11-2017

Climate Change and Food Systems: Assessing Impacts and Opportunities

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A Report Prepared by Meridian Institute

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NOVEMBER 2017

Meridian Institute
Connecting People to Solve Problems

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Suggested citation: Niles, M.T., Ahuja, R., Esquivel, M.J., Mango, N., Duncan, M., Heller, M., Tirado, C. 2017. Climate change and food systems: Assessing impacts and opportunities. Meridian Institute. Washington, DC. Available here.

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Date of publication: 30 November 2017

About Meridian Institute

Meridian Institute is a not-for-profit organization with a mission to help people solve complex and controversial problems, make informed decisions, and implement solutions that improve lives, the economy, and the environment. Meridian accomplishes its mission by applying collaborative problem-solving approaches, including facilitation, mediation, and other strategic consultation services. Meridian works at the local, national, and international levels and focuses on a wide range of issues related to natural resources and the environment, science and technology, agriculture and food security, sustainability, global stability, and health.

About the Global Alliance for the Future of Food

The Global Alliance for the Future of Food is a unique collaboration of philanthropic foundations that have come together to strategically leverage resources and knowledge, develop frameworks and pathways for change, and push the agenda for more sustainable food and agriculture systems globally.

In 2012, the Global Alliance for the Future of Food came together with a shared belief that the current global food system is not sustainable and that many of the values upon which it is based make it an undesirable choice for the future of food on the planet, particularly when coupled with climate change and shifting global economics, politics, and demographics.

Global Alliance members believe that by leveraging our shared expertise, knowledge and resources, and working together with others – and by taking a global, systems-level approach that gets sustainable food and agriculture on the political, economic, and social agenda – we can achieve positive change.

Foreword

At the Global Alliance's recent 2nd International Dialogue: The Future of Food in a Climate Changing World, there was growing consensus that food systems and climate change are inextricably linked. The way we grow, process, distribute, eat, and dispose of food contributes to climate change, and climate change affects the future sustainability, security, and equity of the food system.

There are signs that we as a global community are starting to make the connection - the Paris Agreement calls out the importance of "safeguarding food security and ending hunger," and scientists increasingly acknowledge that food production systems are sensitive to the adverse impacts of climate change. But how much do we really know about the connections between climate change and food systems? And, what's more, how do we move toward a more climate- and food-friendly future?

To answer these questions, the over 250 diverse participants at the International Dialogue, from farmers and policy-makers to corporate executives and grassroots leaders, explored these connections. Participants discussed not just how food systems are a source of the problem, but how they can be a brilliant pathway to the solutions.

A cornerstone of the gathering was the preparation of a white paper to better understand, from the peer-reviewed literature, what policies, programs, regulations, and actions can be taken by a variety of stakeholders to minimize the impact of food systems on climate change and vice versa. As a starting point, we were interested in exploring the challenges, opportunities, priorities, risks, and tradeoffs of addressing climate change through a food systems perspective.

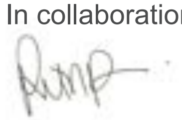
The result of that formidable effort is this report, Climate Change and Food Systems: Assessing Impacts and Opportunities. Meridian Institute led the development of the report – together with a stellar interdisciplinary author team and advisory committee – drawing from their extensive experience working with diverse partners to address complex challenges and advising national governments on sustainability issues.

The report authors identify 10 important and revealing conclusions about our knowledge of climate change and food systems, and what we need to do to harness the latter to address the former. The author team highlights a number of important recommendations, including inclusion of equity considerations in climate change mitigation and adaptation plans; more systems-level research, particularly in the peer-reviewed literature; the need to highlight and bridge local, Indigenous, practitioner, and academic knowledge in designing actions that transform food systems; and the engagement of a diverse array of stakeholders to envision equitable, sustainable, and resilient food systems and develop specific transformation pathways together.

One of the central contributions made by the report authors is the identification of eight Climate Change Food Systems Principles to support stakeholders in making choices about adaptation and mitigation interventions through a food systems lens. These include interconnectedness, equity, resilience, renewability, responsiveness, transparency, scale, and evaluation. The principles are informed by the Global Alliance's principles, applied to climate change and designed to help stakeholders work systemically to avoid siloed approaches, unintended consequences, and limited, narrow, short-term solutions. This is an especially important contribution to all food system stakeholders' efforts to achieve the Paris Agreement's goals, the Sustainable Development Goals, and other critical global imperatives.

We were so pleased when International Dialogue participants provided extensive and critical feedback on the draft report presented in May 2017, making for a stronger report and strengthening the relationships that will be needed to move forward with action. The issues related to climate change and food systems are some of the toughest issues we will face, and the ways forward are not easy, particularly when the path is strewn with diverse and competing views. But for deep and lasting change, we believe these diverse interests need to come together to find common ground and more effectively identify needed solutions. This report is an important first step in that direction.

In collaboration,



Ruth Richardson
Executive Director, Global Alliance for the Future of Food

Executive Summary

Food and agriculture are significant contributors to, and heavily impacted by, climate change, but they also offer opportunities for mitigating greenhouse gas (GHG) emissions. Despite a growing body of literature about climate change and agriculture, relatively little analysis and focus has been put on climate change and *food systems*, more broadly. The narrower focus on climate change and agricultural production prevents consideration of a broad range of mitigation and adaptation strategies as well as the systems-level effects of narrowly targeted interventions. A broader food systems perspective creates opportunities to explore the feedback loops and multiplier effects of specific mitigation opportunities and to identify opportunities for systems transformation. Approaching climate adaptation and mitigation in the context of food systems broadens the range of opportunities to achieve mitigation and adaptation goals and facilitates the consideration of systems-level effects and interactions. A food systems perspective also enables engagement of the full range of stakeholders that should be involved in food systems transformation. Such a perspective is critical to addressing climate change and achieving the Sustainable Development Goals (SDGs), which cover multiple sectors that are linked by food.

This report was written by a team of subject matter experts with input from a diverse advisory committee. Meridian Institute coordinated the development of the report, and funding was provided by members of the Global Alliance for the Future of Food. The objectives of the report are to:

- review and synthesize peer-reviewed literature that examines the mutual impacts of food system activities and climate change, and identify knowledge gaps in that literature;
- illustrate how applying a food systems perspective to climate change mitigation actions can be used to drive transformation and help policymakers anticipate effects from specific mitigation and adaptation opportunities; and
- document opportunities (available online) for incremental changes that support climate mitigation while efforts to drive broader system transformation are pursued.

Food systems include the growing, harvesting, processing, packaging, transporting, marketing, consumption, and disposal of food and food-related items. These systems include pre-production activities such as developing and delivering inputs (e.g., fertilizers, seeds, feed, farm implements, irrigation systems, information, and research and development); the production of crops, fish, and livestock; post-production activities such as storage, packaging, transportation, manufacturing, and retail; consumption activities either in supermarkets, homes, or dining establishments; and the loss (pre-consumer), waste (consumer level), and disposal (post-consumer) that occurs throughout the system. Food systems operate within and are influenced by social, economic, political, and environmental contexts. People are involved throughout these systems as producers; information providers; policymakers and regulators; workers in the fields of health, forestry, trade, and finance and in companies; and consumers.

The following key messages emerged from the literature review and discussions with leading food and agriculture experts who work on climate change adaptation and mitigation. The key messages highlight critical considerations for identifying and evaluating actions for climate change mitigation and food systems transformation.

1. Food systems have significant, adverse effects on climate change, and climate change impacts food systems in many complex ways.
2. A food systems perspective is required for transformative change.
3. Immediate action is possible and needed as a stepping stone to food system transformation.
4. Equity issues should be central to creating fair, sustainable, and resilient food systems.

5. Actions need to consider local, Indigenous, and practitioner knowledge.

6. More peer-reviewed, systems-level information and research is urgently required.

7. More research on the impacts of food system interventions is needed, in particular in low- and middle-income economies.

8. New approaches and decision-support tools are required.

9. Food system transformations require the engagement of a broad range of stakeholders.

10. Governance and institutional innovations are required for system transformation.

The majority of the world's countries have included mitigation and adaptation actions related to crops, livestock, forestry, fisheries, and aquaculture in their Nationally Determined Contributions to the United Nations Framework Convention on Climate Change. Low-income countries put a strong emphasis on these sectors, given the importance of agriculture to their economies and the predominance of their emissions resulting from agriculture. These actions are heavily focused on agricultural production. However, pre-production and post-production activities also contribute significantly to climate change, and as more economies develop we can expect proportionately more emissions from post-production activities overall. More mitigation alternatives for pre-production and post-production should therefore be developed in low-, middle- and high-income countries. For example:

- Pre-production activities have impacts such as energy and water use for agrochemical production as well as packaging and transportation. Pre-production mitigation opportunities should include research, development, and the promotion of climate-positive agricultural practices.

- Post-production emissions are largely associated with energy use. Processing – including milling and removing water – is energy intensive. Packaging and food waste can be a significant component of municipal waste. Transportation contributes less than commonly assumed, with the exception of many vegetables, fish, seafood and livestock products for which time-sensitive distribution involves airfreight. The cold chain, or refrigeration throughout the supply chain, contributes substantially to emissions, and its use is growing.

- Diets and consumption patterns also affect climate change, and their impacts differ across low-, medium-, and high-income countries. In high-income countries, diets tend to negatively affect both the environment and health. Dietary shifts in these countries that include reducing the consumption of meat and processed foods and balancing energy intake and output could drive more sustainable agriculture systems that have the potential to restore natural resources, climate resilience, and human health.
- Waste management should be improved along food systems. Roughly one-third of food – about 1.3 billion tonnes per year – is lost or wasted globally. Waste and loss occur throughout the food supply chain and mostly involve the waste of edible food by consumers in medium- and high-income countries and loss during harvest, storage, and transport in lower-income countries.

To support stakeholders' engagement in developing food system transformation strategies and identifying adaptation and mitigation opportunities through a food systems lens, the report offers eight key Climate Change Food Systems Principles. These include (1) interconnectedness, (2) equity, (3) resilience, (4) renewability, (5) responsiveness, (6) transparency, (7) scale, and (8) evaluation.

In addition, the report provides three examples to illustrate how specific mitigation or adaptation opportunities may have implications, benefits, or unintended consequences in the various parts of the food system. The first example shows how diets impact the environment and health. Generally, the research suggests that diets that are healthier for humans (e.g., higher in plant-based ingredients) also have lower GHG emissions. But there are possible downsides. For example, while reducing red meat consumption could reduce dietary GHG emissions, it could have profound negative impacts on nutrition and livelihoods in low-income countries. Therefore, reducing meat consumption to reduce dietary emissions is a strategy mostly relevant to high-income or some middle-income countries – providing an illustration of how actions should be context-specific.

The second example explores the ways carbon pricing policies affect different stakeholders, including farmers, suppliers, traders, and transporters. Some stakeholders suggest that placing a price on carbon and gradually increasing the cost of carbon dioxide emissions are important tools to direct investments toward climate-neutral or climate-positive activities. However, pricing carbon has to be accompanied by strong social safeguards, and it may not be appropriate in all types of economies. For instance, many are concerned about the impacts of carbon pricing on farmers and low-income consumers.

The final example, on soil carbon sequestration, illustrates tradeoffs. No-till agriculture offers soil organic carbon gains, but it is often used in combination with genetically engineered crops and herbicides for weed control, with implications for equity and sustainability. Some tradeoffs are political or economic, such as potential large-scale land acquisitions (land grabs) for carbon offsets. But soil carbon sequestration also has many co-benefits such as improved soil health and water management and offers great potential for climate mitigation.

Due to the complexity and diversity of food systems, food system governance emerges as a central challenge that needs to be addressed. This report can contribute to the development of governance approaches by identifying relevant literature, gaps, and opportunities across varying scales for policy approaches.

Overall, the report offers a broad perspective on food system activities and seeks to help stakeholders explore new partnerships, share knowledge, and identify diverse communities, sectors, and other stakeholders that have roles to play in support of changes needed within their food systems. We hope the report will contribute to a deeper understanding of food systems and climate change and the thoughtful review and development of actions that will – ultimately – contribute to sustainable, equitable, and resilient food systems.

1. Introduction

The Case for Applying a Food Systems Perspective to Climate Change

Food and agriculture are significant contributors to, and heavily impacted by, climate change, while also offering a range of opportunities for mitigating greenhouse gases (GHGs) through emission reductions and carbon sequestration (Vermeulen et al. 2012; Rosenthal and Kurukulasuriya 2013; Dickie et al. 2014; FAO 2015; Wollenberg et al. 2016). While there is growing discussion and dialogue about climate change and agriculture, relatively little analysis and focus has been put on climate change and *food systems*, more broadly. The narrower focus on climate change and agricultural production prevents consideration of a broad range of mitigation and adaptation strategies as well as the systems-level effects of narrowly targeted interventions. Adopting a food systems perspective is critical to addressing climate change and achieving the Sustainable Development Goals (SDGs), which span multiple sectors that are linked by food (TEEB 2015).

A *food system* includes "all the elements (environment, people, inputs, processes, infrastructure, institutions, etc.) and activities that relate to the pre-production, production, processing, distribution, preparation, and consumption of food and the outputs of these activities, including socio-economic and environmental outcomes" (HLPE 2014). Food systems incorporate the inputs needed and outputs generated at each of these steps. Food systems operate within and are influenced by socio-cultural, economic, political, and environmental contexts. Furthermore, a *sustainable food system* is one that delivers food and nutrition security for all in such a way that the economic, social, and environmental bases to generate food security and nutrition for future generations are not compromised (HLPE 2014). Food systems require human resources (productive and technical labor) along the entire food production process, as well as human resources for research, education, management, and regulation (Ericksen 2007; Cornell University 2013).

Food systems are complex, heterogeneous, and dynamic. They range from long-chain, high-value, and industrial to short-chain, low-value, traditional, and rural. Multiple variations of food systems exist and may occur alongside one another in a given country. Differences in food systems lead to variations in nutrition, health, and sustainability outcomes (IFPRI 2015). Given the variety of food systems, opportunities for climate change mitigation and adaptation should be assessed by diverse stakeholders within each country's contexts and priorities.

Numerous factors drive activities and actors in food systems. These include, but are not necessarily limited to, the key food systems components, processes, and activities shown in Figure 1.

Food System Components, Processes, and Activities

Figure 1: Food system components, processes, and activities

As illustrated in this graphic, the drivers of food systems include the following (not in order of priority):

- **Infrastructure** drivers include physical infrastructure such as roads, rail, irrigation, and energy, which support production and value-addition activities (Westhoek et al. 2016).
- **Society and culture** drivers include traditions, social norms, religion and rituals, social stratification, and gender, which affect food production as well as consumer preferences and behavior (Kearney 2010; Vignola et al. 2010; Vignola et al. 2013).
- **Profits** drive actions by many food system actors, including multinational and local food companies (Reardon and Timmer 2012). The concept of **shared prosperity** focuses on improving the living standards of all people involved in a food system.
- **Economic** drivers include national and individual incomes, prices, and poverty, among others. Income growth is associated with diets shifting from traditional staples and coarse grains to more diversified diets that are richer in sugars, fats, salt, animal-sourced foods, vegetables, and fruits (Westhoek et al. 2016; Global Panel 2016).

- **Politics and policy** drivers include governance structures, policies, rules, and regulations that affect food systems and other systems. The policies may include agricultural policies (such as subsidies and price supports); nutrition and health, food safety, and trade policies; and land tenure laws (Vignola et al. 2013; Westhoek et al. 2016).

- **Research and development** drives **innovation**, including technological innovations such as improved seeds, fertilizers, mechanization, storage, processing, and distribution, but also the development of more nutritious, healthy, and sustainable foods (Floros et al. 2010).

- **Energy** is required for producing, processing, storing, transporting, and cooking food. Food production is energy-intensive. At the same time, agriculture and food, including waste, can provide biomass for energy production.

- **Biophysical and environmental** drivers include land and water for food production and processing, soil for food production, other natural resources (plant and animal biodiversity) and related ecosystem services and dependencies, and climate adaptation and resilience (Westhoek et al. 2016).

- **Power dynamics and equity** issues determine access to – among other things –land and food, resources to grow and buy food, and resources to mitigate and adapt to a changing climate (Jones 2009; FAO, IFAD, and WFP 2015). Climate change raises equity concerns because of the asymmetrical contributions from and impacts suffered by high-income and low-income economies.

- **Demographic** drivers include urbanization, population growth, changing age profiles, and education (Westhoek et al. 2016).

The activities and actors of food systems include, but are not limited to, the following:

- **Pre-production** activities include the development and delivery of a range of inputs, including fertilizers, pesticides, seeds, herd management and animal feed inputs, farm implements, irrigation systems, information, and research and development.

- **Production** activities include agricultural production and the harvest of crops, fish, and livestock. In many countries, producers grow crops for home or local consumption. Sometimes primary producers sell directly to consumers, but in most situations there are multiple other touchpoints before food reaches the end consumer. A portion of initial production is used for livestock feed, industrial inputs, and biofuels.

- **Post-production** includes processing, packaging, transportation, manufacturing, and retail. It also may include storage, various types of treatment and processing (e.g. drying, washing, cooling, ripening), as well as transportation and trading. Once food products are manufactured, retailers, marketers, advertisers, and other actors sell them to consumers.

- **Consumers** purchase the products for home preparation or from establishments where the food is prepared and served onsite. Purchasing decisions can drive production.

- **Food loss** (pre-consumer), **waste** (consumer level), and **disposal** (post-consumer) are prevalent throughout the food system. The Food and Agriculture Organization (FAO) of the United Nations estimates that, each year, approximately one-third of all edible food parts for human consumption is lost or wasted.

People are involved in food systems in a wide variety of ways. They may be employed by companies – from small enterprises to multinational corporations – that are active in pre-production (e.g., manufacturers, traders), production, post-production (e.g., aggregators, processors, transporters, packagers), retail (e.g., retailers, marketers, advertisers), or waste collection. They may be employees of civil society organizations working on issues relating to agriculture, food security, nutrition, public health, trade, the environment, power dynamics, and/or equity. They may be farmers, fishers, ranchers, or other producers and their organizations producing or harvesting raw food products. They may be consumers, research and development experts, extension agents, or other information providers. Or they may be politicians, policy experts, or regulators, working in agencies from the local to the global levels and with expertise in agriculture, public health, the environment, forestry, trade, finance, or planning.

In a sustainable food system, these components, processes, and activities contribute to climate change resilience; provide healthy food and nutrition security; improve social, economic, and cultural well-being; provide secure livelihoods; and enhance biophysical, environmental, economic, and political systems and maintain them for current and future generations. Climate-change-related mechanisms are affecting current food systems in many ways. If consumers worldwide do not have access to an adequate supply of affordable, useable, nutritious food, the purchasing power of wealthier populations will ensure that food flows toward the wealthy, leaving the poor with an insufficient supply and the perpetuation of many related injustices (Myers et al. 2017).

An analysis of the components of food systems would be incomplete without considering the potential that each component has to affect other pieces of the system. Policy, market, socio-cultural, technological, and biophysical environments all influence actors within food systems. Therefore, each component of a food system is linked to its social, economic, and environmental contexts (Godfray et al. 2010; Ingram 2016). The biophysical context, as well as the social and institutional context in which food is produced, distributed, and consumed, must be considered to fully understand the interconnected nature of food systems and the external environments in which the systems operate, thereby allowing for the exploration of future behaviors, changes, and interactions throughout the system (Vignola et al. 2009 and 2015).

As noted above and explored in more depth below, we observe that both discussions and research about climate change, food, and agriculture have focused largely on changes to production practices within existing systems, rather than broader system transformation. While many of these changes in production practices have demonstrable climate benefits, we believe adopting a food systems perspective is imperative if we are to successfully address climate change at the scale and speed required, drive transformation toward sustainability, equity, and resilience in food systems, design climate strategies that anticipate and adapt to unintended consequences on other components of the food systems, and achieve the SDGs.

Objectives and Scope of This Report

Food system stakeholders need to better understand, integrate, and create action related to food systems and climate change, beyond just agricultural production. This focal shift is critical for multiple reasons:

- Food-systems-based approaches have greater mitigation and adaptation potential than a concentration on agriculture alone, because they enable the integration of sustainability options that fall outside of agricultural production (e.g., dietary choices, food waste, public health, technological innovation, clean energy, governance, and insurance as a strategy for risk management).
- A food systems focus enables the exploration of supply-side and demand-side mitigation and adaptation co-benefits, as well as potential synergies or tradeoffs between strategies.
- A food systems perspective supports the integration of equity, sustainability, governance, and other key drivers and components that make up food systems. It enables food systems transformation and can address the inequities inherent in climate change impacts and mitigation burdens.
- A food systems perspective enables stakeholders to identify synergies with broader policy priorities, in particular priorities related to SDGs, thereby using available resources efficiently.
- Food systems and climate change have been under-studied, with clear gaps in strategies that could impact food security in the future (e.g., cold chain expansion, sea-level rise, and food transportation).

This report seeks to support the application of a food systems perspective to climate change mitigation and adaptation. Specifically, the objectives of the report are to:

- review and synthesize peer-reviewed literature that examines the mutual impacts of food system activities and climate change, and identify knowledge gaps in that literature;

- illustrate how applying a food systems perspective to climate change mitigation actions can be used to drive transformation and help policymakers anticipate effects from specific mitigation and adaptation opportunities; and
- document opportunities for incremental changes that support climate mitigation while efforts to drive broader system transformation are pursued.

By articulating a food systems perspective, we provide a starting point to broaden understanding beyond the individual components of food systems. The complexity of food systems and the historical research bias toward narrowly focused work has resulted in a body of literature that largely addresses the individual elements of food systems. We broaden the lens of past efforts by bringing together and summarizing peer-reviewed literature on the broad range of food system activities in sections 3 and 4. In section 5, we discuss eight key Climate Change Food Systems Principles to help stakeholders assess food system transformation opportunities through a food systems lens. These principles include (1) interconnectedness, (2) equity, (3) resilience, (4) renewability, (5) responsiveness, (6) transparency, (7) scale, and (8) evaluation.

The inclusive concept of food systems could be a starting point for those stakeholders who are exploring critical linkages among system components and processes, helping them to identify the wider range of stakeholders that should be engaged in food systems transformation efforts. However, peer-reviewed research on systems-level effects is scarce and urgently required, including analysis of interactions and feedback loops across food system drivers, components, processes, and activities. Our main findings are summarized in the key messages in section 2.

The authors have documented numerous specific mitigation opportunities and their adaptation potential, which are available separately online. However, for immediate actions to result in transitions to sustainable food systems, stakeholders should work together to co-define sustainability and identify their shared interests as well as obstacles to change. Such understanding will enable stakeholders to choose actions that can lead toward sustainability.

The range of opportunities are based on specific country experiences and may be relevant to a range of contexts and conditions. Stakeholders could consider these opportunities within their national or regional contexts, priorities, and strategies. In addition, stakeholders should consider opportunities that are not in the peer-reviewed literature, but are being devised, refined, and promoted by non-academic practitioners, smallholder farmers, Indigenous Peoples, and others.

In writing this report, we recognize the limitations of the current body of peer-reviewed literature. For instance, the peer-reviewed literature on mitigation opportunities across the full range of food system activities (i.e., not just agricultural production) is limited. Also, while we looked at the climate adaptation co-benefits of adaptation opportunities, we recognize that much additional work on adaptation strategies is available and more is needed to bridge local, traditional, Indigenous, practitioner, and academic knowledge and inform decision-making on food systems and climate change.

This report offers a broad perspective on food system activities and seeks to help stakeholders explore new partnerships, share knowledge, and identify diverse communities, sectors, and other stakeholders that have roles to play in support of changes needed within their food systems. We hope the report will contribute to a deeper understanding of food systems and climate change and the thoughtful review and development of actions that will – ultimately – contribute to sustainable food systems.

2. Key Messages

Based on a review of the existing peer-reviewed literature on food systems and climate change, including mitigation opportunities and adaptation co-benefits, we identified the following key messages regarding climate change and food systems.

1. **Food systems have significant, adverse effects on climate change, and climate change impacts food systems in many complex ways**. While it is estimated that agriculture contributes 14 percent of global GHG emissions (Porter 2014), food system activity more broadly is estimated to account for approximately 30 percent of global emissions. (A range of estimates have been published, with conservative estimates at around 30 percent). Changing weather patterns and extreme weather events impact crop yields, food prices, hunger, and social and political stability. And geographically, the impacts of climate change on food systems are unevenly distributed. Given the myriad connections in the food system, *we believe what's needed is a comprehensive and holistic understanding of food systems and the external environment in which they operate, in order to fully understand dynamics, future system behaviors, interactions, and, ultimately, opportunities for reform*.

2. **A food systems perspective is required for transformative change**. We observe that research, policies, and strategies about climate change, food, and agriculture have focused largely on changes to production practices within existing systems, rather than broader food system transformation. We consider these changes, while important, to be largely efficiency improvements that are unlikely to support more transformative change. Transformative change should consider cross-cutting issues. This requires a systems approach to identify mutually reinforcing strategies – for instance, strategies that support multiple SDGs and other global, national, and local goals. *We believe a food systems perspective is imperative to successfully address climate change at the scale required; drive transformation in food systems beyond agriculture; implement climate strategies that do not have unintended consequences; and achieve climate mitigation and adaptation targets and the SDGs*.

3. **Immediate action is possible and needed as a stepping stone to food system transformation.** Even though systems-level research and new decision-support tools are needed, current evidence supports actions that can contribute to creating more sustainable food systems. We document opportunities for incremental change that could be considered in local, regional, and national contexts, as well as priorities and strategies to immediately incite action on food systems change. While these actions are important, they should be considered incremental and insufficient in driving transformative change. *We call for immediate incremental action while research is pursued to fill knowledge gaps and support broader, systems-level analysis and action.*

4. **Equity issues should be central to creating fair, sustainable, and resilient food systems**. Equity is about social justice, fairness, and inclusiveness and can be defined in multiple dimensions, such as rights, resources, capabilities, outcomes, goods, and equality of opportunity among others (Tirado et al. 2013). Equity regarding food systems includes issues related to the ability of all community members to grow, process, transport, trade, and consume food and manage waste in a manner that prioritizes human health; adequate and nutritious food; culture; equitable rights and access to land, water, finance, and other resources; fair and equitable prices and wages; and ecological sustainability and the rights of future generations to inherit natural resources (von Braun and Brown 2003; De Schutter et al. 2015). The achievement of equity in the context of sustainable food systems also includes the comparable distribution of productive resources, opportunities for employment and social services, and gender and ethnic inclusiveness (FAO 2014). The fundamental aspects of equitable food systems include ethical

principles such as: the right to food, the right to healthy environments and other human rights; gender equity; environmental justice; ethical considerations of animal welfare, food waste, and emerging technologies (Tirado et al. 2013). Equity also relates to a food system's contribution to broader economic development opportunities for all community members, as well as control over food system resources and community members' meaningful engagement in policies that influence the system (FAO 2015). *We call for stronger inclusion of equity considerations in climate change mitigation and adaptation plans, particularly in light of the uneven burden of climate change impacts on low-income countries and vulnerable populations*.

5. **Actions need to consider local, Indigenous, and practitioner knowledge**. An extensive body of local, Indigenous, practitioner, and other knowledge exists regarding food system components, processes, and drivers, as well as mitigation and adaptation opportunities. A critical effort is needed to highlight and bridge local, Indigenous, practitioner, and academic knowledge to inform decisions on food systems and climate change, including major drivers (e.g., trade and economic systems; power and equity; governance; natural resources), as well as appropriate mitigation and adaptation opportunities. *We call for efforts to highlight and bridge local, Indigenous, practitioner, and academic knowledge in designing actions that transform food systems*.

6. **More peer-reviewed, systems-level information and research is urgently required**. Systems-level approaches require an equal understanding of the various food system components. Our current scientific understanding includes an extensive body of literature on climate change and agriculture, with a growing focus on consumption, loss, and waste as it relates to climate change. Less research exists on food systems and climate change from a pre-production, processing, distribution, and transportation perspective. Furthermore, knowledge about interactions among food system components is fragmented. *We call*

for more systems-level research, particularly in the peer-reviewed literature, as the available analysis of systems-level impacts is mostly provided in non-peer-reviewed literature.

7. **More research on the impacts of food system interventions is needed, in particular in low- and middle-income economies**. In addition to a lack of systems research, we also find a concerning dearth of research about climate change and food systems in low- and middle-income economies. Given the rapid changes in these regions – including shifts in agricultural production and diets – as well as the importance of food systems for these economies and the uneven impacts of climate change, it is critical that we have greater peer-reviewed research in these regions. *We call for an increase in research on the impacts of potential interventions, particularly with a greater focus on low- and middle-income countries*.

8. **New approaches and decision-support tools are required**. Stakeholders who want to drive change at the country or regional level are considering many specific mitigation and adaptation opportunities. In considering these various interventions, however, systems-level issues need to be considered, requiring new approaches and decision-support tools such as the Climate Change Food Systems Principles. *We recommend application of the Climate Change Food Systems Principles to help inform decision-making, as well as the creation of decision-support tools that help identify systems-level interactions and tradeoffs*.

9. **Food system transformations require the engagement of a broad range of stakeholders**. We face the challenge of creating food systems that will meet human nutritional needs, restore natural resources and maintain ecosystem functioning, maintain cultural diversity, and strengthen social cohesion while the Earth's systems are rapidly transforming. Therefore, we need solutions that support (and adapt to) systems change, instead of limited, narrowly targeted efforts that do not account for the broader context or systems-level effects. For this, we need a confluence of perspectives. *We call for a diverse array of stakeholders to engage together in envisioning equitable, sustainable, and resilient food systems and developing specific transformation pathways that include climate change adaptation and mitigation actions*.

10. **Governance and institutional innovations are required for system transformation**. Existing governance structures are typically organized by sector (e.g., health, agriculture, environment). These structures tend to favor targeted interventions for climate change mitigation and adaptation and fail to fully consider and account for broader, systems-level effects. Food system governance includes governments, markets, traditions, and networks. Effective governance will require the engagement of governments, businesses, civil society, and other stakeholders that coordinate, manage, or steer these systems, as well as changes to the rules, structures, and policies that guide those organizations and institutions. These governance systems should ensure that power and equity issues are addressed as part of all interventions. *We call for advances in governance structures and institutions to support the transformation of food systems in support of climate adaptation and mitigation.*

3. A Review of Agricultural Production and Climate Change

Overview

As noted above, the literature overwhelmingly focuses on research questions regarding different agricultural production systems or specific production activities. More research has been conducted on climate change and agricultural production than on climate change and pre- and post-production activities. Very little research is grounded in a food systems perspective, which would enable a deeper understanding of the consequences – positive, negative, and neutral – regarding how the various parts of the systems are connected and affect each other.

This section provides a brief overview of historic and current literature on climate change, food, and the agricultural production sectors on a global scale. Specifically, we review the literature on historical links among climate change, agriculture, and food production; the impacts of food and agricultural production on climate change; and the impacts of climate change on agricultural production. Given the large body of literature on these topics, we focus on reviews and articles that contribute to the recent advancement of science. We draw largely from Vermeulen et al.'s seminal review article "Climate Change and Food Systems" (2012) and the most recent Intergovernmental Panel on Climate Change food and agriculture assessment from Working Group II (Porter et al. 2014) and Working Group III (Smith et al. 2014), as well as other research published since 2012.

To complement the following summary, we provide a review of recent literature regarding climate change and post-production activities, diet and consumption patterns, and food waste in section 4 of this report. We also provide detailed sets of mitigation opportunities and their adaptation potential online.

History and Context

The global community has long recognized that the worldwide response to climate change is critically important to food production and livelihoods. Roughly 1.3 billion people are employed in the agriculture and food sectors. An estimated 2.5 billion people are involved in full- or part-time smallholder agriculture, while more than 1 billion people living in rural poverty are dependent on agriculture for their livelihoods. In many low-income countries, smallholder farms produce more than 80 percent of the food consumed (FAO 2009).

Agricultural systems are deeply interconnected with weather and climate, as these are dominant factors in agricultural production. Climate shocks – that is, events such as drought, flooding, and heat waves that outstrip the capacity of a society to cope with them (Anderson 2000) – lead not only to loss of life, but also to long-term loss of livelihood through decreased productive assets, impaired health, and destroyed infrastructure. Climate shocks as well as long-term climate variability exacerbate existing risks, in particular to vulnerable populations, and contribute to poverty, conflict, migration, and other effects that undermine economic and social development.

Under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), most of the world's countries have included mitigation and adaptation measures related to the agriculture sectors (crops, livestock, forestry, fisheries, and aquaculture) in their Nationally Determined Contributions (NDCs). The FAO reports that 131 countries refer to agriculture as a "priority area" for climate change adaptation, and 126 countries refer to agriculture as it relates to climate change mitigation (Strohmaier et al. 2016). Low-income countries, in particular, put a strong emphasis on the agriculture sectors. Many of these countries highlight the role of agriculture, forestry,

fisheries, and aquaculture in economic development, particularly in terms of employment, exports, and rural development. Many countries also point to the vulnerabilities of these sectors to climate change.

As noted previously, total emissions from food systems are estimated at 30 percent of global GHG emissions. Agricultural production activities, including land use change, currently contribute about 80–86 percent of these emissions, so the focus on agricultural production and climate change thus far has been justified (Vermeulen et al. 2012). Agriculture and associated land use change account for about 25 percent of global anthropogenic GHG emissions, with 10–14 percent from agricultural production and 12–17 percent from land cover change, including deforestation associated with agriculture (Paustian et al. 2016). Agriculture is responsible for 75 percent of global deforestation (Houghton 2008).

On aggregate, low-income countries produce the most agriculture, forestry, and other land use (AFOLU) emissions and are expected to see the fastest increase in these emissions, in part due to the importance of the agriculture sector to economic development in these countries. Per capita, however, food system emissions from high-income countries are generally much higher than those from low-income countries (see Appendix 1), particularly when considering the percent GDP that agriculture contributes to a given country's economy. In Kenya, for instance, the AFOLU sector accounts for 30 percent of national GDP, and per capita emissions from agriculture are 806.81 kg of carbon dioxide equivalents (CO_2eq). In Brazil, 5 percent of national GDP is from agriculture, and per capita emissions are 2,163.94 kg CO_2eq. In Vietnam, where agriculture accounts for 20 percent of GDP, per capita emissions from agriculture are 689.20 kg CO_2eq, while in the United States, per capita emissions are 1,103.31 kg CO_2eq and agriculture accounts for only 1.3 percent of GDP. UNFCCC reports show that agricultural production alone contributes about 12 percent of GHG emissions in high-income countries (where total GHG emissions are also much higher than in low-income countries) and about 35 percent in low-income countries (Wollenberg et al. 2016) that rely on agriculture as a key economic sector and have a smaller (albeit growing) manufacturing base. Small-scale agriculture in low-income countries is estimated to contribute about one-third of global emissions from agriculture (Vermeulen and Wollenberg 2017).

Over the past 40 years, global agricultural production and associated GHG emissions have doubled. Since 1970, high-income regions have reduced their agricultural area by 118 million hectares (10 percent), whereas low-income countries together have expanded their agricultural area by 447 million hectares (13 percent). While reducing their agricultural area, high-income countries have almost doubled crop production and increased livestock production, while reducing total emissions by 7 percent. In the same period, low-income countries have doubled crop production and almost tripled livestock production, but have increased total emissions by 34 percent (Bennetzen et al. 2016). The globalization of food supply chains is likely to have contributed to the increase in production and emissions in low-income countries. However, middle- and high-income countries such as the United States, European Union members, Japan, South Korea, Canada, and Brazil have the highest overall and per capita GHG emissions (Olivier et al. 2015).

Despite almost three decades of discussions on the anthropogenic causes and mitigation of climate change, the world's countries are at odds over how the burden of climate change mitigation can be distributed to achieve the global goal of keeping average temperature rise to 2 degrees Celsius or less. Currently, high-income countries' emissions are diminishing, while low- and middle-countries´ shared emissions are increasing. However, high-income countries have greater ability to invest in measures to reduce their emissions, while many low-income countries are highly vulnerable to climate change impacts. The asymmetry of emissions and impacts, and the critical timing, makes climate change mitigation a problem that demands a balanced solution – addressing economic development and the environment and minimizing global welfare losses.

The Impacts of Food and Agriculture on Climate Change

Pre-production activities that generate emissions include the production of synthetic fertilizers, animal feed, and pesticides, as well as the manufacture of antibiotics and hormones used for herd and health management in livestock systems (Downing et al. 2017). Of these three, fertilizer production is the biggest source of emissions, mainly because it is energy intensive but also because some nitrous oxide is emitted when synthetic nitrogen is manufactured, and because the production of ammonia, the most important input in fertilizer, still relies on coal in places such as China (Vermeulen et al. 2012). Smith et al. (2014) report that, between 1970 and 2010, global fertilizer use increased by 233 percent, from 32 to 106 megatonnes per year.

In agricultural production, methane and nitrous oxide are the major greenhouse gases emitted. Recent reviews of all available evidence conclude that agricultural soils and enteric fermentation together are responsible for about 70 percent of total non-CO_2 emissions, followed by paddy rice cultivation (9–11 percent), biomass burning (6–12 percent) and manure management (7–8 percent) (Smith et al. 2014). We summarize information about the impacts of key production activities below.

Livestock The livestock sector includes 20 billion animals using 30 percent of the planet's land for grazing (Herrero et al. 2016). Animal feed production accounts for about 45 percent of the livestock sector's emissions – about half from the fertilization of feed crops and pastures and the rest through energy use and land use (Vermeulen et al. 2012). Between 1995 and 2005, the livestock sector was responsible for GHG emissions of 5.6–7.5 gigatonnes CO_2e per year ($GtCO_2$eq/yr). Livestock alone may constitute up to half the mitigation potential of the AFOLU sectors through a combination of management options and reduced demand for livestock products (Herrero et al. 2016). Methane from enteric fermentation, primarily from ruminants (e.g., cows, goats, sheep), is the most important source of emissions, followed by nitrous oxide from feed production and land use for animal feed and pastures, including land change and fertilizer production. In addition, ruminants require more feed of lower digestibility per kilogram than monogastric animals (e.g., pigs and poultry), so their contribution to emissions through consumption of feed is greater (Eshel et al. 2014). Cattle accounts for 64–78 percent of the sector's emissions, followed by pigs, poultry, buffalo, and small ruminants. The sector, and therefore its impact on GHG emissions, is growing. Most growth is projected to be in low-income countries where current per capita consumption of livestock products is relatively low (Herrero et al. 2016).

A range of relevant mitigation interventions for livestock production and their co-benefits have been documented and are summarized in the tables available online. They include, for example, agronomy practices such as silvopastoral systems, management of feeding strategies, increase of forage digestibility, use of lipids and plant compounds to reduce enteric fermentation, improvement in the quality of feeding strategies (e.g., diet intensification, reduced crude protein), grazing management, herd management, and manure and soil management.

Manure Use. The use of manure as an organic fertilizer on cropland and pasture is growing. Applying manure adds nutrients and provides other benefits, but manure decomposition contributes to

Grass-Fed versus Grain-Fed Systems

Debates have increased in recent years over whether grass-fed or grain-fed cattle have lower GHG emissions. Grain-fed cattle are common in high-income countries and are growing more common in middle-income countries. High-quality feeds (for example, grains including corn, but also high-quality pasture) that are more readily digestible can reduce emissions intensity up to 30 percent (GRA 2014). Furthermore, these feeds can enable livestock to achieve slaughter weight more quickly, minimizing additional days of producing methane while on pasture or feed. A recent review of a limited number of lifecycle assessments (LCAs) of cattle production strategies found an overall 28 percent lower global warming potential (GWP) from concentrated feed systems versus grass-based systems (de Vries et al. 2015). Some experts recommend high-energy and dense feeds, including concentrates and corn, for enteric methane reduction on farms (Hristov, Oh et al. 2013). However, more digestible feed can be achieved by alternatives (e.g., more digestible fodder) that are more adapted and available for small-scale farmers in low- and middle-income countries. For these reasons, the FAO has concluded that mixed-farming systems for cattle production (including some crop or crop byproducts) have lower overall emissions per unit of product than entirely grassland-based systems globally (Opio et al. 2013). However, existing LCAs have largely tended to exclude from their scope of assessment the potential soil organic carbon (SOC) gains that may occur in perennial grassland systems. A recent study suggests that carbon sequestration from grazing is limited and depends on the context and the grassland management practices used (Garnett et al, 2017). Additional research is necessary to more completely understand the potential role of SOC sequestration in perennial grasslands and land use change and whether their inclusion in LCA studies would change conclusions about relative GHG emissions in the different systems. Furthermore, efforts looking at the role of concentrates and high-density feeds for reducing enteric fermentation often focus solely on methane, without considering the GHG emissions that result from the production, processing, and transportation of such feeds. Meanwhile, other research has concluded that seafood, pork, poultry, eggs, and plant-based proteins and vegetarian meat substitutes result in fewer GHGs than ruminant meat production (Ripple et al. 2014).

GHG emissions. Eighty percent of manure use is in low-income countries. From 2000 to 2010, manure emissions were greatest in Asia, then Europe and the Americas (Smith et al. 2014). Examples of relevant mitigation interventions and their co-benefits, which are summarized in the opportunities tables online, include manure gestation and storage strategies, biodigesters, composting, and a wide array of application methods.

Fertilizer Use. Emissions from synthetic fertilizers are also growing and will outpace emissions from manure on pastures; fertilizer will be the second-largest source of agricultural emissions after enteric fermentation by 2024 (Smith et al. 2014). From 2000 to 2010, the largest emitter by far was Asia, then the Americas and then Europe. Low- and middle-income countries contribute 70 percent of fertilizer emissions (Smith et al. 2014). Many low-income countries, especially in Africa, where emissions from synthetic fertilizers are currently very low, have nutrient-poor soils and are actively promoting increases in fertilizer use and practices to improve soil fertility, yields, and rural livelihoods. Examples of relevant mitigation interventions and their co-benefits are summarized in the opportunities tables online. Among them, farmers could use integrated nutrient management systems, fertilizer application methods, fertilizer and nitrification inhibitors, and organic fertilizer management and application methods, and switch from anhydrous ammonia to urea.

Paddy Rice Cultivation. Paddy rice cultivation is a major source of global methane emissions, as it contributes about 11 percent of agricultural emissions. The methane is produced by microorganisms in submerged fields. Emissions from paddy rice cultivation have been increasing, mostly in low-income countries, with more than 90 percent from Asia (Smith et al. 2014). Examples of relevant mitigation interventions and their co-benefits, which are summarized in the opportunities tables online, include irrigation water management (such as using renewable energy for water management), water harvesting, and improving water use efficiency.

Land Use and Land Cover Changes. Agriculture utilizes 37 percent of the Earth's land surface, and about 80 percent of new land for crops and pastures comes from removing forests, especially in the tropics (Vermeulen et al. 2012). Of the estimated 25 percent of GHG emissions attributed to agricultural land use, 10–14 percent are from agriculture and 12–17 percent are from land cover change (Paustian et al. 2016). Peatland degradation is estimated to be 25 percent of the total for deforestation and degradation (Paustian et al. 2016). Although soils contribute as much as 37 percent of agricultural emissions (mainly nitrous oxide and methane), improved soil management, as noted in the next section, can change this substantially. Undisturbed waterlogged peatlands, or organic soils, store up to 20–25 percent of the world's soil organic carbon stock and act as net sinks (Smith et al. 2014). Draining peatlands through development or drought increases emissions of carbon and nitrous oxide, and the peat fires that often follow also contribute emissions. Mangrove ecosystems are also important. Mangroves have declined by 20 percent since 1980, which has contributed to emissions (Smith et al. 2014). Up until the 1980s, smallholder farmers were responsible for converting a lot of land to agriculture, but since then large-scale agriculture such as cattle ranching, soybean farming, and plantation agriculture have become more dominant factors in land conversion. This is especially true in Brazil and Indonesia, while in Africa and South Asia, smallholder farmers are still converting land to agriculture (Hosonuma et al. 2012). Examples of relevant mitigation interventions and their co-benefits are summarized online and include changing from ruminants to monogastric livestock, expanding vertical and urban agriculture, and restoring degraded lands.

Soil Degradation. Soil degradation includes erosion, desertification, and other changes in soil that reduce its capacity to provide ecosystem services. Climate change exacerbates the pressures of poor land management and demographic growth on soils through changing rainfall patterns, extreme events such as droughts and floods, and rising temperatures. These effects have greater impact in dryland areas and on sloping lands. During the past 40 years, nearly one-third of arable land is estimated to have been lost to erosion, 25 percent of the Earth's land has been highly degraded or is undergoing degradation rapidly, and the proportion of land mass classified as dry has doubled (UNCCD 2015). Degraded soils have only 50–66 percent of the carbon sink capacity compared to their historic carbon loss of 42–78 Gt (Lal 2013). Examples of relevant mitigation interventions and their co-benefits are summarized online and include amending soil with organic carbon, various control methods to prepare land, and soil conservation techniques.

Machinery. Fossil fuel CO_2 emissions from machinery such as tractors and irrigation pumps adds another 0.4–0.6 $GtCO_2eq/yr$ (Smith et al. 2014). Examples of relevant mitigation interventions and their co-benefits are summarized in the opportunities tables online.

A range of general mitigation strategies have been found relevant for the wide array of emission sources stemming from agricultural production, in addition to those described above. For example, agroforestry and silvopastoral systems, conservation agriculture, and crop diversification attempt to restore and conserve natural resources and ecosystem functions to enhance environmental health. These practices have direct and indirect implications for food systems and the health of human populations (Herrero et al. 2016). The opportunities, with related references and potential food systems implications, are available online.

Organic Production

Organic agriculture has grown increasingly common in high-income countries in recent years as demand for organic products increases annually. Across low- and middle-income countries, many smallholder farmers continue to utilize organic and other agroecological production strategies. For example, they may use agroforestry systems (i.e., growing trees together with crops), silvopastoral systems (i.e., growing trees together with raising animals), agronomy practices (i.e., crop rotations), conservation agriculture (i.e., no tillage), and crop diversification. Scientific data suggests that organic crop production strategies can result in lower energy use (Smith, Williams et al. 2014) and lower fertilizer-related GHG emissions (Pelletier et al. 2008). A recent review of LCAs of beef production systems concluded that organic production systems resulted in a 7 percent lower GWP compared to nonorganic systems (de Vries et al. 2015). Recent global meta-analyses of organic crop production systems found that overall nitrous oxide emissions were lower on a per-area basis, but higher on a yield-scaled basis, indicating that organic production systems would need to increase yields by about 9 percent to be equal to conventional systems (Skinner et al. 2014). However, all of the studies focused on the Northern Hemisphere; evidence from the United Nations concluded that organic cropping production systems in Africa could yield as much or more than nonorganic systems (UNEP and UNCTAD 2008). Other recent reviews conclude that organic production yield is lower than in conventional systems (Reganold and Wachter 2016), with some yield gaps averaging 19 percent lower, but that such gaps did not exist for leguminous plants, annuals versus perennials, or developed versus developing countries (Ponisio et al. 2014). Furthermore, multi-cropping and crop rotations in combination with organic production reduced this yield gap by 9 percent and 8 percent respectively (Ponisio et al. 2014), further providing evidence that a suite of agroecological practices together may provide GHG benefits and yields that are comparable to conventional production. Others have also concluded that while organic agriculture may not currently yield on average as much as conventional, it provides greater ecosystem services, social benefits, and farmer profitability (Reganold and Wachter 2016).

The Impacts of Climate Change on Agricultural Production, Current and Future

The projected impacts of climate change on crop production are geographically very unevenly distributed. Up until 2050, some temperate regions may see favorable changes, including increased crop yields as temperatures and precipitation change (Porter et al. 2014). Beyond 2050, rising temperatures are expected to have a negative impact on food production almost everywhere, though greater impacts are expected in the tropics. Although low-income tropical countries are not the main drivers of climate change, they may suffer the greatest share of the damage in the form of declining yields (resulting from higher temperatures, precipitation changes, and increased weeds, pests, and disease pressure) and greater frequency of extreme weather events (droughts and floods). As a result, smallholder farmers in these countries are expected to be heavily affected (Morton 2007).

The negative effects of climate change on crops and land-based food production is evident in several parts of the world already, with marine and aquaculture production systems being affected as well (Porter et al. 2014). While attention has focused on yields, there is also growing concern about how climate change will affect food quality and food safety (Vermeulen et al. 2012). Changes in the climate and CO_2 levels will “enhance the distribution and increase the competitiveness of agronomically important and invasive weeds” (Porter et al. 2014).

These climate trends appear to have negatively affected wheat and maize production, while the effects to date on rice and soybean yields have been smaller (Lobell et al. 2011). Northeast China and the UK have seen some improvement in yields, given their higher latitudes (Porter et al. 2014). While it is more difficult to quantify the effects of extreme weather events on crops, hot nights damage rice yields and quality, and increasingly high day temperatures have clearly damaged other crops (Smith et al. 2014). In addition, warmer temperatures are affecting the total number of “chill hours,” which are critical for a host of horticultural tree crops (Luedeling at al. 2011). Increases in ozone levels have likely reduced yields of wheat and soybeans as well as maize and rice, especially in India and China (Porter et al. 2014).

Just as climate change is affecting crops differently at different latitudes, there are variances in the impact of climate change on fisheries abundance in the northern and southern ranges – some positive, some negative. Coral reef ecosystems have been damaged and continue to be under threat; their loss would threaten the livelihoods of more than 500 million people who depend on fish that need the reefs (Porter et al. 2014).

Experts believe that climate change has affected livestock production, but there are fewer studies examining these impacts. Available studies suggest that the spread of diseases to livestock has already increased due to climate change. For instance, the blue-tongue virus that affects ruminants and ticks that carry pathogens that cause zoonotic diseases are spreading disease problems for both livestock and human beings, due to climate change (Porter et al. 2014). Furthermore, worldwide 20 percent of livestock production losses are attributable to disease, which has significant implications for GHG emissions in the industry (GRA 2014).

Prices respond to weather changes, among other factors, and spikes often follow climate extremes (Porter et al. 2014). Food price increases are especially worrisome for poor urban dwellers, though their negative impact extends further.

More than 70 percent of agriculture overall is rainfed (as opposed to irrigated), and thus sensitive to changes in rainfall accompanying climate change (Porter et al. 2014). Perhaps as many as 3 billion people rely on groundwater as a source of drinking water, and climate change likely affects groundwater levels now and will in the future. In arid and semi-arid areas, precipitation may decrease by 20 percent over the next century. Increasingly erratic rainfall patterns will affect rainfed agriculture – for example, in Sub-Saharan Africa, where over 90 percent of agriculture is rainfed – and may contribute to poverty, migration, conflict, and other destabilizing developments.

4. A Review of Post-Production Activities, Dietary and Consumption Patterns, Food Waste, and Climate Change

In order to complement the above review of agriculture and food production literature, this section reviews literature relating to climate change and post-production, consumption, food loss, waste, and disposal. While the literature on climate change and agricultural production is rather robust, peer-reviewed literature on the activities described in this section is more recent and less prevalent – in particular, few substantive reviews take a systems perspective. The length of this section reflects the breadth of the topics included, rather than the depth of available research.

Post-Production Activities

Post-production activities include food processing, packaging, distribution (transport), and the cold chain (i.e., continuous refrigeration through the supply chain). As food systems change going forward, post-production emissions may make up a larger share of total emissions (Vermeulen et al. 2012). That share is also likely to vary greatly by country, with larger post-production percentages – perhaps greater than half – occurring in industrial economies. While agriculture and food production GHG emissions stem from a variety of activities, post-production emissions are largely associated with energy use. (One notable exception is the direct release of refrigerants.) Therefore, efforts to lower the emission intensities of electricity grids and transportation fleets will help to mitigate the emission intensities of post-production activities as well. In addition, tracking post-production energy use can help in identifying mitigation priorities, as the relative GHG contributions are likely to mirror the distribution of energy consumption.

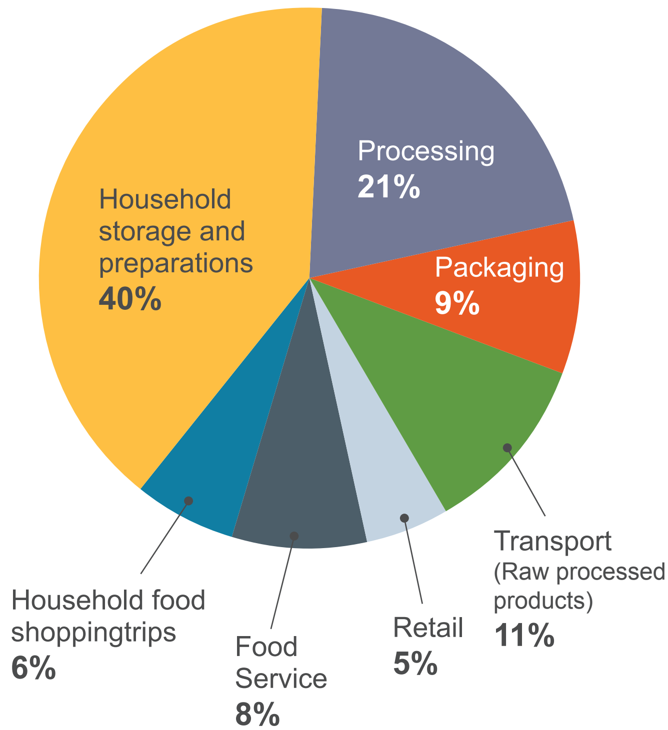


Figure 2. Distribution of the roughly 8.5 EJ consumed post-production annually in the U.S. food systems circa 1995. Data adapted from Heller and Keoleian, 2003. (EJ = 1018 J)

Figure 2 shows the distribution of energy consumption across post-production stages in the U.S. food system, as an example. Food-related energy consumption in the home represents a striking contribution, 55 percent of that contribution is used by refrigerators and freezers, and the balance distributed between cooking and dishwashing.

This section details important aspects of post-production food systems and highlights opportunities for GHG emission mitigation. Summaries of a range of documented mitigation opportunities and their co-benefits are available online.

Food Processing. In its most basic sense, food processing involves converting foods from one form to another in order to improve their stability and storability, their bioavailability and nutrition, and/or their desirability by the end user. Industrial food processes have traditionally been designed with the assumption of abundant and cheap material and energy resources (van der Goot et al. 2016). As a result, many are energy-intensive. Within the U.S. food processing sector, grain and oilseed milling, and particularly wet corn milling, are the largest consumers of energy, both in an absolute sense as well as energy cost per unit of output value (U.S. EIA 2013; Wang 2013). Other energy-intensive processes include removing water during the intermediate or final stages of food processing (often after large quantities of water have been added in a previous stage) and assuring food safety through pasteurization, sterilization, and the like.

Much of the food manufacturing industry relies on highly refined ingredients (e.g., high fructose corn syrup and soy protein isolate) with defined compositions and broad applicability (van der Goot et al. 2016). The manufacture and use of pure (and often dry) ingredients allows for the industrial-scale production of standardized material and promotes the concept of global sourcing. However, making pure ingredients from complex raw materials requires intensive processing and involves large quantities of solvent and often harsh processing conditions. Thus, significant resources go into achieving high purity standards (van der Goot et al. 2016).

Packaging. Packaging is an essential part of post-production food systems. Packaging enables food to get from where it is produced to where it is consumed with an acceptable level of safety, quality, and appearance. Food and beverage packaging accounts for roughly half of all packaging materials (Selke 2012) and can be a prominent component of municipal solid waste.

Transportation. As climate change is contributing to sea-level rise, researchers expect that climate change will likely threaten global food distribution (Brown et al. 2015). A common assumption is that transportation dominates the GHG emissions of a food's lifecycle. However, a literature review of 116 food LCA studies revealed that, for most foods, distribution contributes less than 10 percent of the GHG emissions per kilogram of food (Heller, in review). Exceptions include many vegetables, where the agricultural production impacts per kilogram are low, and fish and seafood, where time-sensitive international distribution is often involved.

An oft-cited input/output LCA study of food for U.S. households found that the direct distribution of foods (from farm or production facility to retail stores) represented only 4 percent of total GHG emissions, with indirect transportation (e.g., delivery of fertilizer to farms) adding an additional 7 percent. Food production (on-farm and processing), on the other hand, represented 83 percent of total emissions (Weber and Matthews 2008).

The Cold Chain (Refrigeration). An estimated 40 percent of all food requires refrigeration, but less than 10 percent of such perishable foodstuffs are currently refrigerated worldwide. About 15 percent of the electricity consumed worldwide is used for refrigeration (James and James 2013). The little data available suggest that the food cold chain (i.e., uninterrupted refrigeration along food product supply chains) currently accounts for approximately 1 percent of CO_2 production globally (James and James 2013). In the absence of notable intervention, this will likely increase as low-income economies acquire cold chain capacity and as global temperatures increase, raising refrigeration energy needs. Experts suggest, however, that with use of the most energy-efficient refrigeration technologies, it would be possible to substantially extend and improve the cold chain without any increase in CO_2 emissions, and possibly even with a decrease (James and James 2013).

The food and drink manufacturing, food retail, and catering sectors are responsible for an estimated 4 percent of the UK's annual GHG emissions, with a little over half of this (about 2.4 percent) due to food refrigeration (although the refrigeration of imported foods could increase this figure to at least 3–3.5 percent) (Garnett 2007). Based on calculated estimates, milk requires the most cooling in the UK, taking an estimated 2.5 times more energy than all other food commodities added together (and 4.5 times more than all types of meat combined) (James and James 2010).

Crops in most locations are seasonal, and there is a need to store food in some way between time of harvest and time of consumption. Consuming local food year-round requires additional or improved storage, leading to impacts typically in the form of energy consumption for refrigeration or freezing. Identifying a minimally impactful consumption strategy would require balancing these impacts with emissions from the transport of nonlocal foods, and this balance likely will vary by season. Such a tradeoff was demonstrated for apples consumed in the UK; eating domestic apples in season resulted in the lowest energy use, but later in the year (during the European spring and summer), apples from the Southern Hemisphere likely would be the lower-energy option (although variability in the data was too large to say this definitively) (Milà i Canals et al. 2007).

Food Transport Refrigeration. Worldwide, there are approximately 1,300 specialized refrigerated cargo ships, 80,000 refrigerated railcars, 650,000 refrigerated shipping containers, and 1.2 million refrigerated trucks in use (James and James 2010). Transport refrigeration systems are typically oversized, and with refrigerated trucks, are invariably driven by an auxiliary diesel engine. These auxiliary engines, combined with the impacts of refrigerant leakage, can result in GHG emissions up to 140 percent that of nonrefrigerated truck transport (Tassou et al. 2009). Furthermore, the performance of insulation materials in such vehicles (and foam-based refrigeration insulation in general) degrades with time, with typical loss of insulation value of 3–5 percent per year. After nine years of operation, this can result in a 50 percent increase in energy consumption and CO_2 emissions (Tassou et al. 2009). Alternatives to current standard transport refrigeration systems are under development and can offer significant reductions in energy consumption and emissions. In fact, the rejected heat from large truck engines is sufficient to drive alternative refrigeration systems under normal long-haul driving conditions. Design and implementation challenges remain, but such alternatives present promise (Tassou et al. 2009).

Refrigerants. When chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants were phased out because they harm the ozone layer, they were replaced to a large extent with hydrofluorocarbon (HFC) refrigerants. HFCs are efficient and not ozone-depleting, but they have a GWP thousands of times greater than that of CO_2. The Montreal Protocol's Kigali Amendment – adopted October 15, 2016 – commits countries to phasing down the production and consumption of HFCs by more than 80 percent over the next 30 years, avoiding more than 80 billion tonnes of CO_2eq emissions by 2050. Developed countries will begin the phase-down in 2019, with most developing nations following suit by freezing the use of HFCs in 2024. A handful of the world's hottest countries were granted a more lenient schedule and will freeze HFC use by 2028.

Cold Chain Expansion. Many parts of the world currently do not have well-developed cold chains, and this lack of refrigeration capacity contributes to food waste. However, the cold chain is a transformative technology and, as such, there are numerous and complex interactions and feedbacks between refrigeration, food production and consumption decisions, infrastructure development, and the global environment that make the accompanying environmental impact of cold chain introduction difficult to predict (Heard and Miller 2016). While refrigeration may decrease post-harvest food spoilage and losses, household refrigeration and altered buying patterns may lead to increases in consumer-level food waste. Combined with dietary shifts and a demand for new product types enabled by refrigeration, the net change in energy and resource use, and subsequently GHG emissions, is ambiguous. Further research and improved data quality are needed to better understand the cumulative influence of cold chain introduction and to help direct such development toward sustainability.

The Impacts of Dietary and Consumption Trends on Climate Change

What people eat has a significant impact on how much food systems contribute to GHG emissions and on the land required for agriculture. In this section, we explore current knowledge about the impacts of dietary and consumption trends on climate change.

There is a growing scientific focus on the potential environmental, health, and social implications of food choices. Individual diets have changed over the past several decades, with an increase in animal products, processed and packaged foods, and empty calories (Tilman and Clark 2014). These trends have a range of potential impacts, including higher prevalence of chronic, noncommunicable diseases, lower overall life expectancy, additional land use changes (Hallström et al. 2015), and up to an 80 percent increase in global GHG emissions from the food system by 2050 (Popp et al. 2010; Tilman and Clark 2014). At the same time, however, poverty in low-income countries has decreased, with corresponding decreases in hunger and malnutrition. In 2015 there were 216 million fewer undernourished people than in 1990–1992 (FAO 2015).

Given that diets can make up a significant portion of an individual's carbon footprint (Macdiarmid 2013), some studies suggest that dietary changes may be more effective than technical agricultural mitigation options in reducing global GHG emissions (Popp et al. 2010; Smith et al. 2013) However, the research also provides insight into factors that may be overlooked in disciplinary-specific studies and has created new debates over how to measure dietary changes and their potential impacts. In this section, we summarize the state of the knowledge on the impact of diets and consumption patterns on climate change. Summaries of a range of documented mitigation opportunities and their co-benefits are available online.

Processed Food. While this topic is not often discussed, some studies suggest that reducing consumption of processed foods may offer opportunities for reducing diet-related emissions (van Dooren et al. 2014; Green et al. 2015). Higher energy requirements for processing, packaging, or transportation result in increased emissions. Recent work from Hanssen et al. (2017) in Norway found that ready-to-eat meals had much higher associated energy use and GHG emissions than their less-processed equivalents. By switching from eating only ready-to-eat dinners to eating only fresh ingredients for dinners, a household could reduce GHG emissions the same amount as if they drove 900 km, or 8 percent of the average total driving distance per household annually (Hanssen et al. 2017). Yet, these benefits could be negated if the fresh ingredients were grown in heated greenhouses or air-freighted (González et al. 2011; Hoolohan et al. 2013). Also, from a systems perspective it is important to distinguish between processed food and ultra-processed food. Some level of processing has resulted in the higher intake of healthy foods such as fruits and vegetables (e.g., bagged salads), which may result in health benefits.

Balancing Energy Intake and Individual Metabolic Demands. Overall, lower-calorie diets are decreasing worldwide as high-calorie diets have grown particularly common in high-income countries (Pradhan et al. 2013). Diets that include more energy intake than individual metabolic demands can result in greater environmental impact (Nelson et al. 2016; van Dooren et al. 2014) and, in areas of overconsumption, can constitute a notable portion of an individual's diet-related carbon footprint. For example, people in Portugal on average consume 41 percent more calories than recommended; shifting to an average diet of 2,500 kilocalories could reduce GHG emissions (Galli et al. 2017). Another study found that adjusting energy intake to meet energy needs could reduce GHG emissions up to 11 percent, depending on physical activity level (Vieux et al. 2012). Others have found that discretionary foods that contribute to additional energy intake (largely alcohol, candy, and baked goods) accounted for up to 39 percent of the average diet in Australia. Researchers have suggested that balancing energy intake and output by reducing discretionary food intake could allow for an increased consumption of vegetables, dairy, and grain, which would have significant health benefits with minimal GHG impact (Hendrie et al. 2016). However, dietary shifts away from discretionary calories and foods may be particularly challenging given that such foods are cheap, convenient, and palatable (Hadjikakou 2017).

Animal Product Consumption in Diets. Increased GHG emissions have been associated with diets higher in animal products (González et al. 2011; Bajzelj et al. 2014; Abbade 2015), and animal-based foods are one of the largest portions of GHG emissions in an individual's diet (Heller and Keoleian 2014; Monsivais et al. 2015; Hendrie et al. 2016; Clune et al. 2017; Hanssen et al. 2017; Vetter et al. 2017). As a result, diets with less animal-based protein have been associated with fewer environmental impacts, including GHG emissions (Martin and Danielsson 2016; Nelson et al. 2016; Nemecek et al. 2016). This has led some researchers to conclude that dietary shifts that include a reduction in animal products – especially in high-income countries with high rates of per capita meat consumption – will be "indispensable" for reaching the 2°C climate goal (Hedenus et al. 2014). It's important to note, however, that much of the relevant research is focused on diets and production systems in high-income countries. Dietary changes may not be appropriate for everyone and are dependent on nutrition status, culture, and other considerations. For example, animal consumption is an important aspect of some indigenous cultures.

Many studies have examined how diet shifts toward certain dietary guidelines (e.g., World Health Organization or country-level dietary recommendations) or alternative animal or plant-based products may result in reduced GHG emissions and other environmental impacts. Below we detail the existing scientific basis for shifting from red meat consumption toward other animal protein sources (pork, chicken, eggs, dairy) and from red meat consumption toward plant-based alternatives. Given the potential nutritional shifts that may also occur as a result, we explore the literature from both a nutritional and an environmental standpoint.

Researchers have found that the environmental impacts per consumed calorie of poultry, pork, dairy, and eggs are all relatively similar, with beef resulting in roughly five times the GHG emissions of these alternatives (Eshel et al. 2014). Studies have confirmed that shifting from red meat consumption toward pork or chicken can offer a reduction in GHGs (Roy et al. 2012), with estimates from Japan coupled with a "healthy and balanced diet" suggesting that up to 54 million tonnes of CO_2eq could be abated annually. Other UK studies have suggested that a complete shift from beef to pork and chicken in the average UK diet would result in an 18 percent reduction in GHG emissions (Hoolohan et al. 2013). Similarly, a 75 percent reduction of beef and sheep meat, replaced by poultry or pork, resulted in a 9 percent reduction in dietary GHG emissions and an average of nearly 2,000 deaths averted annually in the UK

(Scarborough et al. 2012). More modest shifts toward 50 percent reductions in meat consumption could result in a 19 percent reduction in GHG emissions and accompanying decreases in mortality (Scarborough et al. 2012). Many other studies confirm that a reduction in meat consumption or substitution (e.g., with beans) would lead to notable GHG reductions of up to 40 percent (Scarborough et al. 2014; Westhoek et al. 2014; Sabaté et al. 2015).

Shifting meat consumption entirely toward plant-based foods (vegan) or entirely away from meat but still including eggs and dairy (vegetarian) and fish (pescatarian) has also been extensively explored in research. While the literature is nearly universal in the conclusion that vegetarian and/or vegan diets do result in fewer GHG emissions, their potential differences from each other, and their health implications, have been debated. Studies indicate that vegetarian and vegan diets have the potential to reduce food-related GHG emissions in 2050 by up to 70 percent over current diets, largely as a result of the elimination of red meat (Springmann et al. 2016). Current UK diets shifted toward vegetarian or vegan could reduce GHG emissions by 22 percent (vegetarian) or 26 percent (vegan), the equivalent to a 50 percent reduction in vehicle emissions from UK passenger cars if adopted by the entire country (Berners-Lee et al. 2012). The difference between the two – the inclusion of eggs and dairy or no animal products at all – results in varying outcomes for dietary GHG emissions. For example, cheese has been found to have higher dietary emissions than eggs and poultry; conversely milk, cream, and yogurt have much lower dietary GHG emissions than eggs, poultry, and even many vegetables and grains (Hamerschlag 2011; Scarborough et al. 2014). Thus, while the scientific literature consistently demonstrates that a reduction in red meat consumption results in fewer GHG emissions, reductions in dairy consumption do not have the same overall effect and may be more nuanced by product type.

Related research exploring diets associated with particular cultures, such as the Mediterranean or New Nordic diets, have found that these reduce GHG emissions compared with traditional Western European diets (Saxe et al. 2013; Pairotti et al. 2015), though vegetarian diets have the potential to reduce GHG emissions even more (Pairotti et al. 2015; Tilman and Clark 2015).

Health Implications of Dietary Shifts. Many studies have examined how dietary shifts could offer both environmental and public health benefits. Though recent research suggests that healthy diets are often associated with a lower emissions footprint (Fischer and Garnett 2016), it cannot be assumed this is always the case (Macdiarmid 2013). The issue is complex, in part because it depends on whose definition of "healthy" is used, as well as the fact that animal products add valuable nutritional benefits to an individual's diet, and the complete elimination of certain food groups without adequate substitution could result in nutritional deficits, particularly in low-income countries. As such, nutritional perspectives must be considered along with GHG reduction (Vetter et al. 2017).

The literature broadly suggests that dietary shifts away from animal products, especially red meat, do offer modest mortality risk benefits (Aleksandrowicz et al. 2015 and 2016; Westhoek et al. 2014) and that there tend to be synergies between diets low in GHGs and health benefits (Gephart et al. 2016; Irz et al. 2016). However, this is not universal; sugar, for example, has a low GHG impact but negative health consequences (Briggs et al. 2016).

Scholars have argued that the health effects of dietary shifts need to be considered for both their potential positive health benefits (due to potential reductions in morbidity and diet-related chronic diseases), as well as whether such shifts would result in malnutrition, particularly for the world's poorest (Garnett 2011). For example, Springmann et al. (2016) found that, in low-income countries, meat consumption in line with standard dietary recommendations would result in major health benefits through reduced mortality and provide the greatest health and environmental benefits. Tilman and Clark found that vegetarian diets could reduce the risk of Type II diabetes, cancer, and mortality in some cases up to 50 percent overall compared with omnivorous diets. However, other papers that have considered similar shifts have found potential for malnutrition. In a recent systematic review, 64 percent of papers reviewed found that reduced-GHG diets were associated with worse indicators of health, concluding that while these diets were lower in saturated fat and salt, they were usually higher in sugar and lower in essential micronutrients (Payne et al. 2016). Temme, Bakker et al. (2015) found that while vegetarian and vegan diets would decrease saturated fat intake by 9 and 26 percent, vegetarian diets would result in less B12 intake, and vegan diets would result in less intake of calcium, zinc, thiamin, and B12, which could impact childhood malnutrition. Others have suggested that while a vegan diet can reduce environmental impacts, including GHG emissions, it does lead to an inability to meet certain nutrient requirements (e.g., omega-3 fatty acids) (Tyszler et al. 2016).

Importantly, this evidence suggests there appear to be thresholds at which dietary shifts might cause unexpected negative consequences and be less accepted by consumers. Both Milner et al. (2015) and Green et al. (2015) found that dietary shifts (e.g., fewer animal products and processed foods and more fruits, vegetables, and cereals) causing GHG emission reductions of more than 40 percent would be possible but might result in decreases in health outcomes and acceptability. Perignon et al. (2016) observed that moderate GHG reductions from dietary shifts were compatible with nutritional outcomes, while higher reductions impaired nutritional quality and resulted in significant diet changes outside the scope of public acceptability. Others have concluded that a diet with lower meat consumption could reduce GHG emissions by 36 percent and would be much more acceptable to consumers compared to more significant dietary shifts; also, such diets are comparable in cost to average food expenditures (Macdiarmid et al. 2012).

Low- and Middle-Income Country Focus. We and others have found that most diet-related climate impact studies focus on high-income countries (Jones et al. 2016), potentially because the per capita mitigation potential is higher in high-income economies, where high-emission diets are more common. Studies that have explored low-income and emerging economies most often focus on China, India, and Brazil. Pathak et al. (2010), for example, found that most of an Indian's dietary impact comes from the production of the food, since Indians mostly consume fresh, local, vegetarian foods. Nonvegetarian Indian meals with mutton have 1.8 times the GHG emissions of a vegetarian meal. The authors and others confirm that dietary shifts toward increased animal products could result in a significant rise in Indian dietary GHGs (Pathak et al. 2010; Vetter et al. 2017). Results from China confirm that dietary shifts could provide both human health and climate mitigation benefits in that country (Song et al. 2016). In Brazil, 80 percent of the population currently consumes more red meat than is recommended, which if dietary recommendations had been followed would have reduced GHG emissions by 60 million tonnes (Carvalho et al. 2013). Evidence from these countries largely echoes evidence from high-income countries, but the paucity of research from these regions suggests a clear need for additional studies, including on consumer demand for diet alternatives in low- and middle-income countries that have high levels of biological and cultural diversity (Jones et al. 2016).

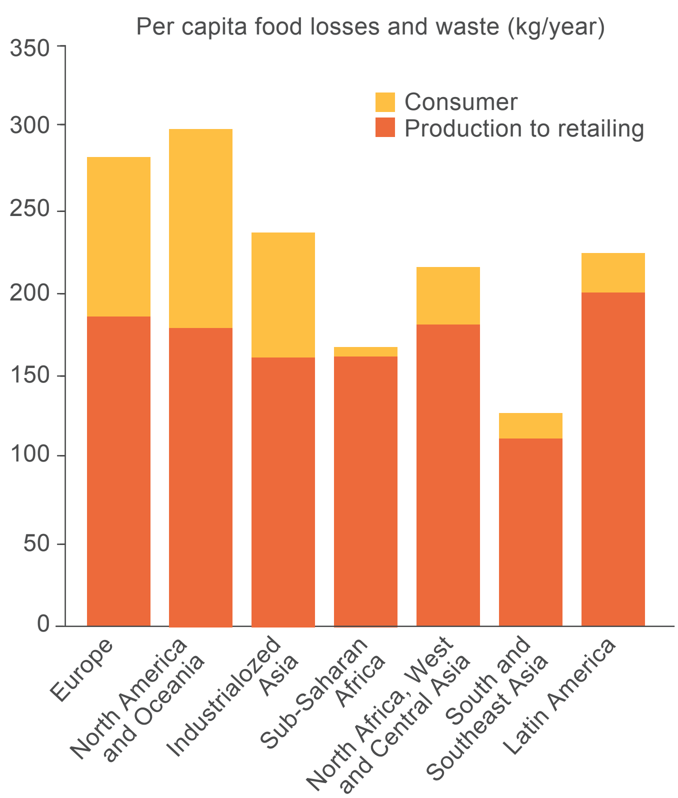
Food Loss and Waste

Roughly one-third of the edible parts of food produced for human consumption gets lost (pre-consumer) or wasted (consumer-level) globally; this equates to about 1.3 billion tonnes of food per year. The FAO estimates that if food loss and waste were a country, it would be the third-largest source of GHG emissions (FAO 2013b). Food waste and the resulting GHG emissions raise both equity and ethical considerations (Tirado et el. 2017).

Food loss and waste not only decreases access to and availability of food, it represents the waste of all emissions associated with the growth, transportation, processing, distribution, storage, and preparation of the food (Garnett 2011; Gustavsson et al. 2011). The further along the supply chain a food is, the more "wasted" emissions are associated with its loss (Bajzelj et al. 2014). Total GHG emissions associated with food loss and waste are estimated at 3.6 $GtCO_2e$ per year, not including emissions from deforestation and organic soils (Gustavsson et al. 2011).

Food loss and waste varies significantly between low-, medium-, and high-income countries, both in quantity and in its causes (Dorward 2012). In medium- and high-income countries, food, to a great extent, is wasted downstream, at the retail and consumer level, where it goes uneaten. However, significant food loss also occurs early in the supply chain. In low-income countries, food is mainly lost during the upstream early and middle stages of the supply chain; much less food is wasted at the consumer level (Gustavsson et al. 2011; FAO 2013b; Blanke 2015). In low-income countries, the wastage prior to consumption occurs primarily during storage and transport, whereas in high-income countries, wastage prior to consumption can result from disposal of food considered to be substandard for consumer preferences. As a result of these differences, the strategies and opportunities to combat food loss and waste must consider the country context and aspects of the supply chain that contribute to such losses, even though all countries can reduce food waste at any part of the food system. Figure 3 shows relative food waste and losses in different global regions. Summaries of a range of documented mitigation opportunities and their co-benefits are available in the opportunities tables available online.

Figure 3: Per capita food losses and waste, at consumption and pre-consumption states, in different regions (Gustavsson et al., 2011)



In high-income countries, many opportunities to reduce food waste at the retail level focus on consumer perceptions. Campaigns in Europe and the U.S. have demonstrated that "ugly" produce or slightly damaged products are still edible and people will purchase them, especially at a discount. In addition, changing stocking strategies so that retail stores do not overstock for appearances is critical, since most retail losses are fruits and vegetables (Scholz et al. 2014). Moreover, retail stores can use packaging and processing technologies that help keep food fresh for longer and can clarify sell-by dates to reduce premature disposal by consumers (Blanke 2015; Wilson et al. 2017). Prevention of consumer food waste must consider complex human behaviors (Quested et al., 2013), but can involve consumer acceptance of "ugly" produce, increased planning and preparation for cooking, better storage techniques, and food sharing (Blanke 2015).

In low-income countries, a lack of infrastructure, including a lack of cold-chain refrigeration, processing facilities, and reliable transportation to bring products to market, is often at the core of these challenges. As a result, crops may rot before they can be fully utilized (FAO 2011). Also, a scarcity of available drying technologies contributes to losses as a result of aflatoxins, which occur when staple crops are not properly dried after harvest (PACA 2013). Minimizing food losses from these dominant sources in low-income countries includes the expansion of transportation, processing, and preservation infrastructure, including cold-chain and drying technologies, as well as increased market opportunities (FAO 2011).

Additional research is needed for improved estimates of global food losses and waste, country-specific loss and waste estimates, and comparisons between different parts of the system that use different metrics for measuring total waste (e.g., production loss and consumption waste) (Bajzelj et al. 2014). Additional efforts are needed to support crop breeding to integrate properties for resilience and nutrition, for instance through new varieties that are both climate (heat) resilient and more nutritious (Global Panel 2015), and to improve disease prevention and control in response to changing disease prevalence.

Gaps in Current Knowledge Regarding Food System Activities and Climate Change

While research on the interactions among climate change, food, and agriculture is growing, many pressing areas require additional study in order to enable researchers, policymakers, and others to fully implement a food systems perspective. Many reports have identified specific research needs that would strengthen knowledge of specific food systems elements. The following is a summary of some of these research needs.

Pre-Production

- Research on alternatives to synthetic fertilizers – for example, on innovations to enable the nutrients present in organic waste materials to be used as waste-based fertilizers
- A global assessment of GHGs associated with pesticide production in the context of contributions to food security and adaptation (Lechenet et al. 2017)
- An assessment of the impacts of various fodder sources and seed resources, and of the application of information management and soil and water management practices

Production

- An improved spatial emissions database, to help countries identify adaptation and mitigation strategies appropriate for their own contexts (Tubiello et al. 2013)
- Improved data on crop production systems (including practices); on grazing areas (including quality, intensity, and management); and on freshwater fisheries and aquaculture (Smith et al. 2014)
- Globally standardized data on soil and forest degradation, and a better understanding of the effects of degradation and rehabilitation on carbon balances and productivity (Smith et al. 2014)
- Studies seeking to understand the costs and consequences of land-use-based mitigation (such as improved agricultural management, forest conservation and restoration, bioenergy production, and afforestation at various scales) (Smith et al. 2014), especially for low-income countries that are expected to have the majority of increases in production and post-production emissions
- Studies and data on yield variability, in the context of climate change influencing price fluctuations. Future scenarios are helpful for making adaptation and mitigation plans, and these models need good yield data that takes into account different scales (Porter et al. 2014)
- GHG emissions data from nontemperate agricultural systems, exploring conventional production, organic production, and alternative production systems such as agroforestry and silvopastoral systems, as well as ecosystem-based adaptation (Skinner et al. 2014; Vignola et al. 2015)
- Food security studies that examine the range of adaptations available to the various food system actors (Porter et al. 2014)
- Global-level farmer surveys and assessments regarding barriers and policies that impede the successful adoption of climate mitigation and adaptation strategies

Post-Production

- Development of new model for food processing that focuses on efficiency, sustainability, and human nutrition, rather than the current "refined ingredients" model used in many high-income countries
- Research to gain a better understanding of the relationships among food packaging, consumer behavior, and food waste – for instance, to improve packaging design to reduce food waste

- Continued research to overcome design and implementation challenges in emerging and alternative mobile refrigeration systems that are aimed at increased efficiency, reduced environmental impacts, and improved resilience
- Studies to help understand the systemwide implications of cold chain expansion into low- and middle-income economies, to ensure that this transformative technology expands in a manner that is mindful of environmental impacts, sustainability, and system resilience
- Careful assessments of the GHG emission balance between the location of food production (local vs. distant, to include location-specific agronomics), transportation, and seasonal supply dynamics

Consumption

- An assessment of vegetarian or vegan meat alternatives from different production technologies. A few LCA studies of soy and other plant-based products exist, but not of emerging technologies.
- Research into dietary shift strategies, including consumer acceptability, and their GHG reduction potentials in low- and middle-income countries
- A systematic assessment of incentives for behavior change among both high-income and low-income consumers (e.g., Afshin et al. 2017)

Food Loss, Waste, and Disposal

- Research into innovative practices to reduce food loss and waste at each stage of the food supply chain (including the production, transportation, retail, and consumption systems), without compromising food and feed safety
- Scientific evidence for the development of legislation related to food and feed waste in high-income countries
- Studies that would facilitate the use of byproducts and the reuse of foodstuffs – for example, for animal feed production – without compromising food and feed safety
- Improvements in the use of date marking and consumer understanding of date marking – in particular, “best before” labeling – while ensuring food safety
- Technology for the transformation of food and feed waste into energy sources and organic fertilizers
- Research into changes in retail-level and consumption-related food waste in low- and middle-income economies
- Empirical evidence and strategies for food waste reduction upstream in low- and middle-income economies, including post-harvest storage, aflatoxin reduction, and transportation
- Development of a widely accepted methodology for quantifying food waste. The data are highly variable at present, which results in a large range of potential impacts (Porter, Reay, et al. 2016).

Food System Externalities

- A universal, widely accepted framework for recognizing, demonstrating, and, where appropriate, capturing the positive and negative environmental, social, and health externalities of food systems (including climate change adaptation) to help ensure that all hidden costs and benefits of different food systems are assessed in their entirety, both in terms of their lifecycle and their impacts on all dimensions of human well-being

The Impacts of Climate Change on Undernutrition, Food Safety, and Food Quality

Climate change, and its consequent global environmental changes, can have significant impacts on food and water security and on undernutrition, particularly in low-income countries.

Undernutrition. Climate change and variability affect the key underlying causes of undernutrition: household food access, access to maternal and child care and feeding practices, and environmental health and health access (Tirado et al. 2013). These determinants of malnutrition are shaped by other socio-economic factors that are also impacted by climate change, such as income, wealth, education, safety nets, food aid, institutional inequities, human rights, trade, economies, infrastructure, resources, and political structures (Tirado et al. 2013). Climate-related extreme weather events and disasters further negatively impact diet quality and nutritional and health outcomes, undermining resilience to climatic shocks and the coping strategies of vulnerable populations and lessening their capacity to adapt to climate change (Tirado 2017).

Changes in temperature and precipitation will very likely contribute to increased global food prices by 2050, with estimated increases ranging from 3 percent to 84 percent (Porter et al. 2014), and which in turn will affect food security. Projections based on high GHG concentrations, high population growth, and low economic growth estimate that the number of people at risk of undernourishment globally will increase by as much as 175 million (above today's level) by 2080 (Brown et al. 2015). Calorie availability in 2050 is likely to decline across low-income countries, resulting in an additional 24 million undernourished children, almost half of whom will be living in sub-Saharan Africa (Nelson et al. 2009). Climate change may also have an impact on rates of severe stunting, which have been estimated to increase by up to 23 percent in central sub-Saharan Africa and 62 percent in South Asia by 2050 (Lloyd et al. 2011).

Food Safety. Climate change may have direct and indirect impacts on the occurrence of food safety hazards at various stages of the food chain, from primary production to consumption (Tirado et al. 2010). It may affect the underlying drivers of food safety, such as agriculture, crop production and plant health, animal production and animal health, fisheries and aquaculture, food trade, distribution, and consumer behavior. These impacts in turn have substantial public health, economic, and social consequences.

Climate-related factors such as temperature and precipitation changes have an impact on microbial populations; the environment; the emergence, persistence, and patterns of occurrence of bacteria, viruses, and parasites in animals and foods; and the corresponding patterns of food-borne and waterborne disease (e.g., viral and bacterial diarrheal episodes, salmonellosis, vibriosis, shigellosis, cryptosporidiosis) (Tirado et al. 2010). These climate factors have an impact on the emergence, redistribution, and changes in the incidence and intensity of plant and animal diseases and pest infestations, all of which could affect food-borne diseases and zoonoses (FAO 2008; Tirado et al. 2010b). Climate change is contributing to the increasing occurrence of natural toxins produced by fungi (including aflatoxins) that can be highly carcinogenic and deadly to consumers, and is also increasingly linked to immune suppression in infants and impaired linear growth of children (FAO 2008; Tirado et al. 2010).

Nutritional Value. Increasing concentrations of CO_2 in the atmosphere can directly affect the nutritional value of plant foods. Elevated CO_2 results in more rapid growth rates but also reductions in the concentrations of protein and micronutrients such as calcium, iron, and zinc in many plant crops (Taub et al. 2008, Taub 2010; Fernando et al. 2012; Myers et al. 2014; Loladze 2014, Ziska et al. 2015, Medek et al. 2017, Smith et al. 2017). Reductions in protein and mineral content in turn result in increases in carbohydrates (mainly starch and sugars) in crops such as wheat, rice, and soybeans, and may contribute to a worsening of the prevalence of micronutrient deficiencies and obesity (Loladze 2014). These and other changes in the nutritional value of foods (including vitamin content) due to increased CO_2 levels can affect nutrition programs and need to be investigated, particularly in low-income countries.

5. Applying a Food Systems Perspective to Climate Change

Systems approaches are utilized in a wide range of disciplines and can be defined as "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects (Arnold and Wade 2015)." Stakeholders involved in efforts to create more sustainable food systems and/or efforts to mitigate climate change should adopt a food systems approach to drive changes at the scale needed for systems-level transformation. Fully adopting a food systems approach will require more research that looks at the systems-level impacts of adopting specific interventions. As illustrated in the overview of mitigation opportunities and their adaptation potential (available online), current literature identifies many examples of specific mitigation and adaptation opportunities in different food and agriculture systems. However, an understanding of the systems-level implications of each intervention is limited.

To support stakeholders in using a systems approach to make choices about mitigation and adaptation interventions, we propose a set of Climate Change and Food Systems Principles. These principles, which can be used by stakeholders to explore the systems-level implications of specific opportunities, should be tested and improved through stakeholder engagement. Decisions can also be improved and supported through additional research on specific food systems activities, and – more importantly – deeper systems-level analysis of how mitigation and adaptation potentially affect the overall food system using analytical frameworks, such as the Framework for Assessing Effects of the Food System in the U.S. (IOM and NRC 2015).

Climate Change Food Systems Principles

- **Interconnectedness**: Examine the overall systems-level impacts (including impacts on health, ecosystems, and equity) of specific mitigation and adaptation interventions.
- **Equity**: Pursue mitigation and adaptation interventions that respect human rights and ethical considerations and support sustainable livelihoods, access to healthy and nutritious food, gender equality, and environmental justice.
- **Resilience**: Support interventions that enhance the adaptive ability of diverse biophysical, economic, socio-cultural, and other systems to a changing climate.
- **Renewability**: Advance interventions that support the restorative capacity of the diverse natural and social resources that are the foundation of a healthy planet and future generations.
- **Responsiveness**: Design interventions that are able to respond to unanticipated rapid or significant changes in an uncertain future.
- **Transparency**: Be transparent about the effects of mitigation and adaptation interventions throughout the system, including impacts on health, equity, diversity, and sustainability.
- **Scale**: Evaluate the scale of impacts – positive, negative, and neutral – from interventions in food systems.
- **Evaluation**: Assess systems-level changes within a system change evaluation framework using appropriate systemic measures of mitigation and adaptation interventions and their interactions.

The principles above include, but are not limited to, those adopted by the Global Alliance for the Future of Food.

Applying a Food Systems Perspective to Identify System-Level Effects – Illustrative Examples

To illustrate the implications, benefits, and unintended consequences of specific mitigation opportunities in food systems, we provide three examples in this section. In these examples, we attempt to show how the Climate Change Food Systems Principles could be used to inform decision-making about mitigation opportunities. (The relevant principles are italicized in the discussion below.) We chose examples of opportunities that may be targeted at a variety of food system components (e.g., production, consumption, policymaking) and that would create feedback loops with other food system components.

Example 1: Diet Interventions

Scientific evidence suggests that diets that are less processed, balance energy intake and individual metabolic demands, and include more plant-based components have lower associated GHG emissions. As a result, an increasing number of scientists, health organizations, and even national dietary guidelines – particularly in high-income countries – are recommending dietary shifts that can improve diet sustainability. Such shifts would have several other potential impacts, including implications for human health and livelihoods. This is particularly true when considering the potential suite of dietary interventions across multiple ***scales***. In some contexts (primarily high-income countries), changing diets would provide environmental and health benefits; in others it could negatively influence equitable livelihoods. Using a systems approach enables a better understanding of these potential impacts and a greater interpretation of the full suite of both anticipated and unanticipated consequences.

Existing research suggests that – while not a universal principle – diets that are healthier for humans also generally have reduced GHG emissions (Fischer and Garnett 2016). For example, diets that are higher in plant-based ingredients and lower in animal products are associated with reduced saturated fat intake (Temme Bakker et al. 2015), and diets that are lower in processed foods have reduced sodium content (Webster et al. 2010). Thus, dietary shifts have the potential to not only offer significant health benefits, but if adopted widely, could also reduce dietary GHG emissions (Springmann et al. 2016).

This could have significant implications for ***renewability***, by advancing diet-driven interventions that would support the restorative capacity of natural systems, through reduced environmental impact, as well as social systems, through improved health outcomes. This co-benefit offers significant opportunity to improve human well-being and health while also improving environmental quality, thereby making progress toward two of the SDGs.

At the same time, it is critical that dietary shifts do not compromise overall well-being and are pursued from an ***equity*** perspective. Less commonly discussed in the existing literature on dietary shifts and GHG emissions are the potential negative consequences of such shifts, particularly related to malnutrition in low-income countries (Garnett 2011). Diet-driven interventions should acknowledge the positive benefits that animal production can have in supporting access to nutritious food, particularly in low-income countries where the consumption of animal products is generally low and provides positive health benefits. As a result, dietary-driven interventions should not be the same across all countries – a consideration of ***scale*** is critical. A focus on high-income countries where meat consumption is significantly higher, and where dietary shifts could have both public health and environmental benefits, would provide an ***equity*** lens through which to consider the issue. Utilizing a systems approach can help to identify both of these potential outcomes and provide mechanisms through which policymakers can make recommendations that enable positive health outcomes in combination with reduced dietary GHGs.

In addition, while reducing red meat consumption has been recommended as one of the most effective strategies to reduce dietary GHG emissions (Martin and Danielsson 2016; Nelson et al. 2016; Nemecek et al. 2016), it is critical to explore the impacts of this potential shift on animal agriculture. From a food systems perspective, ***equitable*** interventions support sustainable livelihoods. Recommendations to reduce red meat consumption should consider livelihood impacts where livestock is central to coupled ecosystems and food systems (HLPE 2016) and contributes to the incomes and food security of nearly a billion people. Further, shifts away from animal agriculture could have an impact on integrated farming systems that include animals – including cows – and that may offer economic and environmental benefits, including climate mitigation solutions (Garrett et al. 2017; Niles et al., in revision). While there is a deep body of literature exploring the GHG emissions of dietary shifts, most of these papers do not discuss or estimate any potential impacts on economic development, jobs, and livelihoods in the animal agriculture sector as a result of dietary changes. This is a critical oversight and a topic of study that is greatly needed to better assess the potential costs, benefits, and alternatives in case of dietary shifts across an entire food system.

Example 2: Carbon Prices

Climate finance includes the "financial flows mobilized by industrialized country governments and private entities that support climate change mitigation and adaptation in developing countries" (Stadelmann et al. 2013). The international community, through the Green Climate Fund, aims to mobilize at least USD 100 billion per year for climate mitigation and adaptation in developing countries. If these funds can be raised, it is expected that only a portion will be allocated to agriculture. As the global community continues to raise funds for climate mitigation and adaptation in low-income countries, many institutions are working to increase the resilience of existing agricultural and post-production investments to reduce risks to natural or human assets as a consequence of climate variability and change, and to ensure that those risks are reduced to acceptable levels. The FAO estimates that developing countries on average invested USD 142 billion (in 2009 U.S. dollars) annually in agriculture over the preceding decade (FAO 2009).

Some stakeholders suggest that increasing the climate resilience of current investments is essential for facilitating the transition to green economies, and that doing so will depend in part on coherent government policies that place a price on carbon and support the gradual increase of the cost of CO_2 emissions (OECD 2013). The economic mitigation potential of supply-side measures in the AFOLU sector is estimated to be 7.18–10.60 $GtCO_2eq$/yr at carbon prices up to USD 100 per tCO_2eq, about a third of which can be achieved at less than USD 20 per tCO_2eq (Porter 2014). These numbers apply to production systems, not food systems. Currently, 40 countries and more than 20 cities, states, and provinces use carbon pricing mechanisms or are planning to implement them (IETA 2016).

However, pricing carbon has to be accompanied by strong ***transparency***, accountability, and governance frameworks supported by strong social safeguards. ***Equity*** should also be an important principle to guide carbon pricing policies, and carbon pricing may not be appropriate in all types of economies, which brings up the issue of ***scale***. Although setting food prices to account for the cost of each product's emissions could deter consumers in high-income countries from buying high-emission food and could generate revenue that could be used to reduce carbon emissions (Costello et al. 2015, Abadie et al. 2016), many are concerned about the impacts of carbon pricing on farmers and low-income consumers. Farmers typically have to absorb higher input prices, for example suppliers of fertilizer and other inputs may increase prices to cover their carbon tax costs, and grain traders and transporters will factor carbon taxes into their prices. As a result, low-income families may disproportionately suffer from increased food costs. Furthermore, carbon price may negatively impact agricultural production, food prices and dietary energy consumption (Frank et al. 2017). Researchers have suggested a range of possible policy options, including exempting from taxation those food groups known to be beneficial for health; selectively compensating the income losses associated with tax-related price increases; and using a portion of tax revenues for health promotion (Springmann et al. 2017).

Carbon pricing could be used in decision-support tools to identify the most cost-effective options for investing in climate-resilient food systems. For example, stakeholders are considering putting an explicit price on carbon emissions to help ensure that analyses of policy options and climate mitigation actions identify the most cost-effective mitigation efforts across the economy (Steckel at al. 2017). Climate measures are much more likely to succeed if they not only aim to reduce emissions or create climate resilience, but also address broader domestic development objectives, such as poverty reduction, food security, energy security, energy access, or transportation (Steckel et al. 2017). To integrate food systems thinking and related GHG mitigation and adaptation impacts into the decision-making process of broader policy objectives will require an understanding of the ***interconnectedness*** of components of the system and appropriate, practical analytical and decision-support tools.

The ongoing ***evaluation*** of current carbon pricing mechanisms in countries and cities should guide further development of those mechanisms and inform the development of schemes that are appropriate for national contexts and priorities and that are responsive – that is, that are able to respond to unanticipated rapid or significant changes in an uncertain future.

Example 3: Soil Carbon Sequestration

Decades of research explore the technical potential of agricultural practices to increase soil organic carbon (SOC) sequestration. Current best estimates vary widely from 1.3 up to 8.0 petagrams CO_2e per year (Sommer and Bossio 2014; Paustian et al. 2016); however, there is significant debate over such estimates. A suite of agricultural practices has been recommended for increasing SOC – ranging from setting aside certain lands to grazing, croplands, and rice management and restoring degraded lands – though many recognize that such practices are limited by policy and behavior change (Paustian et al. 2016). ***Transparency*** about scientific estimates of the mitigation and adaptation potential of SOC practices is important, to ensure that farmers, decision-makers, and others are aware of the varying estimates. It is also critical to note that SOC sequestration potential is grounded in several scientific realities, including that such potential is limited and finite and that SOC gains are reversible.

The technical potential of SOC and the applicability of at least some of these practices in nearly all agricultural landscapes provides the opportunity to mitigate climate change. The ***interconnectedness*** of such practices should be considered from a systems perspective – not merely with a focus on agriculture. For example, an increase in SOC may be possible in certain soils through the addition of nitrogen inputs (Paustian et al. 2016). Such practices would increase pre-production emissions due to fertilizer production, however, and the potential net GHG emission benefits may not be a gain. In addition, water quality may be affected. As such, utilizing an evaluation framework for the suite of potential management practices that could result in SOC gains would enable decision-makers to systematically assess them.

Relatedly, the implementation of no-till agriculture has been widely promoted as a potential opportunity for SOC gains (Neufeldt 2013; UNEP 2015; Paustian et al. 2016), but assessment of the practice across food systems is not often considered, and it has implications for ***renewability***, ***equity***, and ***resilience***. No-till agriculture has particularly expanded in combination with genetically-engineered crops (Bedano et al. 2016), which has implications for ***renewability***. Since herbicides often replace the role of tillage for weed control, herbicide use may increase. For example, in the US adopters of glyphosate-tolerant maize and soybeans have used an increasing amount of herbicides since the introduction of such crops (Perry et al., 2016). As a result, the expansion of no-till agriculture may also likely be accompanied with a rise in herbicide use, which could increase pre-production GHG emissions and threaten other potential SDGs related to land and water quality, while potentially affecting the ***restorative*** capacity of natural resources. However, no-till agriculture is also usually accompanied with a reduction in tractor use and thus diesel fuel emissions and CO_2 reductions, which for farmers at least, could provide important social benefits for their farms and families, and may contribute to better livelihoods.

Transparency should also be considered when evaluating no-till agriculture and its potential for mitigation and adaptation. Its potential for CO_2 reductions has been widely shown in dry soils in particular (Abdalla et al., 2016). It has also been shown to have great potential to increase yields in low-income countries with degraded soils (Lal, 2006). However, in other contexts, the scientific basis for SOC increases in no-till agriculture has been questioned, particularly since some evidence suggests that most SOC changes are not gains per se, but redistributions within the soil profile, and may actually increase nitrous oxide emissions in certain soil and climate conditions (Powlson et al., 2014). A global meta-analysis has suggested that on average across 50 crops, no-till agriculture results in 5% yield declines, which would have significant system impacts on livestock feed and food security (Pittlekow et al., 2015). Thus, ***scale*** is important to consider for no-till agriculture, as research suggests it has great promise in some regions and questionable benefits and potential implications for ***resiliency*** and ***renewability*** in other places.

Here we focused only on a few potential practices that may have SOC implications as an example. All soil carbon sequestration practices likely have both co-benefits and potential consequences throughout the food system, which can either help or potentially hinder achieving important SDGs and have implications for the many food system principles. Thus, we suggest that a food systems lens can help identify practices that may have the potential to increase SOC, but minimize other food system emissions sources and consider potential food security implications.

6. Concluding Comments

Major transformations are needed to create equitable, sustainable and resilient food systems that enable all people to access healthy food and restore Earth's resources. A diverse range of stakeholders should be engaged to create the visions of such food systems and to chart pathways to achieving this vision. Climate change mitigation and adaptation actions will be an important component of creating equitable and sustainable food systems. We believe that a food systems perspective is imperative if we are to successfully achieve climate mitigation and adaptation targets and the SDGs.

In this report, we have brought together existing information about climate change impacts and mitigation opportunities regarding a broad range of food system activities. By summarizing peer-reviewed information on these food system activities, we sought to provide a starting point for stakeholders who are working to build sustainable food systems and who need to understand the linkages, multiplier effects, and interactions among the numerous dimensions of food systems. We recognize the limitations of the current body of peer-reviewed literature, which tends to ignore or discount local and Indigenous knowledge and is largely focused on individual elements of food systems and on opportunities that would result in incremental changes. Building on this report, we propose that additional efforts are needed to highlight and bridge local, Indigenous, and practitioner knowledge with academic knowledge; conduct systems-level research to understand and assess the interactions, feedback, and multiplier effects of specific actions; and fill major food system knowledge gaps in low-income and middle-income economies.

Although major transformations are required to create sustainable food systems, immediate actions – though they may result in only incremental changes – can support a longer-term, more fundamental transition toward sustainability. For any changes to take hold and move the world toward sustainability, it is important that stakeholders define "sustainability" and measure unsustainability. Stakeholders need to work together to understand what interests, ideas, and institutions contributed to the current structures, ideas, institutions, policies, and practices. Processes are needed that enable stakeholders to identify their shared interests as well as obstacles to achieving sustainable systems. Such understanding will enable stakeholders to choose actions that contribute to achieving the SDGs and consider the changes in governance systems needed to support and sustain food systems transformation.

A systems perspective is critical to ensuring that climate mitigation and adaptation measures contribute to positive outcomes of sustainable food systems. The Climate Change Food Systems Principles – interconnectedness, equity, resilience, renewability, responsiveness, transparency, scale, and evaluation – should help stakeholders effectively explore food system transformation strategies and apply a food systems lens to adaptation and mitigation opportunities. We hope this report will help a broad range of stakeholders incorporate a food systems perspective into their decision-making and actions relating to climate change, food security, health, environmental integrity, equity, and profitability.

Appendix 1: Per Capita Emissions from Agriculture and Land Use Change

The table in this appendix lists per capita emissions, by country, from agriculture and land use change. The data were taken from FAOSTAT and the World Bank and provide an indication of relative emissions from agriculture and land use change in the world and differences in the importance of the agriculture sector to the economies of each country. The authors recognize that agricultural data is often incomplete and may be narrowly targeted, which may be due to lack of coordination in data collection across ministries of agriculture and national statistics offices, smallholder agriculture being difficult to measure, and poor analysis of data (Dunmore and Karlsson 2008; Carletto et al. 2015). Some of the results below, therefore, may be the result of incomplete or inaccurate data.

To illustrate how the data could be used to see differences among food systems and their related emissions, Figure 4 shows the top 20 countries by emissions per capita and their GDP. For instance, countries such as the Central African Republic and Mali have relatively high emissions per capita, but their economies are highly dependent on agriculture, and the emissions are disproportionally lower than the percent of their GDP from agriculture. Countries such as New Zealand, Australia, and Ireland also have relatively high emissions per capita. These countries have relatively high production of livestock using pasture- and grazing-based systems that are efficient and intensive. And they are relatively unpopulated, which results in high emissions per capita, while agriculture contributes far less to their GDPs than other countries that have far lower emissions per capita.

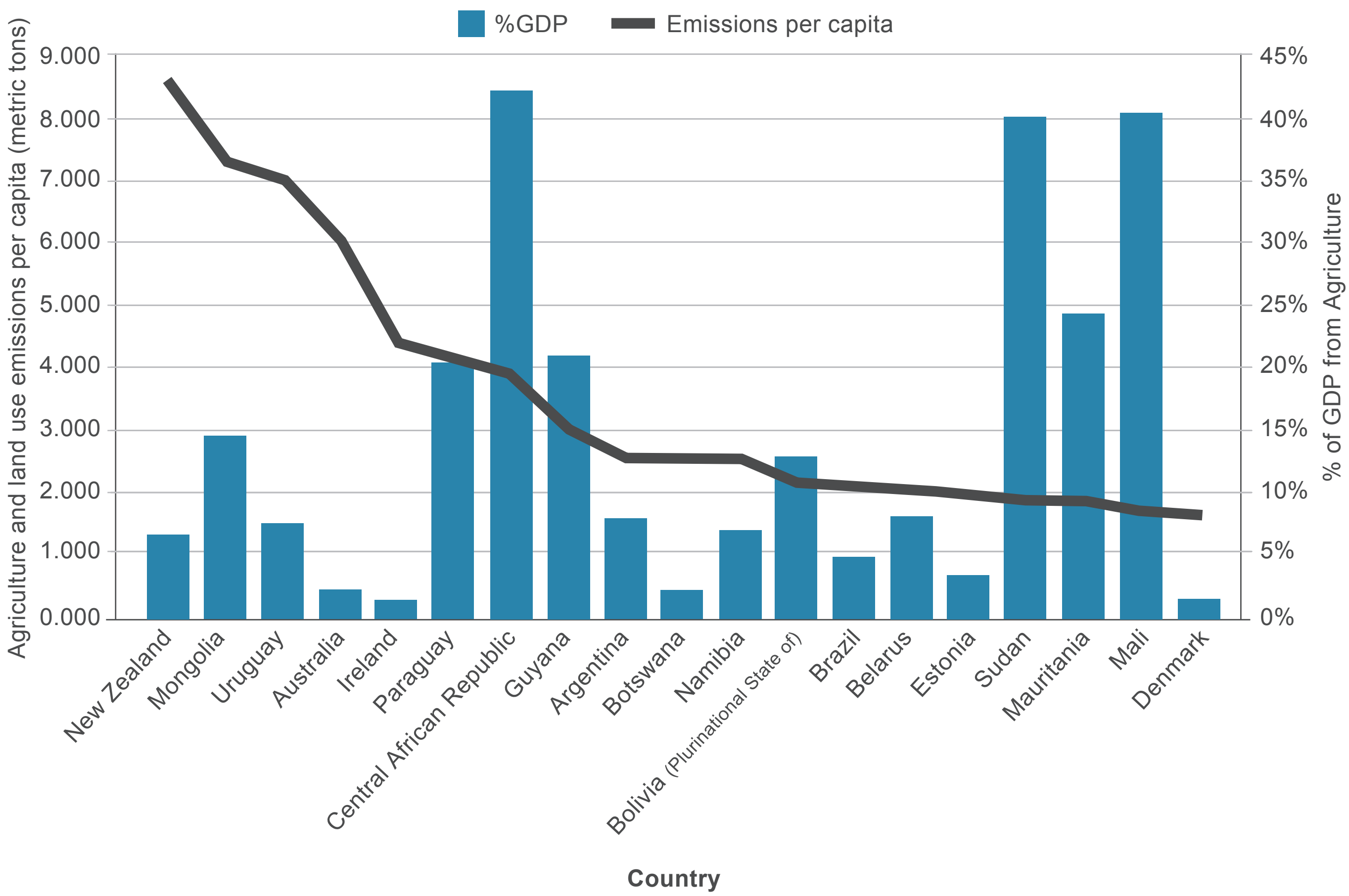


Figure 4: Top 20 countries by agricultural emissions per capita and percentage of GDP from agriculture. (*Note that some countries may not be included due to lack of data on their percentage of GDP from agriculture.)*

Additional work to disaggregate and analyze emissions for nitrous oxide, methane, and carbon dioxide, using non-CO_2 databases, would be helpful to infer more detail about the food system of each country (e.g., GHGs being emitted; the sources of emissions). Such disaggregation would help to explain the differences between and causes of emissions.

Country	**% GDP from Agriculture** (World Bank, 2014)	**Total Emissions from Agriculture and Land Use Change, in gigagrams** (FAOSTAT, 2014)	**Emissions from Agriculture and Land Use Change per Capita, in kilograms** (based on World Bank Population Data, 2014 and Total Emissions)
Afghanistan	23.5	14,794.1149	451.62
Albania	22.9	2,829.8147	979.48
Algeria	11.1	12,794.0571	327.10
American Samoa		4.5959	82.90
Angola		29,584.1187	1,098.95
Antigua and Barbuda	1.8	22.2087	224.61
Argentina	8.0	11,2376.5349	2,614.53
Armenia	20.4	1,366.2158	470.10
Australia	2.4	14,1847.1588	6,046.16
Austria	1.4	6,600.7597	772.78
Azerbaijan	5.7	6,446.8395	676.12
Bahamas	1.9	25.812	67.54
Bahrain	0.3	35.4431	26.52
Bangladesh	16.1	74,593.868	467.95
Barbados	1.7	53.3611	188.30
Belarus	8.3	19,989.2995	2,109.80
Belgium	0.7	8,787.2986	783.95
Belize	15.6	318.4641	905.51
Benin	24.3	4,775.8853	464.28
Bermuda		4.0221	61.75
Bhutan	17.7	452.7952	583.16
Bolivia, Plurinational State of	13.0	23,182.7271	2,194.89
Bosnia and Herzegovina	7.2	2,573.2512	721.61
Botswana	2.4	5,569.4461	2,568.25
Brazil	5.0	441,905.0439	2,163.94
British Virgin Islands		8.211	277.51
Brunei Darussalam	0.9	147.3665	357.94
Bulgaria	5.3	5,492.6693	760.34
Burkina Faso	35.2	19,867.8433	1,129.75
Burundi	39.3	2,221.791	224.61
Cabo Verde	9.6	112.0368	212.82
Cambodia	30.9	19,354.3221	1,267.41
Cameroon	22.2	11,594.5645	521.34
Canada		61,782.8879	1,738.18

Country	% GDP from Agriculture (World Bank, 2014)	Total Emissions from Agriculture and Land Use Change, in gigagrams (FAOSTAT, 2014)	Emissions from Agriculture and Land Use Change per Capita, in kilograms (based on World Bank Population Data, 2014 and Total Emissions)
Cayman Islands		4.3339	73.24
Central African Republic	42.2	17,677.7567	3,915.00
Chad	52.6	19,263.8288	1,419.65
Chile	4.3	9,838.8505	558.59
China	9.1	711,786.8204	521.73
Colombia	6.2	53,627.6623	1,122.11
Comoros		237.411	312.64
Congo	4.8	1,809.6761	371.51
Costa Rica	5.6	3,466.0695	728.54
Cote d'Ivoire	23.5	4,790.1275	212.60
Croatia	4.1	2,572.2249	606.89
Cuba	4.0	10,497.9565	917.67
Cyprus	2.1	368.8479	320.09
Czechia	2.7	6,295.2865	598.11
Democratic People's Republic of Korea		4,541.9334	180.84
Democratic Republic of the Congo	21.3	18,528.2114	251.32
Denmark	1.6	9,444.663	1,673.55
Djibouti		650.1734	712.78
Dominica	15.8	32.7477	449.97
Dominican Republic	5.4	7,783.025	747.95
Ecuador	9.5	12,999.3135	817.41
Egypt	11.1	31,054.7553	338.24
El Salvador	11.3	2,624.717	417.87
Equatorial Guinea	1.3	21.0201	18.61
Estonia	3.6	2,636.2045	2,005.41
Ethiopia	41.9	96,255.7141	988.59
Faroe Islands		26.8334	549.39
Fiji	11.4	881.7914	995.47
Finland	2.8	5,612.3136	1,027.61
France	1.7	72,263.5427	1,089.42
French Polynesia		35.2664	128.02
Gabon	3.9	437.9565	233.49
Gambia, The	20.3	1,209.822	630.82
Georgia	9.3	2,611.7723	700.77
Germany	0.8	60,635.6855	748.75
Ghana	22.4	9,185.1491	340.66

Country	% GDP from Agriculture (World Bank, 2014)	Total Emissions from Agriculture and Land Use Change, in gigagrams (FAOSTAT, 2014)	Emissions from Agriculture and Land Use Change per Capita, in kilograms (based on World Bank Population Data, 2014 and Total Emissions)
Greece	3.7	8,395.5076	770.77
Greenland	16.4	4.6676	82.91
Grenada	7.1	14.4075	135.46
Guam		4.189	26.02
Guatemala	11.0	8,392.886	527.07
Guinea	20.1	11,300.5916	957.23
Guinea-Bissau		1,651.3006	956.86
Guyana	21.1	2,281.608	2,988.77
Haiti		3,903.9492	369.26
Honduras	13.7	5,916.4934	671.63
Hungary	4.7	7,034.471	712.97
Iceland	6.2	451.5443	1,379.24
India	18.0	626,864.1369	484.49
Indonesia	13.3	165,614.2489	649.13
Iran, Islamic Republic of	9.3	34,841.6018	444.35
Iraq		8,577.1363	245.02
Ireland	1.5	20,475.6852	4,434.63
Isle of Man		1.7563	21.27
Israel		1,375.1726	167.38
Italy	2.2	30,073.2959	494.71
Jamaica	7.1	621.3079	217.08
Japan	1.1	20,709.4141	162.71
Jordan	3.8	1,184.5453	134.47
Kazakhstan	4.7	20,711.8599	1,197.96
Kenya	30.4	37,132.7274	806.81
Kiribati		8.1188	73.50
Kuwait	0.4	417.2175	110.30
Kyrgyzstan	17.1	4,536.9515	777.47
Lao People's Democratic Republic	19.7	8,096.849	1,231.20
Latvia	3.5	3,150.132	1,579.98
Lebanon	7.2	751.9419	134.20
Lesotho	5.9	1,447.4822	674.57
Liberia	35.8	419.8026	95.61
Libya		2,554.1662	411.69
Liechtenstein		18.0802	486.98
Lithuania		4,724.4131	1,611.13
Luxembourg	0.3	645.4032	1,160.13

Country	% GDP from Agriculture (World Bank, 2014)	Total Emissions from Agriculture and Land Use Change, in gigagrams (FAOSTAT, 2014)	Emissions from Agriculture and Land Use Change per Capita, in kilograms (based on World Bank Population Data, 2014 and Total Emissions)
Madagascar	26.5	21,957.0593	930.79
Malawi	30.8	5,239.4733	306.96
Malaysia	8.9	14,276.3295	472.29
Maldives	3.5	1.8025	4.50
Mali	40.3	29,721.6107	1,752.16
Malta	1.3	99.2613	232.26
Mauritania	24.3	7,693.1569	1,893.04
Mauritius	3.7	148.2591	117.58
Mexico	3.5	84,719.376	682.00
Micronesia, Federated States of	27.0	16.7477	161.01
Mongolia	14.7	21,475.6504	7,344.87
Montenegro	10.0	384.3903	618.18
Morocco	13.0	13,643.6464	397.56
Mozambique	25.1	17,704.8232	650.62
Myanmar	27.8	66,510.088	1,280.91
Namibia	7.1	6,060.1288	2,555.95
Nauru		1.2141	102.43
Nepal	33.8	22,058.3972	778.81
Netherlands	1.8	18,324.8974	1,086.56
New Caledonia		221.0452	824.80
New Zealand	6.8	38,653.9591	8,571.29
Nicaragua	18.5	7,681.4153	1,277.26
Niger		23,128.2078	1,207.85
Nigeria	20.2	64,238.9645	364.04
Norway	1.6	4,616.4816	898.63
Occupied Palestinian Territory	4.5	273.411	63.66
Oman	1.2	1,578.2554	398.46
Pakistan	24.9	15,0340.771	810.26
Panama	3.1	3,388.5192	867.96
Papua New Guinea		5,658.0659	729.53
Paraguay	20.5	27,645.1634	4,218.97
Peru	7.5	23,263.7588	751.09
Philippines	11.3	53,173.2077	531.19
Poland	2.9	34,158.3425	898.63
Portugal	2.3	6,324.0699	608.02
Puerto Rico		790.0877	223.51

Country	% GDP from Agriculture (World Bank, 2014)	Total Emissions from Agriculture and Land Use Change, in gigagrams (FAOSTAT, 2014)	Emissions from Agriculture and Land Use Change per Capita, in kilograms (based on World Bank Population Data, 2014 and Total Emissions)
Qatar	0.1	822.3746	346.35
Republic of Korea	2.3	12,709.936	250.46
Republic of Moldova	15.5	1,612.8054	453.49
Romania	5.3	13,963.2782	701.36
Russian Federation	4.1	92,227.8254	641.27
Rwanda	30.9	2,996.2725	264.10
Saint Kitts and Nevis	1.4	66.2348	1,232.53
Saint Lucia	2.8	28.3314	160.59
Saint Vincent and the Grenadines	7.8	13.5027	123.47
Samoa		148.6407	773.00
Sao Tome and Principe	12.0	15.6671	81.91
Saudi Arabia	2.2	7,221.133	234.63
Senegal	15.4	10,599.1059	728.66
Serbia	9.3	6,453.2565	905.01
Seychelles	2.6	4.3629	47.76
Sierra Leone	54.0	2,826.0053	399.20
Singapore	0.0	101.7818	18.61
Slovakia	4.4	2,548.7982	470.38
Slovenia	2.4	1,432.5698	694.75
Solomon Islands		61.5191	106.90
Somalia		20,308.8585	1,502.90
South Africa	2.4	30,000.1018	554.05
South Sudan		43,097.5671	3,737.55
Spain	2.5	36,425.482	783.67
Sri Lanka	8.6	5,822.8665	280.34
Sudan	39.9	72,517.346	1,921.60
Suriname	10.2	759.3468	1,385.85
Swaziland	9.8	925.3479	714.50
Sweden	1.3	6,640.142	684.83
Switzerland	0.8	5,191.5369	633.99
Syrian Arab Republic		6,252.7407	325.61
Tajikistan	27.2	5,529.9916	661.27
Thailand	10.1	63,039.5219	921.40
The former Yugoslav Republic of Macedonia	11.7	1,203.1439	579.13
Timor-Leste	19.8	783.8536	646.31
Togo	42.0	2,605.4265	360.42

Country	% GDP from Agriculture (World Bank, 2014)	Total Emissions from Agriculture and Land Use Change, in gigagrams (FAOSTAT, 2014)	Emissions from Agriculture and Land Use Change per Capita, in kilograms (based on World Bank Population Data, 2014 and Total Emissions)
Tonga	19.7	89.3729	844.88
Trinidad and Tobago	0.5	248.6694	183.59
Tunisia	9.7	4,436.2489	398.09
Turkey	7.5	43,192.007	560.71
Turkmenistan		8,076.3655	1,477.50
Uganda	26.6	23,998.5495	617.99
Ukraine	11.7	30,966.5333	684.01
United Arab Emirates		1,675.8194	184.75
United Kingdom	0.7	45,014.3633	696.67
United Republic of Tanzania	31.0	49,695.7024	951.39
United States of America	1.3	351,475.0839	1,103.31
United States Virgin Islands		16.4586	158.00
Uruguay	7.7	24,208.4763	7,079.44
Uzbekistan	18.8	28,194.9205	916.68
Vanuatu	28.2	425.6278	1,644.30
Venezuela, Bolivarian Republic of		36,052.8213	1,172.89
Viet Nam	19.7	62,530.0565	689.20
Yemen	9.9	7,612.0803	290.02
Zambia	7.3	22,953.6775	1,469.41
Zimbabwe	12.2	10,427.793	676.62

Appendix 2: Lead Author Bios

Richie Ahuja, Regional Director, Asia, Environmental Defense Fund

Richie Ahuja is an expert in business development strategies and spearheads the Environmental Defense Fund's (EDF) engagement in India. He was a founding member of the Fair Climate Network (FCN), a network of nongovernmental organizations that have worked together to create innovative ways to scale up low-carbon rural development options, such as clean energy, clean cooking systems, and climate smart agriculture practices. These have now been deployed and tested across tens of thousands of farms and farmer households across the country. Richie helped to facilitate the domestic offset program of IndiGo Airlines, India's largest carrier, which allows passengers to offset their climate pollution from travel, and linked this effort with the FCN to generate carbon finance for the capital expenditures required for deploying low-carbon technologies. He has co-authored publications on climate smart agricultural practices and is a leading voice on these practices, both within India and at the global level, through initiatives such as the Global Alliance for Climate Smart Agriculture, which EDF was integral in launching. In India, he has also helped to facilitate the formation of independent institutions such as the Indian Youth Climate Network, India's largest youth network on climate change, and Climate Parliament, an independent, multi-party body of elected leaders focused on addressing climate change in the country.

Richie holds an MBA in International Business from the Thunderbird School of Global Management.

M. Jimena Esquivel Sheik, Researcher, Environmental Assessments for Sustainable Agriculture (Colombia, Nicaragua, Costa Rica)

Jimena Esquivel Sheik has experience in research, experimental design, training, and the design of scientific and educational materials on the importance of production systems in biodiversity conservation and restoration of degraded soils. She has worked with local, regional, and international institutions on the conversion of conventional systems to sustainable agricultural production systems. Currently, she leads scientific publication proposals and research to increase actual knowledge about ecosystem functioning and services offered by tropical forests and agro-livestock landscapes. Jimena's research interests include the taxonomic and functional diversity of trees and shrubs and natural regeneration within and outside the forest; the effect of different land uses and management on the provision of ecosystem services in agricultural landscapes; carbon sequestration in trees and soil; decomposition of organic matter, nutrient cycling, and maintenance of soil fertility; the design and monitoring of silvopastoral systems for mitigation and adaptation to climate change; and the effect of the interaction between communities of fauna and flora on the provision of ecosystem services and the sustainability of food systems.

Jimena holds an M.S. in Biology and Terrestrial Ecology, specializing in Agroforestry and Tropical Silvopasture from CATIE, Turrialba, Costa Rica, and a Ph.D. from the University of Bangor, United Kingdom, in the analysis of functional diversity and the provision of ecosystem services in agro-livestock landscapes.

Nelson Rading' Mango, Rural Development Sociologist, Independent Consultant

Nelson Mango is a rural development sociologist specializing in agrarian transformation processes with an emphasis on small-scale farming, technology development and social change, endogenous development, and rural livelihoods. His research work has focused on the socio-technical dimensions of maize, zero-grazing dairy farming, and soil fertility (re)production in Western Kenya; livestock, livelihoods, and poverty in sub-Sahara African countries; and the impact of livestock diseases and their control in people's livelihoods in sub-Saharan Africa and Southern Asia. Nelson has also conducted integrated agricultural research for development through multi-stakeholder innovation platforms with integrated soil fertility management and conservation agriculture as entry points in the Southern Africa region, as well as running a U.S. Agency for International Development bean innovations platforms project in Mozambique. Nelson was the coordinator for Malawi and Zimbabwe for a project sponsored by the International Fund for Agricultural Development on increasing smallholder farm productivity, income, and health through widespread adoption of integrated soil fertility management in the Great Lake Regions and Southern Africa. Most recently he has been involved in two research areas, both covering East and Central Africa, on agriculture, nutrition and health, and policy institutions and markets under the Humidtropics CRP program.

Nelson received his M.Sc. and Ph.D. from Wageningen University and Research Centre.

Meredith T. Niles, Assistant Professor, Food Systems Program, Department of Nutrition and Food Sciences, University of Vermont

Meredith T. Niles is an assistant professor at the University of Vermont where she examines food systems sustainability and policy. Her research focuses on food security and climate change, farmer decision-making and the adoption of sustainable practices, and food system policy. Her research is based in the United States and New Zealand and across many low-income countries working with smallholder farmers. Meredith thrives on conducting applied research that can help bring together diverse stakeholders – whether on a farm or working with policymakers – to help solve pressing problems facing our world's food system. Meredith is a passionate advocate for open access research, to make research more publicly available and maximize the potential of science and its benefits for society. She currently serves on the Board of Directors for the Public Library of Science. She previously worked in Washington D.C. as the Cool Foods Campaign coordinator at The Center for Food Safety and as the Public Affairs Coordinator on the President's Emergency Plan for AIDS Relief at the U.S. State Department. She has served as a member of the Climate Action Reserve's nutrient management workgroup and worked on carbon offset protocol development for agricultural offset markets.

Meredith holds a B.A. in Political Science from The Catholic University of America where she graduated summa cum laude and Phi Beta Kappa, and a Ph.D. in Ecology from the University of California, Davis. She completed a post-doctoral fellowship at Harvard University's Kennedy School of Government in the Sustainability Science program.

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