-cost nutrient management systems—including vermicomposting and other methods using recovery of nutrients from waste materials—to help replenish soil nutrients. Policy research on fertilizer use is also needed to better understand financial incentives and other mechanisms to enable access to fertilizers in developing countries that is needed, particularly in Africa, without contributing to over-fertilization and its accompanying GHG emissions and other environmental degradation.

Policy research and awareness building on alternative food choices:

Presentations and discussion at the workshop addressed alternative diets, reduction in food waste, and the importance of demand side management strategies as immediate ways to reduce the impacts of the global food system on climate change and move towards food security. Large amounts of cereal grains, particularly maize and soybean, go into livestock feeds. These crops also use unsustainable water and chemical inputs. Consuming less red meat and using plant-based proteins will help to mitigate greenhouse gas emissions, conserve scarce land and water resources, and also reduce chronic non-communicable diseases. Minimizing food waste across the entire food supply chain will also reduce the environmental footprint of agriculture. However, much more research needs to be done on the policy incentives and awareness building necessary to achieve the benefits of demand side management for food and nutrition security in the context of a changing climate. This research should encompass understanding how consumer behavior changes.

Improvements to crop models and climate projection models:

Current crop models are unable to predict future crop yields with reasonable accuracy, because plant physiology under high temperatures is not well represented in the models. More research is needed, both in greenhouses and in the field, to better understand the underlying physiological mechanisms in plants triggered by heat stresses under a range of agro-ecological conditions. The results can improve the usefulness of crop models. Furthermore, the capability of the models to assess carbon dynamics to the full depth of the rooting system of the world's major crops needs to be improved.

In order to improve the accuracy of the projections of the GCMs and RCMs, much more research is needed to better simulate the convection and boundary layer processes involved in precipitation. Further research in climate models should include the use of Empirical Downscale Models (EDMs). Additionally, research should include the application of machine learning to understand climate change and improve model predictions, an emerging area known as climate informatics. Machine learning offers the possibility of unlocking insights from massive sets of climate data in an inexpensive way.

Develop better methodologies for decision making under deep uncertainty:

Advances in data and decision sciences are necessary to improve risk management under deep uncertainty. Emerging developments in climate change science and data analytics should be further supported: combining artificial intelligence (AI) with physics-based numerical models will help resolve longstanding challenges, as will the emerging ability to extract insights about rare and extreme climate events from massive and complex data, and the use of information theory to better characterize uncertainty.

Dynamic adaptive strategies, including flexible planning that allows for non-stationarity, have been suggested as a way to deal with uncertainty. However, these methods have not been applied in a comprehensive manner to food security under a changing climate. This approach is worth pursuing.

Incorporating geospatial tools to improve crop production:

Remotely sensed images of land use, crop cover, and soil properties over large landscapes such as watersheds and river basins are powerful tools to analyze physical constraints on crop yields. Research is needed to develop analytical tools using precision agriculture models, which can interpret large quantities of geospatial data, and which can be applied to make recommendations on crop cultivar selection and water and fertilizer requirements, so as to optimize crop yield as well as farmers' economic returns.

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Cover Photos: **(top to bottom)**

A rising global population with evolving consumption patterns is projected to place added stress on an already strained global food system. ISTOCK

Climate change is exacerbating the frequency and intensity of extreme weather events, putting crops, farmers, and food supply chains at risk. ISTOCK

Industrialized agriculture has benefited from advances in technology to increase yields, though often at the cost of the health of surrounding ecosystems. ISTOCK

More than 50% of food calories consumed globally, and 70% of food calories consumed in developing countries, are supplied by approximately 475 million smallholder farmers, who often lack access to advanced technologies that support sustainable farming practices. ISTOCK

Minimizing food waste across the entire food supply chain reduces the environmental footprint of agriculture. ISTOCK

Extreme heat, water stress and drought, and other extreme weather events are some of the major climate factors affecting crop productivity. ISTOCK

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Above: Workshop presenters and moderators. ANDI SUTTON, J-WAFS

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