Population and Environment (2023) 45:20
https://doi.org/10.1007/s11111-023-00431-6

REVIEW ARTICLE

Population and food systems: what does the future hold?

Stan Becker[1] · **Jessica Fanzo**[1]

Accepted: 27 June 2023

Abstract

The ability of food systems to feed the world's population will continue to be constrained in the face of global warming and other global challenges. Often missing from the literature on future food security are different scenarios of population growth. Also, most climate models use given population projections and consider neither major increases in mortality nor rapid declines in fertility. In this paper, we present the current global food system challenge and consider both relatively high and relatively low fertility trajectories and their impacts for food policy and systems. Two futures are proposed. The first is a "stormy future" which is an extension of the "business as usual" scenario. The population would be hit hard by conflict, global warming, and/or other calamities and shocks (e.g., potentially another pandemic). These factors would strain food production and wreak havoc on both human and planetary health. Potential increases in mortality (from war, famine, and/or infectious diseases) cannot be easily modeled because the time, location, and magnitude of such events are unknowable, but a challenged future is foreseen for food security. The second trajectory considered is the "brighter future," in which there would be increased access to education for girls and to reproductive health services and rapid adoption of the small family norm. World average fertility would decline to 1.6 births per woman by 2040, resulting in a population of 8.4 billion in 2075. This would put less pressure on increasing food production and allow greater scope for preservation of natural ecosystems. These two trajectories demonstrate why alternative population growth scenarios need to be investigated when considering future food system transitions. Demographers need to be involved in teams working on projections of climate and food security.

Keywords Population projections · Food systems · Food security · Fertility

✉ Stan Becker
sbecker2@jhu.edu

[1] Johns Hopkins University, Baltimore, MD, USA

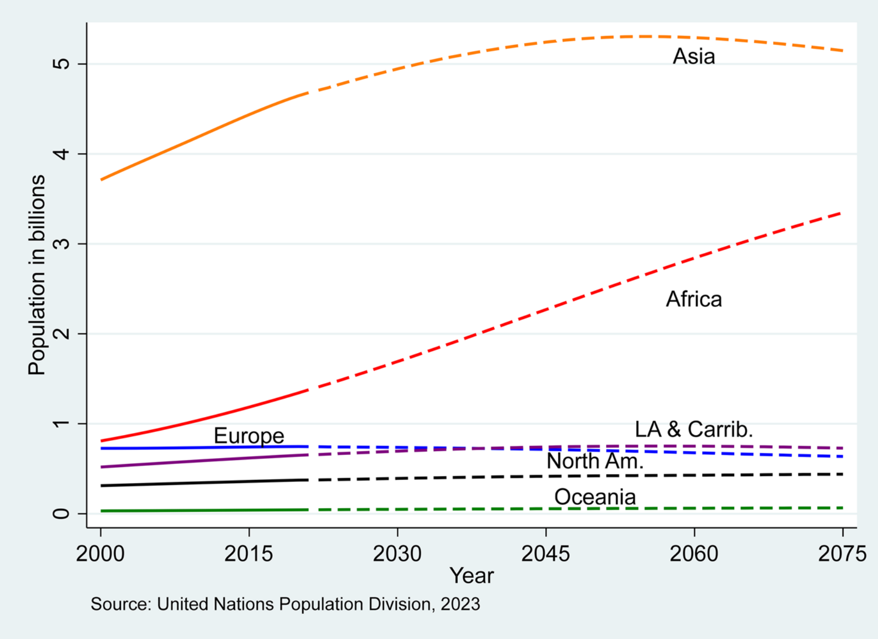

Fig. 1 Population by region from 2000 to 2020 and projected to 2075

Introduction

Projections of food demand into the twenty-first century rely on population projections from demographers as well as historic to present trends of policy choices and priorities in food systems. Similarly, the trajectory of future greenhouse gas emissions depends on population projections in addition to projections of per capita fossil fuel usage, mitigation, and so on. Since 1963, the United Nations Population Division (UNPD) has produced population projections for each nation of the world and in recent decades they have been done every 2 years.[1]

Over the last 70 years, the world population has increased greatly from 2.5 billion in 1950 to 8.0 billion in 2022. [2] World population is still growing by about 70 million persons per year. Figure 1 shows the median projection to 2075 by region. While the populations of Europe, North America, Latin America and the Caribbean, and Oceania remain nearly constant in this century, Africa is growing very

[1] How accurate are population projections? In hindsight, UN projections for individual countries have sometimes had considerable error and the error of course increases the longer the time interval between the projection and the actual population count. From a study in 2000, the mean absolute error across countries at ten years duration was 7% and at 30 years was 16% (National Research Council (USA), 2000). However, for the *world*, the percentage error even at 30 years from projection to actual was less than 4%.

[2] World population reached 1 billion in 1800, 2 billion in 1930, and passed 3, 4, 5, 6 and 7 billion in 1960, 1974, 1987, 1999 and 2011 respectively. This has been very rapid growth in the last century, i.e., a nonagenarian today has seen world population quadruple in his/her lifetime.

fast (adding 33 million persons per year). Africa's population is expected to increase from 1.4 billion in 2022 to 3.3 billion by 2075. Asia is expected to increase from 4.7 to 5.3 billion by 2050 and then decline to 5.1 billion by 2075. [3]

Those countries with populations that have been roughly constant over the last half century (except for the USA) consume beyond their means across all commodities but particularly food. In places such as North America, Europe, and Australia, not only are more calories consumed, but the dietary patterns have become more environmentally intensive with regard to water, land use, and biodiversity loss (Willett et al., 2019). These countries along with a handful of others, including some middle-income countries such as Brazil and Indonesia, have the largest greenhouse gas emissions (GHG) coming from their food systems (Crippa et al., 2021). In contrast, in many low-income countries, populations are not getting enough nutrient-dense foods to meet their nutritional and physiological needs, and these countries are contributing less GHG per capita and environmental degradation in aggregate (Beal et al., 2023).

In this paper, we first provide the current context for population projections and the challenges food systems face to feed the world population. Second, we consider two hypothetical trajectories for population and global food security from now to 2075.[4] In the first trajectory, which is named "stormy future," fertility declines only slowly, and the population will be hit hard by conflict, global warming, and/or other calamities. In the second trajectory, entitled "brighter future," there will be rapid adoption of the small family norm, resulting in a population that increases due to momentum, but then comes back down to 8.4 billion by 2075 without increases in mortality. For each trajectory, the components of population change are first outlined and then possible changes in food production and consumption are described.

Current context

Presently, a major reason for continued rapid population growth is population momentum. This is due to the young age distribution of countries where fertility has declined recently, i.e., even if girls in these countries only have two births each in their lifetimes, the population will continue to grow for decades because there are large numbers in the young ages. The effect of momentum is enormous; most of the population growth projected by the UNPD between now and 2050 is due to momentum (United

[3] Also, with declines in fertility, the population ages so for example, the median age in Mexico in 2020 was 29 years but in 2075 the estimate is 48 years (United Nations Population Division, 2022). Countries need to prepare for this eventuality.

[4] We chose the year 2075 instead of 2100 which many authors use, because very few people alive today will be alive in 2100 so the forecasts for that year depend almost entirely on projections of fertility (and mortality) over the next 77 years. As a rough indication of this, with the world population by age from UNPD and a model life table with expectation of life of 72.5 years (close to the world average now according to the Population Reference Bureau 2022 Data Sheet), 34% of people alive today can be expected to be alive in 2075 but only 4% can be expected to be alive in 2100. Fertility projections even 30 years hence can be quite far off. An example is the extended baby boom after World War II.

Nations Population Division, 2017). But such growth can be counteracted by women having fewer than two births, or below replacement fertility (BRF). However, even with BRF, a large effect of momentum persists. Consider the case of China—its fertility has been less than 2.1 births per woman[5] since 1991 but its population continued to increase from 1.14 billion in that year to 1.43 billion in 2022 and is only now starting to decline (its fertility level in 2022 was 1.2 births per woman).[6]

Thus, we live in a demographically divided world; while over half of the world population lives in countries with two or fewer births per woman, fertility remains high in quite a few countries. Sub-Saharan Africa (SSA) is the region with the highest fertility (with a total fertility rate (TFR), the average number of children that would be born to a woman over her lifetime given current rates of fertility by age, of 4.6), but with great variation from country to country. Projected population levels in the twenty-first century depend greatly on how fast fertility declines in this region.[7] The fertility transition has been slower there than it was in previous decades in Asia and Latin America and it stalled in a number of SSA countries. Stalls in educational improvement in SSA in the period around 2000 help explain the stall in the fertility transition in multiple countries (Kebede et al., 2019). But recent evidence indicates that the transition may be speeding up. For example, the Kenya Demographic and Health Survey (DHS) of 2008–2009 gave a TFR of 4.6, the 2014 survey reported a TFR of 3.9, and the 2022 survey gave an estimate of 3.4 (Kenya National Bureau of Statistics, Kenya Ministry of Health and the DHS Program, 2023). But Niger still has a TFR of 6.8.

How do demographers produce the best forecasts they can for the twenty-first century? Basically, it involves projecting trends of fertility, mortality, and net migration at the national level. The UNPD now uses Bayesian methods to model the trends in these components for each nation (United Nations Population Division, 2022; Azose & Raftery, 2015; Alkema et al., 2011). In total, 200,000 projections are done to the year 2100 and then median values are determined. The UN also produces probability intervals and also projections with TFR levels 1/2 birth above the median level and 1/2 birth below the median level. These projections (which we label as high, median, and low) will be used in this review.

In the last decade, a European group of scientists at several institutions produced population projections as well. In addition to using available data, this group relied on expert opinion to develop future trends. Their projection method has added girls' level

[5] Two children per woman replaces the generation but replacement fertility is technically taken as 2.1 since some births do not survive to reproductive age.

[6] Unless otherwise specified, all population and fertility numbers given in the text are drawn from data (estimates and projections) released by the UNPD in 2022 (United Nations Population Division, 2023).

[7] It is noteworthy that all the United Nations projections use the same downward trend in mortality (United Nations Population Division, 2023). Except for major calamities, trends in fertility are far more important than trends in mortality for determining population forecasts.

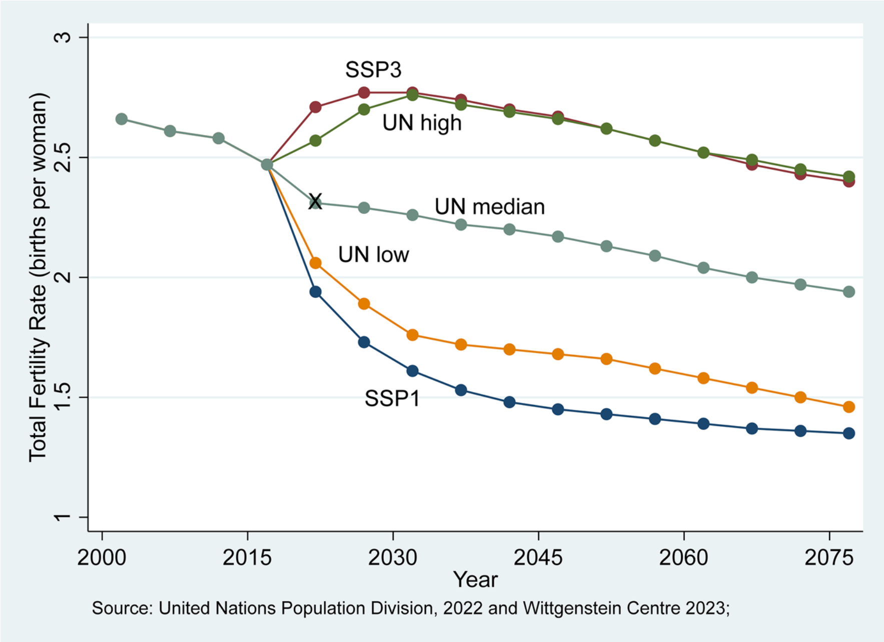

Fig. 2 TFRs for SSP1, SSP3, and UN high, low, and median projections to 2075

of schooling in addition to age and sex.[8] Demographers have long known that the most important socio-economic variable determining levels of fertility is women's schooling (Axinn & Barber, 2001; Lutz & Kc, 2011). Throughout the world, women with more schooling marry later, have lower fertility preferences, and use contraception at higher rates than women with less schooling (Liu & Raftery, 2020). The projections of this group (at the Wittgenstein Centre for Demography and Global Human Capital (WIC) and involving the International Institute for Applied Systems Analysis and the Vienna Institute of Demography) incorporate level of schooling in addition to age and sex and are labeled as Shared Socio-economic Pathways (SSPs) (Lutz et al., 2018). There is a story for each of the five SSPs (KC & Lutz, 2016; O'Neill et al., 2016; Riahi et al., 2017). For this review, we use the SSP1 with relatively low fertility and the SSP3 with relatively higher fertility (Wittgenstein Centre for Demographic Data, 2023). In addition, we compare these with low, high, and median projections of the UNPD. Figure 2 shows the trends of TFRs for these five projections. The SSP scenarios are also paired

[8] After they have estimated trends in fertility and mortality, both groups of demographers utilize the cohort-component method of population projection (Preston et al., 2001). This method uses the population for a given country by age and sex groups at time "t" together with fertility and mortality rates estimated for that time for the country to produce the population by age and sex at time "t+n" where n has typically been 5 years. (However, the UNPD is now using single year age groups and time intervals.) Then, also with a Bayesian approach (Azose & Raftery, 2015) estimated net numbers of immigrants (or emigrants) are added (or subtracted). Also, the European group added another dimension—education—to the model.

with different levels of GHG and mitigation. SSP1 and SSP3 are paired with "Representative Concentration Pathways" (RCPs) which predict how concentrations of GHG in the atmosphere will change by 2100 due to human activities. SSP1 is paired with an RCP of 2.6 which is 2.6 watts of radiative forcing per square meter on earth, relative to its value in the pre-industrial world, i.e., changes since that time. SSP3 is paired with an RCP of 8.5 (Intergovernmental Panel on Climate Change, 2014). The food system literature has used SSPs to project food security and undernourishment scenarios as well as how food supply policies or demand shifts could impact these different scenarios and outcomes (Fujimori et al., 2019; Hasegawa et al., 2018; Intergovernmental Panel on Climate Change, 2019; Van Dijk et al., 2021).

Given that all humans need to eat to survive, one might think that projections of food demand would be straightforward given a population forecast. However, there are multiple complicating factors. First, there are limits to the amount of new land that can be devoted to food production. It is estimated that more than 40% of arable land on the planet is already under cultivation (Fig. 3) and the choice is to sustainably intensify or less optimally, extensively into new lands, some being pristine naturescapes (Willett et al., 2019). Similarly, there are limits to the amount of food that can be harvested from oceans. The Food and Agriculture Organization (FAO) has estimated that 35% of wild fish species are already fished beyond sustainable levels (FAO, 2022). The entirety of blue foods—animals, plants, and algae harvested from freshwater and marine environments—supply protein to over 3.2 billion people, are a key source of nutrients in many coastal, rural, and indigenous communities, and support the livelihoods of over 800 million people (Golden et al., 2021). These foods provide many nutrients for human nutrition but are under tremendous pressure from an environmental perspective (Gephart et al., 2021). Because blue foods are the highest traded commodity, the demand for these foods with a growing population also rises, further straining this resource.

A second important factor that complicates food supply and demand projections is changes in food preferences. In nations where per capita income has increased, there is

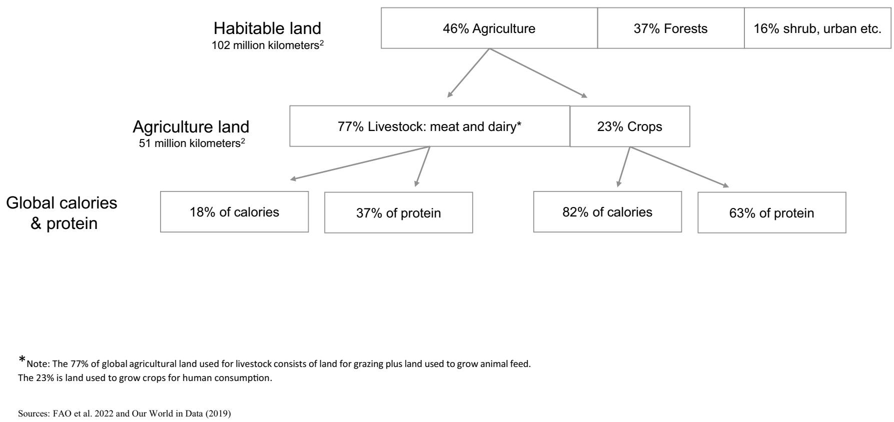

Fig. 3 Habitable land use in the world and calorie and protein from two agricultural land uses (square kilometers and percentages)

increasing demand for more animal-sourced foods (ASF) (Herrero & Thornton, 2013). Figure 4 shows projections of the food production of various ASF to 2050 using a 2012 medium population projection, with significant variations regionally and sub-nationally depending on agroecosystems, culture and traditions, and food environments (Beal et al., 2023). Livestock raised for beef is responsible for 6% of total GHG emissions largely in the form of methane (Crippa et al., 2021). Clearing land for livestock production is also the number one driver of deforestation around the world, reducing the chances for large forest biomes to serve as carbon sinks. Of the 46% of arable land used to grow food, 77% of that land is used for livestock, which only provide 18% of total calories and 37% of protein consumed (Fig. 3) (FAOSTAT, 2023; Poore & Nemecek, 2018). This is one reason for the massive deforestation in the Amazon basin—to produce beef for export or to grow soy to be used for cattle feed (Nepstad et al., 2014). Figure 5 shows a linear extrapolation of deforestation in the Amazon. It has been shown that three quarters of the Amazon rainforest has been losing resilience so a decline greater than linear is a most likely scenario (Boulton et al., 2022).

A third factor that impacts food projections is global warming. The world has already warmed 1.1 °C above pre-industrial levels, impacting the ability to grow food. Global warming puts the quantity, quality, stability, and safety of the global food supply at risk (Intergovernmental Panel on Climate Change, 2023). Increasing surface temperatures, accumulating atmospheric CO2, rising sea levels, and changing weather patterns and less predictable extreme weather events all affect food supply chains (Myers et al., 2017).

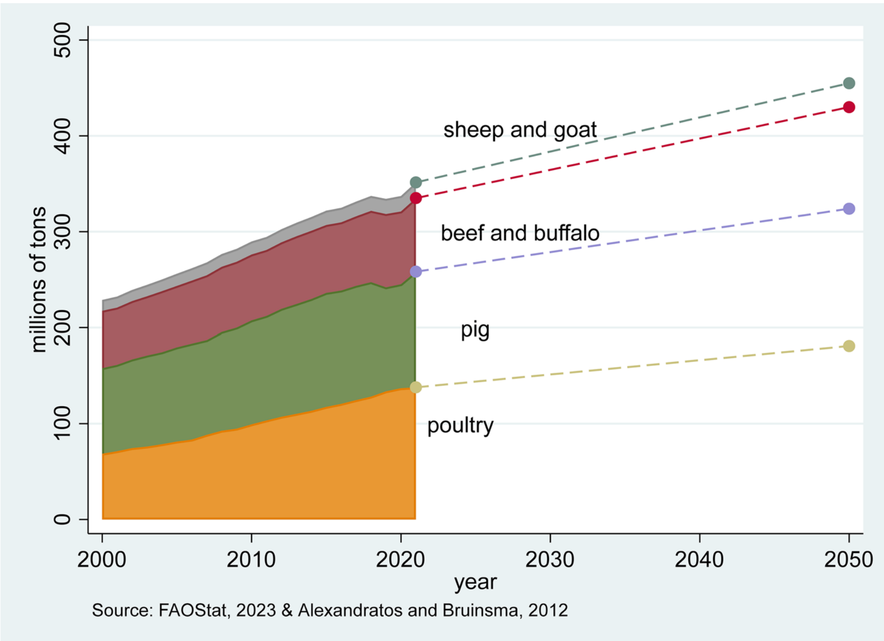

Fig. 4 World meat production 2000–2021 and projections to 2050 by type of meat

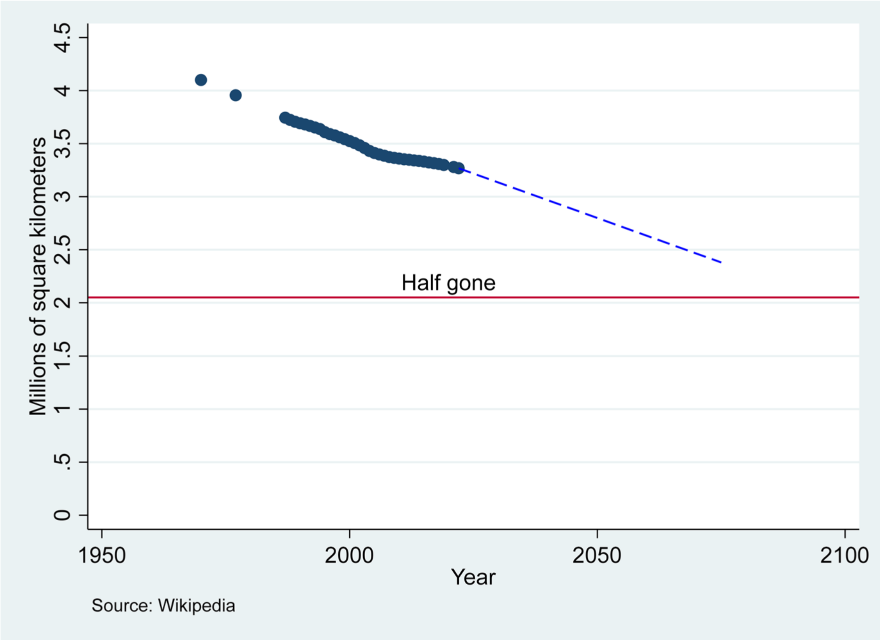

Fig. 5 Estimates of square kilometers of remaining Amazon forest cover by year from 1970 and linear extrapolation to 2075

A fourth factor is how we raise food. The global food system contributes approximately 30% of all GHG (Crippa et al., 2021), and significant environmental degradation (Willett et al., 2019). Of all GHG from food systems, 80–86% come from agriculture, with the remaining emissions coming from downstream food chain actions including food processing, packaging, transportation, and retail (Crippa et al., 2021). Expanding agricultural land use is a major contributor to rising CO2 levels in the atmosphere, declines in freshwater resources and draining of wetlands, and biodiversity loss due to deforestation (Tilman et al., 2017).

Agriculture is designed in such a way that it utilizes only a fraction of the biodiversity readily available on the planet. Over 5500 species are on offer for food but 50% of the world's calories for humans come from just 3 staple crops—wheat, rice, and maize. This puts food systems at significant climate and nutritional risk (Saladino, 2022). Modern agriculture has been designed to be astonishingly efficient using various inputs (e.g., mechanization, fertilizers, pesticides, and herbicides) through monocropping systems that can be scaled to produce a large quantity of crops, feeding many people (Pingali, 2012). While this system has generated sufficient calories in the system, there are concerns about the nutritional diversity of these crops, over extensification into natural biomes (e.g., forest landscapes), and environmental concerns in the ways these foods are grown (Berners-Lee et al., 2018; Nelson et al., 2018).

With increased global warming and food insecurity, as well as poor progress in addressing multiple forms of malnutrition (including undernourishment, stunting, wasting and overweight/obesity), there are recurring debates about whether global food systems can sustainably provide enough nourishing food to feed a growing world population (FAO et al., 2022; Barrett, 2022; Webb et al., 2020; GNR: Global Nutrition Report, 2022). A grand global challenge is how to transform food systems so that they provide nourishment for the worlds' population in a way that is environmentally sustainable, generates nutritious, safe foods for everyone's dietary needs, and is equitable (Fanzo et al., 2021). Policy, technology, and human ingenuity have largely staved off massive famines in the last half century (Byerlee & Fanzo, 2019; Barrett, 2020), but with the lack of concerted action on mitigating global warming, geopolitical fractures, and the growing inequities, this task is all the more daunting, resulting in what is now being called a "polycrisis" (World Economic Forum, 2023).

Recently, there has also been increased recognition that food systems are susceptible to disturbance and shocks (Cottrell et al., 2019). While shocks to food systems can include natural disasters, pandemics, economic instability, and political or social unrest, shocks can also include environmental stressors that push beyond the boundaries of the system. The COVID-19 pandemic demonstrated the fragility of certain parts of current food systems and underscored the interconnectedness of each component of the system (Barrett et al., 2020). In 2022 into 2023, we have seen the impacts of war between two breadbasket countries (Ukraine and the Russian Federation), rising food prices, an ongoing pandemic, and extreme weather events (Hendriks et al., 2022). The poorest and most vulnerable are and will continue to be disproportionately impacted by high food prices stemming not only from the war, but market uncertainties as a result of a multitude of shocks (Behnassi, M., & El Haiba et al., 2022; Abayalso et al., 2023).

Stormy future trajectory

High population growth

Under the high population projection of the UNPD and the SSP3 of WIC, fertility declines slowly so population continues to increase quite rapidly to reach 10.3 (SSP3) or 10.5 (UN) billion by 2050 and 12.0 (SSP3) or 12.6 (UN) billion by 2075 (see the upper two lines of Fig. 6). SSP3 is characterized by regional rivalry, slow economic growth, and low priority for environmental and social goals (Riahi et al., 2017). With regard to GHG emissions and global warming, under this scenario, CO2 emissions roughly double by 2100. The Intergovernmental Panel on Climate Change (IPCC) estimates that this increase in emissions will lead to warming of about 4 °C by 2100. This level of warming could prove catastrophic for ecosystems and humans. Specifically, extreme weather events will be much more numerous and some places on the planet will become uninhabitable. As living conditions worsen in places greatly affected by global warming, people will migrate. Efforts have been made to predict international migration flows resulting from global warming (Rikani, Frieler & Schewe, 2022). However, other than low island nations (e.g., Vanuatu and Tuvalu) and nations with millions of people living in low-lying areas (e.g. Bangladesh), other specific countries affected and the scale of emigration as distinguished from internal migration are largely unknowable. However, it is clear that global warming affects the middle latitudes the

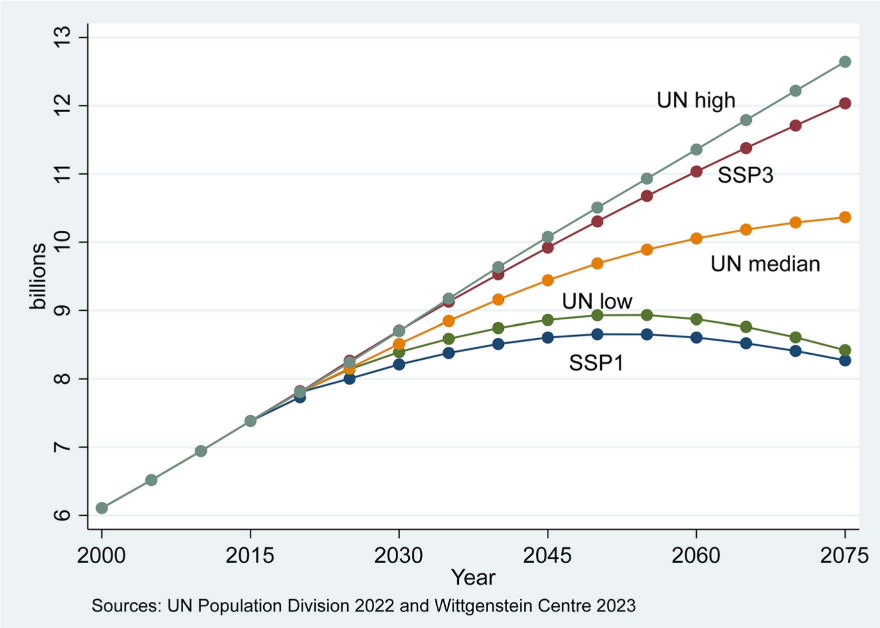

Fig. 6 Selected United Nations and Shared Socioeconomic Pathways (SSPs) population projections to 2075

most and therefore movement will be toward more northern climes and more developed regions, specifically countries of North America and Europe (including Russia). Estimates of flows of international migration during the last several decades have been done (e.g., Abel & Sander, 2014; Azose & Raftery, 2015) and UNDP and WIC incorporate net migration in their projections. But based on data from prior years, clearly past projections have been considerably off for countries like Syria and Ukraine.

Increases in mortality can also be expected. Estimates of excess deaths due to given levels of warming have been made. One estimate from a systems dynamics model with 180 equations and parameters and using a more optimistic scenario (SSP2) is 800,000 excess deaths per year in 2050 compared to model outputs with no global warming effects. But incorporating additional deaths due to economic damage raises the estimate to 4–5 million per year (Homer, 2020). Another estimate using a completely different model is in the same range—4.6 million excess yearly deaths by the end of the century compared to United Nations projections which do not take account of global warming (Bressler, 2021).

Other authors have concluded that, unless drastic measures are taken, we are headed for global collapse before or by midcentury (Kareiva & Carranza, 2018; Ripple et al., 2021). Collapses of earlier local populations have been documented (Diamond, 2011; Brozovic, 2023). In 1798, Thomas Malthus predicted that when a population exceeds the supply of food necessary for its survival, then there will be increases in mortality due to war, pestilence, and famine. Despite no shortage of food on a global level in the aggregate presently, all three checks are more likely under this trajectory. We now consider two of the three checks—war and pestilence. It should be noted that the timing, location, and magnitude of occurrences of war and pestilence are nearly impossible to predict. Famine is considered in the next subsection.

Higher levels of mortality from conflicts over resources are likely in this trajectory. For example, fresh water will become scarcer in several regions. Currently, there are rising tensions between Ethiopia and Egypt over the former's construction of a huge dam on the Nile River (Mersle, 2020). Also, Pakistan and India, both with nuclear weapons, have several times been at the brink of war. The possibility of a direct confrontation, even if by accident, between Russia and the USA in Ukraine is ever present and could lead to a nuclear war. Similarly, tensions are rising between the USA and China. The Doomsday clock of the Bulletin of Atomic Scientists (2023) is 90 s to midnight; it estimates the assessed risk of global catastrophe. This is the closest it has ever been to midnight. It has been estimated that a nuclear attack on US or Russian cities with 100 1-megaton bombs (for comparison, the Hiroshima bomb was 15 kilotons of TNT equivalent) would result in about 70 million deaths (Leaf, 1986).

Conflicts, as well as extreme weather events, including hurricanes, exceptional heat, droughts, and flooding may cause massive movement of persons within and across national borders. The war in Syria has been linked to the poor response of the government to the droughts there (Linke and Reuther, 2021); approximately seven million Syrians left the country and are refugees mainly in Turkiye (United Nations High Commissioner for Refugees (UNHCR), 2023). The current conflict in Ukraine has also led to huge numbers of displaced persons, with an estimated 5.7 million Ukrainians outside of the country (UNHCR, 2023). If no action is taken to address global warming, the world will witness more of both internally displaced people and refugees (Intergovernmental Panel on Climate Change, 2023).

Pestilence will rise: It is estimated that HIV/AIDS took the lives of 36 million persons between 1980 and 2020 (WHO, 2022). A recent estimate of excess deaths due to the COVID-19 pandemic for the period 2020 to 2021 using World Health Organization data is 14.8 million with an uncertainty interval of 13.2 to 16.6 million (Msemburi et al., 2023). The probability of future pandemics is raised considerably in this trajectory due to increased population density, destruction of wild habitats, and sped-up global warming (Intergovernmental Panel on Climate Change, 2022). An estimate of case fatality of the Delta variant of COVID-19 from meta-analyses mainly of data from hospital cases early in the pandemic was 10% (Alimohamadi et al., 2021). However, the case fatality with the Omicron variant and with treatment interventions has been considerably lower. Thus, a current overall estimate of known deaths to known cases since the beginning of the pandemic is 1% and for a recent 28-day period is 0.7% (Johns Hopkins University Coronavirus Resource Center, 2023). Unfortunately, cases and associated deaths in many middle- and low-income countries are seriously under-reported. The levels of transmissibility and case fatality of the next pandemic are obviously unknown. There is also a serious concern about future pandemics because of the rise of antimicrobial-resistant pathogens as well as the shrinkage or destruction of natural habitats so wildlife is forced to migrate which puts them in closer proximity to humans and domesticated animals, increasing the risk of future zoonotic spillover events (Rusic et al. 2021).

Table 1 Authors who have published estimates of sustainable human population size with brief listing of key model parameters used and possible reasons the estimate could be wrong

Author(s)/year	Key model parameters	Estimate (in billions)	Possible reason(s) estimate could be wrong
Daily et al. (1994)	Sustainable energy consumption (6 TW); 3 kW per capita (now at 12 kW in USA)	2	New energy sources (fusion, fission….)
Ferguson (2005)	Max gigatons of CO2 that can be absorbed; 4.2 tons per person per year	2.1	Negative emissions technologies
Pimentel et al. (2010)	Land needed to provide food (0.5 ha per capita)	2	Hydroponics, more intensive cultivation, vegetarian diets
Lianos and Pseiridis (2016)	Ecological footprint-biocapacity ratio	3	Uses per capita product of $11,000; world production (maximum sustainable) is ROUGH estimate
DasGupta et al. (2021)	Trends in GDP and stock and use of natural capital	3.3	Assumes GDP per capita of $20,000; at $12,000, the estimate is 9 billion (2011 prices)

More concerning, in the peer-reviewed literature over the last 30 years, there have been five groups of ecologists who have independently estimated the maximum sustainable population size for the planet (Daily et al., 1994; DasGupta et al., 2021; Ferguson, 2005; Lianos & Pseiridis, 2016; Pimentel et al., 2010). All the estimates are between 2.0 and 3.3 billion. Table 1 shows these estimates and the basic ingredients of the models used to estimate the sustainable population size.[9] It is clear from these ecological analyses that the human population is in overshoot, i.e., we are effectively living on the "principal" of the planet to use a banking analogy. In short, our current level of extraction of resources cannot continue indefinitely (e.g., fossil fuels and rare minerals are non-renewable). This is one reason why the estimates in Table 1 are so far below the current population size of 8 billion. The last column of the table gives possible reasons why the estimates could be too low. Malthusian limits have been proved wrong repeatedly in the past so that could happen again if new technologies like fusion energy allow for a sustainable population above 4 billion. (see the "The brighter future trajectory")

But unfortunately, there are planetary boundaries which when passed can lead to major instability. A rise of 2 °C above pre-warming levels constitutes one of these boundaries and past that level, the positive feedbacks will lead to disasters (Rockstrom et al. 2009). It has been recently argued that we are at risk of passing

[9] Note that sustainable population size is clearly less than maximum size.

multiple climate tipping points and urgent action is needed to avoid dangerous futures (McKay et al., 2022). Two examples of positive feedbacks are (1) the melting of permafrost (e.g., in Alaska) which releases huge quantities of methane, leading to further warming (Elder et al., 2021); (2) melting Arctic ice leads to increased warming as open water absorbs much more sunlight and thus heat, than does ice (Knudsen et al., 2015).

Stormy future food security

Because optimal food production requires specific conditions (for example, certain crops may only thrive in a narrow band of temperatures), disruptions to environmental and climatic conditions along with extreme weather events will negatively impact crop yields, the nutrient content of crops, and the broader ecosystems that support food production (Clark et al., 2019; Springmann et al., 2018; Willett et al., 2019). Models suggest that maize, soy, and rice yields will decline with more CO2 in the atmosphere, particularly across the lower latitudes of the planet (Jägermeyr et al., 2021). In addition to affecting the quantity of food, rising atmospheric CO2 levels may also diminish the quality of food; certain staple crops such as rice and wheat are projected to have decreased protein, iron, and zinc content when grown under high CO2 conditions (Myers et al., 2014; Smith et al., 2018).

In this stormy future, many countries, particularly in sub-Saharan Africa, will continue to rely on food assistance to meet their basic caloric needs (Cohen, 2019; Haddad et al., 2016). The food security outlook in East Africa is dire. Prices of food are spiking worldwide (due to the shadow of COVID-19, the Ukraine-Russia conflict, and climate-related extreme weather events), undernourishment is rising, and child and maternal undernutrition are stagnant or worsening after some years of progress (GNR: Global Nutrition Report, 2022; Van Dijk et al., 2021). Globally, FAO data show that the food price index for 2022 was 14% above its level for 2021 and 46% above its level for 2020 (FAO, 2023). This is in an environment where already 3.3 billion people cannot afford what is considered a healthy diet (Herforth et al., 2020). Also, FAO and others (2022) estimate that 9.3% of the world population is undernourished and 2.3 billion people are moderately or severely food insecure.

Countries with inadequate agricultural production to feed their growing populations but which have adequate other resources (i.e., from mining or agriculture commodities for export (e.g., palm oil from Indonesia)) to buy food with foreign exchange are in a better situation than those countries which do not (DeFries et al., 2015; Remans et al., 2014; Wood et al., 2018).[10] As the world's population continues to rise in this trajectory, food hoarding, export bans, and protectionism will put countries which are reliant on food imports for most of their food basket at serious risk (Barrett, 2020).

[10] Maurice King and co-authors (1995) defined a population as demographically trapped if "it has exceeded or is projected to exceed the combination of 1) the carrying capacity of its own ecosystem, b) its ability to obtain products, and particularly food, produced by other ecosystems except as food aid, and c) its ability to migrate to other ecosystems in a manner which preserves (or improves) its standard of living (up-migration)."

Famines have occurred throughout human history (World Atlas, 2022). In China, and South Asia, millions have died from famines. In East Africa, prolonged droughts have been devastating for the agricultural and pastoralist sectors. As nations impose restrictions on exports of foodstuffs, the food situation in would-be receiving nations will deteriorate (Ives, 2022). The escape valve for such countries in this situation has been emigration. However, as thousands and thousands of economic and environmental refugees add to the 29.4 million current refugees (UNHCR, 2023), neighboring countries and developed countries are closing their borders (Piguet, 2021).

The brighter future trajectory

Toward population stabilization

In this trajectory, fertility declines rapidly in countries where fertility is now considerably above replacement and the world population would only be 8.3 to 8.4 billion in 2075 (SSP1 scenario of WIC and UN low fertility scenario respectively). In SSP1, “educational and health investments accelerate the demographic transition” (Riahi et al., 2017). For example, Nigeria which had a TFR of 4.9 in 2022 would have a level of 2.5 in 2050 and 1.7 in 2075 under the UN low projection. These declines could be driven in good part by increases in girls schooling. With more schooling, young women marry and begin childbearing later. Also very important is the small family norm, in particular the one-child family. As noted above, the two-child family would lead to continued population increase for many decades due to population momentum. Aside from China which had coercive policies, two countries that have undergone rapid fertility transitions and now have near or below replacement fertility are Thailand and Iran. In Iran, fertility declined from 4.0 to 2.0 in only 8 years. Incentives for small families will be needed in some places.

Lower population growth increases the chances that nations can focus on lowering levels of poverty. For a country such as India, providing for its current population of 1.41 billion is easier than providing for a population of 1.68 billion expected in 2075 under the UN median projection. But under the low fertility projection, it is estimated that India will only have a population of 1.35 billion in that year. Given the expected increases in extreme heat and drought in India (Gupta et al., 2020), this decline in population would ease pressure on food systems.

Slower population growth also allows countries to spend more resources on health care so mortality from infectious and chronic diseases can be reduced and life expectancy increased. Of course, with low fertility, populations necessarily have a period of population ageing. Many authors have given proposals for accommodating an older population on average, including increasing the age of retirement (Lewis, 2005; Rozen-Bakher, 2020). Finally, lower population growth allows countries to preserve natural resources, in particular forests and species; clearing of forests for agricultural production can be minimized if population is not increasing since *ceteris paribus* less additional land is needed for agriculture.

In the final report of the International Conference on Population and Development in Cairo in 1994, the chapter "Reproductive Rights and Reproductive Health" has the following text "…recognition of the basic right of all couples and individuals to decide freely and responsibly the number, spacing and timing of their children…" (United Nations Fund for Population Activities, 2004). Most organizations working in reproductive health focus on "freely." But population scientists who know that the current level of fertility in some countries is not sustainable often need to remind policymakers of the "responsibly" part. Whether we admit it or not, reproduction is in the commons (Hardin, 1968). Thus, there are choices at both the individual and the societal level and social institutions need to guide those choices more than they have in the recent past.

Individual or couple level: Even with fertility falling rapidly to 1.6 births per woman worldwide in this trajectory, the population in 2075 is still higher than at present due to population momentum. Therefore, with the small family norm, most women and couples would willingly choose to have one child or no children. Those who chose none may wish to adopt.

Societal level: Nearly all governments of low- and middle-income countries with above replacement fertility have population policies which seek to lower population growth rates. Voluntary family planning is the means to this end, but demand has been low in most countries of sub-Saharan Africa where desired family size is considerably above 2; in fact, Bongaarts (2020) estimated that the average level of wanted fertility in 25 SSA countries was 4.4 children. Clearly governments and non-governmental organizations need to encourage the small family norm. The United Nations reports that governments of 69 nations have policies to reduce fertility, either by raising the age at first marriage or union formation, by raising the age at first birth for women, or by increasing the duration between births (United Nations Department of Economic and Social Affairs, 2021). Research has shown that dramas provide a very cost-effective way to change reproductive behavior—telenovelas have been used in many countries in this effort (Population Media Center, 2023).

One solution to the problem of rapid population growth that is often cited is the education of girls (Shapiro, 2012). As noted above, education gives women alternatives to early marriage and childbearing, and it is obviously a societal good in its own right. However, its effect on population growth is delayed in time. On the other hand, expansion of contraceptive programs can lead to fertility declines in the near term. Contraceptive services must be made available to entire national populations either without cost or at minimal cost. Developed countries need to increase assistance for contraceptive programs in developing countries. This will bring the unintended and unwanted pregnancy rates down.

Another way to slow population growth is to increase the length of the generation. A simple example illustrates the point. If women in two populations both have an average of three children with the same inter-birth intervals, but in the first population, women have their first birth at age 15 while in the second they have their first birth at age 30, the former population will grow about twice as fast as the latter. This is true even though in both, women are having 3 births. China included this aspect in its "Longer, later, fewer" family planning messaging.

Brighter future food security

There are various pathways to ensure that food systems could feed a world of 8.4 billion in 2075 if the world can shift to this trajectory. With lower population, food systems could potentially provide healthy diets and feed the world in environmentally sustainable ways. Some pathways will involve doing agriculture differently and managing land in innovative ways that benefit nature, some will involve helping consumers access healthy diets, and others will ensure that vulnerable populations are cared for and protected.

Many of the socio-technical solutions for the food system being tested and developed currently could be important to mitigate and adapt to global warming (Barrett et al., 2020). By not over-taxing the global food system to push out more calories to feed 10 to 12 billion people, agricultural systems could move toward systems that are more diverse in the types of foods grown, and not extensify into forest landscapes that are vital for biodiversity and that act as carbon sinks (Willett et al., 2019). With fewer mouths to feed, some efficiency could be sacrificed for more resilience in agriculture, for example, agroecology approaches (Bezner Kerr et al., 2021; Struik & Kuyper, 2017).

To encourage farmers to shift from monocropping that efficiently produces loads of calories to feed the masses, toward more diverse and resilient landscapes, countries could redesign agricultural subsidy policies toward fruits, vegetables, nuts and legumes, and other nutritious foods. A recent study suggests that if half of all agricultural subsidies worldwide were repurposed to support the growing of foods that benefit human health as well as the environment, it could increase the cultivation of fruits and vegetables by as much as 20% and reduce greenhouse-gas emissions from agriculture by 2% (Springmann & Freund, 2022).

There are a range of available technologies to protect crops against extreme weather events, increase potential yields of crop commodities, and improve the nutritional quality of crops including genetically modified organisms (GMOs), Crispr technology, and biofortification (Glass & Fanzo, 2017; Kim & Kim, 2016; Shew et al., 2018). GMOs and Crispr technology are being used to make crops drought-tolerant or wind-resistant with sustained or increased yields (Abdallah et al., 2021). There is technology to artificially create photosynthesis of certain crops to grow in the dark (Hann et al., 2022). Biofortification is the process of increasing the density of vitamins and minerals in a crop through plant breeding or agronomic practices. It is a cost-effective and sustainable means of providing more micronutrients in the food basket of the poor who have insufficient access to a high-quality and diverse diet (Bouis & Saltzman, 2017; Bouis et al., 2011). Vertical agriculture in urban areas has potential that needs to be further explored.

Agriculture can move toward net zero carbon emissions with significant reductions in methane from livestock and other systems and nitrous oxide emissions from chemical fertilizers (Reay, 2020). Certain practices could be adopted such as improving soil care, carbon concentration, and sequestration, reducing nutrient leakage from fields, utilizing low input organic systems and renewable energies as a replacement for fossil fuel to heat greenhouses, and enhancing the efficiency of crop water use and drip irrigation (Springmann et al., 2018). Carbon sequestration in agricultural soils and above ground could be increased significantly and practices such as conservation tillage or riparian buffers can help limit greenhouse gas emissions. Moreover, feed additives and feed reformulation for livestock also show promise for lowering emissions (Górniak et al., 2022). Instituting technologies and behaviors that minimize food loss and waste are also critical (Bajželj et al., 2014; Global Panel on Agriculture & Food Systems for Nutrition, 2018).

This brighter future trajectory requires considerable changes. Some individuals, communities, and countries will need to decrease their environmentally intensive meat consumption, while others, which do not get enough access to animal-sourced foods, could afford to increase their intake to meet nutritional needs (Bai et al., 2022; Laborde et al., 2021). A modeling study suggests that if the world can move more toward the SSP1 scenario, global food security would improve, with a marked decrease in populations at risk of hunger (Sulser et al., 2021). In a SSP1-RCP 2.6 scenario, roughly 282 million people would be undernourished in 2050 whereas in a SSP3-RCP 8.5, 916 million would be undernourished, with South Asia and sub-Saharan Africa disproportionately suffering (Table 2).

There are ways to encourage those who over-consume meat to eat less of it. To address the high demand for ASF, some tech companies have come up with a solution —alternative proteins—which include lab-grown meat, plant-based meat, and single-cell proteins from yeast or algae (Sexton et al., 2019). The lab- and plant-based innovations mimic the taste, smell, and texture of meat and would lessen the need for people to raise and consume animals. To ensure these foods are accessible and acceptable to people all over the world, their production will have to be scaled in massive and affordable ways for everyone.

Countries on a trajectory to reduce their undernutrition burden should not fall into the same trap as high-income countries with significant burdens of obesity and diet-related non-communicable diseases, also known as the nutrition transition (Popkin et al., 2020). Innovations along the supply chain and within food environments including taxes on unhealthy foods and beverages, subsidy to increase the

Table 2 Millions of persons projected to experience hunger* in SSP1 and SSP3 scenarios in 2050

Region	SSP1-RCP 2.6	SSP3-RCP8.5
East Asia and Pacific	80.0	141.2
Europe	5.9	6.1
Former Soviet Union	4.4	7.5
Latin America and Caribbean	15.9	48.4
Middle East and North Africa	26.9	50.5
North America	3.8	3.1
South Asia	67.9	271.6
Sub-Saharan Africa	78.0	388.1
World	**282.8**	**916.4**

*Definition of hunger used is FAO's prevalence of undernutrition (POU) also called hunger production and sale of healthy foods, and front-of-pack labeling that increases transparency of the nutritional content of foods, their source, and their environmental footprints for consumers (An et al., 2021; Popkin et al., 2021) are all being tested and tried in food environments around the world (Caro et al., 2020; Fanzo & Davis, 2021; Niebylski et al., 2015; Popkin et al., 2021).

While populations will stabilize in this trajectory, there remains a need for governments to undertake grand food systems transformation (Intergovernmental Panel on Climate Change, 2019). Currently, food systems are constrained, are vulnerable to shocks, and are not achieving the desired outcomes of delivering healthy diets and contributing to environmental sustainability.

Conclusion

Scientists who study planetary health are clear that decisions made in this decade with regard to fossil fuel emissions, population policies, and food systems will determine whether the world in the decades ahead is closer to the stormy or to the brighter future trajectory illustrated in this paper (Ripple et al., 2021). Because there is no global government that can direct the changes that are needed, countries must work together to bring about these changes. The UN convenes government leaders to encourage countries to agree to lower GHG and to convert to renewable energy sooner rather than later. Yet the world is lagging behind in the emission targets made at the Paris Climate Summit in 2015 (United Nations Framework Convention on Climate Change (UNFCCC), 2016); the latest Intergovernmental Panel on Climate Change (IPCC) report shows net GHG have not declined in recent years and unless declines begin soon or there are major breakthroughs in mitigation, then warming above 2 degrees centigrade this century is very likely (Intergovernmental Panel on Climate Change, 2023). There are a range of policies, innovations, and incentives that need to be put in place to ensure food systems can transform in positive ways.

While some of the solutions proposed are critical for both trajectories, in a brighter future, SSP1 type scenario, the demographic, political, economic, and social environments would more easily facilitate and prioritize food-based climate-positive solutions. However, if no action is taken on changing food systems such as sustainable agriculture practices, dietary changes, and reducing food waste, the world will not meet the Paris climate targets (Clark et al., 2020). On population, similarly, the UN can sponsor conferences and its demographers and those of the European group can project rapid fertility declines as described herein, but governments need to prioritize family planning programs and find the means to fund them.

With regard to fertility, the estimate for 2022 at the world level (TFR of 2.31; see X in Fig. 2) is close to neither the high UNPD (or SSP3) lines nor to the low estimates of the two groups. It remains to be seen if there will be a rebound in fertility post-COVID taking it toward the high trajectory or if fertility will further decline due to the relatively poor current economic situation in many countries.

The brighter future projections with rapid declines of fertility to replacement levels do not bring world population size down below its present level of 8.0 billion by 2075.[11] To realize this future, nations, particularly those in Sub-Saharan Africa, need to put greater emphasis on family planning programs. Furthermore, efforts are needed to encourage the small family norm, particularly the one-child family.

Both climate scientists, including the IPCC, and researchers who study food systems typically take as given the population projections to 2050 and even to 2100. However, those projections are simply based on extrapolations of current trends. Extrapolation of trends of fertility and mortality does not consider the possibility of abrupt changes which could occur as global warming negatively affects more and more people on the planet and tipping points in global ecosystems are passed. More generally, they do not consider feedback mechanisms between population, climate, and food production. A recent review article on the role of population science in research on the environment (Muttarak, 2021) argues forcefully that climate impacts on population need to be given greater consideration.

The present world has been built on fossil fuels and converting all sectors to renewable energy will require an unprecedented effort; some have drawn parallels to the shift in the British and US economies and sacrifices that were necessary to triumph in World War II. Both food systems researchers and climate scientists need to involve demographers more in their interdisciplinary teams when modeling future scenarios. The current business as usual leads to the stormy future trajectory in which food systems will struggle to feed the population. Inadequate action on global warming, military conflicts, and other grand challenges exacerbate a taxed global food system further. There are already cracks in the current operationalization of food systems, and their ability to provide healthy diets for everyone in environmentally sustainable ways is questionable. The brighter future trajectory is one that could ensure food system sustainability and resilience if the actions and behavior changes outlined here are instituted.

Acknowledgements Staff of Johns Hopkins libraries assisted with securing some references and Fannie Fonseca-Becker assisted with checking of reference citations. We also thank the reviewers for their very helpful suggestions on earlier versions of the manuscript.

Author contributions Stan Becker drafted the population sections. Jessica Fanzo drafted the food sections. Both worked on tables, figures, and references as well as the "Introduction" and "Conclusion" sections and approved the final version of the text

Data availability This is a review paper so all of the population and food data used in the paper are from the peer-reviewed literature or are publicly available (e.g., the United Nations and Wittgenstein for population data and FAO for food data).

[11] Therefore, the sustainable population size of 2–4 billion cannot be achieved in the foreseeable future with these trajectories. An alternative is the one-child family norm, but aside from the coercive program in China, there is no country that provides an example for this level of fertility, though some European countries do come close (Spain and Italy both have TFR values of 1.3.) Though it has been recommended before (King et al., 1995), adoption of the one-child family norm in Africa is clearly not feasible at this point.

References

Abdallah, N. A., Hamwieh, A., Radwan, K., Fouad, N., & Prakash, C. (2021). Genome editing techniques in plants: A comprehensive review and future prospects toward zero hunger. *GM Crops & Food, 12*(2), 601–615. https://doi.org/10.1080/21645698.2021.2021724

Abayalso, K. A., Breisinger, C., Glauber, J., Kurdi, S., Laborde, D., & Siddig, K. (2023). The Russia-Ukraine war: Implications for global and regional food security and potential policy responses. *Global Food Security*, *36*, 100675. https://doi.org/10.1016/j.gfs.2023.100675

Abel, G. J., & Sander, N. (2014). Quantifying global international migration flows. *Science, 343*(6178), 1520–1522.

Alimohamadi, Y., Tola, H. H., Abbasi-Ghahramanloo, A., Janani, M., & Sepandi, M. (2021). Case fatality rate of COVID-19: A systematic review and meta-analysis. *Journal of Preventive Medicine and Hygiene, 2021*(62), E311–E320. https://doi.org/10.15167/2421-4248/jpmh2021.62.2.1627

Alkema, L., Raftery, A. E., Gerland, P., Clark, S. J., Pelletier, F., Buettner, T., & Heilig, G. K. (2011). Probabilistic projections of the total fertility rate for all countries. *Demography, 48*(3), 815–839. https://doi.org/10.1007/S13524-011-0040-5

An, R., Shi, Y., Shen, J., Bullard, T., Liu, G., Yang, Q., Chen, N., & Cao, L. (2021). Effect of front-of-package nutrition labeling on food purchases: A systematic review. *Public Health, 191*, 59–67. https://doi.org/10.1016/j.puhe.2020.06.035

Axinn, W. G., & Barber, J. S. (2001). Mass education and fertility transition. *American Sociological Review, 66*(4), 481–505. https://doi.org/10.2307/3088919

Azose, J. J., & Raftery, A. E. (2015). Bayesian probabilistic projection of international migration. *Demography, 52*(5), 1627–1650. https://doi.org/10.1007/s13524-015-0415-0

Bai, Y., Herforth, A., & Masters, W. A. (2022). Global variation in the cost of a nutrient-adequate diet by population group: An observational study. *The Lancet. Planetary Health, 6*(1), e19–e28. https://doi.org/10.1016/S2542-5196(21)00285-0

Bajželj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi E., & Gilligan, C. A. (2014). Importance of food-demand management for climate mitigation. *Nature Climate Change, 4*. https://doi.org/10.1038/nclimate2353

Barrett, C. B. (2020). Actions now can curb food systems fallout from COVID-19. *Nature Food*. https://doi.org/10.1038/s43016-020-0085-y

Barrett, C. B. (2022). The global food crisis shouldn't have come as a surprise. *Foreign Affairs*. July 25.

Barrett, C. B., Benton, T. G., Cooper, K. A., Fanzo, J., Gandhi, R., Herrero, M., James, S., Kahn, M., Mason-D'Croz, D., Mathys, A., Nelson, R. J., Shen, J., Thornton, P., Bageant, E., Fan, S., Mude, A. G., Sibanda, L. M., & Wood, S. (2020). Bundling innovations to transform agri-food systems. *Nature Sustainability, 3*(12), 974–976. https://doi.org/10.1038/s41893-020-00661-8

Beal, T., Gardner, C. D., Herrero, M., Iannotti, L. L., Merbold, L., Nordhagen, S., & Mottet, A. (2023). Friend or foe? The role of animal-source foods in healthy and environmentally sustainable diets. *The Journal of Nutrition, 153*(2), 409–425. https://doi.org/10.1016/j.tjnut.2022.10.016

Behnassi, M., & El Haiba, M. (2022). Implications of the Russia-Ukraine war for global food security. *Nature Human Behaviour, 6*(6), 754–755. https://doi.org/10.1038/s41562-022-01391-x

Berners-Lee, M., Kennelly, C., Watson, R., & Hewitt, C. N. (2018). Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. *Elementa: Science of the Anthropocene*, *6*. https://doi.org/10.1525/elementa.310

Bezner Kerr, R., Madsen, S., Stüber, M., Liebert, J., Enloe, S., Borghino, N., Parros, P., Mutyambai, D. M., Prudhon, M., & Wezel, A. (2021). Can agroecology improve food security and nutrition? A review. *Global Food Security*, *29*(100540), 100540. https://doi.org/10.1016/j.gfs.2021.100540

Bongaarts. (2020). Trends in fertility and fertility preferences in sub-Saharan Africa: The roles of education and family planning programs. *Genus*, *76*(32). https://doi.org/10.1186/s41118-020-00098-z

Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. *Global Food Security, 12*, 49–58. https://doi.org/10.1177/15648265110321S105

Bouis, H. E., Hotz, C., McClafferty, B., Meenakshi, J. V., & Pfeiffer, W. H. (2011). Biofortification: A new tool to reduce micronutrient malnutrition. *Food and Nutrition Bulletin, 32*(1 Suppl), S31-40. https://doi.org/10.1016/j.gfs.2017.01.009

Boulton, C. A., Lenton, T. M., & Boers, N. (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s *Nature Climate Change, 12*(3), 271–278. https://doi.org/10.1038/s41558-022-01287-8

Bressler, R. D. (2021). The mortality cost of carbon. *Nature Communications, 12*, 4467. https://doi.org/10.1038/s41467-021-24487-w

Brozović, D. (2023) Societal collapse: A literature review. *Futures, 145*, 103075 https://doi.org/10.1016/j.futures.2022.103075

Bulletin of Atomic Scientists. (2023). 2023 Doomsday Clock Statement. A time of unprecedented danger: It is 90 seconds to midnight. Available at: https://thebulletin.org/doomsday-clock/current-time/

Byerlee, D., & Fanzo, J. (2019). The SDG of zero hunger 75 years on: Turning full circle on agriculture and nutrition. *Global Food Security, 21*, 52–59. https://doi.org/10.1016/j.gfs.2019.06.002

Caro, J. C., Valizadeh, P., Correa, A., Silva, A., & Ng, S. W. (2020). Combined fiscal policies to promote healthier diets: Effects on purchases and consumer welfare. *PLoS One, 15*(1), e0226731. https://doi.org/10.1371/journal.pone.0226731

Clark, M. A., Domingo, N. G. G., Colgan, K., Thakrar, S. K., Tilman, D., Lynch, J., Azevedo, I. L., & Hill, J. D. (2020). Global food system emissions could preclude achieving the 1.5° and 2 °C climate change targets. *Science* (New York, N.Y.)*, 370*(6517), 705–708. https://doi.org/10.1126/science.aba7357

Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences of the United States of America, 116*(46), 23357–23362. https://doi.org/10.1073/pnas.1906908116

Cohen, M. J. (2019). Let them eat promises: Global policy incoherence, unmet pledges, and misplaced priorities undercut progress on SDG 2. *Food Ethics, 4*(2), 175–187. https://doi.org/10.1007/s41055-019-0004-2

Cottrell, R. S., Nash, K. L., Halpern, B. S., Remenyi, T. A., Corney, S. P., Fleming, A., ... & Blanchard, J. L. (2019). Food production shocks across land and sea. *Nature Sustainability*, *2*(2), 130–137. https://doi.org/10.1038/s41893-018-0210-1

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food, 2*(3), 198–209. https://doi.org/10.1038/s43016-021-00225-9

Daily, G. C., Ehrlich, A. H., & Ehrlich, P. R. (1994). Optimum population size. *Population and Environment, 15*(6), 469–475. https://www.jstor.org/stable/27503368

Dasgupta, P., Dasgupta, A., & Barrett, S. (2021). Population, ecological footprint and the sustainable development goals. *Environmental and Resource Economics*. https://doi.org/10.1007/s10640-021-00595-5

DeFries, R., Fanzo, J., Remans, R., Palm, C., Wood, S., & Anderman, T. L. (2015). Metrics for land-scarce agriculture. *Science, 349*(6245), 238–240. https://doi.org/10.1126/science.aaa5766

Diamond, J. (2011). *Collapse* (2nd ed.). Penguin books.

Elder, C. D., Thompson, D. R., Thorpe, A. K., et al. (2021). Characterizing methane emission hotspots from thawing permafrost. *Global Biogeochemical Cycles, 35*(12), e2020. https://doi.org/10.1029/2020GB006922

Fanzo, J., Haddad, L., Schneider, K. R., Béné, C., Covic, N. M., Guarin, A., Herforth, A. W., Herrero, M., Sumaila, U. R., Aburto, N. J., Amuyunzu-Nyamongo, M., Barquera, S., Battersby, J., Beal, T., Bizzotto Molina, P., Brusset, E., Cafiero, C., Campeau, C., Caron, P., … & Rosero Moncayo, J. (2021). Viewpoint: Rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. *Food Policy*, *104*, 102163. https://doi.org/10.1016/j.foodpol.2021.102163

Fanzo, J., & Davis, C. (2021). Policies affecting food environments and consumer behavior. In J. Fanzo & C. Davis (Eds.), *Global food systems, diets, and nutrition: Linking science, economics, and policy* (pp. 131–152). Springer International Publishing.

FAO, IFAD, UNICEF, WFP, & WHO. (2022). The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO. https://doi.org/10.4060/cc0639en

FAO. (2022). State of the World Fisheries and Aquaculture in 2022. Available at: https://www.fao.org/3/cc0461en/online/sofia/2022/status-of-fishery-resources.html

FAO. (2023). Food Price Index. Available at: https://www.fao.org/worldfoodsituation/foodpricesindex/en/

FAOSTAT. (2023). Retrieved April 2, 2023, from https://www.fao.org/faostat/en/

Ferguson, A. R. B. (2005). Intractable limits to a sustainable human population. *Medicine, Conflict and Survival, 21*(2), 142–151. https://doi.org/10.1080/13623690500073463
Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B. L., ... & van Vuuren, D. (2019). A multi-model assessment of food security implications of climate change mitigation. *Nature Sustainability*, *2*(5), 386–396. https://doi.org/10.1038/s41893-019-0286-2
Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., & Troell, M. (2021). Environmental performance of blue foods. *Nature, 597*(7876), 360–365. https://doi.org/10.1038/s41586-021-03889-2
Glass, S., & Fanzo, J. (2017). Genetic modification technology for nutrition and improving diets: An ethical perspective. *Current Opinion in Biotechnology*. https://www.sciencedirect.com/science/article/pii/S0958166916302488
Global Panel on Agriculture and Food Systems for Nutrition. (2018). Preventing nutrient loss and waste across the food system: Policy actions for high-quality diets. Available at: https://www.glopan.org/wp-content/uploads/2019/06/GlopanFoodLossWastePolicyBrief.pdf
GNR: Global Nutrition Report. (2022). *Stronger commitments for greater action*. GNR. https://globalnutritionreport.org/reports/2022-global-nutrition-report/
Golden, C. D., Koehn, J. Z., Shepon, A., Passarelli, S., Free, C. M., Viana, D. F., Matthey, H., Eurich, J. G., Gephart, J. A., Fluet-Chouinard, E., Nyboer, E. A., Lynch, A. J., Kjellevold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K. M., … & Thilsted, S. H. (2021). Aquatic foods to nourish nations. *Nature*. https://doi.org/10.1038/s41586-021-03917-1
Górniak, W., Popiela, E., Szuba-Trznadel, A., Konkol, D., & Korczyński, M. (2022). Smart feed additives for livestock. In K. Chojnacka, & A. Saeid (Eds.), *Smart agrochemicals for sustainable agriculture* (pp. 103–138). https://doi.org/10.1016/B978-0-12-817036-6.00008-X
Gupta, V., ASCE, S.M., Jain, M. K, Singh, V. P., & ASCE, P. (2020). Multivariate modeling of projected drought frequency and hazard over India. *Journal of Hydrologic Engineering, 25*(4). https://doi.org/10.1061/(ASCE)HE.1943-5584.0001893
Haddad, L., Hawkes, C., Waage, J., Webb, P., Godfray, C., & Toulmin, C. (2016). Food systems and diets: Facing the challenges of the 21st century. Global Panel on Agriculture and Food Systems for Nutrition.
Hann, E. C., Overa, S., Harland-Dunaway, M., Narvaez, A. F., Le, D. N., Orozco-Cárdenas, M. L., Jiao, F., & Jinkerson, R. E. (2022). A hybrid inorganic–biological artificial photosynthesis system for energy-efficient food production. *Nature Food, 3*(6), 461–471. https://doi.org/10.1038/s43016-022-00530-
Hardin, G. (1968). Tragedy of the commons. *Science, 162*(3859), 1243–1248. http://www.jstor.org/stable/1724745
Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B. L., Doelman, J. C., ... & Witzke, P. (2018). Risk of increased food insecurity under stringent global climate change mitigation policy. *Nature Climate Change*, *8*(8), 699–703. https://doi.org/10.1038/s41558-018-0230-x
Hendriks, S. L., Montgomery, H., Benton, T., Badiane, O., de la Mata, G. C., Fanzo, J., ... & Soussana, J. F. (2022). Global environmental climate change, covid-19, and conflict threaten food security and nutrition. *bmj*, *378*. https://doi.org/10.1136/bmj-2022-071534
Herforth, A., Bai, Y., Venkat, A., Mahrt, K., Ebel, A., & Masters, W. A. (2020). *Cost and affordability of healthy diets across and within countries: Background paper for The State of Food Security and Nutrition in the World 2020. FAO Agricultural Development Economics Technical Study No. 9* (Vol. 9). Food & Agriculture Org.
Herrero, M., & Thornton, P. K. (2013). Livestock and global change: Emerging issues for sustainable food systems. *Proceedings of the National Academy of Sciences of the United States of America, 110*(52), 20878–20881. http://www.jstor.org/stable/23761824.
Homer, J. (2020). Modeling global loss of life from climate change through 2060. *System Dynamics Review, 36*(4), 523–535. https://doi.org/10.1002/sdr.1674
Intergovernmental Panel on Climate Change. (2014). AR5 future climate changes, risks and impacts. Available at: https://ar5-syr.ipcc.ch/topic_futurechanges.php
Intergovernmental Panel on Climate Change. (2019). Climate change and land. Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. [Internet]. IPCC; 2019. Available from: https://www.ipcc.ch/report/srccl/

Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Impacts, adaption and vulnerability–Summary for policymakers. Available at: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

Intergovernmental Panel on Climate Change. (2023) Synthesis Report of the IPCC Sixth Assessment Report (AR6). https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

Ives, M. (2022). Food export bans in Asia prompt fears of more protectionism. New York Times. June 10.

Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J. A., Fuchs, K., Guarin, J. R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A. K., Kelly, D., Khabarov, N., Lange, S., … & Rosenzweig, C. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, *2*(11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

Johns Hopkins University Coronavirus Resource Center. (2023). Retrieved February, 2023, from https://coronavirus.jhu.edu/

Kareiva, P., & Carranza, V. (2018). Existential risk due to ecosystem collapse: Nature strikes back. *Futures, 102*, 39–50. https://www.sciencedirect.com/science/article/abs/pii/S0016328717301726?via%3Dihub

KC, S., & Lutz, W. (2016). The human core of the Shared Socioeconomic Pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environtal Change*. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Kebede, E., Goujon, A., & Lutz, W. (2019). Stalls in Africa's fertility decline partly result from disruptions in female education. *Proceedings of the National Academy of Sciences of the United States of America, 116*, 2891–2896.

Kenya National Bureau of Statistics, Nairobi, Kenya, Ministry of Health, Nairobi, Kenya, & The DHS Program, ICF, Rockville, Maryland, USA. (2023). Kenya demographic and health survey 2022. Key Indicators Report. Available at: https://dhsprogram.com/pubs/pdf/PR143/PR143.pdf

Kim, J., & Kim, J.-S. (2016). Bypassing GMO regulations with CRISPR gene editing. *Nature Biotechnology, 34*(10), 1014–1015. https://doi.org/10.1038/nbt.3680

King, M., Elliott, C., Hellberg, H., Lilford, R., Martin, J., Rock, E., & Mwenda J. (1995). Does demographic entrapment challenge the two-child paradigm? *Health Policy and Planning, 10*(4), 376–383. Available at: https://doi.org/10.1093/heapol/10.4.376

Knudsen, E. M., Orsolini, Y. J., Furevik, T., & Hodges, K. I. (2015). Observed anomalous atmospheric patterns in summers of unusual Arctic sea icemelt. *Journal of Geophysical Research, 120*(7), 2595–2611. https://doi.org/10.1002/2014JD022608

Laborde, D., Herforth, A., Headey, D., & de Pee, S. (2021). COVID-19 pandemic leads to greater depth of unaffordability of healthy and nutrient-adequate diets in low- and middle-income countries. *Nature Food, 2*(7), 473–475. https://doi.org/10.1038/s43016-021-00323-8

Leaf, A. (1986). New perspectives on the medical consequences of nuclear war. *New England Journal of Medicine, 315*(14), 905–912. https://doi.org/10.1056/NEJM198610023151437

Lewis, M. (2005). Working later? Raising the effective age of retirement. *Public Policy Research, 12*(3), 174–182.

Lianos, T. P., & Pseiridis, A. (2016). Sustainable welfare and optimum population size. *Environment, Development and Sustainability, 18*, 1679–1699. https://doi.org/10.1007/s10668-015-9711-5

Linke, A. M., & Ruether, B. (2021). Weather, wheat and war: Security implications of climate variability for conflict in Syria. *Journal of Peace Research, 58*(1), 114–131.

Liu, D. H., & Raftery, A. E. (2020). How do education and family planning accelerate fertility decline? *Population and Development Review, 46*(3), 409–441.

Lutz, W., Goujon, A., Kc, S., Stonawski, M., & Stilianakis, N. (2018) Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries, EUR 29113 EN Publications Office of the European Union 978-92-79-78024-0 (online),978-92-79-78023-3 (print), https://doi.org/10.2760/835878 (online), https://doi.org/10.2760/41776 (print), JRC111148.

Lutz, W., & Kc, S. (2011). Global human capital: Integrating education and population. *Science, 333*(6042), 587–592.

Malthus, T. (1798). *An essay on the principle of population*. Available online at: http://www.esp.org/books/malthus/population/malthus.pdf

McKay, D. I. A., Staal, A., Abrams, J. F., (...), Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science, 377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Mersle, A. (2020). The Ethiopian-Egyptian water war has begun. *Foreign Policy*. Sept. 22.
Msemburi, W., Karlinsky, A., Knutson, V., et al. (2023). The WHO estimates of excess mortality associated with the COVID-19 pandemic. *Nature, 613*(7942), 130–137.
Muttarak, R. (2021). Demographic perspectives in research on global environmental change. *Population Studies, 75*(S1), 77–104. https://doi.org/10.1080/00324728.2021.1988684
Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., ... & Huybers, P. (2017). Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, *38*, 259–277. https://doi.org/10.1146/annurev-publhealth-031816-044356
Myers, S. S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A. D. B., Bloom, A. J., Carlisle, E., Dietterich, L. H., Fitzgerald, G., Hasegawa, T., Holbrook, N. M., Nelson, R. L., Ottman, M. J., Raboy, V., Sakai, H., Sartor, K. A., Schwartz, J., Seneweera, S., Tausz, M., & Usui, Y. (2014). Increasing CO2 threatens human nutrition. *Nature, 510*(7503), 139–142. https://doi.org/10.1038/nature13179
National Research Council (USA). (2000). *Beyond six billion: Forecasting the world's population*. Available at: https://nap.nationalacademies.org/catalog/9828/beyond-six-billion-forecasting-the-worlds-population
Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T. B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., & Rosegrant, M. (2018). Income growth and climate change effects on global nutrition security to mid-century. *Nature Sustainability, 1*(12), 773–781. https://doi.org/10.1038/s41893-018-0192-z
Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Seroa da Motta, R., & Armijo, E. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science, 344*(6188), 1118–1123.
Niebylski, M. L., Redburn, K. A., Duhaney, T., & Campbell, N. R. (2015). Healthy food subsidies and unhealthy food taxation: A systematic review of the evidence. *Nutrition (*Burbank, Los Angeles County, Calif.*), 31*(6), 787–795. https://doi.org/10.1016/j.nut.2014.12.010
O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2016). The roads ahead: Narratives for Shared Socioeconomic Pathways describing world futures in the 21st century. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2015.01.004
Our World In Data. (2019). Global land use for food production. Available at: https://ourworldindata.org/global-land-for-agriculture. Accessed August 29, 2023.
Piguet, E. (2021). The 'refugee crisis' in Europe: Shortening distances, containment and asymmetry of rights - A tentative interpretation of the 2015–16 events. *Journal of Refugee Studies, 34*(2), 1577–1594. https://doi.org/10.1093/jrs/feaa015
Pimentel, D., Whitecraft, M., Scott, Z. R., Zhao, L., Satkiewicz, P., Scott, T. J., Phillips, J., Szimak, D., Singh, G., Gonzalez D. O., & Moe, T. L. (2010). Will limited land, water, and energy control human population numbers in the future? *Human Ecology, 38*(5), 599–611. http://www.jstor.com/stable/40928150
Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the United States of America*, 109(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109
Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science, 360*(6392), 987–992. https://doi.org/10.1126/science.aaq0216
Popkin, B. M., Barquera, S., Corvalan, C., Hofman, K. J., Monteiro, C., Ng, S. W., Swart, E. C., & Taillie, L. S. (2021). Towards unified and impactful policies to reduce ultra-processed food consumption and promote healthier eating. *The Lancet. Diabetes & Endocrinology, 9*(7), 462–470. https://doi.org/10.1016/S2213-8587(21)00078-4
Popkin, B. M., Corvalan, C., & Grummer-Strawn, L. M. (2020). Dynamics of the double burden of malnutrition and the changing nutrition reality. *The Lancet, 395*(10217), 65–74. https://doi.org/10.1016/S0140-6736(19)32497-3
Population Media Center. (2023). Information available at: https://www.populationmedia.org/our-approach/shows/
Population Reference Bureau. (2022). Population Data Sheet. Available at: https://www.prb.org/collections/data-sheets/
Preston; S.H., Heuveline, P., & Guillot, M. (2001). *Demography: Measuring and modeling population processes*. Blackwell.
Reay, D. S. (2020). Land use and agriculture: Pitfalls and precautions on the road to net zero. *Frontiers in Climate*, 2. https://doi.org/10.3389/fclim.2020.00004

Remans, R., Wood, S. A., Saha, N., Anderman, T. L., & DeFries, R. S. (2014). Measuring nutritional diversity of national food supplies. *Global Food Security, 3*(3–4), 174–182. https://doi.org/10.1016/j.gfs.2014.07.001

Riahi, K. Van Vuuren, D.P., Kriegler, E., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rikani, A., Frieler, K., & Schewe, J. (2022) Climate change and international migration: Exploring the macroeconomic channel. *PLoS One, 17*, e0276764. https://doi.org/10.1371/journal.pone.0276764

Ripple, W. J., Wolf, C., Newsome, T. M., Gregg, W. W., Lenton, T. M., Palomo, I., Eikelboom, J. A. J., Law, B. E., Huq, S., Duffy, P. B., & Rockström, J. (2021). World scientists' warning of a climate emergency. *BioScience, 71*(9), 894–898. https://doi.org/10.1093/biosci/biab079

Rockström, J., Steffen, W., Noone, K., et al. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472–475.

Rozen-Bakher, Z. (2020). The raising of the normal retirement age (NRA) in the ageing era in the advanced countries: The dilemma between securing the stability of the pension system versus the risk of increasing unemployment. *Policy Studies, 41*(6), 641–662. https://doi.org/10.1080/01442872.2018.1554805

Rusic, D., Vilovic, M., Bukic, J., (...), Modun, D., & Bozic, J. (2021). Implications of COVID-19 pandemic on the emergence of antimicrobial resistance: Adjusting the response to future outbreaks. *Life, 11*(3), 220: 1–15. https://doi.org/10.3390/life11030220

Saladino, D. (2022). *Eating to extinction: The world's rarest foods and why we need to save them.*

Sexton, A. E., Garnett, T., & Lorimer, J. (2019). Framing the future of food: The contested promises of alternative proteins. *Environment and Planning E Nature and Space, 2*(1), 47–72.

Shapiro, D. (2012). Women's education and fertility transition in sub-Saharan Africa. *Vienna Yearbook of Population Research, 10*, 9–30. https://www.jstor.org/stable/41940995

Shew, A. M., Nalley, L. L., Snell, H. A., Nayga, R. M., Jr., & Dixon, B. L. (2018). CRISPR versus GMOs: Public acceptance and valuation. *Global Food Security, 19*, 71–80. https://doi.org/10.1016/j.gfs.2018.10.005

Smith, M. R., & Myers, S. S. (2018). Impact of anthropogenic CO2 emissions on global human nutrition. *Nature Climate Change, 8*(9), 834–839. https://doi.org/10.1038/s41558-018-0253-3

Springmann, Marco, Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., … & Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature, 562*(7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0

Springmann, M., & Freund, F. (2022). Options for reforming agricultural subsidies from health, climate, and economic perspectives. *Nature Communications, 13*(1), 82. https://doi.org/10.1038/s41467-021-27645-2

Struik, P. C., & Kuyper, T. W. (2017). Sustainable intensification in agriculture: The richer shade of green. A review. *Agronomy for Sustainable Development, 37*(5). https://doi.org/10.1007/s13593-017-0445-7

Sulser, T., Wiebe, K. D., Dunston, S., Cenacchi, N., Nin-Pratt, A., Mason-D'Croz, D., Robertson, R. D., Willenbockel, D., & Rosegrant, M. W. (2021). *Climate change and hunger: Estimating costs of adaptation in the agrifood system.* Intl Food Policy Res Inst.

Tilman, D., Clark, M., Williams, D. R., Kimmel, K., Polasky, S., & Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. *Nature, 546*(7656), 73–81. https://doi.org/10.1038/nature22900

UNHCR. (2023). Figures at a glance. Available at https://www.unhcr.org/en-us/figures-at-a-glance.html

United Nations Department of Economic and Social Affairs. (2021). World Population Policies 2021: Policies related to fertility.

United Nations Framework Convention on Climate Change (UNFCCC). (2016). The Paris agreement. Available at: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf

United Nations Fund for Population Activities. (2004). Programme of Action adopted at the International Conference on Population and Development, Cairo September 1994. https://www.unfpa.org/sites/default/files/event-pdf/PoA_en.pdf

United Nations Population Division. (2017). The impact of population momentum on future population growth. Available at: https://population.un.org/wpp/publications/Files/PopFacts_2017-4_Population-Momentum.pdf

United Nations Population Division. (2022). *World population prospects, 2022. Methodology Report*. Available at: https://population.un.org/wpp/Publications/Files/WPP2022_Methodology.pdf

United Nations Population Division. (2023). Online data available at https://population.un.org/wpp/
van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food, 2*(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9
Webb, P., Benton, T. G., Beddington, J., Flynn, D., Kelly, N. M., & Thomas, S. M. (2020). The urgency of food system transformation is now irrefutable. *Nature Food, 1*(10), 584–585. https://doi.org/10.1038/s43016-020-00161-0
WHO. (2022). HIV/AIDS Global situation and trends. Available at: https://www.who.int/data/gho/data/themes/hiv-aids
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … & Murray, C. J. L. (2019). Food in the Anthropocene: The EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet, 393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4
Wittgenstein Centre for Demographic Data. (2023). Data available at: http://dataexplorer.wittgensteincentre.org/wcde-v2/
Wood, S. A., Smith, M. R., Fanzo, J., Remans, R., & DeFries, R. S. (2018). Trade and the equitability of global food nutrient distribution. *Nature Sustainability, 1*(1), 34–37. https://doi.org/10.1038/s41893-017-0008-6
World Atlas. (2022). The deadliest famines in history. Available at: https://www.worldatlas.com/articles/the-deadliest-famines-ever.html
World Economic Forum. (2023). *The global risks report 2023.* https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf.