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Invited State of Science

Harnessing the connectivity of climate change, food systems and diets: Taking action to improve human and planetary health☆

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ABSTRACT

With climate change, the COVID-19 pandemic, and ongoing conflicts, food systems and the diets they produce are facing increasing fragility. In a turbulent, hot world, threatened resiliency and sustainability of food systems could make it all the more complicated to nourish a population of 9.7 billion by 2050. Climate change is having adverse impacts across food systems with more frequent and intense extreme events that will challenge food production, storage, and transport, potentially imperiling the global population's ability to access and afford healthy diets. Inadequate diets will contribute further to detrimental human and planetary health impacts. At the same time, the way food is grown, processed, packaged, and transported is having adverse impacts on the environment and finite natural resources further accelerating climate change, tropical deforestation, and biodiversity loss. This state-of-the-science iterative review covers three areas. The paper's first section presents how climate change is connected to food systems and how dietary trends and foods consumed worldwide impact human health, climate change, and environmental degradation. The second area articulates how food systems affect global dietary trends and the macro forces shaping food systems and diets. The last section highlights how specific food policies and actions related to dietary transitions can contribute to climate adaptation and mitigation responses and, at the same time, improve human and planetary health. While there is significant urgency in acting, it is also critical to move beyond the political inertia and bridge the separatism of food systems and climate change agendas that currently exists among governments and private sector actors. The window is closing and closing fast.

1. Introduction

The world faces alarming trends and potential tipping points related to climate disruption, continued conflicts, and the COVID-19 pandemic (IPCC, 2022; Boehm et al., 2022). The Paris Agreement of 2016 set out to limit global warming to well below 2 °C, preferable to 1.5 °C, compared to pre-industrial levels. However, the window to meet that goal is closing. Climate tipping points occur when changes to large parts of the climate system become self-perpetuating beyond a warming threshold. Such tipping points include sea level rise from collapsing ice sheets, dieback of biodiverse biomes such as the Amazon rainforest or warm-water corals, and carbon release from thawing permafrost. Modeling data suggest that nine core tipping elements could become more likely within the Paris Agreement goals of 1.5 to < 2 °C warming. Additional tipping points become possible at the ~2.6 °C warming expected under current climate trajectory (Armstrong McKay et al., 2022). As it stands now, global greenhouse gas (GHG) emissions need to be cut by 45% to avoid catastrophic consequences (Anon et al., 2022). Food systems are integral to reducing those emissions and avoiding calamitous tipping points.

It is essential to consider how vital food systems are to thwart these catastrophic events for human welfare and planetary resilience. Without prioritization across various food system actions, scenarios suggest that the world will not meet the Paris Agreement (Clark et al., 2020). The energy sector sped up the transition towards renewable resources – this acceleration was due to a range of policy interventions such as

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regulation, legislation, technology, investment, and price declines. In contrast, current inaction in transitioning food systems is problematic for climate mitigation and adaptation as food systems continue to generate 25–30% of total GHG emissions (Crippa et al., 2021; Poore and Nemecek, 2018).

Without full acknowledgement of their contribution to climate mitigation, food system functionality continue to be deeply impacted by laissez-faire governance and the dietary choices, behaviors, and lifestyle-driven factors of eight billion people that have resulted in a leaden anthropogenic footprint on earth systems. Inequalities and inequities factor significantly into what actions are taken moving forward, with nuanced questions arising, such as *who* must take on more responsibility, *what* responsibilities they must enact in the near term, and *how* the world holds those responsible to account. The United Nations (UN) Secretary-General stated during the UN General Assembly in September 2022: "The climate crisis is a case study of moral and economic injustice. The G20 emits 80% of GHG emissions. The poorest and most vulnerable, those who contributed least to this crisis, bear its most brutal impacts" (Guterres, 2022).

This paper provides a state-of-the-science iterative review of the relationship between climate change and food systems, and how dietary trends and foods consumed worldwide impact human health, climate change, and environmental degradation. The second section delves into how food systems and climate change influence global diets and the macro forces shaping food systems and diets. Last, the paper articulates food policies related to dietary transitions that can contribute to climate adaptation and mitigation responses that benefit both human and planetary health.

2. How are climate change and food systems connected?

Climate change is and will continue to impact how food systems function, some due to the frequency and intensity of extreme events such as droughts, floods, cold spells, and other disrupting events (Mbow et al., 2019). Global crop models that examine dimensions of climate-related changes in temperature and precipitation to the end of the century suggest that climate change will adversely impact crop yields (Myers et al., 2022). As land temperatures increase, tropical low-latitude areas will experience decreased crop yields, while higher-latitude regions may experience increased yields (Hoegh-Guldberg et al., 2018). For example, rising atmospheric carbon dioxide (CO2) will reduce major staple commodities, including maize, soybean, and rice, by the end of the century, with maize projected to decrease by 24% in the worst-case scenario. In contrast, wheat yields could increase up to 18% with higher CO2 concentrations, particularly in high-latitude areas (Jägermeyr et al., 2021). These data also suggest that crops will be impacted much sooner than anticipated, affecting major breadbasket-growing regions.

Temperature increases will also result in the temporal and spatial proliferation and emergence of infectious pathogens through food pathways that may decimate crop production and storage and harm human health (Chochlakis et al., 2019; Polgreen and Polgreen, 2017; Gallana et al., 2013; Patz and Olson, 2006; Patz, 2018). For example, global warming is likely to increase aflatoxins—carcinogenic and immunosuppressive pathogens produced by certain molds that are harmful to human health— further afflicting crops such as maize and peanuts in tropical regions (Pleadin et al., 2023; Yu et al., 2022; Cardwell and Henry, 2004).

Lower and unstable yields of major crop commodities can drive up food prices threatening food security, dietary diversity, and nutrition outcomes. Poor households and those with little purchasing power will disproportionately suffer, exacerbating their inability to access or afford essential or healthy diets (Gupta et al., 2021; Hirvonen et al., 2020). Already, the current polycrisis of climate change, the long tail of the COVID-19 pandemic and now, the Ukraine Russia war, is causing significant food inflation and critical levels of food insecurity in certain parts of the world (World Economic Forum, 2023).

Data suggest that with global warming and a CO2 fertilization effect—higher amounts of GHG emissions in the atmosphere—the nutrient content of macro- and micronutrients (e.g., protein, zinc, iron) in staple commodities (e.g., maize, soy) as well as fruits and vegetables will decline (DeFries et al., 2018; Myers et al., 2014; Beach et al., 2019). The effects of climate change on human health are not limited to impacts on crop yields and the nutrient content of those crops. Extreme weather events, such as floods and heat stress, will impact the health and welfare of animals, critical sources of nutrient-dense foods (Fanzo et al., 2018; Beal et al., 2023).

Climate change constrains the entirety of supply chains, not only in the quantity and quality of food produced (Jägermeyr et al., 2021), although models assessing impacts are less characterized. There are potential widespread implications for the "middle of the supply chain" including food transportation, processing, packaging, and selling, that come with extreme weather events and shocks (the COVID-19 pandemic gave us a small glimpse into a global shock's impact on food systems) (Davis et al., 2020). More modeling is needed to understand how extreme weather events and climate-related shocks could create blocks and breakdowns in the links of supply chains under various conditions, resulting in deleterious diet access and nutrition outcomes (Fanzo et al., 2018).

Food systems in turn, instigate and perpetuate climate change and global environmental change. Food systems contribute up to 30% of total GHG emissions (Crippa et al., 2021), and an estimated 70% of these GHG emissions come from dairy, rice, and ruminant meat (Ivanovich et al., 2023). Because food systems are dependent on fossil fuels across many of its activities, they contribute to a range of GHG emission types including CO2 emissions; methane is produced from livestock and rice systems; and NO2 is produced from fertilizers. In addition, the way we grow our food has a significant impact on water and land use, and their pollution and degradation. Agriculture production uses roughly 70% of all freshwater resources, and nutrient run-off from fertilizers and animal waste (e.g., pig farms) pollute waterways, including rivers, coastal waters and lakes, creating algae blooms (Watson et al., 2000). These algae blooms produce toxins that can decimate aquatic foods that are important contributors to dietary quality and human health (Glibert et al., 2018; O'Neil et al., 2012). Agriculture also contributes to significant biodiversity loss by displacing native plants and animals from their natural and wild habitats, some due to tropical deforestation driven by soya bean, cattle, and palm oil production (Bélanger et al., 2019; DeFries et al., 2013; Jaroenkietkajorn and Gheewala, 2021; Downs et al., 2021).

3. What does the world eat, and how have diets changed?

The world's dietary patterns and choices have critical implications on various societal issues, including human health, climate change, the environment, politics, culture, and traditions. Understanding what people eat, their dietary patterns, and how diets change over time is necessary to understand and relate the alarming trends of rising malnutrition, poor public health outcomes, environmental degradation, and climate disruption. Interestingly, globally comparable dietary data has only recently become available, enabling large-scale assessment of diet quality, context, and impact (Miller et al., 2022a).

Global food systems deliver enough calories to feed the global population. Since 1961, the average global per capita food supply (i.e., food available in the country for human consumption that is produced or imported) has increased from 2181 to 2920 kcal in 2019, making an additional 740 kilocalories available per person daily (Fig. 1) (FAOSTAT, 2022). Every region has seen an upward trajectory in the kilocalories available. However, in some regions, such as North America and Europe, the calories available are beyond what is needed to sustain human health for the average adult (depending on body size and physical activity levels). While global average per-capita energy availability surpassed the 2500 kcal/person threshold in the early 1980 s,

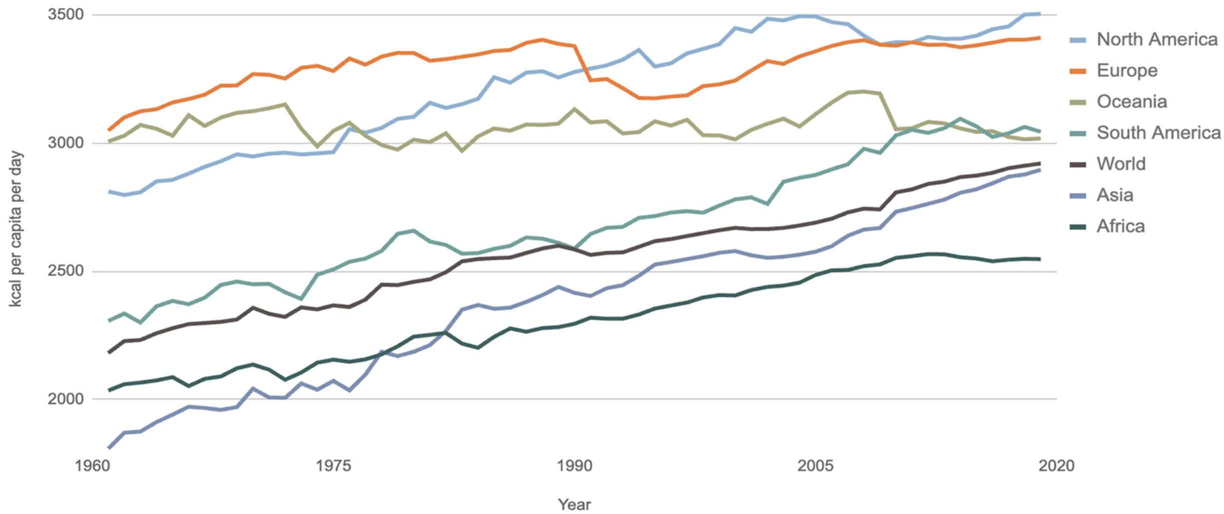

Fig. 1. Per capita kcal/person/day shown regionally in the food supply, 1961–2019.
Source: (FAOSTAT, 2022) retrieved from (Roser et al., 2013).

that only occurred in the mid-1990 s in Asia and the mid-2000 s in Africa (FAOSTAT, 2022). Nevertheless, a significant proportion of calories still come from staple grains, roots, and tubers, which make up 50% of energy in the food supply (FAOSTAT, 2022), and an even larger share among low-income populations, mainly in the form of refined flours and grain products (Milani et al., 2022).

While staples are an essential energy source, a high-quality diet also depends on the consumption of nutrient-dense foods such as vegetables, fruits, nuts, legumes, and animal-source foods, including meats, eggs, and dairy products (WHO, 2018). Data from the Global Dietary Database (GDD) shows that most regions are not meeting the recommended intake of fruits and vegetables (at least 400 g per day), legumes, nuts, whole grains (at least 250 g per day), and fiber (at least 25 g per day). At the same time, most regions are exceeding recommendations for added sugars (less than 10% of total kcal from sugars) and sodium (less than 5 g per day) but are within the recommendation to consume between 10% and 30% of energy from fats (Fig. 2). Changes over the last 30 years show some regions nearly meeting the dietary recommendations for certain food groups (e.g., Asia's increase in vegetable intake and the Middle East & North Africa, and South Asia regions' increase in fiber intake). However, added sugars surpass the recommendation of < 10% daily energy in three regions (despite the region of Latin America & the Caribbean's reduction in calories from sugar), and sodium intake exceeds the recommendation in all but sub-Saharan Africa.

Only modest improvements in diet quality have occurred since 1990 when comparing global and regional means to a healthy diet index. Increased consumption of less healthy foods such as sugar-sweetened beverages (SSBs), red meat, and processed meats has limited larger improvements to diets on average (Miller et al., 2022a). Globally, diet quality is generally higher among women and those with a higher level of education, whereas there is no difference in diet quality between children and adults, and between rural and urban areas. However, differences are observed at the regional and country levels (e.g., urban residents in Central/Eastern Europe, Central, East, and Southeast Asia have higher diet quality than rural residents) (Miller et al., 2022a). In addition, new data from the Global Diet Quality Project corroborates higher diet quality among the more educated and higher-income groups and highlights that while the consumption of healthy foods increases as incomes rise, it is often accompanied by increases in unhealthy food consumption as well (Global Diet Quality Project, 2022).

Interesting trends related to the change in three dietary components—ultra-processed foods (UPF), dairy, and animal-source foods (ASF)—have potential effects on the health and sustainability of diets. The retail sale of UPF is on the rise globally: both in total sales and in the types of UPF across all regions (Fig. 3) (Monteiro et al., 2013; Scrinis and Monteiro, 2022; Baker and Friel, 2016; Baker et al., 2020; Menichetti et al., 2021). UPF intake has been linked to increased total daily energy consumption (Hall et al., 2019) and the displacement of nutrient-rich foods in people's diets (Micek et al., 2021). Consumption of unhealthy foods, including SSBs, packaged snacks, deep-fried foods, and other UPF tends to be higher among men and rural residents (Global Diet Quality Project, 2022). Early research to understand the environmental impacts of UPF point to disproportionate impacts on biodiversity loss, energy use, GHG emissions, land use, as well as food waste and plastic pollution (Willett et al., 2019; Tufts University, 2022; Menichetti et al., 2021).

Another important change in dietary patterns has been the increased demand for ASF (Fig. 4) (Herrero et al., 2021; Miller et al., 2022b; Ritchie et al., 2017). Global per capita "consumption" (measured by proxy as the availability in the food supply) of terrestrial animal meat increased from 63 g/day to 118 g/day between 1961 and 2013, nearly doubling in fifty years (FAOSTAT, 2022). The sharpest increase in meat availability occurred in food systems of fast-growing economies (primarily China and Brazil), and meat consumption remains higher for countries with larger Gross Domestic Product (GDP) per capita (Anon et al., 2022; Ritchie et al., 2017). Growing demand for poultry has been one of the main drivers for the increase in total meat consumption since the 1990s (Herrero et al., 2021). The demand for red meat increased by 8 g/person/day globally, but it increased by 78 g/person/day in East Asia, compared to the recommendation to limit the intake of unprocessed red meat to below 50–70 g/day (IARC, 2018; World Cancer Research Fund/American Institute for Cancer Research, 2018). Globally, ASF consumption is higher among those with higher levels of education, urban residents, and among men in some low- and middle-income countries (LMICs) (Global Diet Quality Project, 2022; Miller et al., 2022b). There has been some progress in reducing red meat consumption in industrialized countries (Herrero et al., 2021), including in Europe, where there has been a small reduction in red meat consumption in Western, Central, and Eastern Europe (van Daalen et al., 2022).

There was a large increase in demand for milk globally and in most regions between 1990 and 2020, except for sub-Saharan Africa, Southeast Asia and the Pacific (Willett et al., 2019) (Fig. 5). However, there is no quantitative WHO global dietary recommendation on milk and dairy, and national dietary guidelines vary in their recommended amounts. For example, the Dietary Guidelines of America (DGA) recommends 2–3 cups/day of milk or equivalent, or between 488 g and 732 g of milk (Arnold et al., 2021). The food-based dietary guidelines in the WHO

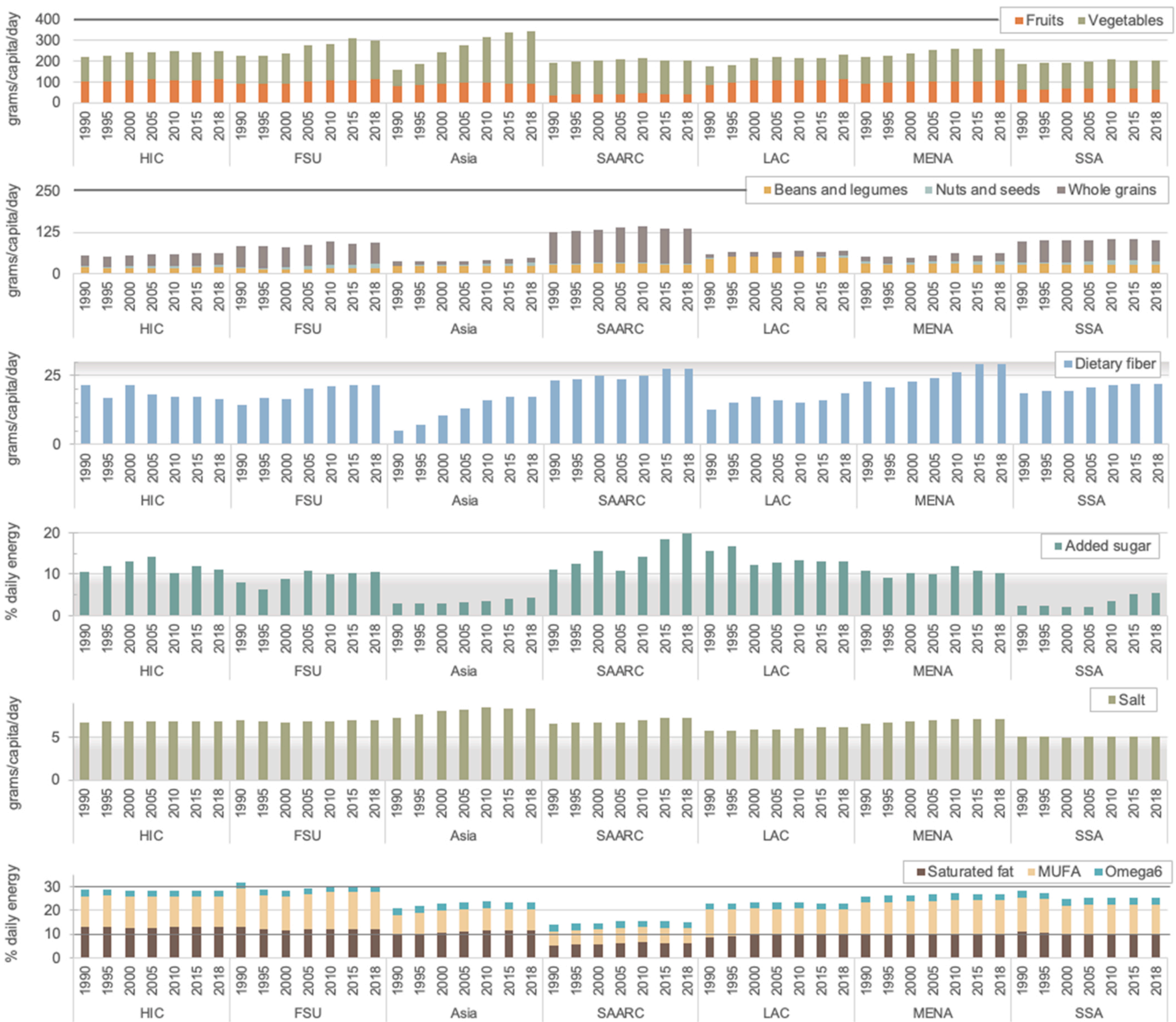

Fig. 2. Key components of healthy diets across regions, 1990–2018. Notes: HIC: high-income countries including Australasia, Western Europe, Canada, and the United States; FSU: former Soviet Union; Asia: includes East and Southeast Asia, Asia-Pacific, and Oceania; SAARC: South Asian Association for Regional Cooperation; LAC: Latin America and the Caribbean; MENA: Middle-East and North Africa; SSA: Sub-Saharan Africa; MUFA: monounsaturated fatty acids; Omega6: total omega-6 fat. Healthy diet components from (WHO, 2018): at least 400 g/day of fruits and vegetables (target line); 25 g/day of dietary fiber (shaded area); < 10% total daily energy from free sugars (shaded area), but < 5% of daily energy for additional health benefits (the figures depict added sugars, which do not consider naturally occurring sugars in honey, fruit juice, or concentrate - thus added sugars will be lower than free sugars); < 5 g/day of salt (shaded area)(converted from sodium in a ratio of 1000 mg sodium per 2.5 g of salt); < 30% of total daily energy from fats and < 10% energy from saturated fats (target lines). The WHO recommends the intake of whole grains, nuts, and legumes as part of a healthy diet but does not specify quantities. Recommended intakes from EAT-*Lancet* Commission were used to establish a quantitative target of 250 g/day (target line) for these three foods, consisting of 25 g of nuts, 100 g of legumes, and 125 g of whole grains (Willett et al., 2019).
Source: Authors, based on data from (Tufts University, 2022).

Europe region recommends 3 cup equivalent of milk (732 g), similar to the DGA (Tufts University, 2022). In contrast, the EAT-*Lancet* Commission of 2019, which established a Planetary Health Reference Diet (PHD) (a plant-dominant diet), recommends 250 g, with a range of 0–500 g/day, though “optimal intake will usually be at the lower end of this range” (Monteiro et al., 2013). Current food supply availability of milk is 400–600 g/day in North America, Central Asia, Oceania, and Europe, 200–400 g/day in Central and South America, Western Asia, and < 100 g/day in East, West, and Middle Africa, East and Southeast Asia (Tufts University, 2022). Estimated intakes are much lower, hovering around 250 g/day for milk, yogurt, and milk combined in high-income countries and the former Soviet Union, between 150 and 200 g/day in Middle East & North Africa and Latin America & the Caribbean, and between 50 and 100 g/day in South Asia, Asia, and sub-Saharan Africa (Fig. 5) (Scrinis and Monteiro, 2022). Nonetheless, plant-based milk alternatives are growing in popularity, with the potential to decrease the environmental impact of traditional dairy products (Bridges, 2018; Research, Markets ltd, 2022; Paul et al., 2020).

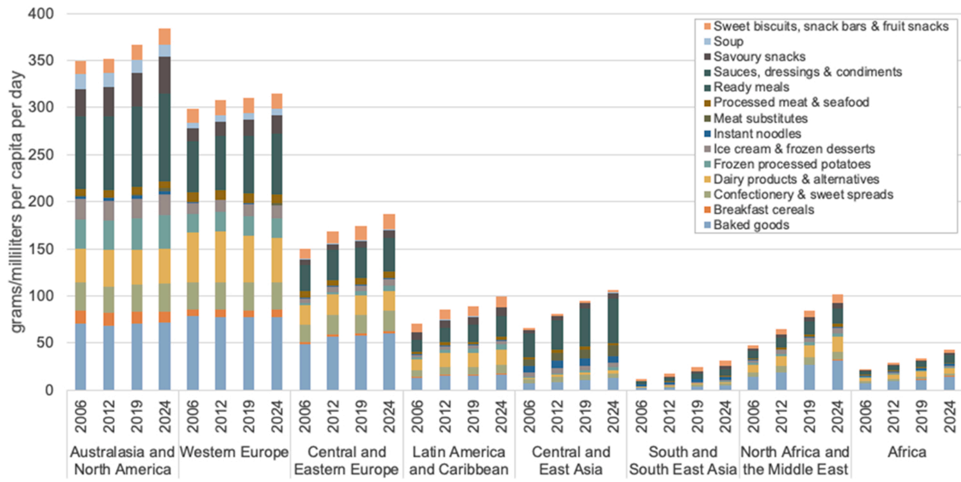

Fig. 3. Sales of ultra-processed food (g/capita) categories, 2006–2024. Notes: Source data were converted from kilograms or liters/capita/year to grams or milliliters/capita/day to facilitate interpretation.
Source: Authors, based on data from (Micek et al., 2021).

Region	Fish, Seafood	Milk	Eggs	Poultry	Red Meat
Eastern Asia	57.5	58.4	34.0	31.2	77.8
Southern Asia	8.5	137.3	6.0	7.7	-4.1
Southeast Asia and Pacific	49.6	27.4	10.7	28.8	21.1
West Asia and North Africa	9.0	81.4	3.0	26.0	15.1
Sub-Saharan Africa	-0.5	13.4	0.0	8.5	-1.1
Latin America	2.7	73.2	15.9	71.2	26.0
Industrialized Countries	2.2	48.5	1.6	42.2	-27.7
World	16.7	54.0	9.9	23.3	7.9

Fig. 4. Change in demand for animal-source foods, 1990-2020 (grams/person/day). Notes: All regional definitions use UN definitions. Source data were converted from change in kilograms/capita/year to change in grams/capita/day to facilitate interpretation..
Source: (Herrero et al., 2021)

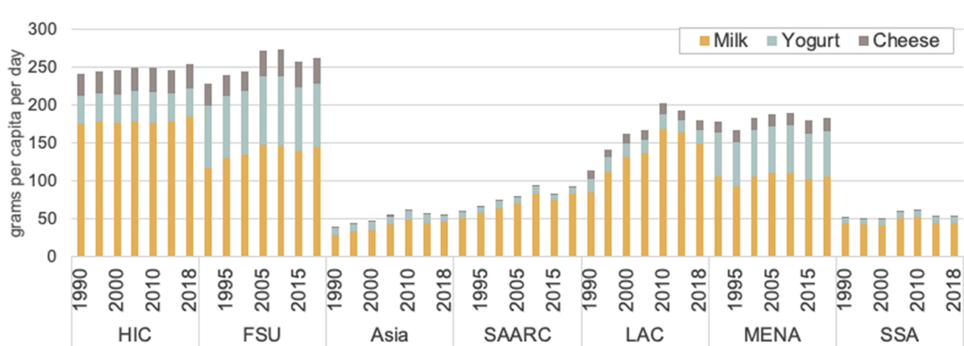

Fig. 5. Change in consumption of dairy products regionally, 1990-2018. Notes: HIC: high-income countries including Australasia, Western Europe, Canada, and the United States; FSU: former Soviet Union; Asia: includes East and Southeast Asia, Asia-Pacific, and Oceania; SAARC: South Asian Association for Regional Cooperation; LAC: Latin America and the Caribbean; MENA: Middle-East and North Africa; SSA: Sub-Saharan Africa..
Source: Authors, based on data from (Scrinis and Monteiro, 2022)

4. What are the consequences of diets and dietary trends & demands?

Diets have impacts on both human health outcomes as well as environmental sustainability. Dietary quality, along with other factors, contributes to the growing burden of all forms of malnutrition: undernutrition (stunting, wasting, and underweight), micronutrient deficiencies, overweight and obesity, and non-communicable diseases (Micha et al., 2020) and no other risk factor looms as prominent in the global burden of disease (Afshin et al., 2019). Improvements in the global burden of undernutrition have occurred. For example, there have been reductions in the prevalence of stunting among children under five, which declined to 22% in 2020 from 26.2% in 2012 (Food and Agriculture Organization of the United Nations, 2022). Nonetheless, 5.7% of children under five were obese in 2020, and 13.1% of adults were obese, both of which increased since the last time estimates were updated (Food and Agriculture Organization of the United Nations, 2022).

Even before the Ukraine-Russia war, after years of progress on undernutrition and food insecurity, the COVID-19 pandemic, climate-related extreme weather events, and civil wars have reversed those positive trends. Now, 13.6 million more children are acutely malnourished (also known as wasting), a 30% increase over three years (Headey et al., 2020; Osendarp et al., 2021, 2022). In addition, over 3.6 million more children are chronically undernourished (also known as stunting), and 822 million people are hungry - rising for the fourth consecutive year (Food and Agriculture Organization of the United Nations, 2022). These alarming statistics show that after decades of slow progress, undernutrition is rising once again.

Diets in most countries and regions do not contain recommended amounts of nutritious foods, contributing to a high burden of micronutrient deficiencies. Globally, an estimated 30% of women ages 15–49 are anemic (Food and Agriculture Organization of the United Nations, 2022), and 69% have at least one micronutrient deficiency (Tufts University, 2022; Afshin et al., 2019; Nutrition Profiles, 2022; NCD-RisC, NCD-RisC N-R, 2021). Similarly, 56% of children under five have at least one form of micronutrient deficiency (Fig. 6). These deficiencies may indicate two patterns. First, without meeting healthy diet recommendations, even diets high in ASF (such as diets from high-income countries) are insufficient for micronutrient adequacy, as 48% of women in high income countries have at least one micronutrient deficiency. Second, most diets are not delivering necessary nutrients—either through excess UPF, or diets made up predominantly of staple grains that are calorie-rich and nutrient-poor.

Dietary composition is also impacting morbidity and mortality. Fig. 7 shows the impacts of different dietary components that contribute to deaths. Inadequate diets are responsible for approximately 12 million deaths (26%) among adults in 2018 (Nutrition Profiles, 2022; Global Nutrition Report, 2021). Compared to almost a decade early, that has increased by 15% (data not shown). Most diet-related deaths are from cardiovascular heart disease, followed by cancer and stroke. Interestingly, most dietary risk relates to a low intake of healthy components of the diet, such as low intake of fruits, vegetables, and whole grains. Other avoidable deaths are related to energy intake and weight (both underweight and overweight).

Diets have impacts on the environment as well. Fig. 8 shows environmental pressures — GHG emissions, land use, freshwater use, and nitrogen and phosphorus application (e.g., nutrient run-off into waterways). Beef and lamb are the most significant contributors to GHG emissions and land use pressures (Nutrition Profiles, 2022; Global Nutrition Report, 2021). Though ASFs can be important nutrient sources, they are also significant sources of GHG emissions in human diets (Poore and Nemecek, 2018; Springmann et al., 2018, 2020; Willett et al., 2019; Food Balance Sheets, 2001; Nutrition Profiles, 2022). They contribute significantly to negative food system pressures on freshwater use, nutrient pollution, and habitat disturbances (Willett et al., 2019). Ruminants (including dairy and beef herds) have the highest GHG emission and take up the most significant amount of land, while pig farming has been shown to use more water and produce more nutrient pollution (Willett et al., 2019; WHO, 2018). Fruits, vegetables, sugar, and grains use an abundance of water. Pork and poultry, fruits, vegetables, and grains contribute to eutrophication. It is important to note that foods can have different and varying environmental impacts depending on where and how they are grown, and on the type of agroecological, cropping, or animal production system (Springmann et al., 2018, 2016).

When examining global environmental targets for food systems (also known as planetary boundaries) established by the EAT-*Lancet* Commission, diets and food system practices exceed most boundaries or targets (data not shown). To stay within the planetary boundaries, adopting healthy and sustainable diet recommendations (Monteiro

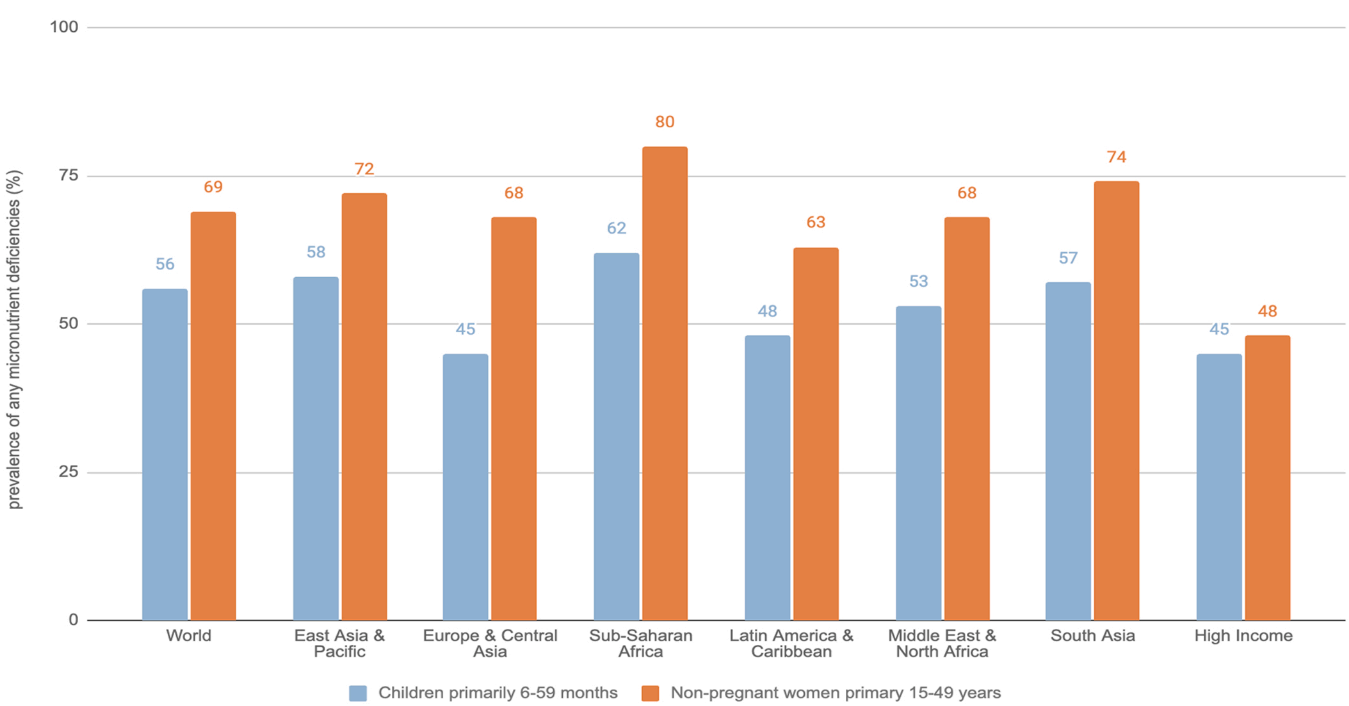

Fig. 6. Prevalence of deficiencies in one or more of three core micronutrients, world, and different regions, 2003 – 2019. Notes: This analysis estimates the prevalence of deficiency in at least one of three micronutrients for preschool-aged children (iron, zinc, and vitamin A) and non-pregnant women of reproductive age (iron, zinc, and folate), globally, in high-income countries (HIC), and seven regions using 24 nationally representative surveys done between 2003 and 2019.
Source: (Stevens et al., 2022).

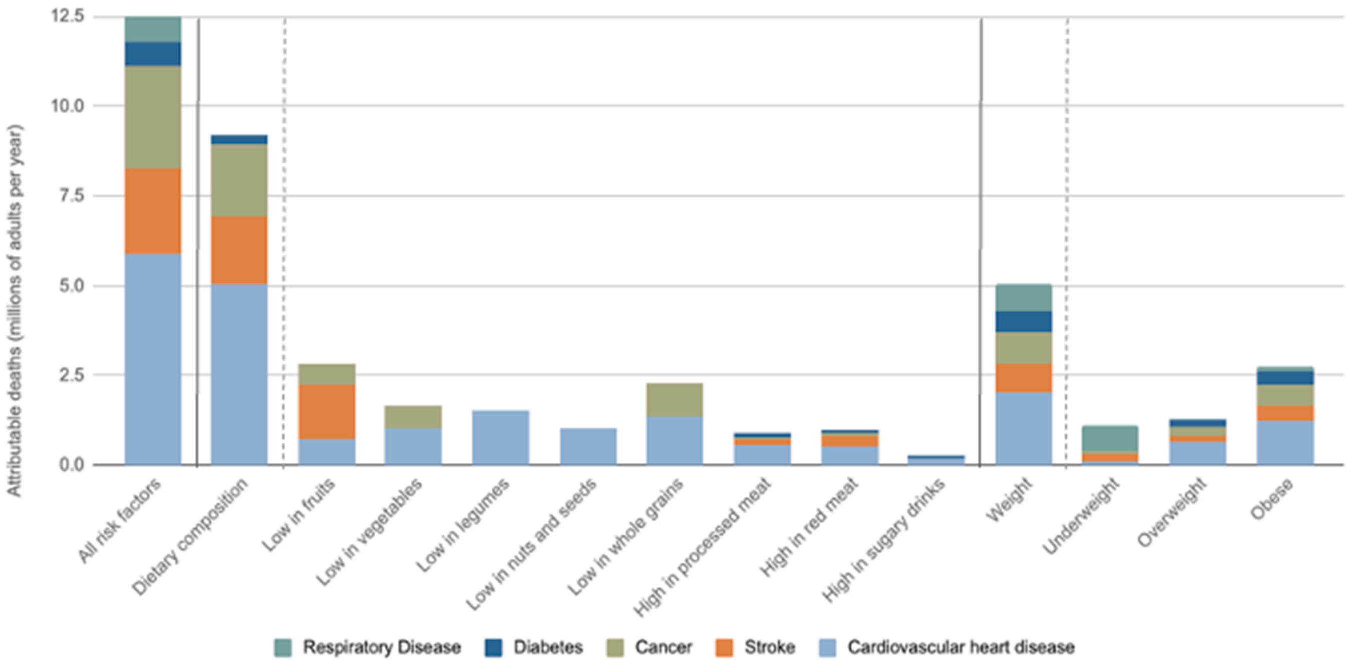

Fig. 7. Deaths attributable to dietary risk factors by cause of death for risks related to dietary composition and weight levels, 2018. Notes: The combined risk is less than the sum of individual risks because individuals can be exposed to multiple risks, but mortality is ascribed to one risk and cause.
Source: (Scrinis and Monteiro, 2022; Afshin et al., 2019; Nutrition Profiles, 2022; NCD-RisC, NCD-RisC N-R, 2021).

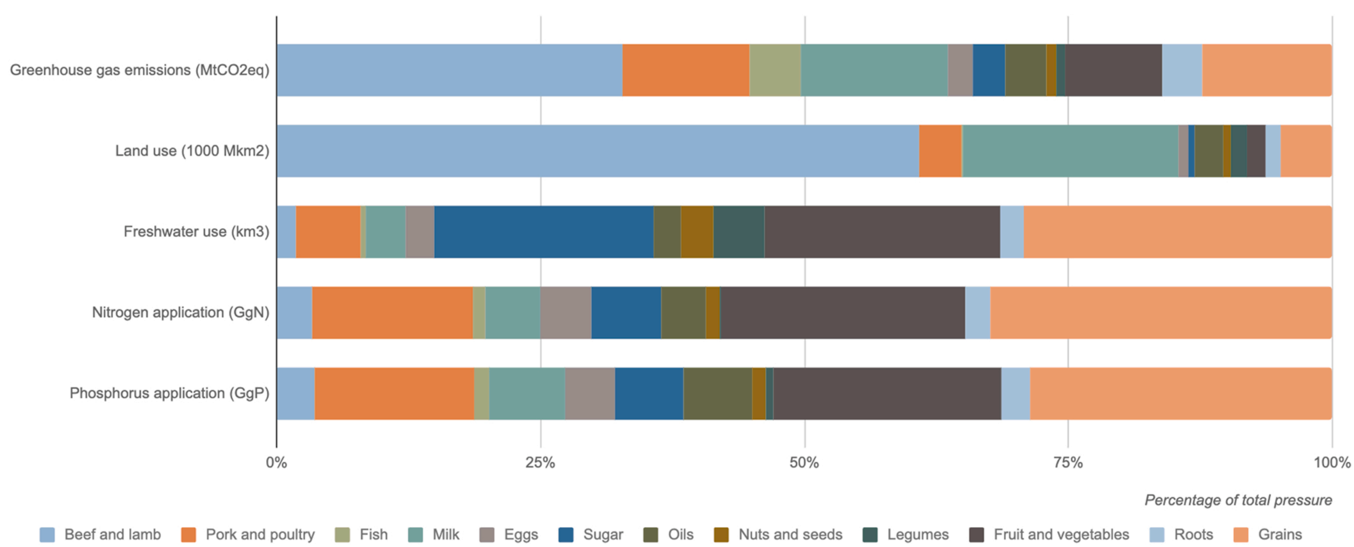

Fig. 8. Pressure of different commodities of the food system on environmental factors as a percentage of total pressure. Notes: The footprints consider all food production, including inputs such as fertilizers and feed, transport, and processing, e.g., of oil seeds to oils and sugar crops to sugars. The displayed total pressure is in the units stated for each environmental domain and rounded to the nearest ten units.
Source: (Monteiro et al., 2013; Poore and Nemecek, 2018; Springmann et al., 2018, 2020; Food Balance Sheets, 2001; Nutrition Profiles, 2022).

et al., 2013) would substantially reduce the environmental impact of diets. The EAT-*Lancet* dietary recommendations focus on the consumption of whole grains, pulses, nuts, legumes, fruits, and vegetables in larger quantities than the targets established by the WHO (Monteiro et al., 2013; WHO, 2018). In addition, these recommendations call for even lower amounts of unprocessed red meat (14 g/day), which is below the amount recommended by the Global Burden of Disease Study (23 g/day) (Afshin et al., 2019) and the International Agency for Research on Cancer (IARC) (< 50–70 g/day) (IARC, 2018; World Cancer Research Fund/American Institute for Cancer Research, 2018). While there is not a single accepted measure of the environmental impact of diets (Luzzani, 2022), shifting consumption to more sustainable diet patterns is being increasingly called for as a required radical transformation to reduce the food system's environmental burden (Boehm et al., 2022; Anon et al., 2022).

5. How do food systems impact dietary trends?

Food systems worldwide have undergone tremendous changes in the last 50 years, shifting from more deeply rural- and traditional-based systems to industrialized, consolidated and globalized systems. These changes have resulted in positive and negative effects across various dietary, nutrition and health, environmental sustainability, and livelihood outcomes. One analysis revealed that although the affordability of a recommended diet has improved over time, current food systems are falling short of delivering optimal nutrition and health outcomes, environmental sustainability, and inclusion and equity for all (Ambikapathi et al., 2022). More specifically, recommended diets have become more affordable among some populations as food systems have transitioned from more rural types to more industrialized ones. However, access depends on poverty levels which vary within food system types. Increasing diet affordability is a function of multiple forces related to overall structural and rural transformation and food system transition. The transition process determines who can access an affordable diet and who gets left behind. Still, food availability across supply chains and food access within micro food environments influence the quantity and quality of diets for households on a daily level.

5.1. Insufficient food availability

During the writing of this paper, the range of systems (economic, health, food, education, and energy) that sustain world order and functionality have been weakened due to major drivers known as the "3Cs"—climate change, conflict, and the COVID-19 pandemic. These 3Cs, in turn, alter mediating factors of food systems known as the "5Fs"—food, fodder, fertilizer, fuel, and finance (Hendriks et al., 2022). Moreover, the current war between Ukraine and Russia shows that global and regional food supplies are fragile when conflict ensues among critical breadbasket countries (Barrett, 2022). As a consequence of these crises, the prevalence of undernourishment increased from 8% in 2019 to 9.8% in 2021, which equates to 828 million people (Food and Agriculture Organization of the United Nations, 2022). In addition, 2.3 billion people are moderately or severely food insecure, nearly 30% of the global population (Food and Agriculture Organization of the United Nations, 2022).

While current food systems remain fragile, studies suggest that the world has enough food in aggregate at the global level to feed the existing population. However, by 2050, the scenario will change. Some estimates suggest that food production would need to increase by 50–110% to feed 9 billion people, depending on the analysis and climate scenarios (Tilman et al., 2011; Alexandratos and Bruinsma, 2012; van Dijk et al., 2021). The primary reasons for this increase are the surge in demand for more diverse foods (van Dijk et al., 2021) and the feed necessary for ASF production systems (Tilman and Clark, 2015). Others argue that the priority in feeding 9 billion should focus instead on equitable food distribution with radical social changes (Berners-Lee et al., 2018; Ehrlich and Harte, 2015; Hunter et al., 2017). Regardless, there is a need to meet demands in a way that is environmentally sustainable — for example, by halting extensification into tropical forests, reducing food loss and waste, and decreasing methane emissions.

Subsidy policies are crucial in ensuring food is available; however, most of what agriculture subsidies support are staple grain commodities, oils, and sugar (Food and Agriculture Organization of the United Nations, 2022). The decline in agricultural biodiversity places the food supply at climate, dietary, and nutritional risks because of the homogenization and research and development (R&D) focus and investment on only a handful of crops (Khoury et al., 2014). Of the 6000 plant species cultivated for food use, only 200 dominate the agriculture landscape, and 9–10 crops account for 66% of total crop production (Bélanger et al., 2019). The historical paradigm of agriculture policy, research, and development has been dominated by a distinct set of crops mainly consisting of staple grains—maize, rice, and wheat—oil crops, including soya and palm, and sugar, with approximately 37% of the world's food supply calories coming from wheat, rice, and maize alone (FAOSTAT, 2022).

The decision to focus most of R&D on staple grain commodities primarily comes from goals to stave off famines and the Green Revolution—the introduction of high-yielding varieties of mainly rice and wheat in the 1960 s in Asia and Latin America to increase food production and alleviate hunger and poverty (Clapp, 2022). While the Revolution vastly improved the sufficiency of calories, hindsight, it did not address what is considered significant challenges and associated risks faced today, including climate disruption, nutrition insecurity, and degraded environments and natural resources (Pingali, 2012).

The Ukraine-Russia war is an example of how insufficient agricultural diversity can lead to catastrophic results with an overreliance on two countries to produce almost 50% of a major crop commodity—wheat—within the milieu of the global trade system. However, significant shifts will be required to diversify agriculture systems and ensure that more diverse foods are available in food supplies.

5.2. Insufficient food access

Food produced from agriculture and available in the global supply has allowed for more food access over the last five decades (Fig. 1). However, there are still populations unable to access enough calories, and even more of the global population cannot access what is considered a healthy diet that meets nutrient needs and is health protective. Access to food can come in many forms, including physical and economic access, and both interact with each other.

Physical access occurs when food is available because people can grow their food or go to the market and bring food home. Once acquired, they can physically prepare and cook food. The physical proximity of where people live to food markets is a marker to assess physical access. Research and data suggest distinct differences in the type and density of food retail options within and across countries (Schneider et al., 2023). Proximity can be worse if one lives in areas with high poverty levels or places with higher densities of minoritized populations (Beaulac et al., 2009; Savary et al., 2020). While physical proximity is weakly related to diet quality (Beaulac et al., 2009), shorter distances to travel to markets could reduce disparities in the time it takes to acquire food and benefit people with disabilities and other mobility limitations (Schneider et al., 2023). In LMICs, distance to markets plays a more important role in consistent access to improved diet diversity and quality, along with UPF sales (Sibhatu and Qaim, 2018a, 2018b; Khonje et al., 2022).

Economic access is the affordability of foods—the relative relationship between food prices and individual resources. The latest UN Food and Agriculture Organization (FAO) data suggest that almost 3.1 billion people (42% of the world's population) could not afford a healthy diet in 2020—an increase of 112 million more people than in 2019. Most of the 3.1 billion live in Asia (78 million more than in 2019), followed by Africa (25 million more) (Monteiro et al., 2013; Scrinis and Monteiro, 2022; Baker and Friel, 2016). This increase was driven mainly by inflation in consumer food prices, with the average cost of a healthy diet globally in 2020 being USD 3.54 per person per day, 6.7% more than in 2017 (Food and Agriculture Organization of the United Nations, 2022). Nutritious foods are more expensive relative to staples, with leafy green vegetables, vitamin A-rich fruits and vegetables, and many ASF being especially expensive in many parts of the world (Headey and Alderman, 2019). In addition, the cost of nutritious foods increased more than other foods during the COVID-19 pandemic (Bai et al., 2022). Meanwhile, lower-cost UPFs (shown in Fig. 3), including SSBs, processed and packaged snacks, and processed meats, have become more present in our diets (Baker and Friel, 2016; Baker et al., 2020; Hall et al., 2019), contributing to lowering diet quality (Miller et al., 2022a).

Fig. 9 shows countries of different income classifications and geography to demonstrate the inequities in who can afford a healthy diet, the lowest cost set of foods available that would meet region-specific food-based dietary guidelines. A diet is deemed unaffordable if it costs more than 52% of a household's income. The cost of ASF relative to the starchy staples in a least-cost healthy diet is also prohibitive, as shown in Fig. 10. The data also suggest that in certain regions (e.g.: sub-Saharan Africa) and in specific countries (e.g.: Kuwait, Italy, Maldives, Malawi, Bangladesh, and Jordan) nutrient-dense ASF are costly compared to less nutritious starchy staples.

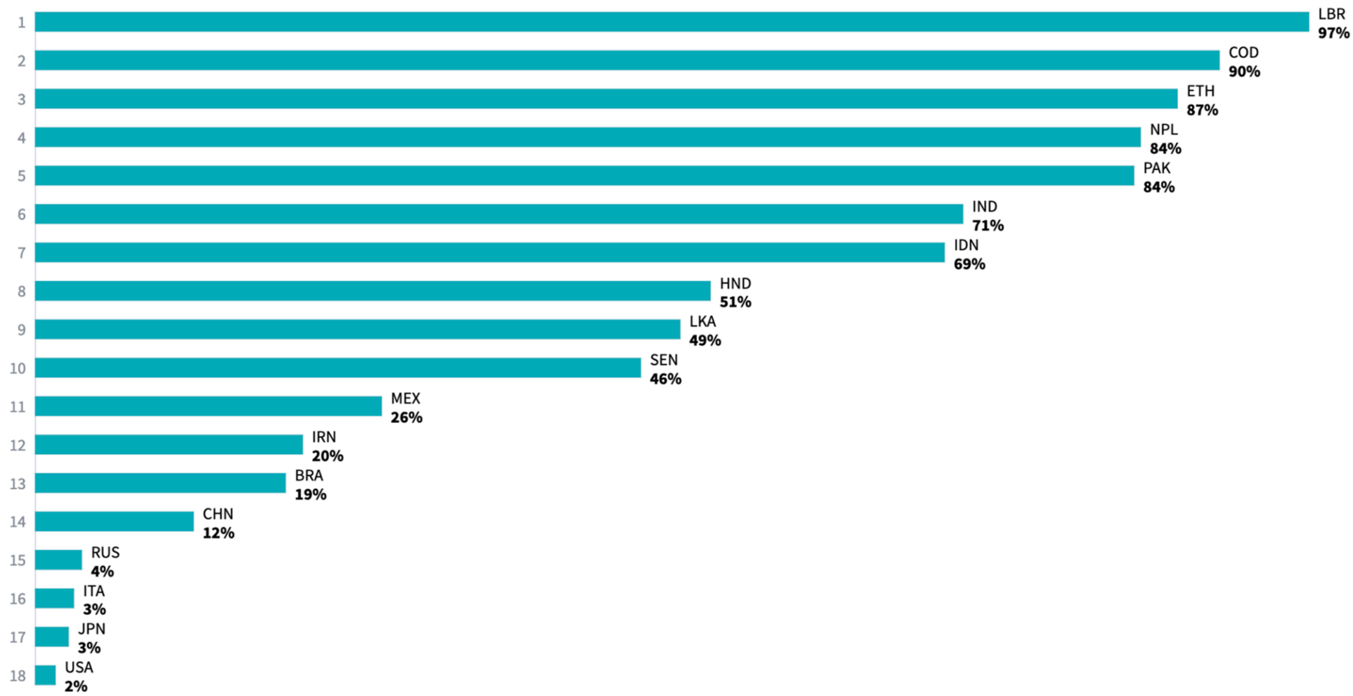

Fig. 9. Percent of the population who cannot afford a healthy diet at 52% of income. Notes: Proportion of the population whose food budget is below the cost of a healthy diet. The food budget is defined as 52% of household income, based on the average share of income that households in low-income countries spend on food. Income data are provided by the World Bank's Poverty and Inequality Platform. A value of zero indicates a null or a small number rounded down at the current precision level. Data are currently available for 2017, 2018, 2019, and 2020. LBR = Liberia; COD = Democratic Republic of the Congo; ETH = Ethiopia; NPL = Nepal; PAK = Pakistan; IND = India; IDN = Indonesia; HND = Honduras; LKA = Sri Lanka; SEN = Senegal; MEX = Mexico; IRN = Iran; BRA = Brazil; CHN = China; RUS = Russia; ITA = Italy; JPN = Japan; USA = United States of America.
Source: (Johns Hopkins University and the Global Alliance for Improved Nutrition GAIN, 2022; Herforth et al., 2020).

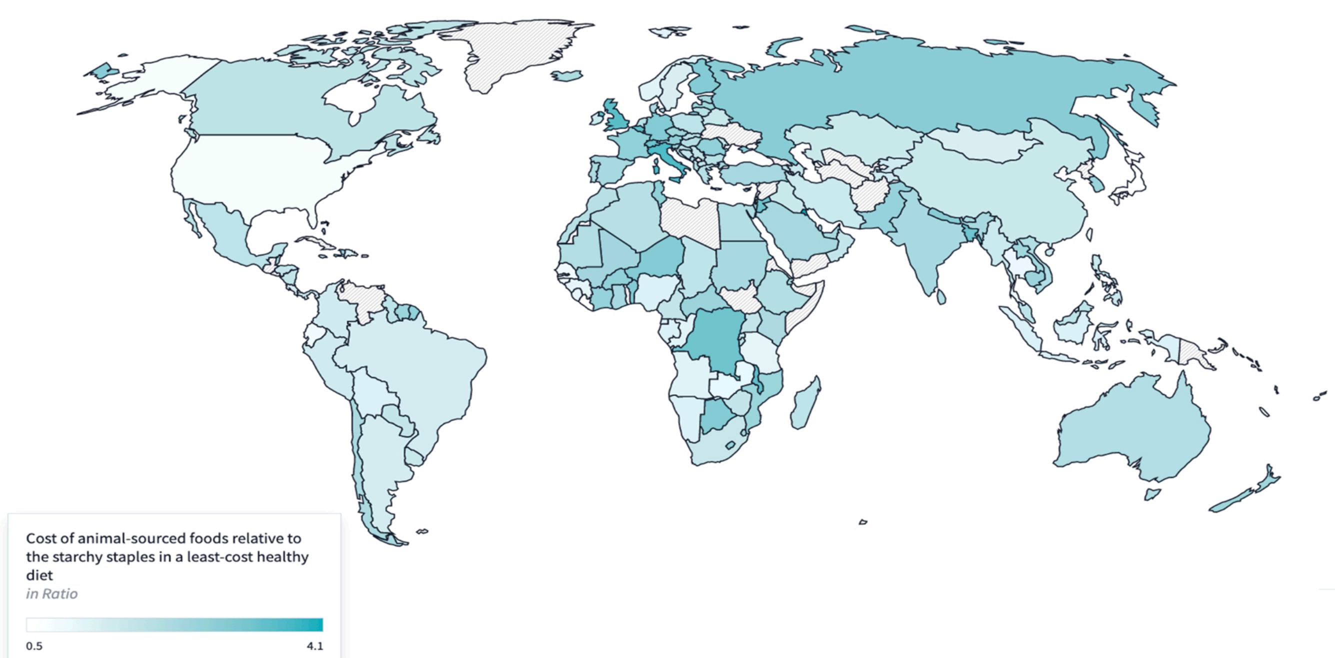

Fig. 10. Cost of animal-sourced foods relative to the starchy staples in a least-cost healthy diet. Notes: The map shows the cost of the least expensive animal-source foods as a multiple of the least expensive starchy staples to meet intake levels recommended in food-based dietary guidelines.A ratio greater than 1 indicates a high-cost food group. A ratio of less than 1 indicates the food group costs less than the cost of starchy staples. Data are available for 2017.
Source: (Johns Hopkins University and the Global Alliance for Improved Nutrition GAIN, 2022).

6. What macro forces and drivers shape dietary transitions & trajectories?

Various macro forces and drivers shape current trends and future trajectories of diets and the food systems that produce and provide those diets (HLPE, 2017). Some of these forces and drivers are exogenous to food systems that suggest world transition, development, or fragility. Some are influenced by political and economic decisions or power control and dynamics (Cottrell et al., 2019). Several factors involve technology and innovation responses to contexts and needs. Some factors are due to the behaviors and incentives of people—food system workers and companies or the eight billion consumer decisions and demands. Furthermore, disruptions and shocks are impacting food systems and people's diets, some due to conflict in certain areas of the world, more recently because of the pandemic, but increasingly due to climate-related extreme weather events (Cottrell et al., 2019; Barrett, 2020).

6.1. World transitions: population pressure and urbanization

Population pressure and expanding urbanization are major world transitions impacting dietary trends (Popkin, 1999). As a result, these two dynamic processes have ushered in demographic, epidemiologic, and nutrition transitions (Popkin et al., 2012). With eight billion people living on the planet, more people are leaving rural areas to seek services and employment in secondary cities and densely urban areas (Glaeser, 2014; Warr, 2018). Migration of populations within and across borders brings a mixing of cultures, changes in lifestyles, and new professional opportunities (Food and Agriculture Organization of the United Nations, 2019a; Ruel et al., 2017; Haddad et al., 2016). As a result, the available, accessible, and affordable foods change along with food habits and dietary preferences. Epidemiological trends suggest that as countries and people urbanize, obesity and diet-related non-communicable disease increase, and undernutrition and communicable disease decline (Lee et al., 2021; Lowe et al., 2021; Anik et al., 2019; Ford et al., 2017; Gao et al., 2020). Of course, countries in the middle of this transition are faced with a complex double burden of undernutrition and overweight and obesity (Fig. 11) (Popkin et al., 2020).

Some areas of the world are facing significant population pressure, which is putting strain on habitats resulting from the expansion of urban areas into the hinterland where diverse habitats exist (Laurance and Engert, 2022; Seto et al., 2011). This encroachment is changing the milieu of zoonotic spillover events due to a shrinking or destroying of wild habitats; increasing the vulnerability to warming due to the dismantling of forestscapes and biodiversity; and expanding reliance on longer, globalized food supply chains (DeFries et al., 2013; Borelli et al., 2020; Aiyar and Pingali, 2020; Hassell et al., 2017). In addition, other countries and, more broadly, regions of the world have undergone significant population dynamics influencing dietary trends. In Africa, for example, the "youth bulge" shapes the kinds of foods being demanded, how they are delivered, and where they are consumed. Younger people are seeking new job opportunities that bring new individual wealth and increased purchasing power is influenced by widespread access to social media. In other places like Europe and Asia and especially China, food and health care systems are adjusting to deal with a large elderly population demanding of greater chronic disease care and specialized diets.

Data suggest that in Latin America, the growth of supermarkets, multi-national food processors, and fast-food chains have led to an expansion in fast food and UPF consumption concomitant with the rise in obesity. This trend is similar to what occurred in Asia a decade ago (Reardon et al., 2012). Supermarkets have also resulted in access to more diverse foods, safer foods, and convenience for consumer (Schipmann and Qaim, 2011; Wanyama et al., 2019; Chege et al., 2015; Kimenju et al., 2015; Reardon et al., 2003). At the same time, cheaper and more convenient foods (prior to the COVID-19 pandemic and the Ukraine-Russia war), leave more time for women, in particular, to enter

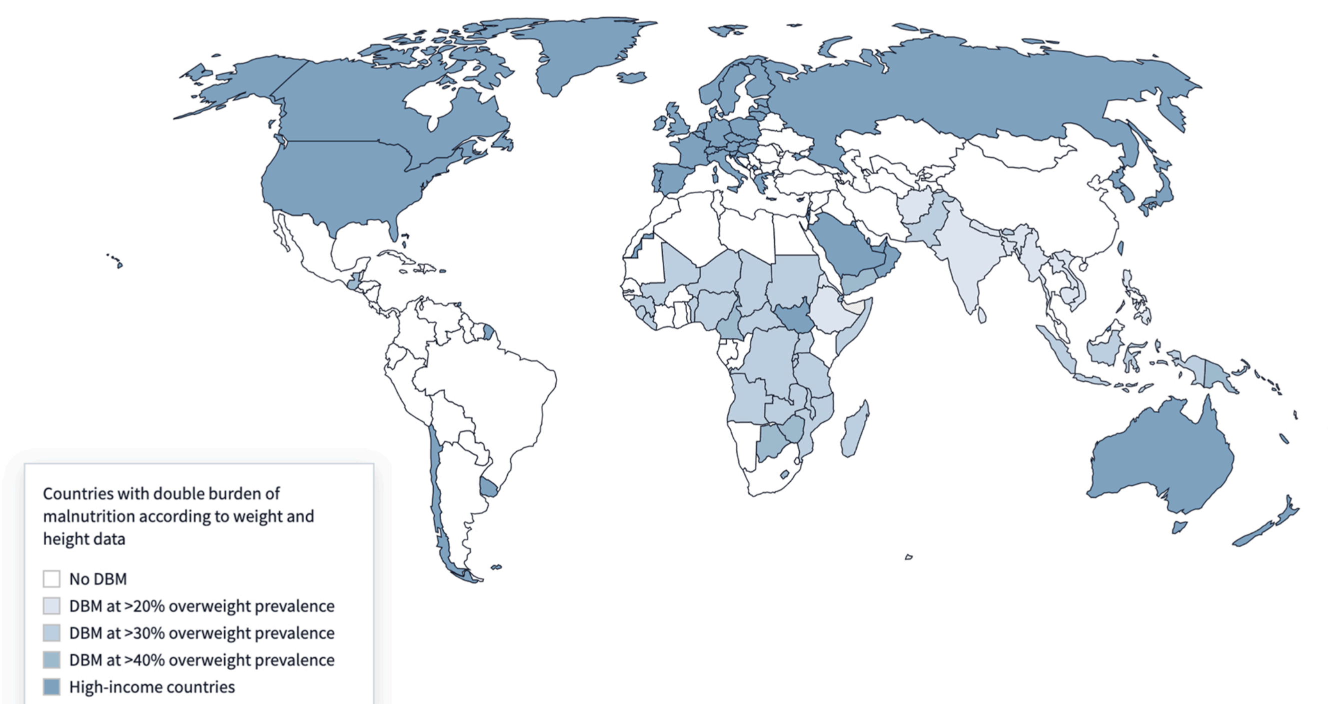

Fig. 11. The double burden of malnutrition. Notes: The double burden of malnutrition is defined as a high prevalence of undernutrition and overweight in at least one population group. A high prevalence of undernutrition is defined as the prevalence of wasting > 15% or stunting > 30% in children under 5 years or the prevalence of being underweight in women > 20%. A high prevalence of overweight is defined as adult or child overweight prevalence greater than 20%, 30%, or 40%.
Source: (Johns Hopkins University and the Global Alliance for Improved Nutrition GAIN, 2022; Popkin et al., 2020).

the labor force (Popkin and Reardon, 2018). In sub-Saharan Africa, some of the same patterns have emerged. Increased consumption of nutrient-poor, UPF, and purchases of foods away from home have been associated with the rise in overweight and obesity, along with stubbornly high levels of stunting and wasting among young children. However, most of the African processed food sector's growth has been driven by informal, small- and medium-scale enterprises (Reardon et al., 2021).

6.2. Political and economic decisions and power

Much of what drives food systems toward being more or less sustainable is motivated by economic and political forces (Béné et al., 2020). Food systems are impacted by a "wide array of governance regimes that are constituted by distinct sets of actors, forums, discourses, interests, which affect one another through their norm-setting tasks, the creation of rules and diffusion of paradigms (McKeon, 2021)." Strong political economy forces in national and global food systems often hinder necessary reforms, and governments are increasingly distracted by many concurrent crises. Governing food systems is incredibly complex because of their multi-dimensionality in time, scale, and sectors with vast ranges of activities and drivers (Béné et al., 2020; Fanzo et al., 2021a). Unstructured governance mechanisms leave power imbalances unfettered, often resulting in food industries with an increased market and corporate concentration and pervasive influence on prices, products, policies, research, and innovation (Clapp et al., 2018; Clapp and Scrinis, 2017). Among competing food system outcomes, economic growth often tends to influence decision-making, incentives, and priorities for governments and corporations (Fanzo et al., 2021a; Béné et al., 2022), eclipsing environmental and human health priorities.

In governing food systems towards more sustainable outcomes to adapt and mitigate climate change, much more can be done to better integrate food into goal-committing moments, such as the Conference of Parties (COP) climate change meetings. To date, the COPs have failed to recognize the role of food systems in the climate change agenda (Food and Agriculture Organization of the United Nations, 2019b). Although 89% of the Nationally Determined Contributions (NDCs)—commitments by each country to reduce national emissions and adapt to the impacts of climate change—mention agriculture production, emission reductions coming from food systems are usually vaguely considered within larger land use targets (Shulte et al., 2020). In addition, only 3% of governments' financial commitments to address climate go directly toward food and agriculture systems (Global Alliance for the Future of Food, 2022). Proposing targets or instituting policies to shift populations towards more sustainable diets has been largely ignored, most likely due to government fears of paternalistic policy failures involving infringing on individuals' voluntary choices and freedoms (Wellesley et al., 2015).

There are also issues of dominant authority, in which blanket recommendations are directed towards all governments to take bolder steps to reduce emissions and institute regulations across food systems. However, not all countries are created equal and their contributions to climate change also differ. Regulations such as food carbon taxes may not be relevant in certain countries' food systems in which diet-related GHG emissions and environmental footprints of local food systems contribute much less to global warming. Wealthy nations hold structural power in the international system that allow them to force other states to contribute to solving collective action problems they did not cause (Clapp, 2022). This displacement of responsibility further constrains strong global governance of food systems in light of climate change, both "we are all in this together" types of challenges that require multilateralism and cooperation (Fanzo, 2020). With only six major economies—Brazil, China, the European Union, India, Indonesia, and the United States contributing over half of the world's food system GHG emissions, the onus rests with those countries (Crippa et al., 2021). Perhaps future inclusion of food systems should be considered as part of the COP 27's "Loss and Damage" Fund for Vulnerable Countries.

6.3. Technology and innovation responses

Technology and innovation over the last six decades have positively and negatively shifted food systems. The Green Revolution is the classic example of a technological-driven solution that improved yields of major staple grains across South Asia and Latin America with some benefits to food security but also significant trade-offs for the environment, biodiversity, and nutrition (Pingali, 2012, 2019; Negin et al., 2009). Other technologies, such as genetically modified organisms and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), have potential positive and negative externalities (Glass and Fanzo, 2017; Sarkar et al., 2021; Jacobsen et al., 2013; Klümper and Qaim, 2014; Kovak et al., 2021). Some would argue that relying solely on technological fixes (which to some include climate-smart agriculture) interferes with longer-term sustainability (Clapp et al., 2018).

Innovations across food supply chains that are both climate- and nutrition-smart are becoming more sophisticated; however, more can be done to ensure technologies have a "double duty" effect (Fanzo et al., 2018). Consumer-oriented technologies such as digital technology interfaces, social media, and personalized nutrition will continue to influence dietary aspirations, demand, and choice (Barrett et al., 2020). Cellular agriculture—foods created by tissue engineering, synthetic biology, and fermentation—along with new seaweed feeds that reduce methane emissions among cattle are the next frontier of technology that could be game changers for climate change (Gruber, 2022; Lean et al., 2023), the environment, and animal welfare (Holmes et al., 2022). The challenge will be to scale these technologies and their reach to all populations while considering the social, political, and distributive justice trade-offs (Barrett et al., 2020) that come with the contraction of industries such as the livestock sector employment (Mason-D'Croz et al., 2022).

6.4. Disruptions, shocks, and extreme weather events

Disruptions and shocks to food systems can come in multiple forms (Hamilton et al., 2020). Shocks such as climate and extreme weather events, geopolitical and economic events, mismanagement and policy change, and a global pandemic can all disrupt and lead to food system shocks (Cottrell et al., 2019). What is clear is that these various shocks are increasing in frequency and impact across crops, livestock, fisheries, and aquaculture (Cottrell et al., 2019; Béné, 2020).

The outlook is not promising. Models suggest that even holding at 1.5 °C will trigger multiple climate tipping points such as ice sheet "collapses," forest "diebacks," and permafrost "abrupt thaws." In addition, projections anticipate multiple breadbasket failures in which extreme weather events such as heat waves, droughts, flooding, and cold spells will lead to devastating crop failures of major crops such as wheat, maize, soybean, and rice. Furthermore, climate change increases the risk of extreme global weather events co-occurring at multiple cropping locations (Gaupp et al., 2019). These events will have differing impacts on diets and nutrition outcomes. A study examining children's diets in 19 countries found that higher long-term temperatures were associated with lower dietary diversity whereas higher rainfall compared to the long-term average was associated with higher dietary diversity (Niles et al., 2021). Another study modeled the potential impacts of climate-induced changes in diets and their potential harms and found that risk factors related to reductions in fruits and vegetable consumption cause over 500,000 deaths by 2050 (Springmann et al., 2016). In addition, climate change will have profound impacts on foodborne illness. One study found that 58% (218 out of 375) of known human infectious diseases were worsened by climate-related extreme weather events. Of the approximately 1000 unique pathways in which climate hazards impact pathogenic diseases, 50 were foodborne (Mora et al., 2022).

The global food trade has become increasingly critical but crippled by extreme weather events, conflicts that result in protectionist policies that limit the exportation of food, and agriculture production decisions (Willett et al., 2019). Yet, the global trade of food remains critically important to ensure that nutrients are moving around the world, with the growing trend of food being consumed away from producer regions. Without trade, there would be substantive increases in micronutrient and protein deficiencies such as iron, zinc, and protein (Wood et al., 2018). However, other studies suggest that trade could be more equitable in that it does not improve the nutrient adequacy of most LMICs and instead relies on a few major trade partners for important cereals rather than micronutrient-rich food products (Willett et al., 2019). Moreover, with the trading of food comes GHG emissions. Emissions largely depend on a country's consumption patterns and agricultural emission intensities relative to its trading partners as well as its domestic production and local trade. This is particularly relevant in the trade of high-emission food products, such as ruminant milk, meat products, and rice (all of which produce significant amounts of methane) (Foong et al., 2022).

These trends and patterns suggest that a new paradigm in how food systems function and what is grown and consumed. Fig. 12 models a comparison of a business-as-usual scenario based on current dietary intake patterns and continued loss and waste of approximately 30% of food globally, versus the world consuming the EAT-*Lancet* PHD, with food loss and waste cut in half. Agriculture production would need to be wholly reoriented by 2050. This reorientation would involve moving away from cereal production and investment, contracting the livestock sector, and increasing yields of fruits, vegetables, nuts, legumes, seeds, and fish, mainly aquaculture (Monteiro et al., 2013). At the same time, an entire resource use rebalance will need to occur across production systems to meet both human and planetary health needs. Analysis suggests that currently, no country meets basic needs—such as nutrition, sanitation, and access to electricity—for its citizens at a globally sustainable level of resource use. To meet global needs, resource use would increase 2–6 times more than current usage (O'Neill et al., 2018).

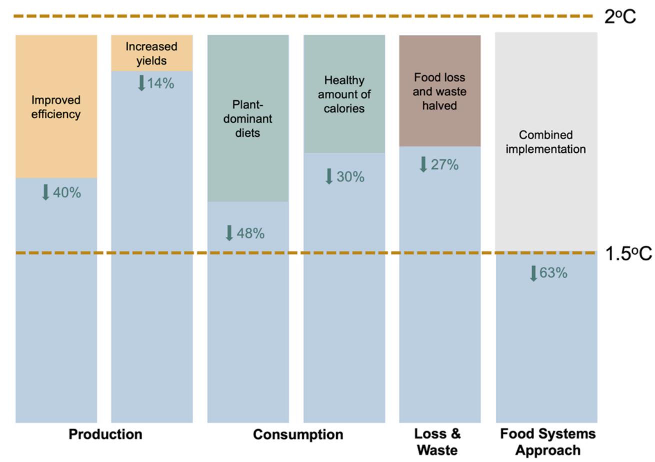

Fig. 13. The mitigation potential of food system actions. Notes: Each bar shows a food system change that leads to emission reductions equivalent to 1.5 °C. The blue bars are business-as-usual emissions. The yellow bars are food production changes that improve efficiency in which GHG emissions are reduced by 40% per unit of food produced and increase yields by 14% above the current maximum yields. The green bars indicate changes to dietary patterns in which a plant-dominant diet and consumption of 2100 daily kilocalories per person are maintained. The brown bar signifies a reduction in food loss and waste. The gray bar shows the combined changes of all five strategies, which gets closer to the 1.5 °C goal.
Source: (Clark et al., 2020; Loken, 2022).

7. What combined climate & food system actions are needed to shift towards sustainable, healthy diets?

The holistic nature of food systems allows for a broad range of policy and programmatic innovations and interventions to provide diets that are both healthy for populations and sustainable for planetary health. For example, one modeling study suggests that under certain assumptions, achieving the Paris Accord climate targets could be possible if action is taken across various food systems activities (Clark et al., 2020)

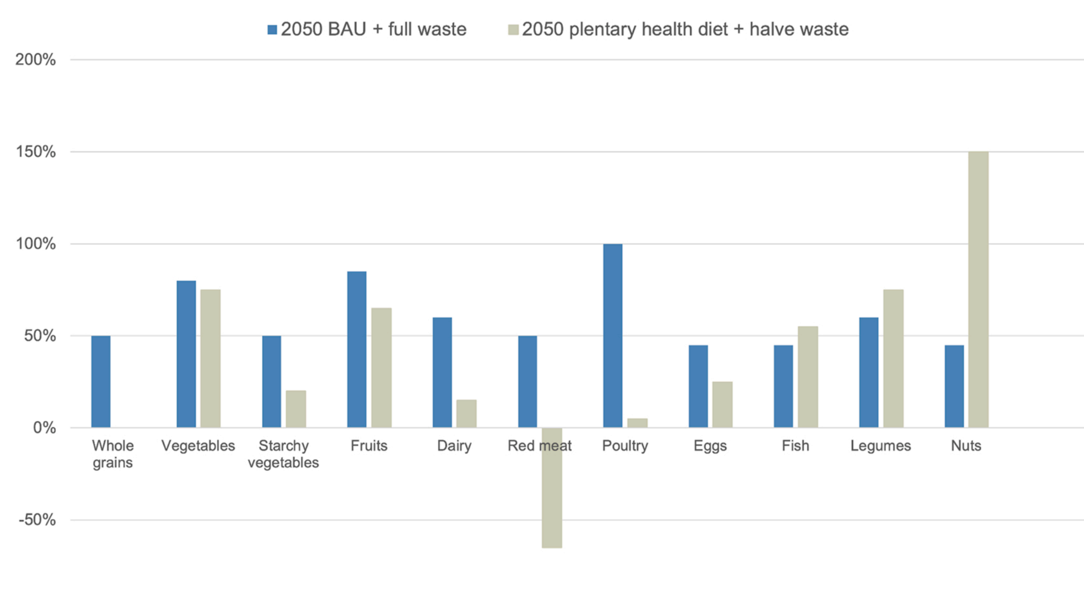

Fig. 12. Modeled projections of global food production, diet, and food waste changes in 2050 using two different scenarios. **Notes:** These results present are estimated from a particular modeling exercise of the EAT-Lancet Commission with particular scenario assumptions. See additional methodological details from the source.Blue bars show a business-as-usual scenario in 2050 of current food production practices and maintaining current levels of food loss and waste. Green bars show a scenario of how food production would need to change if the world were to consume the EAT-*Lancet* planetary health diet and cut food loss and waste in half..
Source: (Monteiro et al., 2013).

(Fig. 13). Actions include:

- improving efficiency on farms,
- increasing yields of foods without extensification into biodiverse landscapes,
- moving toward plant-dominant diets,
- consuming only what one needs to maintain a healthy weight, and
- reducing food loss and waste.

On the supply side, a range of farm production policies can be implemented to ensure that what is produced, processed, and transported is more sustainable (Fanzo et al., 2018). The EAT-*Lancet* PHD, while controversial for various reasons, provides one possible roadmap to diversity production, reduce GHGe, improve soil and water management on production landscapes, minimize food loss and waste, and shape the demand for healthier diets. Rosenzweig et al. (2020) calculated the total technical mitigation potentials — the maximum amount of GHG mitigation achievable through technology diffusion — as well as total economic mitigation potentials at specified carbon prices of both crop, livestock, and agroforestry activities (supply side) and dietary changes (demand side). On the supply side, technical mitigation provides 2.3–9.6 GtCO2e/year, and the economic potential provides mitigation of 1.5–4.0 GtCO2e/year. On the demand side, the technology provides a broader range of mitigation potential of 0.7–8.0 GtCO2e/year and economic potential of 1.8–3.4 GtCO2e/year (Rosenzweig et al., 2020). The authors examined various adaptation and mitigation strategies across food systems, highlighting their synergistic potential and co-benefits across the multiple outcomes that food systems have the potential to fulfill.

As shown in Fig. 14**,** the range of responses cut across improving crop and livestock management and food supply chains, instituting, and disseminating climate services, and managing demand for specific diets. However much of these interventions need to be supported in a political environment that is conducive to making significant food system transformations. This means commitment, prioritization, and policy packaging by governments (Resnick, 2020) as well as social mobilization and participation and instituting accountability mechanisms (Baker et al., 2021). Without that supportive political ecosystem in place, it will be difficult to optimize these solutions (Barrett et al., 2020; Herrero et al., 2020).

Fig. 14. Mitigation and adaptation potential of food system responses. Notes: The blue and gray colors indicate different levels of synergy between mitigation and adaptation to climate change (from none to very high) associated with each food system response.
Source: (Rosenzweig et al., 2020).

7.1. Food supply actions for healthy and sustainable diets

According to the FAO, “low levels of productivity, high production risks and insufficient diversification towards the production of more nutritious foods are key drivers of the cost of healthy diets, especially in low-income countries (Bongaarts, 2021).” Much of this reduced food productivity is driven by an insufficient infrastructure of roads, storage, and markets, as well as inadequate food preservation and processing capacity, especially for highly perishable, nutrient-dense foods such as fruits, vegetables, and animal-sourced foods (Headey and Alderman, 2019; Headey et al., 2018). This can lead to inefficiencies along food supply chains and food loss that increase the cost of healthy diets, creating more barriers for poor households in rural and urban areas (Shafiee-Jood and Cai, 2016).

Food supply policies to support producers, including direct and indirect food production subsidies, have mainly focused on starchy staples, making calories from these foods relatively cheaper and widely available (Food and Agriculture Organization of the United Nations, 2022). At the same time, small-scale producers and farmers face significant challenges in getting perishable foods to markets that meet food safety, food quality, and price standards. These challenges, particularly in a hot world, include inadequate infrastructure, delayed-time market price information, and power asymmetries, leaving them in poverty and threaten their livelihoods (Thornton et al., 2011; Davis et al., 2022). These challenges are exacerbated and perpetuated for women food system actors (Othman et al., 2020; Murray et al., 2016; Tsige et al., 2020). Some of these food supply constraints are why diets delivering minimum needed nutrients cost three times more than diets meeting only dietary energy needs through starchy staples. Even more so, healthy diets that meet nutrient needs and are health-protective are five times more expensive (Herforth et al., 2020).

Reorienting subsidy policies: Current agriculture subsidy support accounts for 540 billion USD globally annually, concentrating on staples, sugar, and animal-source foods (Food and Agriculture Organization of the United Nations, 2022; Gautam et al., 2022). This support is uneven and inequitable and is considered harmful to the human health and the environment (Fao UAU, 2021). In the United States (U.S.), 56% of all calories consumed were from subsidized food commodities — corn, soy, rice, wheat, sorghum, dairy, and livestock (Food and Agriculture Organization of the United Nations, 2022), a diet not aligned to the DGA. If the world’s population were to consume the recommended serving of fruits and vegetables (400 g/capita/day), their prices would rise since production of both food groups is currently inadequate and will remain so into the future (Mason-D’Croz et al., 2019). This is a clear call for a reorienting of subsidy policies.

If subsidies were repurposed, the availability of nutritious foods would increase because they would be more affordable (Willett et al., 2019; Rosenzweig et al., 2020; Ranganathan et al., 2016). But there is a range of trade-offs, including impacts on producers’ incomes and potential increases in poverty and undernourishment (Fao UAU, 2021). To offset these negative implications, it is important that subsidies be redirected to ensure infrastructure is adhering to localized environments and that research and development focus on climate-resilient and nutritious crops.

If current agriculture subsidies stay the course (i.e., a business-as-usual approach), GHG emissions from agriculture will increase by 58% (Gautam et al., 2022). A study found that if the world were to reorient subsidies towards those that produced healthier, sustainable foods, modeling suggests that there are multiplier effects with positive impacts on diets, mortality, and GHG emissions (Springmann and Freund, 2022). Changing subsidy policies is a juggernaut in the food policy world, and reorienting these policies is entrenched with a host of political interests that stymy change. Thus, conversations to redesign subsidy policies are a start, it must be acknowledged that the political economy road to change those policies is long and sorted.

Investing in infrastructure for small-scale producers: A wide range of supply chain infrastructure innovations from the farm to the end-user can help minimize producer and consumer costs while reducing the food system’s environmental footprint by reducing the land, water, and energy needed per unit of the nutritious foods needed for a healthy diet (Monteiro et al., 2013; Rosenzweig et al., 2020; Ranganathan et al., 2016). While international trade will play an essential role in climate change to ensure diverse foods and nutrients reach consumers worldwide (Wood et al., 2018; Geyik et al., 2021; Foong et al., 2022), domestic production could be a localized primary source of nutritious foods in most countries. There is a need to invest in infrastructure and capacity to support the ability of small-scale producers to grow nutritious, climate-resilient foods and to minimize food loss post-farmgate. This applies to open, competitive markets and institutional public procurement, such as schools, where daily meals are served to school-aged children. However, it is difficult for small-scale producers and small- and medium-scale food processors to meet public procurement buyers’ food quality, safety, volume, and yield regularity requirements, but country exemplars, like Brazil’s homegrown school feeding, could be emulated (Nordhagen et al., 2021). Evidence shows that investments in credit, extension, and price information infrastructure are necessary for producers to effectively link to markets and public procurement platforms (Nehring et al., 2017).

Gains in small-scale producers’ productivity and poverty reduction are far greater when complementary interventions in infrastructure are invested in. These infrastructures include basic “asks” such as water for irrigation, energy, and rural roads (Hanjra and Williams, 2020). There are also other benefits of investing in infrastructure, such as decreased food prices. For example, public investments in the road networks of African countries could help raise the affordability of nutrient-adequate diets (Herforth et al., 2020; Shively and Thapa, 2017), and lack of roads correlates with higher stunting prevalence (Shively, 2017). Evidence also shows that strengthening markets and improving market access is key to optimizing the dietary diversity benefits of the diverse production systems already standard on small-scale farms (Muthini et al., 2020). Of course, with infrastructure investments, there can be trade-offs with the environment that need to be considered.

Improving food access: Policy interventions include addressing physical access to healthy foods. Food deserts—geographic areas that lack an adequate supply of affordable healthy foods, such as fresh fruit and vegetables—are prevalent worldwide and impact communities with high poverty rates (Karpyn et al., 2019). Policy actions to improve the physicality of the retail food environment, such as regulating the number of retailers who sell primarily unhealthy food products and partnering with local growers to offer alternative options at farmers’ markets, are potential opportunities to spur local economies (Freedman et al., 2016; Chenarides et al., 2021). There is a range of interventions that can also take place at the point where people purchase food, also known as the food environment, described below.

The high cost of nutrient-rich foods and overall diets, combined with climate change and food inflation worldwide, implores that safety nets and other social protection measures are in place for resource-constrained households and individuals who are vulnerable and marginalized (IFPRI 2021; Raza, 2017). Affordability of low-cost healthy items is essential, but more is needed to ensure access to and consumption of healthy diets. Therefore, a wide range of policy interventions is needed to ensure food items being served and sold meet consumer needs and aspirations without causing harm (Fanzo et al., 2021b).

7.2. Food demand actions for healthy and sustainable diets

Most people acquire food in nearby food environments. Food environments refer to the physical, economic, and sociocultural surroundings in which people engage with food systems to make their decisions about acquiring, preparing, and eating food. The food environment creates prompts that shape dietary preferences and choices (Swinburn et al., 2014). Food environments are varied around the world, from "wild" food environments in which communities get their food from rivers or forests to "cultivated" in which people grow food (Downs et al., 2020), to very globalized, with increasingly interconnected regional and international markets (Hawkes, 2006; Downs et al., 2022). Food environments can consist of physical spaces where food is purchased, as well as the features of that environment that persuade and shape purchases (Gustafson et al., 2012). People also bring their cultural, aspirational, and acceptability preferences to food environments (HLPE, 2017) that also impact their decision-making. Evidence is emerging on how to ensure these food environments are providing healthy food choices but much less is known on how to promote environmentally sustainable options (Constantinides et al., 2021; Turner et al., 2019).

Changing the choice architecture: When it comes to marketing and retail, many food environments could be better designed, also known as "choice architecture," which shapes dietary choices and decisions (Hollands et al., 2013). Choice architecture is a way to design food environments so that specific foods are convenient to see, order, and choose from, are at the right price point, are attractive in their appearance and packaging, and are easy to cook, serve, and consume (Fanzo and Davis, 2021; Kraak et al., 2017). Unfortunately, however, a large number of food environments that trigger and encourage unhealthy and unsustainable choices. For example, checkout lines of grocery stores are often stocked with highly palatable ultra-processed foods that are easy to grab and relatively cheap. Interventions to change detrimental designs include:

- making healthier foods more visible and prominent than unhealthy foods in markets,
- reducing the size of plates and trays in canteens,
- ensuring they can be quickly packaged for takeaway,
- reducing portions of unhealthy packaged foods, and
- increasing sustainable packaging of healthy foods.

Part of the design in food environments is through nudging, defined as "any aspect of choice architecture that alters people's behavior in predictable ways without restricting any options or significantly changing their economic incentives such as time or money (Thaler and Sunstein, 2009)." Nudges are unobvious ways to persuade dietary choices in the places where people live, shop, work, and learn. For example, fast food chains could automatically serve salad as the default side choice with the main meal instead of french fries. Another emerging nudge is the range of alternative meats available on store shelves. These foods mimic the taste, smell, and look of meat requiring minimal adjustment for the eater concerning palatability or cooking preparations. While the health of these foods are in question due to their high levels of processing, they could be important substitutes for consumers who value animal welfare or the environmental footprint of their diets (Kraak, 2022; Harnack et al., 2022; Narayanan Nair, 2021).

Guiding towards healthier, sustainable food choices: There are ways to help guide populations towards healthier and more sustainable food choices, including providing health and environmental information and declarations on food product packaging and instituting national food-based dietary guidelines. Nutrition labels on food packages are influential for food producers and consumers. They are purposed to encourage healthier individual choices and prompt the food industry to reformulate products with more nutritious ingredients. This information is often found on the "back of the package." The Codex Alimentarius Commission, established by the United Nations, has developed standards for nutrition guidelines on food products. However, these labels require some degree of nutritional literacy, are context-dependent, and are difficult to interpret for many people. In addition, many products carry misleading "front of the pack" claims on the health, nutrition, and environmental benefits of foods, an ungoverned territory of packages. The food industry often designs the product's packaging to ensure that consumers immediately see these statements.

For this reason, there have been recent moves to adopt easy-to-read and interpret labels (e.g., traffic lights, star ratings, etc.) on the front of the package or store shelves. Consumers can more easily interpret graphic front-of-package labels that incorporate colors, symbols, and text to indicate nutrition or health compared with labels that only emphasize numeric information (Reyes et al., 2020; An et al., 2021). Evidence suggests that both health and environment impact labels impact purchasing behaviors (Reyes et al., 2020; Langellier et al., 2022; Taillie et al., 2020; Muzzioli et al., 2023). For example, a study in the U. S. found that a simple label indicating climate impacts on foods had a strong influence on fast food choices (Wolfson et al., 2022). Interestingly, putting information about calorie, fat, sugar, and salt content or carbon footprint metrics on restaurant menu items has been shown to have less impact on choices (Fernandes et al., 2019).

National food-based dietary guidelines can steer people toward healthier and more sustainable food choices by increasing consumer knowledge and awareness (Mozaffarian and Ludwig, 2010). They are critical for three major reasons. First, guidelines can provide a unified voice to the public on where the government stands on the latest dietary advice for health promotion and disease prevention. Second, they serve as the foundation for food and nutrition policies instituted within a country and guide budgetary allocations for such programs as school meal programs. Third, the food and beverage industries often respond to changes proposed in dietary guidelines by reformulating products and answering consumer demands (Scott et al., 2017). Many recommendations extend across countries, such as consuming a variety of foods; consuming fruits and vegetables, legumes, and ASF; and limiting salt, sugar, and fat (Herforth et al., 2019). However, few guidelines address environmental factors such as greenhouse gas emissions and water pollution or sociocultural factors such as labor conditions, although incorporating sustainability has benefits (Springmann et al., 2020). Unfortunately, only a handful of countries have guidelines that specifically promote diets and food systems that are both healthy and sustainable. In some cases, governments actively oppose the inclusion of environmental sustainability into dietary guidelines, such as the U.S.

Regulating towards healthy sustainable diets: Techniques to market and advertise foods can influence consumer behavior positively or negatively. Examples include social media, print and television advertising, in-school marketing, sports sponsorship, toys, and products with brand logos, packaging, and product placements (Campbell et al., 2014; Story and French, 2004; Carter et al., 2012). Television ads are particularly influential, as advertisers often use child-oriented persuasion to promote UPF (Silva et al., 2021; Correa et al., 2020; Norman et al., 2018). Governments can intervene by banning companies from advertising unhealthy foods marketed to children, however very few governments have taken this approach with the exception of Canada, Norway, Sweden and the UK (Buse et al., 2017; Popkin et al., 2021).

Food and beverage companies see marketing and advertising, product placements, pricing policies, and packaging as a response to consumer demand. This view puts more responsibility on the consumer to make the "right" choice, even though the current balance of power highly favors multinational food and beverage corporations. As part of efforts to create healthier food environments and to protect and inform consumers, there should be more transparency about where food originates, how it is produced, and its potential impacts on health, environment, and livelihoods.

8. Conclusion

It is increasingly recognized through evidence and data that global food systems and their resulting diets play important roles in mitigating climate change. Moving towards more sustainable food systems that produce healthy diets is also a pathway to adaptation. However, the window of opportunity is closing to address climate change, and food systems' action must be taken seriously and swiftly.

Historically, the climate community and political leaders engaged in climate mitigation and adaptation negotiations have understated the vital part that food systems play in addressing climate change. That lack of prioritization is changing. In the last two years, and now with the Ukraine-Russia war, the transformation of food systems has risen to the top of international development agendas as one path to address climate change. This priority has been reflected by the UN Secretary General's call for a global UN Food Systems Summit, held in 2021. The preparation for the Summit involved hundreds of food system dialogues engaging numerous stakeholders, including governments, private sector actors, civil society, multilateral agencies, and food system workers and agencies. This large convening effort produced more than 110 national Food System Pathway documents describing the priority actions countries have identified to transform their food systems. Commitments from governments have led to tremendous momentum and opened new and expanded existing political opportunities for transformation.

Other commitments by governments will be essential to transform food systems. For example, the United Nations agreed High Seas Treaty in 2023, the first of such an ocean treaty since 1982, will turn 30% of the world's international waters into protected areas by 2030. The 15th meeting of the Conference of the Parties (COP 15) to the Convention on Biological Diversity (CBD) in 2022 also agreed to adopt a Global Biodiversity Framework to protect biodiversity in substantive ways to 2030. Global commitments are critical to draw attention to areas that need more political cooperation, and these will all have downstream impacts on food systems and climate, but global goal setting is only one part of a more complex equation.

To make the grand food transformation that is being called for that ensures food systems are climate resilient and able to produce healthy diets for everyone in equitable ways, a plethora of actors at different scales need to modify behaviors, take action, and be held to account. However, transformation will have trade-offs (Mausch et al., 2020) due to certain food system actor ideology and power, national interests, and policy incoherence, which can result in stymied disagreement and tension (Béné, 2022). There may be significant challenges in ensuring that health, environment, and equity contribute equally to achieving the different dimensions of food system sustainability. For example, policies and investments that target social and food security and nutrition dimensions of transformation are projected to have a greater effect on the sustainability of food systems than investments to improve environment or economic domains. Of course, the emphasis on where to intervene depends on country contexts, resources, and subnational policies (Béné et al., 2022).

Attention must be paid to the political economy dimensions of reform, recognizing how the costs and benefits of food systems transformations and reforms affect constituencies differently and identifying the conditions under which politically viable options have been pursued. Political leaders and agri-food industry players worldwide are under increasing pressure to address the drivers of climate change. The eight billion eaters, consumers, and citizens are increasingly aware of the links between food systems and their health, the climate, and the welfare of people around the globe. Both access to data and solution streams and awareness of enabling political conditions for reform can empower civil society and the media as they advocate for governments and businesses to pursue the necessary changes outlined in this paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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