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Climate change and food system activities: a review of emission trends, climate impacts and the effects of dietary change

by
Confidence Duku
Carlos Alho
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Abstract

Food system activities are inextricably linked with climate and weather, environmental resources and human health. This article reviews the contribution of food system activities to climate change, the positive feedback on food systems and the effects of dietary change on food system outcomes. It combines a systematic literature review with analyses of publicly available international data. The article shows that whereas emissions from food production continue to increase in most regions, emissions from land use change have been decreasing. Despite these decreasing trends, emissions from land use change are huge and in some regions are greater than emissions from food production. Climate change also affects food system activities and there is strong scientific consensus that it negatively affects food production, especially in Africa and Asia. However, from the available scientific evidence, the impacts of climate change on post-production activities are unclear. The article also shows that dietary change as a transformation strategy has large potential for reduction of greenhouse gas emissions but, regionally, is associated with substantial environmental trade-offs. Despite its potential, the costs and feasibility associated with dietary change are not well understood and require further research. Strategies to reduce emissions should focus on further reduction in land use change or stopping land use change altogether, because the current rate of reduction is inadequate to achieve a targeted reduction in greenhouse gas emissions. Strategies must also address meat consumption in those world regions and social systems where it is excessive, to usher in dietary changes away from animal products and towards consumption of plant products instead.

Keywords: climate change, food system, dietary change, greenhouse gas emission

1. Introduction

Food system activities are inextricably linked with climate and weather, environmental resources and human behaviour. Globally, food system activities contribute 21-37 per cent of total anthropogenic greenhouse gas (GHG) emissions, compared with about 10 per cent from food production alone and 18-29 per cent from food production and land use change (Rosenzweig et al., 2020). On the one hand, food system activities drive land use change; biodiversity loss; freshwater depletion; water, air and soil pollution; and nitrogen and phosphorus runoff in water bodies (Springmann et al., 2018a). On the other hand, climate change affects food system activities and threatens food security (Myers et al., 2017), especially in world regions that are already vulnerable to hunger and malnutrition (Wheeler and von Braun, 2013). These regions will experience the strongest increase in climatic variability and extremes (Bathiany et al., 2018), and have little or no coping capacities (Vermeulen, Campbell and Ingram, 2012). In general, the Global South, which contributes least to climate change, will face the largest climate change impacts.

Because food system activities contribute to and are affected by climate change, transformation is required. Food system transformation faces a dual challenge: how to reduce the contribution of food system activities to climate change and other detrimental impacts to the environment and human health, and how to cope with climate change impacts on food system activities. Transformation strategies to address these challenges need to address concurrently ongoing demographic and socio-economic changes and developments around the world. If technological and behavioural changes do not occur, the impact of food system activities on GHG emissions could increase by 50-90 per cent by 2050 (Springmann et al., 2018a). Transformation strategies that integrate environmental and social sciences are needed to tackle these contemporary and future multifaceted challenges (Bai et al., 2016). Trade-offs, synergies, lags and feedbacks embedded within each transformation strategy must be identified and, if possible, quantified.

Strategies that increase synergies should be favoured, whereas potential adverse environmental and/or socio-economic impacts and environmental trade-offs should be limited. In this regard, dietary change is increasingly recognized as a major consumer-focused transformation strategy to reduce food systems' GHG emissions and other environmental impacts (Springmann et al., 2018a; Springmann et al., 2016; Springmann et al., 2018b; Tilman and Clark, 2014). Such transformation probably requires a substantial reduction in consumption of animal-sourced foods (e.g. bovine meat and dairy products) in areas of overconsumption and increases in plant-based foods (e.g. nuts, fruits, vegetables) to meet people's energy and nutritional demands with the lowest possible environmental impacts (Springmann et al., 2016). Despite global efforts to promote this transformation strategy, local specificities cannot be neglected (Godfray and Garnett, 2014) and regional insights on the environmental and health outcomes of dietary change are essential.

In this article, we review the contribution of food systems to climate change, the positive feedback on food systems and the effects of dietary change as a food system transformation strategy. Specifically, we identify trends and regional patterns of GHG emissions by key food system activities and processes, highlight impacts of climate change on food system activities and provide regional insights on the effects of dietary change based on literature review. We primarily analyse publicly available international data and data from peer-reviewed scientific publications focusing mostly on the operational regions of the International Fund for Agricultural Development (IFAD). Available country-level data are reaggregated according to IFAD's regional classification (IFAD, undated) and interpreted within this context. IFAD's regional classification consists of Asia and Pacific (ASPA), East and Southern Africa (ESAF), West and Central Africa (WCAF), Latin America and the Caribbean (LACB), and North Africa, Near East and Eastern Europe (NNEC).

2. Greenhouse gas emissions from food system activities

Food system activities continue to drive anthropogenic GHG emissions. The quantities of and trends in GHG emissions across different food system activities vary strongly in different regions of the world. This section presents regional (IFAD operational regions) trends in GHG emissions from land use change and food production, transportation and processing.

Data describing country-level GHG emissions from enteric fermentation, manure, rice cultivation, synthetic fertilizer and land use change for the period 1990 to 2017 were obtained from the Food and Agricultural Organization's Corporate Statistical Database emission database (FAOSTAT, 2022; Tubiello et al., 2013). The FAOSTAT emission database was preferred over other emission databases, e.g. the Emissions Database for Global Atmospheric Research (EC, 2022; Crippa et al., 2020) because it provides best coverage of the relevant sectors. Despite being based on activity data reported by countries and the lack of independent verification, GHG emission data from FAOSTAT cover a considerably longer period (1961-2017) compared with the other databases, and all data follow at least the Intergovernmental Panel on Climate Change (IPCC) 2006 Tier 1 guidelines (Roman-Cuesta et al., 2016; Tubiello et al., 2015). The FAOSTAT database is also transparently documented by providing elaborated metadata (Roman-Cuesta et al., 2016).

2.1 Land use change

Land use change, especially deforestation, forest degradation and peatland conversion, contributes to substantial GHG emissions (Figure 1). Except for NNEC, all other IFAD regions are net carbon dioxide (CO_2) emitters into the atmosphere. Deforestation in the LACB region produces more emissions than deforestation in the other regions. Emissions from deforestation in LACB accounted for half of the total gross forest emissions worldwide between 1990 and 2017. Brazil alone contributed about 60 per cent of the total emissions. Commercial agriculture (specifically agribusiness or commercial cattle ranching, soybean farming and plantation agriculture) and, to a lesser extent, smallholder agriculture are the main drivers of deforestation (FAO and UNEP, 2020). Emissions from deforestation and forest degradation, however, decreased between 2005 and 2016. These reductions are a result of a series of interconnected factors that include retractions in soy and cattle production, increased monitoring and punitive measures for illegal deforestation, and the creation of new protected areas (Nepstad et al., 2014).

Like LACB, emissions from deforestation and forest degradation in WCAF and ESAF have decreased by almost one third over the past 30 years, despite increasing deforestation. This decreasing emission trend (Figure 1) is a result of substantial increases in carbon storage in intact African forests offsetting some of the deforestation emissions. Carbon storage in tropical African forests increased by 0.63 megagram per hectare per year between 1968 and 2007 as old-growth forests developed (Lewis et al., 2009). Enhanced productivity in these forests is, however, insufficient to offset all deforestation emissions and to convert Africa's forests into a net carbon sink. Forests in WCAF and ESAF are still net emitters of GHGs (Keenan et al., 2015; Lewis et al., 2009). From 1990 to 2017, net emissions from African deforestation and forest degradation accounted for 38 per cent of the global total. Deforestation in Africa is driven largely by expanding smallholder agricultural production and to a lesser extent by commercial agriculture (FAO and UNEP, 2020).

Forests in ASPA are also net emitters, although they emit considerably lower amounts of GHGs than the other regions. However, ASPA's forest emissions continue to increase. The bulk of ASPA's emissions come from Indonesia. The forests in the other ASPA countries are probably a net carbon sink. Increasing trends in GHGs are therefore determined by Indonesian deforestation rates, which are driven by commercial agriculture (i.e. expansion of tree plantations such as oil palm, rubber and rubber monocultures) and to a lesser extent by smallholder agriculture and mining (FAO and UNEP, 2020). For instance, almost all oil palm plantations planted in Kalimantan between 1990 and 2010 were previously forested areas (Carlson et al., 2012).

2.2 Food production

Here, we focus specifically on regional emissions from four key food production processes: enteric fermentation from livestock, manure application, synthetic fertilizer application and rice cultivation. These activities and processes account for 85 per cent of GHG emissions from food production, excluding land use change (Tubiello et al., 2013).

2.2.1 Enteric fermentation

In the IFAD operational regions, LACB contributes the most methane (CH_4) emissions (Figure 1). This region produces an annual average of 324 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq) and exceeds the emissions from any other region by a factor of two. CH_4 emissions are also increasing and the annual rate of increase is among the highest across all IFAD regions. LACB's substantial CH_4 emissions are best attributed to the specialized production of beef in large production systems. The emission intensity of specialized beef herds is about four times greater than that produced by dairy herds, probably because the dairy herds produce both milk and meat, and are fed more grains (Gerber et al., 2013). Despite the relatively low CH_4 emissions in ASPA, WCAF and ESAF, these emissions have also increased over the past 30 years. In WCAF, for example, total CH_4 emissions have increased by 160 per cent since 1990. The major factor explaining these increasing trends is expanded production to meet increasing demand driven by rising incomes and population growth. Also, these regions are probably dominated by grazing livestock productions systems. Grazing cattle, which directly consume permanent pasture, produce considerably more emissions per kg of meat or milk than cattle fed on concentrated grain feeds (Harper et al., 1999). This is attributed to the high fibre content and consequently lower digestibility of pasture feed.

2.2.2 Manure

GHG emissions from manure include manure deposited by grazing livestock, manure applied to crops as organic fertilizer and emissions from manure handling, storage and processing (i.e. manure management). Across all IFAD regions, more than half of emissions from manure are from manure deposited on pastures (Tubiello et al., 2013). This can be attributed to grazing livestock production systems, which are the dominant system across IFAD regions (Gerber et al., 2013). Additionally, low emissions from manure fertilizers are a result of the lack of agronomic awareness, appreciation and capacity to utilize manure as fertilizer by extension officers and farmers in most of these regions (Teenstra et al., 2014). Manure application is, for example, considered too labour intensive. This discourages its large-scale adoption and use by farmers (Ketema and Bauer, 2011). The LACB region produces most (i.e. 80 per cent) of all such manure emissions in the IFAD regions. Over the past 30 years, emissions from manure deposited on pastures increased in all regions (Figure 1) despite a reduction in emission intensity of livestock.

2.2.3 Synthetic fertilizer

GHG emissions from synthetic fertilizers increased substantially in the ASPA region driven mostly by increases in China and India. In China, emissions increased by two thirds between 1990 and 2017, and more than doubled in India. Increased emissions were stimulated by policies that subsidized fertilizer use, reduced fertilizer prices and enhanced affordability (Li et al., 2013). These GHG emissions from the ASPA region constituted 60 per cent of worldwide anthropogenic emissions from synthetic fertilizer with China being responsible for half of them, i.e. 30 per cent of global nitrous oxide (N_2O) emissions, and India for a quarter (i.e. 15 per cent).

Generally, N_2O emissions from synthetic fertilizers follow national income status. Low-income countries emit relatively few N_2O emissions, compared with middle- and high-income countries. Nonetheless, the past developments in China and India show that effective government subsidy programmes could stimulate fertilizer use, and this is likely to result in excessive fertilizer use that produces sub-optimal yields and surplus N_2O emissions. On the other hand, Cui et al. (2018) showed that adoption of enhanced management practices involving increased fertilizer use efficiency in these same countries can reduce N_2O emissions considerably while simultaneously ensuring optimal yields. Furthermore, emissions decreased in the European Union, which shows that public policies have the potential to slow down or reduce N_2O emissions. Between 1990 and 2017, European Union N_2O emissions were halved (Tubiello et al., 2013) following successive reforms of the Common Agricultural Policy, which shifted from price support to targeted decoupled payments.

2.2.4 Rice cultivation

GHG emissions related to rice stem from anaerobic decomposition of organic matter in wet paddy fields. ASPA, especially China, contributes most to these emissions. This region emits twice the combined emissions of the other IFAD regions. ASPA's emissions increase is also accelerating faster than elsewhere. Adding organic material, such as green manure, animal waste and crop straw to rice fields drives these increases, depending on the timing of the addition, and often doubles them (Yan, 2003). The flooding regimes of rice fields are also a major factor. Average CH_4 emissions from intermittently irrigated rice fields are only half the amount of those from continuously flooded rice fields (Yan, 2003). Flooding regimes also affect N_2O emissions in addition to CH_4. N_2O emissions from intermittently flooded paddy fields could also be 30-45 times higher than those from continuously flooded fields (Kritee et al., 2018).

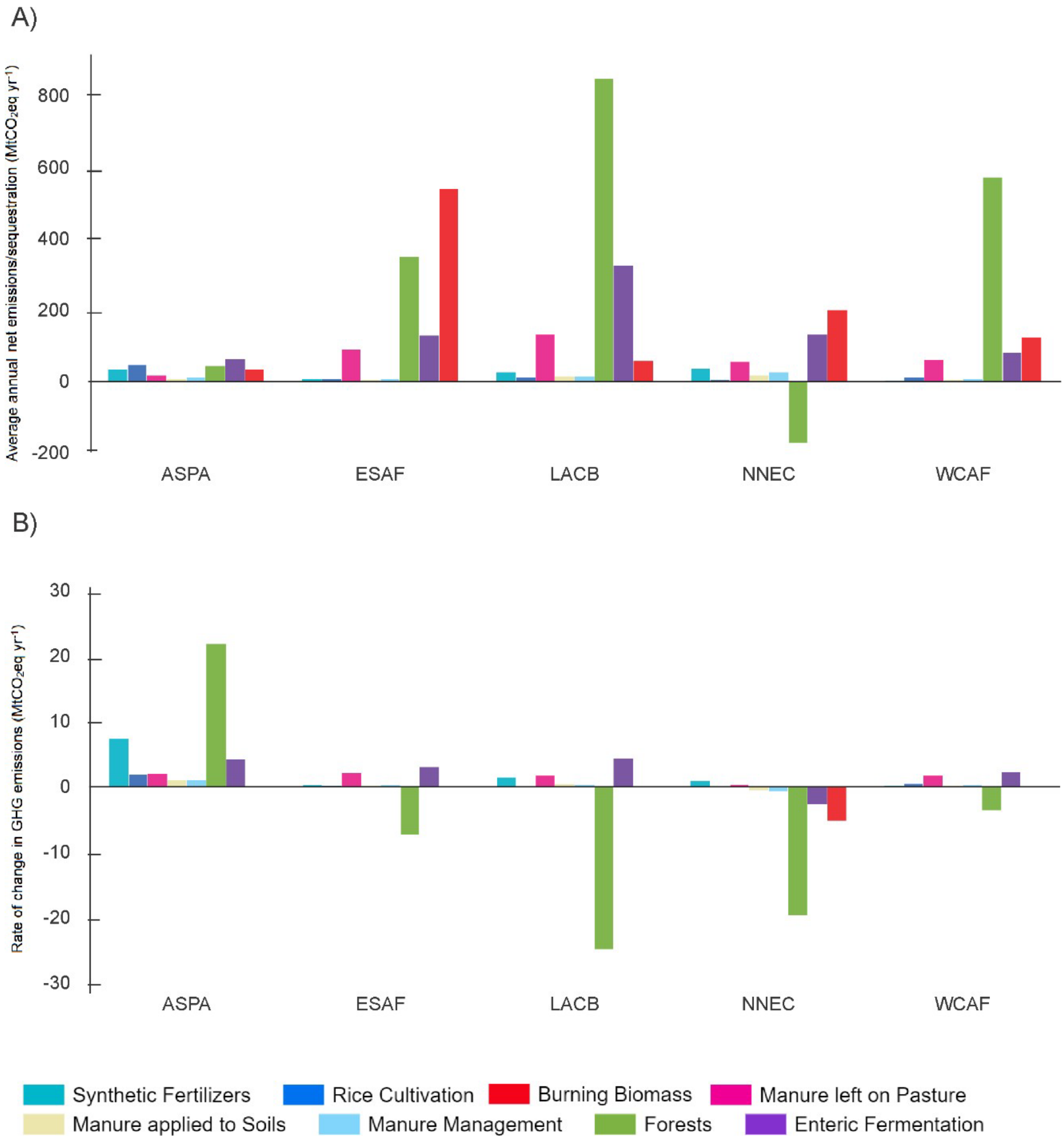

Figure 1: GHG emissions from 1990 to 2017. A) Average annual GHG emissions from major food production activities, deforestation, burning and organic soil land use change. Positive values indicate emissions and negative values indicate sequestration. B) Rate of change in greenhouse gas emissions. Positive values indicate increasing emission trends and negative values indicate decreasing emission trends. Categories without values have no significant trend. Asia and Pacific (ASPA), East and Southern Africa (ESAF), West and Central Africa (WCAF), Latin America and the Caribbean (LACB) and North Africa, Near East and Eastern Europe (NNEC).

2.3 Post-production activities

Post-production food system activities contribute to GHG emissions, albeit to a lesser extent compared with production-related and land use activities. Post-production food system activities account for 18 per cent of total GHG emissions from the global food system compared with 58 per cent from food production and 24 per cent from land use change (Poore and Nemecek, 2018). Unlike GHG emissions produced during agricultural production, country-level emissions data of food system activities post-production are poorly documented. Hence, we focused specifically on food transportation and processing, and food loss and waste.

2.3.1 Transportation

GHG emissions from transportation depend on several factors, including mode of transport, travel distance and the volume of product that is traded locally, nationally or internationally. Poore and Nemecek (2018) reported that sea or inland water transport has the least GHG emissions. For every tonne-kilometre (transport of 1 tonne of goods over a distance of 1 km), air transport emits over 100 times more GHG emissions than sea transport; road transport emits 10-33 times more; and rail transport emits only 3-5 times more. International supply chains considerably affect GHG emissions and are driven by demand for specific food items. Poore and Nemecek (2018) also present the GHG emission intensities of various food products during different post-production activities (Figure 2). the most sustainable mode of transport overall. Thus in reality emissions are likely to be substantially larger than reported in Figure 3 if different modes of transportation are used.

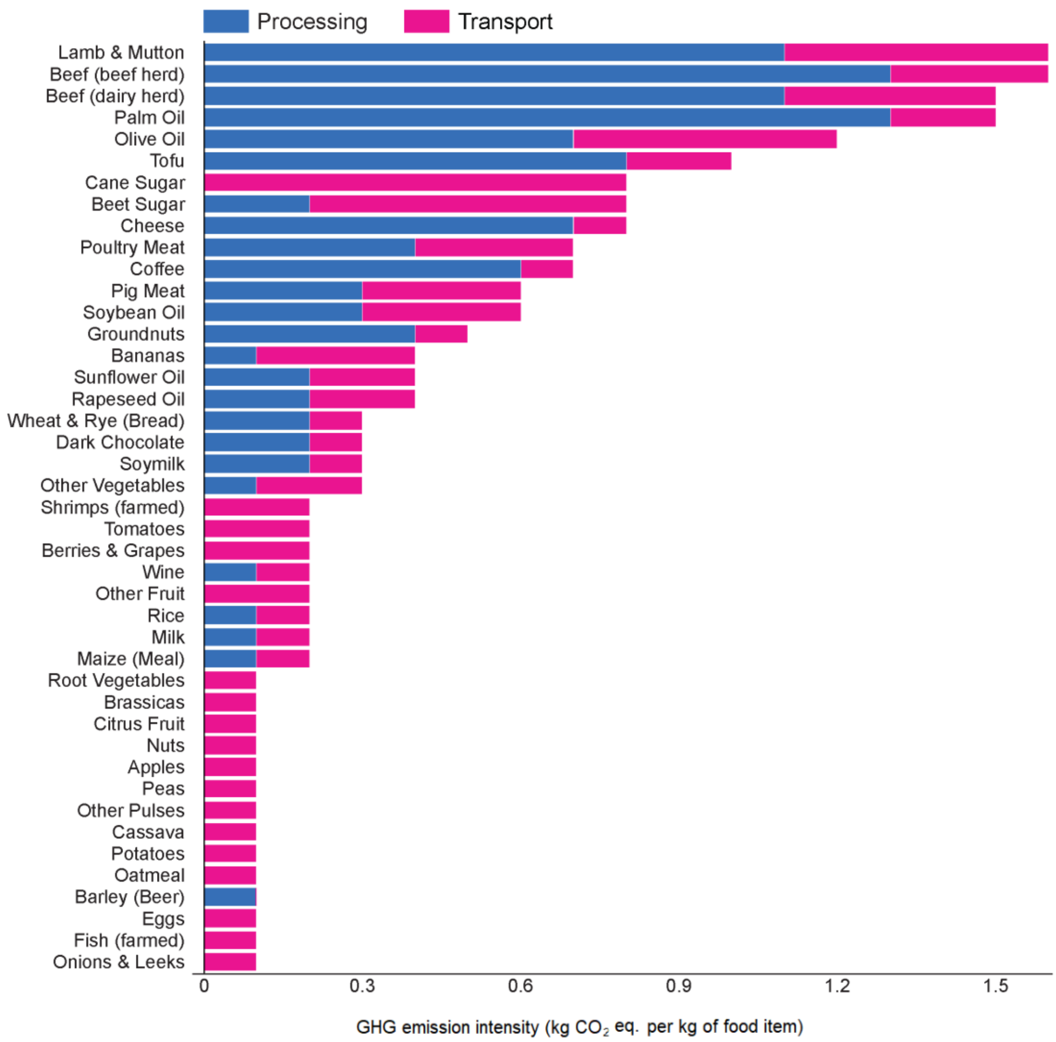

Figure 2: GHG emission intensities of various food products during food transportation and processing. Data obtained from Poore and Nemecek (2018).

The high emission rates that are associated with the transportation of some products, such as cane sugar, result from the long distances associated with the international supply chains and the huge volumes of trade between countries. For example, Figure 3 presents the estimated GHG emissions produced by exporting cane sugar from Brazil to the rest of the world in 2017. Cane sugar has the highest GHG emissions during the transportation phase, i.e. for every 1 kg cane sugar transported, 0.8 kg CO_2-eq is emitted, which is twice the emissions from the transportation of beef (Figure 2; Poore and Nemecek, 2018). The figure also shows the international supply chain of cane sugar from Brazil. GHG emissions produced from trade with India, Bangladesh and Malaysia were twice that of emissions from trade between Brazil and the entire African continent. For illustration purposes, we assumed that mode of transport between Brazil and its trade partners in South America was by rail, which is the most sustainable land-based travel, and between Brazil and the rest of the world was by ship, which is the most sustainable mode of transport overall.

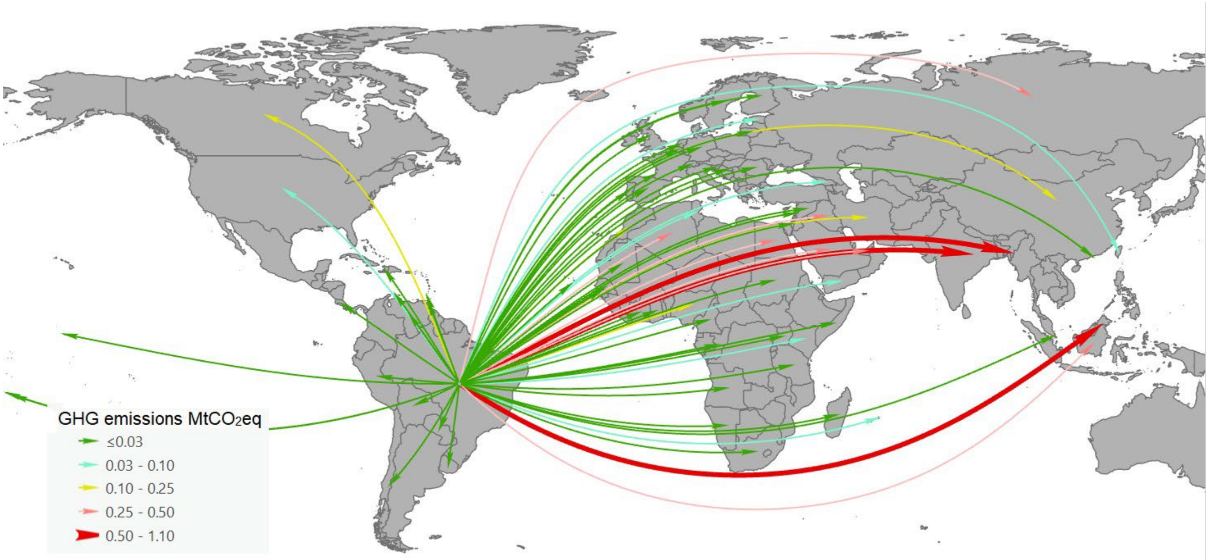

Figure 3: Greenhouse gas emissions from international trade of cane sugar between Brazil and the rest of the world for 2017. Emission factors for the various modes of transport were obtained from Poore and Nemecek (2018). Detailed trade data were obtained from the FAOSTAT Database. Travel distances between countries were calculated using the geodesic distance, which is defined as the shortest distance between two points on the Earth's spheroid. For the computation, the centroids of the countries were used as reference points.

2.3.2 Processing

Food processing produces GHG emissions as a result of energy use. Emissions from energy use are determined mainly by the type of processing and the food item. For instance, canning requires twice as much energy as freezing (Brodt, 2007). Poore and Nemecek (2018) reported that processing of beef and palm oil have the highest emission intensities. For instance, for every kg of beef or palm oil processed, the GHG emitted is more than twice that for olive oil. Food safety policy and regulation also probably influence energy used for processing. In Europe, for example, the energy used to process a tonne of meat increased from 14 to 48 per cent between 1990 and 2005 as a result of stricter food hygiene and safety regulations (Ramirez, Patel and Blok, 2006). Beyond energy use, wastewater generated during food processing, especially slaughterhouse effluent, emits CH_4 and N_2O (Poore and Nemecek, 2018).

2.3.3 Food loss and waste

Food loss and waste account for between a quarter and a third of total global primary production (Guo et al., 2020; Gustavsson et al., 2011), and a 75 per cent reduction is likely to result in a 10 per cent decrease in GHG emissions (Springmann et al., 2018a). Vegetables and fruits make up almost half of the global total food lost and wasted. The resulting GHG emissions, however, are relatively small, accounting for 16.8 per cent of total emissions from food loss and waste. On the other hand, bovine meat accounts for less than 1 per cent of food lost and wasted. The resulting GHG emissions are almost the same as those for vegetables and fruits, i.e. 16.3 per cent (Guo et al., 2020). Dairy also accounts for about 7 per cent of food lost and wasted, with the resulting GHG emissions making up 10 per cent of the global total. Apart from the consumer stage, the ASPA region generates the most GHG emissions from food loss and waste in all post-production activities. At the consumer stage, however, most GHG emissions are produced in North America and Oceania (Guo et al., 2020).

Generally, the causes of food loss and waste vary between low-income and high-income countries. Food loss dominates in low-income countries and is caused by inefficient supply chains. These include managerial and technical limitations in harvesting techniques, storage, transportation, processing, cooling and packaging (Gustavsson et al., 2011). In medium- and high-income countries, food waste dominates. Efficient supply chains reduce post-production losses considerably. But food waste at the consumer stage is substantial and is greatly influenced by consumer behaviour (Gustavsson et al., 2011).

3. Impacts of climate change on food system activities

Food system activities are directly and indirectly affected by climate change. The effects are complex and largely variable across the globe (Thornton et al., 2014). Understanding these variations is critical for developing tailored agricultural practices to cope with local stresses caused by climate change (Hatfield et al., 2011).

3.1 Land use

Climate change is likely to affect land use for food system activities and processes in several ways. Among these are the increasing spatial extent of drylands and the frequency of wildfires. In recent decades, aridity has been increasing globally. There are uncertainties in the attribution of the causes as well as the projected changes; nevertheless, increasing aridity is being attributed to land evaporation growing faster than precipitation increases (Berg et al., 2016). Temperatures in drylands are reported to be increasing at twice the rate of the global average, leading to increased frequency of droughts (Lickley and Solomon, 2018). As a result, large areas of temperate drylands are projected to shift to subtropical drylands with a consequent reduction in soil moisture availability and reduction in length of the growing season (Jia et al., 2019; Schlaepfer et al., 2017). Prolonged drought and heat stress are likely to substantially increase the frequency and intensity of wildfires in Australia, Central Asia, North America, South America, southern Europe and southern Africa (Liu, Stanturf and Goodrick, 2010). Jolly et al. (2015) reported that between 1979 and 2013, the fire weather season increased by 18.7 per cent globally. About 25 per cent of the global land surface covered with vegetation experienced increases in fires, whereas only 11 per cent experienced decreases. Huang, Wu and Kaplan (2015) also reported that the frequency of fires will increase by 27 per cent globally by 2050 relative to 2000. Increasing temperatures and declining precipitation are expected to be the most important drivers, in addition to land cover changes.

3.2 Food production

3.2.1 Crop production

Climate change will affect all components of crop production (e.g. crop yields, areas suitable for crop production and cropping intensity). The impact on crop production is a function of several interacting factors, some of which probably neutralize or accelerate the final impacts (Knox et al., 2012; Myers et al., 2017).

Climate change scenarios applied to crop models indicate that crop productivity in higher latitudes is likely to increase as a result of increased atmospheric CO_2 concentrations and warmer temperatures (Myers et al., 2017). In temperate regions, temperature increases initially (i.e. up to 2050) favour crop growth and increase yields (Solomon et al., 2007). Increased frequency and intensity of extreme weather conditions are also likely to decrease crop productivity, particularly in the tropics (Solomon et al., 2007). Water stress will probably also increase in the tropics and this could reduce crop yields even further (Solomon et al., 2007). In Africa (WCAF and ESAF) and Asia (large parts of ASPA), crop production will thus be substantially reduced. This affects food security and the livelihoods of many people (Battisti and Naylor, 2009; Lipper et al., 2014; Lobell, Schlenker and Costa-Roberts, 2011; Springmann et al., 2016).

In tropical regions, rainfall patterns and to a lesser extent temperature sensitivity are the dominant climatic factors that determine agricultural production levels (Battisti and Naylor, 2009). Knox et al. (2012) conducted a meta-analysis of climate impact studies that involved eight major African and Asian food and commodity crops (covering over 80 per cent of total crop production). They reported that crop yields could be reduced by up to 40 per cent depending on the climate change scenario, crop type and applied crop model. For example, maize yields could reduce by more than one half in south Asia, one half in eastern Africa, one third in central Africa, one quarter in southern Africa, one fifth in western Africa and one tenth in northern Africa. Sorghum yields could reduce by one quarter in southern Africa, one third in western Africa and one half in India. Very small changes in rice yield are expected across Africa, but the impacts in southern Asia are likely to be varied. In India, rice yields are very likely to decrease, whereas in Sri Lanka, they are likely to increase (Knox et al., 2012). However, very few studies included in the meta-analysis reported yield increases, with only maize grown in eastern, western and northern Africa likely to increase.

In addition to crop yield effects due to climate change, elevated CO_2 levels affect crop quality through the so-called CO_2 fertilization effect. This effect alters the nutrient concentration of the edible portions of several cultivars of rice, wheat and maize. Myers et al. (2014) showed that elevated CO_2 levels significantly decreased the concentrations of zinc and iron in all C3 crops (C3 plants are those in which the initial product of the assimilation of carbon dioxide through photosynthesis is 3-phosphoglycerate, which contains three carbon atoms). For example, wheat kernels grown at elevated CO_2 levels had 10 per cent lower zinc content and 5 per cent lower iron content than those grown at ambient CO_2 levels. McGrath and Lobell (2013) and Loladze (2002) reported similar observations. Millions of people who have limited alternatives to mineral supply, apart from staple foods, are likely to be at risk of mineral deficiency. Myers et al. (2015) estimated that 138 million people worldwide (of which 80 million live in ASPA, 30 million in ESAF and WCAF, 7 million in LACB and 15 million in NNEC) could be exposed to zinc deficiency by 2050.

3.2.2 Livestock production

Climate change directly affects the quantity and quality of feed, increases livestock heat stress and probably promotes livestock diseases and vectors. Much research has focused on temperate regions, with few studies conducted in the tropics and subtropics. Climate change impacts on livestock production are thus poorly assessed in the IFAD regions.

Nonetheless, feed quantity and quality are sensitive to changes in temperature, precipitation and atmospheric CO_2 levels and these changes affect pasture production. High temperatures cause low accumulation of dry matter because the plant maturity period shortens and developmental stages are completed earlier. As a result, grain crop and forage grass yields reduce (Giridhar and Samireddypalle, 2015). Coret et al. (2005), for example, reported that shortening the maturity period reduced spring wheat seed yield by 18 per cent and maize grain yield by 29 per cent. In addition, increased temperature, especially in arid conditions, increases lignin content in plants and this reduces digestibility. This process is accelerated by CO_2 fertilization, which also decreases nutrient availability (Rojas-Downing et al., 2017; Thornton et al., 2009).

Heatwaves, which will occur more frequently under a changing climate, also affect livestock production through increased heat stress on livestock. The severity of this stress depends on the actual temperature, humidity, species, breed, life stage and nutritional status. Generally, heat stress reduces feed intake. In pigs, for example, feed intake can reduce by up to 50 per cent (Collin et al., 2001). In cattle, heat stress affects beef more than dairy herds. Livestock in tropical and subtropical regions are more resilient to drought and higher temperatures, and probably cope better with heat stress than livestock in temperate and boreal regions (Thornton et al., 2009).

3.3 Post-production activities

The climate change impacts on food systems are not limited to crop, feed and livestock production, but are also experienced across the entire food supply chain. Here, because of the lack of available data and/or literature, we focus on the impacts on food transportation and processing.

3.3.1 Transportation

Sustained high temperatures and frequency of extreme events such as sea-level rise, storm surges and flooding as a result of climate change are expected to severely affect transportation activities and infrastructure, and consequently food access. Transportation infrastructure is particularly vulnerable to freeze-thaw cycles. Sustained high temperature is likely to result in road and rail buckling. In coastal areas, sea-level rise, and the associated increase in frequency and intensity of storm surges and flooding, seriously threatens transportation infrastructure and networks. For example, Jacob, Gornitz and Rosenzweig (2007) estimated that a global sea-level rise of 1 metre would increase the frequency of coastal storm surges and flooding incidences in the New York metropolitan area by a factor of 2-10. Currently, about 40 per cent of the global population lives within 100 kilometres of the coast, with food transportation in most of these areas subject to similar risks. Increased frequency of heavy rainfall is likely to lead to road submersion and underpass flooding. For example, increased flooding events could well reduce transportable road networks by one quarter by the middle of this century in Mozambique (Arndt et al., 2011). Even in a no-flooding scenario, increasing temperatures probably damage road infrastructure and this reduces accessibility to markets and production needs, which probably leads to higher food prices. However, decreased frequency of cold days is expected to have positive effects on transportation, especially in temperate regions. These include reduced winter maintenance costs for road and rail. It is also expected to have positive effects on marine transportation in these regions.

3.3.2 Processing

Climate change is expected to affect food processing requirements (i.e. stage and type of food processing) as a result of its effects on food safety, quality and waste. Climate change affects the safety and quality of staple products, especially during post-harvest storage (e.g. through attack by fungi). Fungi that naturally occur on crops produce mycotoxins, which are likely to adversely affect health when consumed by humans and animals. The most toxic mycotoxins are aflatoxins, which are produced by the fungus *Aspergillus*. Increasing temperatures, especially in temperate and humid regions, are likely to increase aflatoxin contamination in maize (Battilani et al., 2016). Temperature, aflatoxins and pest concentrations are also clearly correlated, since increased temperature amplifies pest occurrence and increases condensation in grain silos (Magan, Medina and Aldred, 2011). This results in wet pockets, which accelerates the production of aflatoxins.

4. Dietary change as a food system transformation strategy

We obtained simulated data on potential national effects of various dietary-change scenarios on GHG emissions, nitrogen and phosphorus application, freshwater use, cropland use and premature deaths from Springmann et al. (2018b). The obtained data were for the years 2030 (i.e. based on multiple scenarios of dietary change under the second Shared Socioeconomic Pathway) and 2010 (i.e. based on current dietary patterns). National-level data were reaggregated according to IFAD's regional classification and reinterpreted within this context. The defined nutrient levels in each dietary-change scenario from Springmann et al. (2018b) were based on energy-balanced varieties of the flexitarian, pescatarian, vegetarian and vegan dietary patterns defined by the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems (Willett et al., 2019). We should emphasize that the dietary guidelines of the EAT-Lancet Commission have been criticized for, among other reasons, unaffordability (Hirvonen et al., 2019). Nevertheless, the analysis and data by Springmann et al. (2018b) following the EAT-Lancet dietary guidelines are the most comprehensive yet to quantify the environmental footprint of dietary-change scenarios.

4.1 Effects of dietary change on environmental outcomes

Globally, dietary change offers substantially greater potential for GHG reduction than supply-side mitigation strategies; however, the costs and feasibility of achieving this potential are not well understood. Shifting to a solely plant-based diet more than halves GHG emissions compared with traditional diets, assuming no additional land use change occurs (Springmann et al., 2018b). Dietary change also simultaneously reduces the use of cropland and freshwater, and worldwide nitrogen and phosphorus emissions. Global GHG mitigation potentials of dietary change are confirmed by several studies (e.g. Stehfest et al., 2009; Tilman and Clark, 2014). Stehfest et al. (2009) concluded, for example, that global GHG emission reductions generally are proportional to the magnitude of animal-based food restrictions. Hence, veganism produces the largest reduction in GHG emissions. The same source shows that the cumulative emission reduction with a worldwide vegan diet adds up to 17 per cent for CO_2, 24 per cent for CH_4 and 21 per cent for N_2O emissions reductions.

Regionally, dietary change also offers enormous potential for GHG reduction. However, effectiveness and concurrent benefits in reducing other environmental impacts differ strongly regionally and are not always guaranteed. At these levels, the impacts of dietary change on GHG emissions and environmental footprints are generally determined by existing cultural and traditional diets, which change only slowly. Almost all national and regional evidence stems from northern high-income countries (e.g. Laroche et al., 2020; Saez-Almendros et al., 2013).

Evidence from low-income countries remains limited. Only Springmann et al. (2018a) provide evidence that spans different income classes and country-specific details for more than 150 countries. They assessed the national effects of dietary change scenarios on the environment and human health. Their scenarios include replacing all animal-sourced foods with plant-based foods, while keeping the diets' caloric balance constant (ANI-100); 100 per cent reduction in underweight, overweight and obesity levels by creating proper caloric balances (CAL-100); replacing all animal-sourced foods with either fish and seafood or legumes (PSC); and replacing all animal-sourced foods with fruits and vegetables (VGN). The study spanned 2010 and 2030 and used IPCC's Shared Socio-economic Pathways (SSPs; O'Neill et al., 2014). These pathways assume different future socio-economic developments but no climate policies. For our analysis, we reaggregated the results from Springmann et al. (2018b) for the five IFAD regions and computed their relative changes. This approach facilitated the identification of suitable dietary change strategies for each IFAD region.

Scenarios ANI-100 and VGN reduced GHG emissions by the greatest amount. Both scenarios reduced GHG emissions by at least 80 per cent in all IFAD regions (Figure 4). In relative terms, LACB experienced the largest reduction (96 per cent). Across the IFAD regions, LACB consumes the most bovine meat per capita. On average, people in LACB consume three times as much meat as those in WCAF and twice that of ESAF and ASPA. In absolute terms, however, the largest emission reduction is in ASPA, with 2,600 $MtCO_2$-eq reduction. This is caused by the reduction in demand for emissions-intensive animal-sourced foods. This translates in the ASPA region into larger absolute numbers because of its relatively larger population compared with other IFAD regions.

Across all IFAD regions, the CAL-100 scenario reduces GHG emissions least. This scenario reduces GHG emissions by 16 per cent in ASPA, 17 per cent in LACB, and 1 per cent in ESAF. In NNEC, this scenario had no substantial effect on GHG emissions, whereas in WCAF, this scenario increased GHG emissions by 3 per cent. In WCAF, the increase in GHG emissions is probably attributed to the current high levels of undernourishment (FAO et al., 2020). It would require a substantial calorific increase to halt undernourishment.

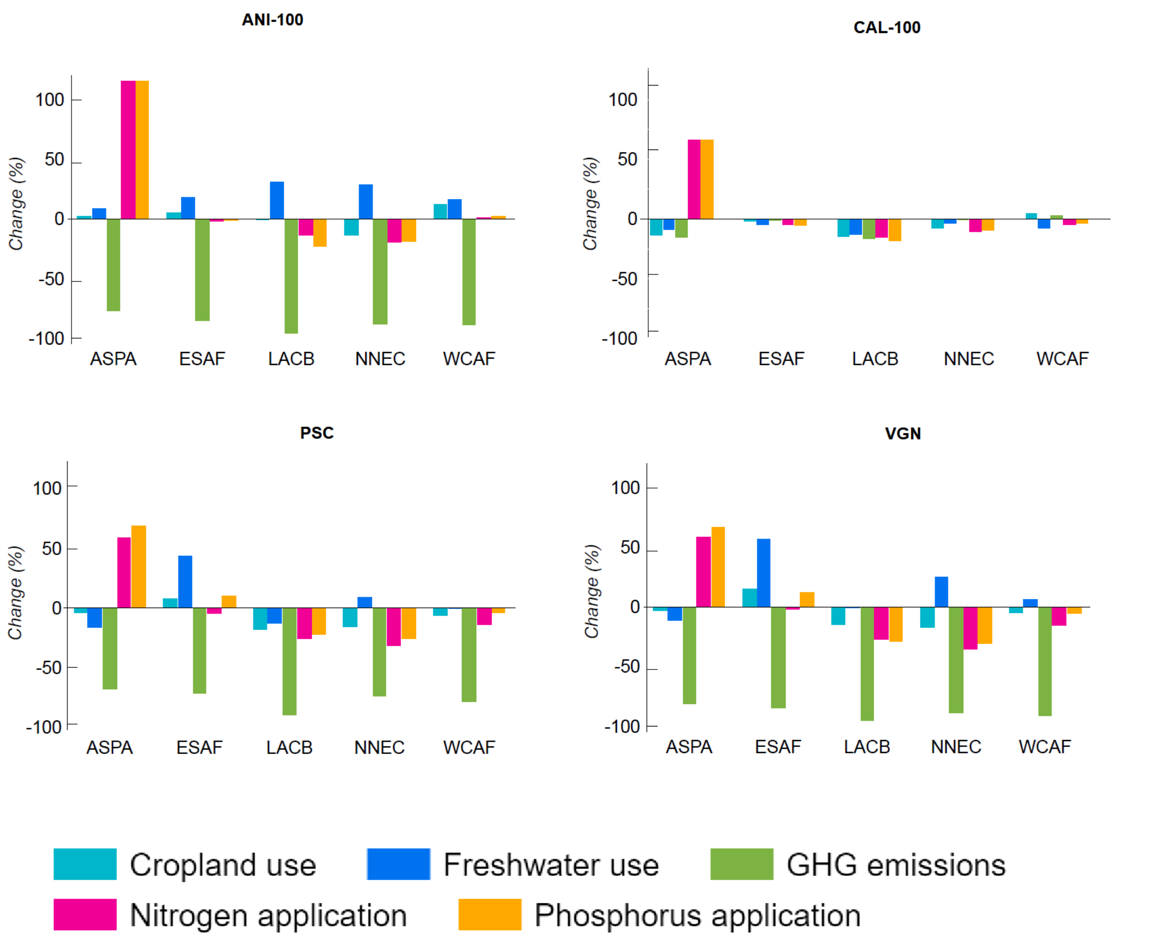

Figure 4: Regional changes in GHG emissions and environmental impacts of dietary change. The scenarios include diets in which all animal-sourced foods have been replaced by plant-based ones (ANI-100), diets with optimal energy intake and weight levels (CAL-100), and diets based on public health guidelines, i.e. pescatarian (PSC) and vegan (VGN). These results are for SSP2. Data were obtained from Springmann et al. (2018b). Asia and Pacific (ASPA), East and Southern Africa (ESAF), West and Central Africa (WCAF), Latin America and the Caribbean (LACB), and North Africa, Near East and Eastern Europe (NNEC).

4.2 Synergies and trade-offs

In addition to GHG emission reductions, dietary change is likely to produce concurrent health benefits in regions with high beef consumption. Current dietary patterns strongly contribute to strokes, coronary heart disease, cancer, type-2 diabetes mellitus and other weight-related diseases (Springman et al., 2018b; Figure 5). Across all scenarios, mortality and disease burden attributable to dietary risk factors was considerably reduced. In all scenarios, premature mortality was substantially reduced. The VGN scenario reduced premature mortality by the greatest amoung. Under this scenario, by 2030, premature mortality is reduced by over 6 million in ASPA, 2 million in NNEC, 1 million in LACB and 0.5 million in ESAF and WCAF. Similar health benefits and ranges are expected with the PSC scenario. In ASPA, LACB and NNEC, the health benefits of VGN and PSC relate to reduced coronary heart disease and stroke, whereas in ESAF and WCAF they are mostly weight-related dietary risks.

Despite the reduction in GHG emissions and concurrent health benefits across almost all regions and all scenarios, dietary change as a food system transformation strategy probably results in trade-offs between different environmental objectives and food system outcomes. Dietary change affects nitrogen and phosphorus runoff, freshwater demand and land use change associated with livestock production. Unlike GHG emissions, freshwater use increases in all regions under the ANI-100 scenario, where the larger dietary share of plant-based foods increased water use. Freshwater use increased least in ASPA (9 per cent) and most in LACB (31 per cent). Freshwater use increased because of growing demand for thirsty crops such as legumes, vegetables and fruits. VGN and PSC scenarios also increased freshwater use in ESAF, WCAF and NNEC, where increased consumption of plant-based foods is likely to increase the demand for environmental resources, in part because of inefficient production systems and current diets reliant on staple crops. Dietary change also increases cropland area, especially in low-income countries. In these countries, the use of less intensive feeds and fertilizers, and less efficient production systems leads to lower yields and thus probably requires expansion of cropland areas to meet calorific and nutritional demands. Hence, cropland area increased the most in ESAF and WCAF. Cropland area increases because of increased consumption of plant-based foods. Nitrogen and phosphorus application and their consequent emissions are also affected by dietary change. The most affected region is ASPA where substantial increases in nitrogen and phosphorus runoff are projected under all scenarios.

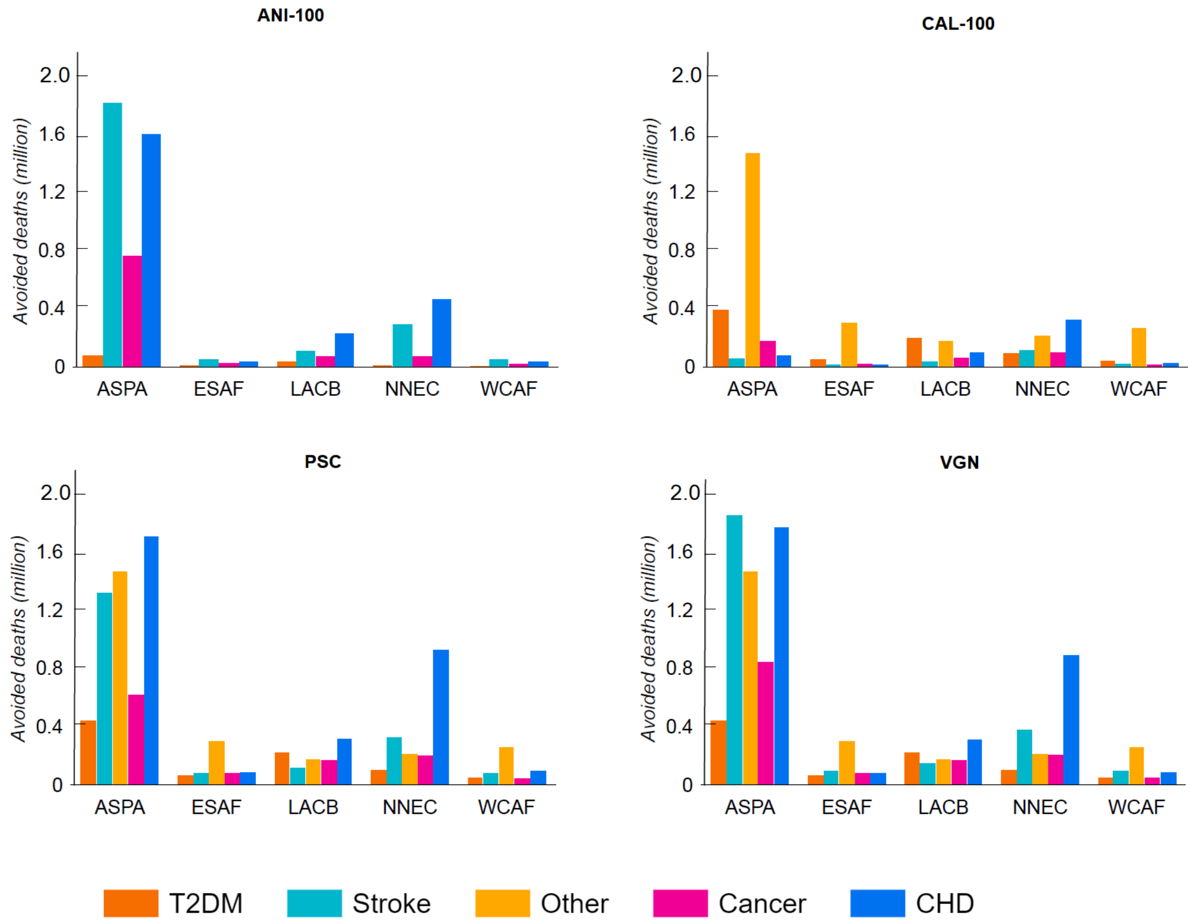

Figure 5: Regional changes in premature mortality as a result of dietary change. The scenarios include diets in which all animal-sourced foods have been replaced by plant-based ones (ANI-100), diets with optimal energy intake and weight levels (CAL-100), and diets based on public health guidelines. i.e. pescatarian (PSC) and vegan (VGN). These results are for SSP2. CHD refers to coronary heart diseases; T2DM is type-2 diabetes mellitus; Other refers to other weight-related causes of death. Data were obtained from Springmann et al. (2018b). Asia and Pacific (ASPA), East and Southern Africa (ESAF), West and Central Africa (WCAF), Latin America and the Caribbean (LACB), and North Africa, Near East and Eastern Europe (NNEC).

4.3 Drivers of dietary change

Several factors drive dietary change. These include incomes, food prices, technological innovation, trade liberalization, nutritional diversity of food supply, health policy and education, and consumer behaviour (Kiff, Wilkes and Tennigkeit, 2016). Incomes and food prices are the most important factors. In low-income countries, especially ESAF and WCAF, dietary choices are far more sensitive to incomes and food prices than in high-income countries (Muhammad et al., 2017). Income elasticities for processed meat consumption in ESAF and WCAF, for example, are eight times larger than those in LACB. Consumption of different food items also responds differently to changes in incomes and food prices. Consumption of processed meat and fruit are affected most strongly, whereas consumption of plant-based food (except for fruits and whole grains) is affected least. Consumption of nuts and legumes is negatively related to rising incomes (Muhammad et al., 2017).

Diversity of food production and supply is another major driver of dietary change. Whereas in low-income countries dietary diversity is limited to locally produced food items, in middle- and high-income countries dietary diversity is greater because of food imports (Remans et al., 2014). For example, in terms of local production, ESAF and WCAF have greater diversity than LACB; however, in terms of food supply (i.e. local production and imports), the diversity is smaller (Remans et al., 2014).

Urbanization accelerates dietary changes, especially in low-income countries, where the urban and rural dietary patterns are much more heterogeneous compared with high-income countries. In high-income countries, market penetration into rural areas is much more developed and this homogenizes dietary patterns across the rural-urban divide. Nevertheless, urbanization generally accelerates a shift towards better availability of fats and sugars and reduces reliance on starchy carbohydrates as dietary staples (Popkin, 1999).

Liberalization and consumer behaviour are also major drivers of dietary change, especially in high-income countries and countries with rising incomes. Liberalization involves the removal of trade and investment barriers, and is likely to increase dietary diversity beyond locally produced food items. For example, trade in processed food now constitutes 30-60 per cent of all agricultural trade in Africa (Badiane, Odjo and Collins, 2018). Consumer behaviour, especially increasing environmental awareness, has recently become a major driver of dietary change in high-income countries (HLPE, 2017). In these regions, awareness of the intricate relationship between the environment and dietary choices has increased. Hence, in addition to healthy living and animal welfare awareness, environmental concerns now influence consumers' dietary preferences.

5. Conclusions

Food system activities are undoubtedly major contributors to climate change. GHG emissions from food production and land use change are considerably greater than emissions from other food system activities. Whereas emissions from food production continue to increase in most regions, emissions from land use change have been decreasing (except for ASPA, where increasing emissions are driven by Indonesia). Despite decreasing trends, emissions from land use change remain substantial especially in WCAF and LACB, where they are greater than emissions from food production. Climate change affects all food system activities. However, the scientific evidence is not clearly documented for all activities. Whereas the effects on food production are clearly documented, effects on post-production activities are poorly documented, especially in low-income countries.

There is strong scientific consensus that climate change negatively affects the production and the quality of several staple foods, especially in Africa and Asia. In effect, despite the gains made in improving food security across the globe, the current food system has major deficiencies and transformation is required. Dietary change towards increasing consumption of plant-based foods is increasingly recognized as a consumer-focused transformation strategy in areas with high meat consumption. The scientific evidence suggests that whereas increasing intake of plant-based foods is universally effective in reducing GHG emissions and diet-related diseases (e.g. obesity and diabetes) compared with modern diets high in meat, fat and sugar, this strategy is likely to increase freshwater use, especially in African lower-income countries, and raise nutrient emissions, especially in Asian countries.

Despite its potential, the costs and feasibility associated with dietary change are not well understood and require further research. Hence, strategies to reduce emissions should focus on further reductions in land use change because the current rate of reduction is inadequate to achieve a targeted reduction in GHG emissions. Strategies must also address meat consumption in those world regions and social systems where it is excessive to usher in dietary changes away from animal products and towards the consumption of plant products instead.

References

Arndt, C. et al. 2011. Adapting to climate change: an integrated biophysical and economic assessment for Mozambique. *Sustainability Science*, 6(1): 7-20.

Badiane, O., Odjo, S.P. and Collins, J. 2018. Africa agriculture trade monitor 2018. Technical Centre for Agricultural and Rural Cooperation ACP-EU (CTA), Wageningen, The Netherlands.

Bai, X. et al. 2016. Plausible and desirable futures in the Anthropocene: A new research agenda. *Global Environmental Change*, 39: 351-362.

Bathiany, S., Dakos, V., Scheffer, M. and Lenton, T.M. 2018. Climate models predict increasing temperature variability in poor countries. *Science Advances*, 4(5).

Battilani, P. et al. 2016. Aflatoxin B1 contamination in maize in Europe increases due to climate change. *Nature Scientific Reports*, 6(1): 24328.

Battisti, D.S. and Naylor, R.L. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science*, 323(5911): 240-4.

Berg, A., Findell, K., Lintner, B., Giannini, A., Seneviratne et al. 2016. Land–atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change*, 6(9): 869-874.

Brodt, S., 2007. Assessment of Energy Use and Greenhouse Gas Emissions in the Food System: A Literature Review. Agricultural Sustainability Institute, University of California Davis, Davis, CA.

Carlson, K.M., Curran, L.M., Asner, G.P., McDonald Pittman, A., Trigg, S.N. and Adeney, J.M. 2012. Carbon emissions from forest conversion by Kalimantan oil palm plantations. *Nature Climate Change*, 3(3): 283-287.

Collin, A., van Milgen, J., Dubois, S. and Noblet, J., 2001. Effect of high temperature and feeding level on energy utilization in piglets. *Journal of Animal Science*, 79(7): 1849-57.

Coret, L., Maisongrande, P., Boone, A. and Logo, A. 2005. Assessing the impacts of the 2003 hot and dry spell with SPOT HRVIR images time series over south-western France. *International Journal of Remote Sensing*, 26(11): 2461-2469.

Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E. et al. 2020. High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Nature Scientific Data*, 7(1): 121.

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W. et al. 2018. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 555(7696): 363-366.

EC. 2022. Emissions Database for Global Atmospheric Research. European Commission. https://edgar.jrc.ec.europa.eu/

FAO, IFAD, UNICEF, WFP and WHO. 2020. The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Food and Agriculture Organization of the United Nations, International Fund for Agricultural Research, United Nations Children's Fund, World Food Programme and World Health Organization.

FAO and UNEP, 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Food and Agriculture Organization of the United Nations and United Nations Environment Programme.

FAOSTAT. 2022. Food and agriculture data. Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data

Gerber, P.J. Steinfeld, H., Henderson, B., Mottet, A., Opio, C. et al., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations, Rome.

Giridhar, K. and Samireddypalle, A. 2015. Impact of Climate Change on Forage Availability for Livestock. In: Sejian V., Gaughan J., Baumgard L., Prasad C. (eds) Climate Change Impact on Livestock: Adaptation and Mitigation. Springer, New Delhi.

Godfray, H.C. and Garnett, T. 2014. Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B Biological Sciences*, 369(1639): 20120273.

Guo, X., Broeze, J., Groot, J.J., Axmann, H. and Vollebregt, M. 2020. A worldwide hotspot analysis on food loss and waste, associated greenhouse gas emissions, and protein losses. *Sustainability*, 12(18): 7488.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. 2011. Global food losses and food waste: extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome.

Harper, L.A., Denmead, O.T., Freney, J.R. and Byers, F.M. 1999. Direct measurements of methane emissions from grazing and feedlot cattle. *Journal of Animal Science*, 77(6): 1392-401.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C. et al. 2011. Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, 103(2): 351-370.

Hirvonen, K., Bai, Y., Headey, D. and Masters, W.A. 2019. Cost and affordability of the EAT-Lancet diet in 159 countries. *The Lancet*, 8(1): E59-E66.

HLPE. 2017. Nutrition and food systems: A report by the Highlevel Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Huang, Y., Wu, S. and Kaplan, J.O. 2015. Sensitivity of global wildfire occurrences to various factors in the context of global change. *Atmospheric Environment*, 121: 86-92.

IFAD. Undated. Regional classification. International Fund for Agricultural Development. https://www.ifad.org/en/web/operations/regions

Jacob, K.H., Gornitz, V. and Rosenzweig, C. 2007. Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: inferences for urban coastal risk management and adaptation policies. Managing coastal vulnerability. Elsevier, Amsterdam.

Jia, G., Shevliakova, E., Artaxo, P., De Noblet-Ducoudre, R., Houghton, R. et al. 2019. Land–climate interactions. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner et al. (eds) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change.

Jolly, W.M., Cochrane, M.A., Freeborn, P.H., Holden, Z.A., Brown, T.J. et al. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6(1): 7537.

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A. and Lindquist, E. 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *Forest Ecology and Management*, 352: 9-20.

Ketema, M. and Bauer, S., 2011. Determinants of manure and fertilizer applications in Eastern Highlands of Ethiopia. *Quarterly Journal of International Agriculture*, 50(3): 237-252.

Kiff, L., Wilkes, A. and Tennigkeit, T. 2016. The technical mitigation potential of demand-side measures in the agri-food sector: a preliminary assessment of available measures. CCAFS Report No. 15. CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen.

Knox, J., Hess, T., Daccache, A. and Wheeler, T. 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3): 034032.

Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J. et al., 2018. High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. Proceedings of the National Academy of Sciences of the USA, 115(39): 9720-9725.

Laroche, P.C., Schulp, C.J., Kastner, T. and Verburg, P.H. 2020. Telecoupled environmental impacts of current and alternative Western diets. *Global Environmental Change*, 62: 102066.

Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T. et al. 2009. Increasing carbon storage in intact African tropical forests. Nature, 457: 1003-1006.

Li, Y., Zhang, W., Ma, L. and Huang, G. 2013. An analysis of China's fertilizer policies: Impacts on the industry, food security, and the environment. *Journal of Environmental Quality*, 42(4): 972-81.

Lickley, M. and Solomon, S. 2018. Drivers, timing and some impacts of global aridity change. *Environmental Research Letters*, 13(10): 104010.

Lipper, L., Thornton, P., Morgan Campbell, B. and Baedeer, T. 2014. Climate-smart agriculture for food security. *Nature Climate Change*, 4: 1068.

Liu, Y., Stanturf, J. and Goodrick, S. 2010. Trends in global wildfire potential in a changing climate. *Forest Ecology and Management*, 259(4): 685-697.

Lobell, D.B., Schlenker, W. and Costa-Roberts, J. 2011. Climate trends and global crop production since 1980. *Science*, 333(6042): 616-20.

Loladze, I. 2002. Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry? *Trends in Ecology and Evolution*, 17(10): 457-461.

Magan, N., Medina, A. and Aldred, D. 2011. Possible climate change effects on mycotoxin contamination of food crops pre- and post-harvest. *Plant Pathology*, 60(1): 150-163.

McGrath, J.M. and Lobell, D.B. 2013. Reduction of transpiration and altered nutrient allocation contribute to nutrient decline of crops grown in elevated CO_2 concentrations. *Plant, Cell and Environment*, 36(3): 697-705.

Muhammad, A., D'Souza, A., Meade, B., Micha, R. and Mozaffarian, D. 2017. How income and food prices influence global dietary intakes by age and sex: evidence from 164 countries. *British Medical Journal Global Health*, 2(3).

Myers, S.S. Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. et al. 2014. Increasing CO_2 threatens human nutrition. *Nature*, 510(7503): 139-142.

Myers, S.S., Wessells, K.R., Kloog, I., Zanobetti, A. and Schwartz, J. 2015. Effect of increased concentrations of atmospheric carbon dioxide on the global threat of zinc deficiency: a modelling study. *Lancet Global Health*, 3(10): e639-45.

Myers, S.S., Smith, M.R., Guth, S. Golden, C.D. Vaitla, B. et al. 2017. Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, 38: 259-277.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A. Azevedo, A. et al. 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, 344(6188): 1118-1123.

O'Neill, B.C., Kriegler, A., Riahi, K., Ebi, K.L., Hallegatte, S. et al. 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3): 387-400.

Poore, J. and Nemecek, T. 2018. Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392): 987-992.

Popkin, B.M. 1999. Urbanization, lifestyle changes and the nutrition transition. *World Development*, 27(11): 1905-1916.

Ramirez, C., Patel, M. and Blok, K. 2006. How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy*, 31(12): 2047-2063.

Remans, R., Wood, S.A., Saha, N., Anderman, T.L. and DeFries, R.S. 2014. Measuring nutritional diversity of national food supplies. *Global Food Security*, 3(3-4): 174-182.

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. and Woznicki, S.A. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, 16: 145-163.

Roman-Cuesta, R.M., Herold, M., Rufina, M., and Rosenstock, T., Houghton, R., et al. 2016. Multi-gas and multi-source comparisons of six land use emission datasets and AFOLU estimates in the Fifth Assessment Report, for the tropics for 2000–2005. *Biogeosciences*, 13(20): 5799-5819.

Rosenzweig, C., Mbow, C., Barioni, L., Benton, T., Herrero, M., et al., 2020. Climate change responses benefit from a global food system approach. *Nature Food,* 1(2): 94-97.

Saez-Almendros, S., Obrador, B., Bach-Faig, A. and Serra-Majem, L. 2013. Environmental footprints of Mediterranean versus Western dietary patterns: beyond the health benefits of the Mediterranean diet. *Environmental Health*, 12(1): 118.

Schlaepfer, D.R., Bradford, J.B., Lauenroth, W.K., Munson, S.M., Tienjen, B., et al. 2017. Climate change reduces extent of temperate drylands and intensifies drought in deep soils. *Nature Communications*, 8(1): 14196.

Solomon, S., Manning, M., Marquis, M. and Qin, D. 2007. Climate change 2007 - the physical science basis: Working group I contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press.

Springmann, M., Godfray, H.C., Rayner, M. and Scarborough, P. 2016. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences of the USA*, 113(15): 4146-51.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsy, B.J., et al. 2018a. Options for keeping the food system within environmental limits. *Nature*, 562(7728): 519-525.

Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T., Rayer, M., et al. 2018b. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail*. The Lancet Planetary Health*, 2(10): e451-e461.

Stehfest, E., Bouwman, L., van Vuuren, D., den Elzen, M., Eichout, B. and Kabat, P. 2009. Climate benefits of changing diet. *Climatic Change*, 95(1-2): 83-102.

Teenstra, E., Vellinga, T., Aektasaeng, N., Amatayakul, W., Ndambi, A., et al. 2014. Global assessment of manure management policies and practices. Livestock Research, Wageningen University and Research, Wageningen.

Thornton, P.K., van de Steeg, J., Notenbaert, A. and Herrero, M. 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems*, 101(3): 113-127.

Thornton, P.K., Ericksen, P.J., Herrero, M. and Challinor, A.J. 2014. Climate variability and vulnerability to climate change: a review. Global Change Biology, 20(11): 3313-28.

Tilman, D. and Clark, M. 2014. Global diets link environmental sustainability and human health. *Nature*, 515(7528): 518-22.

Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N. and Smith, P. 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, 8(1): 015009.

Tubiello, F.N., Salvatore, M., Ferrara, A., House, J., Federici, S., et al. 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990-2012*. Global Change Biology*, 21(7): 2655-2660.

Vermeulen, S.J., Campbell, B.M. and Ingram, J.S.I. 2012. Climate change and food systems. *Annual Review of Environment and Resources*, 37(1): 195-222.

Wheeler, T. and von Braun, J. 2013. Climate change impacts on global food security. *Science*, 341(6145): 508-13.

Willett, W., Rockstrom, J., Loken, B., Springmann, M., Lang, T., et al. 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170): 447-492.

Yan, X. 2003. Methane emission from rice fields in mainland China: Amount and seasonal and spatial distribution. *Journal of Geophysical Research*, 108(D16).

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