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Climate change mitigation beyond agriculture: a review of food system opportunities and implications

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Abstract

A large body of research has explored opportunities to mitigate climate change in agricultural systems; however, less research has explored opportunities across the food system. Here we expand the existing research with a review of potential mitigation opportunities across the entire food system, including in pre-production, production, processing, transport, consumption and loss and waste. We detail and synthesize recent research on the topic, and explore the applicability of different climate mitigation strategies in varying country contexts with different economic and agricultural systems. Further, we highlight some potential adaptation co-benefits of food system mitigation strategies and explore the potential implications of such strategies on food systems as a whole. We suggest that a food systems research approach is greatly needed to capture such potential synergies, and highlight key areas of additional research including a greater focus on low- and middle-income countries in particular. We conclude by discussing the policy and finance opportunities needed to advance mitigation strategies in food systems.

Introduction

It is estimated that agriculture and associated land use change account for 24% of total global emissions (Smith *et al.*, 2014), while the global food system may contribute up to 35% of global greenhouse gas (GHG) emissions (Foley *et al.*, 2011; Vermeulen *et al.*, 2012). As a result, food systems—not just agricultural production—should be a critical focus for GHG mitigation (i.e., reduction in, or removal of, current and expected future emissions) and adaptation (i.e., building resilience for emerging and long term climate impacts) strategies. While a significant focus of climate change (CC) research and policy has been on agriculture (e.g., Thornton *et al.*, 2009; Challinor *et al.*, 2014; Varanasi *et al.*, 2016), there is a growing recognition that our food will be affected by CC beyond just production aspects. The anticipated disturbances include sea-level rise that will likely threaten global food distribution (Brown *et al.*, 2015), the occurrence of food safety hazards throughout the food chain (Tirado *et al.*, 2010) and impacts on nutritional quality of certain foods (Myers *et al.*, 2014). Further, CC may result in up to 600 million more people suffering from hunger by 2080 (Yohe *et al.*, 2007), with an additional 24 million undernourished children, almost half of whom would be living in sub-Saharan Africa (Nelson *et al.*, 2009). These changes will impact rates of severe stunting, estimated to increase by 23% in central sub-Saharan Africa and up to 62% in South Asia (Lloyd *et al.*, 2011). As a result, we argue here that there is a need to better understand, integrate and create action related to the food system and CC, beyond agricultural production. This focal shift is critical for multiple reasons, including (1) for greater mitigation potential; (2) for exploration of mitigation and adaptation co-benefits, synergies or trade-offs; (3) to identify clear research gaps; and (4) to integrate options that fall both inside and outside of agricultural production (e.g., dietary choices, food waste).

Approach

A food system ‘gathers all the elements (environment, people, inputs, processes, infrastructure, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food and the outputs of these activities, including socio-economic

and environmental outcomes' (HLPE, 2014). Food systems operate within and are influenced by social, economic, political and environmental contexts (Fig. 1). Further, 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).

Here we synthesize the existing research briefly on pre-production and production, while providing greater detail and context for food system emissions beyond agriculture for the majority of the review. We conclude by discussing some of the pathways or barriers to action—which mechanisms may enable greater shift toward such mitigating behaviors and where future research may be necessary. We consider these opportunities in different country contexts with varying food and economic

systems (Table 1). Further, though the focus of this review is primarily on opportunities to mitigate emissions in food systems, we also detail some potential adaptation co-benefits of various mitigation strategies and how they may influence other components of the food system (Table 2). We focus our attention on recent research that builds on the review by Vermeulen *et al.* (2012).

Opportunities, co-benefits and implications

CC adaptation and mitigation strategies in the food system require finding more sustainable, resilient and efficient ways of producing, trading, distributing, marketing and consuming diverse and nutritious foods (Tirado *et al.*, 2013). Given the complexity of a food system, and its potential to have non-linear feedbacks and cross-cutting impacts throughout the system, it is

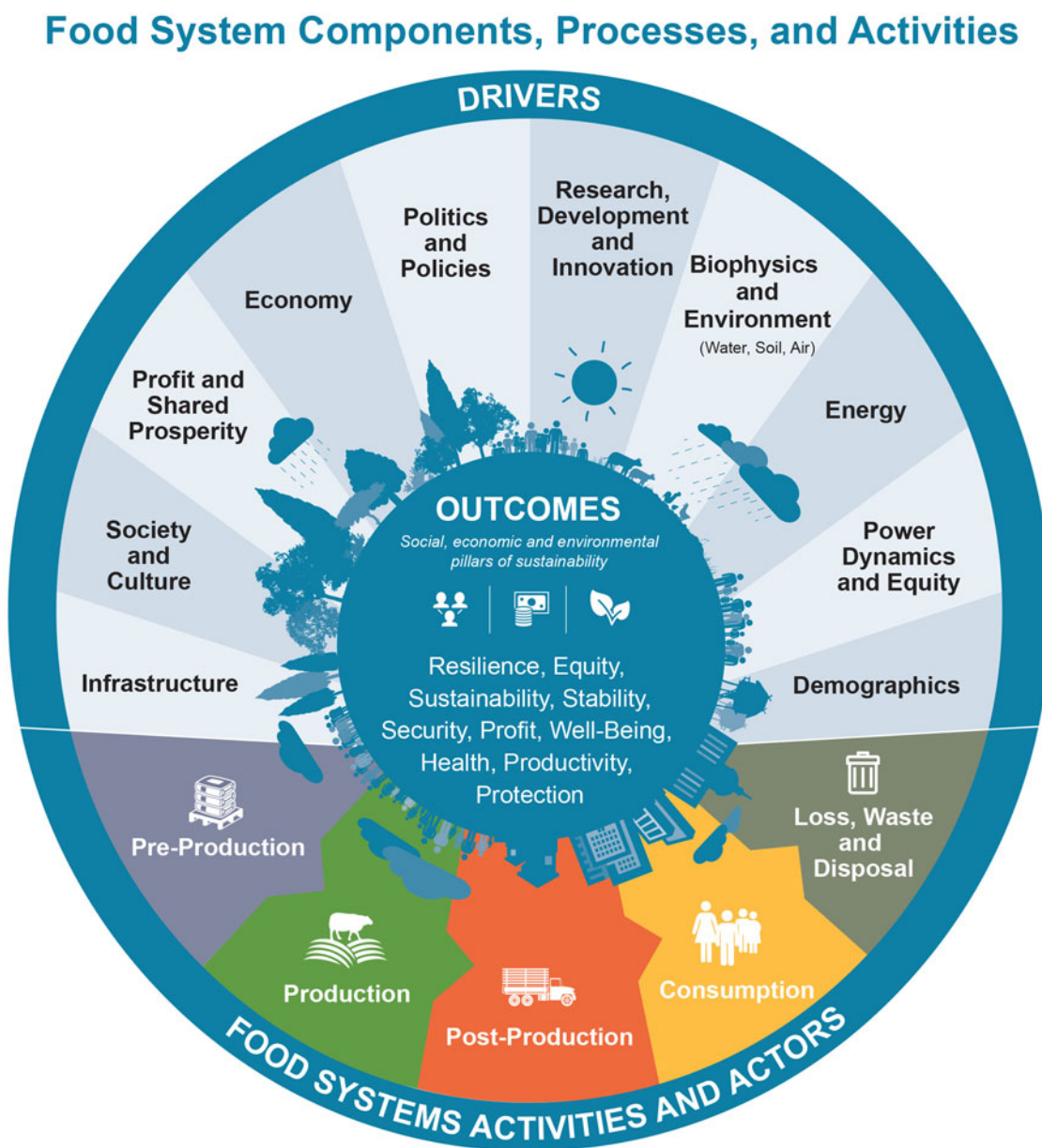


Fig. 1. Identified components, processes and activities within food systems, which are influenced by a diversity of different drivers ranging from infrastructure to demographics. Such drivers within food systems lead to different outcomes fundamental for sustainable development including resilience, equity, sustainability, stability, security, profit, well-being, health, productivity and protection. (Niles *et al.*, 2017).

Table 1. Food system GHG mitigation opportunities across extensive and intensive low-/middle-income and high-income countries. Given the varying economic and food systems of different countries, these details potential mitigation opportunities as relevant for these contexts. We provide country examples below demonstrating some examples; however, we acknowledge that these system categories are not universal for a given place. For example, while Brazil, a middle-income country, has intensive agricultural soy and beef systems, it also has vast pasture systems that are not fertilized (Niles et al., 2017)

Food system component	Low-/middle-income		High-income	
	Extensive (e.g., pastures in Ethiopia, Colombia)	Intensive (e.g., China, Brazil)	Extensive (e.g., pastures in New Zealand, Ireland)	Intensive (e.g., Japan, United States)
Pre-production	Emissions from these systems are low per hectare, but high per unit of output. Using inputs such as fertilizers can provide benefits for food security and minimize agricultural expansion when coupled with land governance and sustainable efficiencies, providing net reductions to GHGs. Agroecological practices with known production benefits (e.g., manure incorporation, crop rotation, diversification, push-pull technologies) can also provide yield gains and be an alternative to GHG-intensive inputs and keep smallholder farmer costs at a minimum	Reduction in manufactured agricultural inputs where over applied can reduce GHGs. Switch to renewable and/or non-coal energy sources for input production. Incorporation of agroecological practices could help reduce the need for manufactured inputs	Despite extensive pasture systems, production still relies on manufactured inputs. Utilizing high-tech precision agriculture technologies can help farmers reduce or better target inputs. Shifting toward agroecological practices if possible at large scale may help minimize inputs and costs	Precision agriculture can minimize unnecessary inputs and reduce farmer costs. Inputs, if made domestically, could utilize best available technologies to reduce GHGs. Shifting toward agroecological practices if possible at large scale may help minimize inputs and costs
Production	Increase nutrient use efficiency, crop diversification, increase in of perennial crops, trees cover inside crop and livestock systems, increased livestock efficiencies, improved pastures and forage, increase forage diversity and availability, increase recycling of production wastes	Reduced input use where over applied, increased nutrient efficiency, cover crops, nitrification and urease inhibitors, perennial crops, manure management, enteric feeding strategies, improved pasture quality, concentrates, animal health	Reduced input use where over applied, increased nutrient efficiency, cover crops, nitrification and urease inhibitors, perennial crops, enteric feeding strategies, improved pasture quality, animal health	Reduced input use where over applied, increased nutrient efficiency, cover crops, nitrification and urease inhibitors, perennial crops, manure management, enteric feeding strategies, improved pasture quality, concentrates, animal health
Processing and transportation	Lack of infrastructure often prevents processing, manufacturing and transportation of highly perishable food and is a significant cause of food waste in low-income countries. Expansion of processing and manufacturing with best available sustainable technologies and renewable energies can minimize GHGs	High-efficiency systems for processing, refrigeration and manufacturing will help minimize GHG emissions. Renewable energy sources can also reduce GHG emissions	Given the high reliance on processing, manufacturing, refrigeration and transportation, systems with low GHG refrigerants can reduce GHGs. Renewable energy sources can also reduce GHG emissions. Transportation mode shifts can reduce GHGs	
Consumption	Rising incomes in low- and middle-income countries are driving dietary shifts, which will influence both public health and GHG emissions. Opportunities to reduce diet-related emissions should balance the role of livestock in small-scale farmers' livelihoods and nutritional outcomes for poor consumers		Dietary shifts toward less intensive animal products or more plant-based foods could reduce GHG emissions, particularly if publicly acceptable. Moderate dietary shifts can also provide potential health benefits	
Food waste and disposal	Most losses are upstream, so better processing, post-harvest, transportation and market opportunities are critical. Aflatoxins may be a key threat, and should be considered for prevention strategies	Most losses are upstream, and in Asia particularly in cereals and vegetables. Better processing, post-harvest and transportation opportunities are critical	In high-income countries, most losses are downstream, largely at the retail and consumer level, involving fundamentally different challenges, mostly focused on behavior change with some technological opportunities. Changing retail stocking and sourcing, consumer acceptance of different quality products, better consumer planning and preparation, and food preservation technologies can reduce waste and save consumers money	

Table 2. Adaptation co-benefits and system-level implications of mitigation opportunities. Drawing upon mitigation opportunities described in Table 1, adaptation co-benefits and system-level impacts are detailed below (Niles *et al.*, 2017)

Food system component	Implications	
	Adaptation co-benefits	System-level
Pre-production	Generation of manufactured inputs with renewable and/or non-coal energy sources could reduce GHGs and future climate impacts. Adoption of agroecological practices could provide resilience for future shocks, spread farmer risk and mitigate the impact of droughts (McDaniel <i>et al.</i> , 2014; Altieri <i>et al.</i> , 2015; Vignola <i>et al.</i> , 2015, 2017)	Shift away from manufactured agricultural inputs would have significant financial impacts on agricultural input dealers. Without adequate adoption of agroecological practices, could reduce yields and increase farmer risk. Adoption of agroecological practices to substitute for manufactured inputs could provide environmental benefits (<i>i.e.</i> , water quality, biodiversity) (Altieri <i>et al.</i> , 2015)
Processing and transportation	Cold-chain expansion can help minimize food safety concerns with warming temperatures (James and James, 2010)	Cold-chain expansion will provide opportunities to minimize food waste, increase nutrition and improve food safety, but with costs to emissions. Demand side changes (<i>e.g.</i> , demand for processed foods, frozen foods, out of season produce, etc.) could drive further growth in emissions from food transport and processing (Heard and Miller, 2016)
Consumption	Dietary shifts toward livestock breeds and crop varieties suited to likely future climates; pre-emptive shifts will encourage efficiency gains (Rippke <i>et al.</i> , 2016)	Dietary shifts toward less GHG-intensive animal products and/or plant-based foods could significantly influence the agricultural industry. Given that one billion people globally rely on livestock and their complementary industries for their livelihoods (FAO, 2011b), this has significant implications for global incomes and employment. However, shifts toward other foods would likely provide new employment opportunities
Food waste and disposal	Increased access to post-harvest technologies including cold-chain refrigeration will raise food availability in the future under warmer conditions, but potentially raise emissions (James and James, 2013)	Food waste reductions are complex and involve the entire system; for example, benefits for food security from reducing food waste are not automatic. Downstream food waste reductions could minimize agricultural land expansion and reduce other environmental impacts (FAO, 2011a)

critical to explore opportunities to mitigate and adapt to CC both within various components and actors interacting within a food system, and across its parts. To facilitate this approach, we highlight key sources of GHG emissions and mitigation opportunities within different stages of the food system (Fig. 1), their relevance across varying country contexts (Table 1), and the potential adaptation co-benefits and food system-level implications of such strategies (Table 2).

Pre-production

Pre-production emissions generally result from the manufacture and distribution of agricultural inputs such as synthetic fertilizers and biocides (*e.g.*, herbicides, pesticides, fungicides), as well as concentrates, supplements or antibiotics for livestock systems. The production of synthetic fertilizer is a significant source of GHG emissions, especially when it relies on coal (Vermeulen *et al.*, 2012) and global fertilizer use has increased 233% between 1970 and 2010 (Smith *et al.*, 2014). Mitigation strategies for pre-production include opportunities to increase the efficiency of input production systems, shift toward renewable or less GHG-intensive energy sources for its production, or shift toward more sustainable agricultural inputs required for agroecological practices (which would occur in the production phase). In high- and many middle-income countries, shifting away from high input use will be necessary to reduce GHGs, especially in areas of overapplication (Vitousek *et al.*, 2009). In many low-income countries, the addition of agricultural inputs could have significant benefits for food security (Vitousek *et al.*, 2009; Rockström *et al.*, 2017a, b) and help minimize agricultural land

expansion and associated GHG emissions, through appropriate natural resource governance (Byerlee *et al.*, 2014) and sustainable efficiencies. Opportunities for economically efficient agroecological alternatives to manufactured inputs include using organic sources of fertilizer such as manure or leguminous crops, crop rotations, companion plantings (Altieri *et al.*, 2015), push-pull cropping strategies (Khan *et al.*, 2014) and/or integrated pest and weed management (West and Post, 2002; Eagle *et al.*, 2012).

Production

We divide this section into three kinds of production to better demonstrate how existing research differs across these systems.

Cereals, grains and staple crops

Significant reviews have explored the myriad opportunities to reduce yield scaled net emissions in cropping systems, with a strong focus on nitrous oxide emissions resulting from soil management (*e.g.*, Eagle *et al.*, 2012; Montes *et al.*, 2013; Mangalassery *et al.*, 2015; Di and Cameron, 2016; Thapa *et al.*, 2016). Relevant strategies include: crop breeding for increased yield and/or adaptation to future CC impacts; fertilizer and input management including reduced application rates, increased efficiency, timing, fertilizer type, and application methods of manure and fertilizers (*e.g.*, injection); cover crops; nitrification and urease inhibitors; increases in perennial crops; organic production; reduced or minimal tillage, crop rotation, water use efficiency and crop diversification. Additional research also suggests cropping systems could be critical for increasing soil carbon sequestration, with agricultural practices having the potential to sequester between

1.3 and 8.0 Pg CO₂eq yr⁻¹ (Sommer and Bossio, 2014; Paustian et al., 2016)

Horticulture (fruit, vegetable, perennials)

Very few reviews exist for horticulture climate mitigation, a clear need for future research. Many noted strategies include: soil amendments, crop residue removal, cover crops, organic production, water use efficiency and improved drainage and compaction prevention in tree crops, many of which may also be relevant for other cropping systems (Aguilera et al., 2013; Congreves and Van Eerd, 2015; Rezaei Rashti et al., 2015; Swarts et al., 2016; Niles et al., 2017).

Livestock/animal systems

Livestock mitigation has been the subject of many reviews (e.g., Thornton et al., 2009; Hristov et al., 2013; Montes et al., 2013; Global Research Alliance, 2014; Knapp et al., 2014). Focus has been largely on ruminant animals, due to their enteric fermentation emissions. Strategies generally focus on improving feed conversion efficiency (e.g., improved pasture quality, forage processing and digestibility, concentrates), controlling enteric emissions (e.g., feeding of edible oils, ionophores, vaccines, animal genetics), improving manure management (e.g., methane digesters, storage time, manure covers), grazing management (e.g., intensive grazing, reduced grazing in wet conditions, soil carbon sequestration), silvopasture and incorporation of woody plants and trees, and optimizing animal health (vaccines, animal genetics, heat stress prevention, access to veterinary care). Mitigation opportunities also exist in monogastric systems, particularly around manure management.

Post-production manufacturing, processing and transportation

Globalization and demand for processed foods may likely increase emissions from this portion of the food system (Vermeulen et al., 2012). Post-production activities including food processing, packaging, distribution (transport) and the cold chain (i.e., unbroken refrigeration throughout the supply chain for many products) contribute to GHG emissions, though the extent varies by country. While not exclusively, most mitigation opportunities in this component of the food system come from reducing demand for fossil energy sources and lowering emission intensities of both electricity generation and transport fuels.

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 material and energy resources (van der Goot et al., 2016). As a result, many are energy intensive; among the most intensive processes are oil-seed and wet corn milling and refining [e.g., soy oil, high fructose corn syrup (Wang, 2013)], water removal, and food safety practices including sterilization and pasteurization. Wang suggests that a 25–34% energy savings in the British food processing industry is possible through technically feasible and economically practical improvements (Wang, 2013). Other authors call for a more fundamental redesign of food processing, away from highly refined, pure ingredients and toward mildly fractionated, complex and diverse ‘functional fractions’ (van der Goot et al., 2016).

Refrigeration

Refrigeration is another critical aspect of post-production GHG emissions. Around 40% of all food produced requires refrigeration and 15% of the electricity consumed worldwide is used for refrigeration (James and James, 2013). With today's electricity generation methods, this results in notable GHG emissions; for example, roughly 2.4% of the United Kingdom's GHG emissions are from food refrigeration (Garnett, 2007). Thus, utilizing more efficient refrigeration systems and increasing the use of renewable energies are critically important mitigation strategies for food systems. Currently, <10% of perishable foodstuffs are currently refrigerated worldwide (James and James, 2013). Crops in most locations have seasonality and thus require managed storage, often through refrigeration or freezing in order to provide year-round consumption. Trade-offs between storage and out-of-season production GHG emissions and food transport emissions can vary greatly by season, product and location, as well as production and transportation strategies. While some studies demonstrate that local food production could result in lower GHG emissions (Lampert et al., 2016; Rothwell et al., 2016), other studies show situations where imported food results in lower emissions (Milà i Canals et al., 2007; Ledgard et al., 2011). While ozone-depleting refrigerants have largely been phased out, popular replacements [e.g., hydrofluorocarbons (HFCs)] have global warming potentials sometimes thousands of times higher than CO₂ (Zhang et al., 2011). Recent changes to the Montreal Protocol will require withdrawal of HFCs in the coming 30 yr (Kigali Amendment, 2016), providing excellent opportunities to reduce cold-chain refrigerant GHG emissions. If cold-chain expansion is combined with improvements in energy efficiency, it is estimated that it could continue into new regions without increasing GHG emissions and possibly even reduce emissions, as food waste lessens (James and James, 2010).

Transportation

While food distribution may be an easily identifiable mitigation target, from a food systems perspective, it often proves to be a less significant contribution to GHG emissions than assumed, and trade-offs exist with both production and storage stages. In the US, direct distribution of foods (from farm or production facility to retail stores) represented only 4% of the total greenhouse gas emissions of food, with indirect transportation (e.g., delivery of fertilizer to farms) adding an additional 7% (Weber and Matthews, 2008). Others have found that consumers driving more than 7 km in the UK to purchase organic vegetables is more GHG intensive than the cold chain, transportation and storage of regionally produced vegetables delivered to a consumer directly (Coley et al., 2009). Opportunities to reduce transportation emissions are largely driven by either increased efficiencies or mode shifts, e.g., from road to rail. Refrigeration can also be a notable component of the food transportation system. Mobile refrigeration systems, especially in trucks, are commonly oversized and driven by auxiliary diesel engines, and can result in GHG emissions up to 140% of non-refrigerated trucks (Tassou et al., 2009). Thus, efforts to increase refrigeration efficiencies in transport vehicles are also an important strategy for reducing transportation emissions.

Consumption

Assessing the role of diets and food consumption patterns on CC is a growing research area (Nemecek et al., 2016), as diets

consistently shift toward increased consumption of animal products, processed and packaged foods, lower micronutrient densities and greater energy intake in general (Pradhan *et al.*, 2013; Tilman and Clark, 2014). Diet shifts—the ‘nutritional transition’—are increasingly common as more countries shift toward more western-style diets (Popkin, 2001; Popkin *et al.*, 2012). Since diet has the potential to be a significant portion of an individual’s contribution toward GHG emissions (Macdiarmid, 2013), some studies have suggested that managing diets and demand-side approaches may be more effective than technical agricultural mitigation options in reducing global emissions (Popp *et al.*, 2010; Smith *et al.*, 2013; Bajzelj *et al.*, 2014). These mitigation options may be especially relevant to high-income countries where diets with high GHG emission profiles are more common, while low- and middle-income countries are often focused on ensuring food and nutrition security.

Household storage and utilization

A 2008 estimate placed the total number of domestic refrigerators worldwide at about one billion, twice as many as 12 yr prior (Coulomb, 2008). The expansion of the cold chain into developing economies certainly means increased energy consumption at the consumer stages of the food system, but its net impact on GHG emissions for food systems as a whole is complex and uncertain (Heard and Miller, 2016). Estimates suggest that household refrigeration represents upwards of 17% of the total energy used by the US food system (Heller and Keoleian, 2003); appliance efficiency gains have been countered by growing refrigerator size and increased prevalence of second refrigerators (Kim *et al.*, 2006). The addition of household refrigeration in developing economy food systems has the potential to decrease spoilage, improve food safety, diversify food choices and may lead to reduced food waste while improving nutritional outcomes. But it can also have indirect effects such as increased access, and likely greater consumption, of meat, dairy and prepackaged or frozen ready-made foods; shifts to larger, supermarket-style shopping patterns; and may in fact result in greater food waste if changes in consumer purchasing patterns facilitate overbuying (Heard and Miller, 2016). As Heard and Miller discuss, the balance of these factors on food system environmental impacts is challenging to assess and requires further study and evaluation.

Processed foods

Reducing consumption of processed and ultra-processed foods could help minimize emissions associated with their processing, packaging and transportation (van Dooren *et al.*, 2014; Green *et al.*, 2015). At least two recent studies found that ready-to-eat meals had much higher energy and GHG emissions compared with using fresh ingredients (Schmidt Rivera *et al.*, 2014; Hanssen *et al.*, 2017). As well, GHG emissions for the creation of bagged salads is largely due to both the agricultural phase and the use of water and energy in the processing phase (Fusi *et al.*, 2016). However, efforts to minimize processed foods should balance potential benefits, such as contributions to nutrition and potential to reduce food waste as well as the balancing of seasonal supply and demand (Weaver *et al.*, 2014).

Balancing energy intake and individual metabolic demands

As higher calorie diets become more prevalent, evidence grows that diets that exceed individual metabolic demands can result in greater environmental impact (van Dooren *et al.*, 2014; Nelson *et al.*, 2016). Avoiding energy consumption beyond

individual needs could reduce GHG emissions up to 11% (Vieux *et al.*, 2012). Further, some evidence suggests that a significant portion of additional calories (up to 39% in the average Australian diet, *e.g.*) come from discretionary foods including alcohol, candy and baked goods, which, if reduced, could allow for greater intake of vegetables, dairy and grain providing health benefits (Hendrie *et al.*, 2016). Thus, reducing discretionary food to meet and not exceed metabolic demands could have both GHG emission benefits and potential health gains.

Animal products

A large body of recent work exploring the GHG emissions of different diet types typically highlights animal-based foods as a priority. Diets higher in animal products are associated with greater GHG emissions (González *et al.*, 2011; Bajzelj *et al.*, 2014; Abbade, 2015) and animal-based foods are the largest portion of GHG emissions in a typical diet (Heller and Keoleian, 2015; Monsivais *et al.*, 2015; Hendrie *et al.*, 2016; Clune *et al.*, 2017; Hanssen *et al.*, 2017; Vetter *et al.*, 2017). Opportunities to reduce GHG emissions, particularly in economies with high levels of meat consumption, have focused on switching to different types of meat and animal products, low-animal or substantially reduced animal product consumption, for example, through Mediterranean, vegetarian or vegan diets. Beef production results in roughly five times the GHG emissions per calorie of non-ruminant animal food sources like poultry, pork, dairy and eggs (Eshel *et al.*, 2014). Switching to less GHG-intensive animal protein is an opportunity to reduce GHG emissions, with partial substitution of red meat with pork or chicken offering between a 9% (Scarborough *et al.*, 2012) and 19% reduction in GHGs (Hoolohan *et al.*, 2013) and full substitution up to 40% (Scarborough *et al.*, 2014; Westhoek *et al.*, 2014; Sabaté *et al.*, 2015).

Shifting from animal products toward plant-based foods likely offers more significant reductions to dietary GHG emissions. Studies range in their estimates with reductions of 22% (vegetarian) or 26% (vegan) (Berners-Lee *et al.*, 2012) to potential reductions by 2050 of up to 70% over current diets (Springmann *et al.*, 2016). The inclusion of eggs and dairy (vegetarian) or no animal products at all (vegan) has resulted in varying outcomes for GHG emissions, given these products. For example, cheese has been found to have higher dietary emissions than eggs and poultry; conversely milk, cream and yoghurt have much lower dietary GHG emissions than eggs, poultry and even many vegetables and grains (Hamerschlag, 2011; Scarborough *et al.*, 2014). Related research exploring diets such as the Mediterranean or New Nordic diets have found that these reduced 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 more (Pairotti *et al.*, 2015; Tilman and Clark, 2015).

Considering nutritional outcomes is critical in evaluating potential dietary shifts (Vetter *et al.*, 2017). Potential micronutrient shifts have been explored (Temme *et al.*, 2015; Payne *et al.*, 2016), as well as the implications of recommending dietary shifts in low-income and middle-income economies where food insecurity and hunger may still be prevalent (Garnett, 2011). Diet shifts away from animal products, especially red meat, offer mortality risk benefits (Westhoek *et al.*, 2014; Aleksandrowicz *et al.*, 2016) and there are general synergies between diets low in GHGs and health benefits (Tilman and Clark, 2014; Gephart *et al.*, 2016; Irz *et al.*, 2016), though this is not universal [sugar, *e.g.*, has a low GHG impact but negative health consequences

(Briggs et al., 2016)]. However, there has been significantly less research on dietary shifts and GHG emission reductions in low- and middle-income countries (Jones et al., 2016), despite the nutritional transition many are undergoing. Overall, existing research indicates that dietary shifts toward non-ruminant protein sources will provide reductions in GHG emissions, though the extent of these reductions is variable depending on the protein replacement.

Loss, waste and disposal

Food loss (pre-consumer), waste (consumer-level) and disposal (post-consumer) represent a significant source of GHG emissions since up to one-third of all food produced is lost or wasted globally each year (FAO, 2011a), and food waste tripled between 1960 and 2011 (Porter and Reay, 2016). The FAO estimates that if food waste were a country, it would be the third largest emitter of GHG emissions in the world (FAO, 2013). The food groups where losses matter most to GHG emissions and other environmental impacts are cereals, vegetables and meat (FAO, 2013).

In low-income countries, the majority of food is lost and occurs at the production, post-harvest and processing/transportation phases. These losses are often due to a lack of infrastructure including cold-chain refrigeration, processing facilities and reliable transportation to bring crops to market. As a result, crops may spoil before they can be fully utilized (FAO, 2011a). A lack of available drying technologies or improper storage can also contribute to losses due to aflatoxins, poisonous carcinogens produced by molds in staple crops under high moisture, high temperature conditions (PACA, 2013). Opportunities to minimize food loss and waste in low-income countries include the expansion of transportation infrastructure, processing and preservation infrastructure including the cold chain, drying technologies and increased market opportunities (FAO, 2011a), though many of these may result in increased use of energy or resources. Nevertheless, given that agricultural production is the majority of GHG emissions during the production of most food (Vermeulen et al., 2012), efforts to minimize loss and waste, even at the expansion of emission sources from other aspects of the food system, would likely result in overall benefits.

Conversely, in high-income countries, most food is wasted at the retail and consumption levels (FAO, 2013; Blanke, 2015). Opportunities to reduce food waste in retail include changing consumer perceptions about food appearances, reducing overstocking, reducing portion sizes in restaurants, utilizing packaging and processing technologies that help keep food fresh for longer, and clarifying the meaning of sell-by and use-by dates for consumers (Blanke, 2015; Schanes et al., 2016; Wilson et al., 2017). Prevention of consumer food waste must consider complex human behaviors (Quested et al., 2013) but might involve consumer acceptance of 'ugly' produce, increased planning and preparation for cooking, better storage techniques and food sharing (Blanke, 2015).

In addition to the impacts associated with producing food that is not eaten, food disposal in landfills is also a source of methane emissions as food decomposes anaerobically. Globally, landfills are the third largest source of methane emissions (Global Methane Initiative, no date), though not all is attributable to food waste. Opportunities to reduce methane emissions from landfills include diverting food waste for animal feed, and compost and employing methane capture technologies, which can also be used to generate electricity (Krause et al., 2016).

Implications for action

Policy and funding mechanisms

There are multiple opportunities to reduce GHG emissions throughout the food system, although these vary with country contexts. Policies and funding will be critical catalysts for positive change. While high-income and low-income countries face different present-day challenges, experts contend that there is a global need for contraction and a convergence toward universal access to nutritious, low-emissions diets (Rockström et al., 2017a). Reductions in emissions from food systems will require actions from all value chain participants, including consumers, manufacturers, farmers and input suppliers.

Public policy will play a major role in driving change toward a lower food system GHG footprint in balance with other goals for food systems, such as health, jobs, incomes, biodiversity and gender equality. As governments recognize the opportunities with interlinked nutritional and environmental functions of food systems as well as the urgency for action, policy discourse is shifting from a focus on voluntary measures—such as consumer education, purchasing guidelines, commodity roundtables and good practice guidelines (Foresight, 2011)—to other complementary actions such as stronger regulatory and fiscal incentives, including food taxes, particularly in industrialized countries, mandatory industry standards, renewable energy subsidies and controls on land use change (De Pinto et al., 2016; Mason and Lang, 2017; Springmann et al., 2017). Further integration of sustainability criteria in food dietary guidelines could also be a driver for changing dietary patterns toward healthy, sustainable GHG diets (Fischer and Garnett, 2016). However, this is currently only happening in four countries (Brazil, Germany, Qatar and Sweden) with recommendations in countries such as the US unsuccessful thus far (Dietary Guidelines Advisory Committee, 2015; Merrigan et al., 2015).

A shortfall in dedicated public and private finance to catalyze the necessary transition remains a critical barrier—for example, the US\$2.5 trillion cost for agricultural mitigation estimated by 50 parties to the Paris Agreement is far in excess of globally available finance (Richards et al., 2016). Climate finance offers opportunities to achieve mitigation across a global context and refers to the 'financial flows mobilized by high-income country governments and private entities that support CC mitigation and adaptation in low- and middle-income countries (Stadelmann et al., 2013). The international community aims to mobilize at least US\$100 billion per year for mitigation and adaptation in low- and middle-income countries. Unfortunately, only a small portion of global climate finance (\$6–8 billion of \$391 billion in 2015) is allocated to agriculture, and it is unclear how much can be traced directly to climate-smart agriculture and climate-friendly food systems.

Climate measures are much more likely to succeed if they not only aim at reducing emissions or creating climate resilience, but also integrate broader domestic development objectives, such as poverty reduction, food security, energy security, energy access or transportation (Jakob et al., 2014). We argue that it is important to incorporate food systems thinking and related GHG mitigation and adaptation impacts into the decision-making process, which are adapted to the socio-institutional context (Vignola et al., 2017), as policies are developed and investments are mobilized for achieving a variety of other sustainable development goals. A systems approach on the whole food value chain is necessary for assessing current climate finance and re-directing

investments in climate-friendly food systems. To support decision-making, stakeholders are considering the potential utility of putting an explicit price on carbon emissions to help ensure that analysis of policy options and climate mitigation actions identify the most cost-effective mitigation efforts across the economy (Steckel et al., 2017). To actually develop carbon pricing schemes, however, would require significant additional research and work to develop schemes appropriate for national contexts and priorities. Global Climate Fund and other multilateral funds and the growing green bonds market could be utilized to generate low cost capital and catalyze broader investments for climate-friendly food systems.

Research needs

The recent growth in food system and climate research is timely and laudable. Yet there remains much additional work, particularly in low-income countries and across multiple components of the food system. For example, although the greatest increases in GHG emissions from food loss and waste in recent decades are coming from low- and middle-income countries (Porter et al., 2016), barely any empirical research explores how to overcome these challenges (Nemecek et al., 2016; Porter et al., 2016). Further, the rapid dietary shifts in low- and especially middle-income countries toward high GHG diets (Clonan et al., 2016) has not resulted in a commensurate increase in research on assessing dietary changes and their climate implications in these contexts, and the majority of available studies focus on high-income countries (Jones et al., 2016). Understanding the myriad benefits and impacts of cold-chain expansion, including unintended feedback and rebound effects, is also a priority research topic. Other research priorities we have identified include improved post-harvest management (food storage, transformation, handling and processing) to reduce food contamination and losses (Tirado et al., 2013, 2015), as well as an increased focus on mitigation opportunities in horticulture. Given quickly evolving contexts, we argue that it is critical to increase food systems and CC research in low- and middle-income countries across these, and likely many other, topics.

Conclusion

Our global and local food systems need urgent action to reduce GHG emissions in ways that enable resilience and sustainability. Though an extensive body of research explores how we can mitigate and adapt to CC in agriculture, substantially less work has focused across the food system to explore opportunities for climate mitigation and adaptation more comprehensively. Here, we highlight some of the key strategies across the food system to mitigate emissions, and their applicability in varying country contexts. We have illustrated ways in which certain mitigation options in specific food system components could have profound impacts on other areas and also potentially offer adaptation co-benefits. However, the majority of existing peer-reviewed literature does not examine CC in food systems through this lens. Thus, future systems-level research is critical to assess connections to other sustainable development goals and ensure that mitigation of food system emissions does not have untold impacts in other sectors. Conducting this work in low- and middle-income countries is especially important as the policies and investments they put into place today will have a profound impact on their food systems, including its mitigation and adaptation capacity.

While many policy and funding mechanisms have been proposed, far fewer have been implemented to meet the need/aim of sustainable food systems in a changing climate. Such efforts can be informed by empirical research, including reviews such as these but will ultimately require political will and clear, equitable and resilient funding mechanisms. Increased efforts to implement research, policies and funding mechanisms simultaneously are necessary to achieve climate mitigation and adaptation goals now and into the future inside a sustainable food system development.

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