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Resilient foods for preventing global famine: a review of food supply interventions for global catastrophic food shocks including nuclear winter and infrastructure collapse

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ABSTRACT

Global catastrophic threats to the food system upon which human society depends are numerous. A nuclear war or volcanic eruption could collapse agricultural yields by inhibiting crop growth. Nuclear electromagnetic pulses or extreme pandemics could disrupt industry and mass-scale food supply by unprecedented levels. Global food storage is limited. What can be done?. This article presents the state of the field on interventions to maintain food production in these scenarios, aiming to prevent mass starvation and reduce the chance of civilizational collapse and potential existential catastrophe. The potential for rapid scaling, affordability, and large-scale deployment is reviewed for a portfolio of food production methods over land, water, and industrial systems. Special focus is given to proposing avenues for further research and technology development and to collating policy proposals. Maintaining international trade and prioritizing crops for food instead of animal feed or biofuels is paramount. Both mature, proven methods (crop relocation, plant-residue- and grass–fed ruminants, greenhouses, seaweed, fishing, etc.) and novel resilient foods are characterized. A future research agenda is outlined, including scenario characterization, policy development, production ramp-up and economic analyses, and rapid deployment trials. Governments could implement national plans and task forces to address extreme food system risks, and invest in resilient food solutions to safeguard citizens against global catastrophic food failure.

KEYWORDS

Global catastrophic risk; existential risk; food security; abrupt sunlight reduction scenario; global catastrophic infrastructure loss

Introduction

The current global agriculture system heavily depends on reliable environmental conditions including sunlight, temperature, and precipitation, all of which could be severely impacted by global catastrophes (Denkenberger and Pearce 2015). It also depends on complex supply chains supported by a massive global infrastructure, which brings key benefits but also increases systemic vulnerability, such that a disruption in a given point could affect the entire system (Maynard 2015). Abrupt climate change, crop pathogens, superweeds, super bacteria, and super crop pests could all severely affect agriculture (Denkenberger and Pearce 2015). Climate change is already increasing the likelihood of a multiple breadbasket failure (Gaupp et al. 2019), and even worse climate change scenarios are possible (Richards, Gauch, and Allwood 2023). These are categorized as global catastrophic risks (GCRs), risks to global well-being potentially imperiling human civilization (Bostrom and Cirkovic 2008), which are severely underprioritized by governments (Boyd and Wilson 2023b). However, even worse scenarios are on the table, which could suddenly upend both the environmental conditions and the infrastructure on which our global food system depends, and thus require monumental adaptation efforts to prevent global famine. The current review focuses primarily on adaptations to the most extreme global catastrophic food shock scenarios: an abrupt sunlight reduction scenario (ASRS), a global catastrophic infrastructure loss (GCIL), and the worst case: a combination of both.

An ASRS originates from a sudden event that projects vast amounts of aerosol material such as sulfates or black carbon (soot) into the stratosphere, where they could become entrapped for years (Coupe et al. 2019). This is likely to result in a rapid reduction in sunlight irradiation, which could cause global temperature, sunlight, and precipitation levels to fall dramatically, thereby devastating global agricultural production (Xia et al. 2022). The three main avenues which could lead to an ASRS are: a volcanic winter caused by a large volcanic eruption, a direct impact of an exceptionally large asteroid or comet, and a nuclear winter triggered by a nuclear war in which numerous cities have been targeted (Bostrom and Cirkovic 2008; Denkenberger and Pearce 2015). Models simulating plausible nuclear winter

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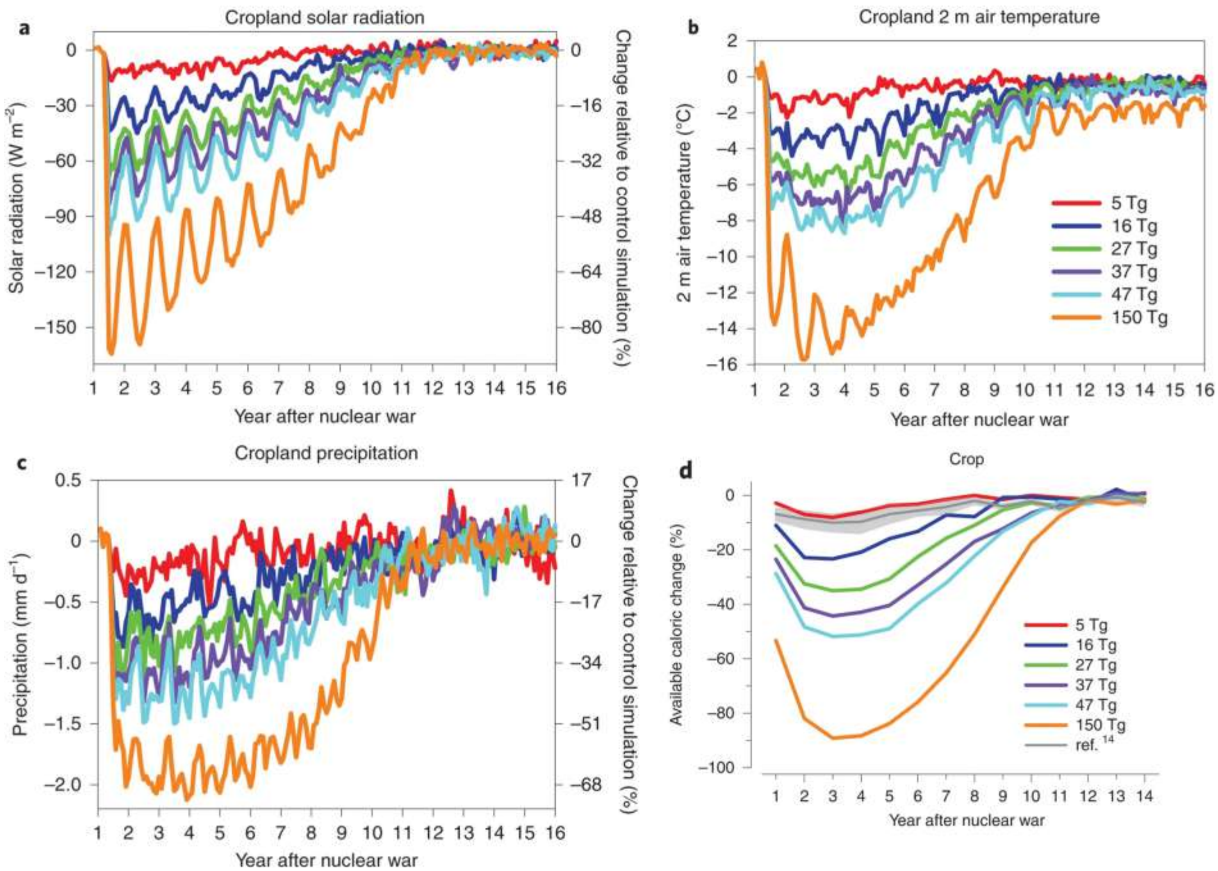


Figure 1. a-c: Changes in a) solar radiation, b) surface temperature, and c) precipitation, averaged over global crop regions following six stratospheric soot-loading scenarios of nuclear winter of varying degrees of severity (measured as teragrams (Tg) or million tonnes of soot load in the atmosphere); d) Global average annual crop calorie production changes (%; maize, wheat, rice and soybeans, weighted by their observed production (2010) and calorie content. Material adapted from: Lili Xia, Alan Robock, Kim Scherrer, Cheryl S. Harrison, Benjamin Leon Bodirsky, Isabelle Weindl, Jonas Jägermeyr, Charles G. Bardeen, Owen B. Toon & Ryan Heneghan, Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection, *Nature Food*, published 2022 by Springer Nature (CC BY 4.0 license, minor changes made).

scenarios with varying degrees of severity estimate a loss of up to ~90% of global staple crop production in the worst year of the catastrophe, see Figure 1 (Xia et al. 2022).

GCIL describes a scenario where the electrical grid and/or industrial infrastructure has been majorly disrupted globally. Since the current agricultural system requires critical industrial inputs (e.g., processing machines, vehicles, fuel, fertilizer, pesticides) to maintain current yields, it is extremely likely that without industry, these yields would collapse leading to mass starvation in the absence of a significant response (Moersdorf et al. 2024). Reductions in the agricultural yield of staple crops in the absence of synthetic fertilizer, pesticides, irrigation and mechanization have been estimated as −35% for rice, −41% for soybeans, −48% for corn, and −37% for wheat, see Figure 2 (Moersdorf et al. 2024). The main mechanisms which have been proposed as a potential cause of GCIL are: electric grids disabled and electronic circuits destroyed due to high-altitude electromagnetic pulse (HEMP) from a nuclear weapon, solar storms disabling transformers and transmission lines, electrical grids and industries disrupted via coordinated cyberattacks, and extreme pandemic leading to mass death and absenteeism from critical infrastructure work leading to supply chain failure (Denkenberger et al. 2021). In addition, rapid progress in artificial intelligence (AI) could become an important GCIL risk factor: leading AI scientists are now calling for stronger action on AI risks from world leaders, citing concerns including large-scale cybercrime and development of novel biological weapons (Bengio et al. 2024).

Notably, a full-scale nuclear war presents the risk of a combined ASRS and GCIL catastrophe, in which both the environmental conditions and critical infrastructure that sustain the current food system are disrupted (Denkenberger et al. 2017). Rapid AI progress has also been noted as a potential risk factor for increased nuclear war risk (Maas, Lucero-Matteucci, and Cooke 2023).

The COVID-19 pandemic highlighted the fragility of food systems and the insufficient preparedness of global governments to handle the shocks to the food system and supply chains that would occur during a global catastrophe (Laborde et al. 2020; Liu, Lauta, and Maas 2020). Current preparedness to feed the surviving global population following a catastrophe is sorely lacking (Boyd et al. 2024; Boyd and Wilson 2023b; Wilson, Prickett, and Boyd 2023). This is because there are only enough food stocks to feed the global population for around 6 months (Denkenberger and Pearce 2014), and little to no preparation to deploy interventions capable of offsetting a sudden food production loss. The

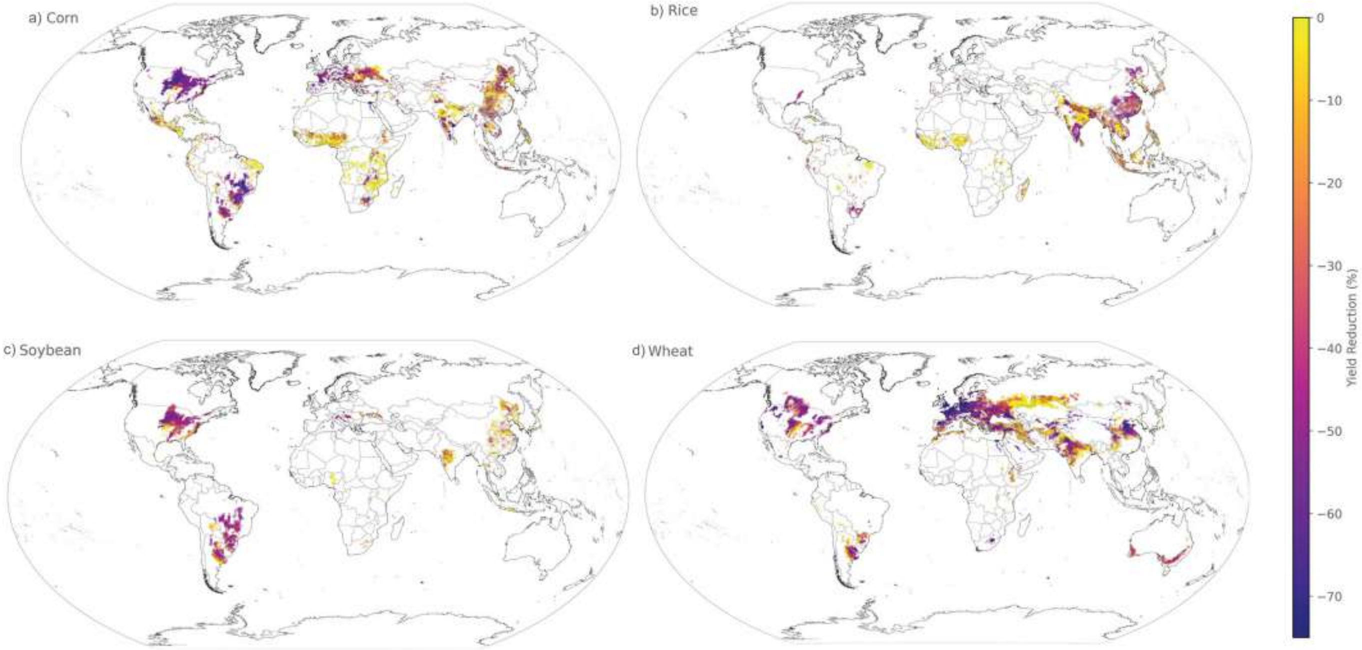


Figure 2. Spatial distribution of yield loss for staple crops—a) corn, b) rice, c) soybeans, d) wheat—in a scenario with no industrial inputs (synthetic fertilizer, pesticides, irrigation and mechanization). Material adapted from: Jessica Moersdorf, Morgan Rivers, David Denkenberger, Lutz Breuer, Florian Ulrich Jehn, The Fragile State of Industrial Agriculture: Estimating Crop Yield Reductions in a Global Catastrophic Infrastructure Loss Scenario, *Global Challenges*, published 2024 by Wiley (CC BY 4.0 license, minor changes made).

decline in crop yields resulting from a global catastrophic food failure would lead to increased food prices, further worsening global food insecurity (Janetos et al. 2017). Without proper planning and preparation, billions could die of starvation (Xia et al. 2022).

Thus, many researchers have agreed that to mitigate the severity of a global catastrophe, resilient food solutions should be developed (Avin et al. 2018; Baum et al. 2019; Boyd and Wilson 2023a; Denkenberger et al. 2022; Ord 2020; Pinsent and Tan 2024; Ruhl 2023; Sepasspour 2023; Siva and Anderson 2023). These are defined as interventions capable of producing substantial quantities of calories and essential nutrients even during a global catastrophe when conventional methods of food production would be inadequate to feed the global population (Pham et al. 2022). To be considered a resilient food technology, a food production method must: 1) provide sufficient food to reliably feed a significant portion of the global population, 2) be able to maintain high production during the resource-constrained period of a global catastrophe, and 3) have the ability to rapidly ramp up production so it can be available before stored food runs out. Research and development of these food solutions and technologies facilitate feeding the global population in a catastrophe, and in the most dire scenarios they could also reduce the risk of global civilizational collapse by contributing to maintaining nodes of civilizational complexity (Boyd and Wilson 2023a; Ulloa Ruiz et al. 2024)—reducing existential risk in doing so. Pham et al. analyzed nutritional combinations of resilient foods in ASRS and concluded that they could provide a life-sustaining diet according to dietary guidelines (Pham et al. 2022).

The aim of this literature review is to present the state of the field of practice in food system interventions with the potential to prevent mass starvation following a global catastrophe, with a focus on proposing avenues for further research and pilot testing. First, a group of food conservation interventions focused on optimizing crop uses for saving lives in a catastrophe is discussed (Section "Food conservation interventions"). Next addressed are three groups of interventions called "resilient food solutions" (Section "Resilient food solutions") focused on raising the food production baseline to counter catastrophic crop yield reductions. Then, a review of the policy work done so far to mitigate the risk is presented (Section "Policy work on resilient food solutions and related interventions"). Finally, the discussion is focused on the uncertainties involved and future work to address these (Section "Discussion and future work").

This work has a partner study titled "*Food without agriculture: Food from CO_2, biomass and hydrocarbons to secure humanity's food supply against global catastrophe*" (see Section 3.3); combined they seek to update the original work that kickstarted the research field of foods resilient to global catastrophic food failure: the book "*Feeding Everyone no Matter What*" (Denkenberger and Pearce 2014).

Food conservation interventions

Redirection of crops used in animal agriculture for human consumption

One fundamental way to feed people during a protracted, catastrophic food shortage is to redirect food that is currently used to feed animals (mostly for poultry, beef, pork, egg, and milk production) (Ritchie, Rosado, and Roser 2017), and instead use it as food for people directly. Feeding animals grains is an extremely inefficient way to obtain calories. Chickens, which are one of the most efficient feed to calories converting animals, still require about 8 calories in for every 1 calorie out; this ratio is over 30 for cattle (Cassidy et al. 2013). It should be pointed out, however, not all of the feed that is given to animals can be reallocated to people as humans are not able to digest lignocellulosic material (e.g., grass, hay, bark) that other animals, such as ruminants and some insects, are able to digest. Animals not capable of digesting lignocellulosic material were not considered a food resilient to ASRS, see discussion on Appendix B.

Animal feed accounts for 36% of the calories and 53% of the protein produced by the global crop supply (Cassidy et al. 2013). An additional 9% of the calories produced by the global crop supply does not go toward human or animal consumption, but other purposes such as biofuels (Cassidy et al. 2013). Based on this, it is estimated that if all crops grown only went toward human consumption, then the availability of calories globally would increase by about 70%—thereby enabling the world to feed up to an additional ~4 billion people (Cassidy et al. 2013). This is particularly pronounced in countries with a very strong meat industry, for example, Ulloa Ruiz et al. estimated that in Argentina the gross calorie production is equivalent to the caloric requirements of ~600 million people—13 times the country's population—but the net calorie production (after accounting for crop use in meat and biofuel production) for internal food consumption and imports is reduced to ~110 million (Ulloa Ruiz et al. 2024). This difference is so large that in extreme ASRS conditions (150 Tg) Argentina would not be able to feed its population without changes in its meat and biofuels industries, but not using crops for meat or biofuels would enable feeding almost 4 times its population (Ulloa Ruiz et al. 2024). The ASRS food production estimates from (Xia et al. 2022) and (Rivers et al. 2024) indicate other countries that appear to similarly be able to not only avoid starvation but also feed many times their population through redirection, which include Brazil, Paraguay, and Guyana. Others such as the United States, Bolivia, Panama, Ireland, Eswatini, Malaysia, and Indonesia may be able to obtain enough calories to fulfill the minimum requirement of their population using mostly redirection—as shown in Figure 3. Finally, New Zealand, Australia, and Uruguay may not need to employ redirection to feed their population even in a 150 Tg ASRS, but doing so would free up large amounts of food that could be used to prevent famine elsewhere. All in all, (Rivers et al. 2024) estimate that rapid redirection of feed and biofuel crops for food in combination with rationing, optimized food stock management and food waste reduction would vastly increase food availability compared to no adaptations, from 15% to 51% of the global caloric requirement. For discussion on biofuel crop redirection and food waste reduction, see the following sections.

Redirecting human-edible food used as animal feed is a practical method to quickly increase the amount of food available to the surviving population in the event of a global catastrophe. Due to the inefficiency of feed to output calorie ratio of animals, it seems logical that the human-digestible portion of the food typically fed to animals would be more efficiently utilized if it was given to people instead (Sandström et al. 2022). Likewise any land currently dedicated to fodder crops that is suitable for growing staple crops for people would be more efficiently utilized that way in a food catastrophe, whenever possible. This response would likely be incentivized by economic conditions after a large crop yield loss, as suggested from economic modeling of nuclear winter (Hochman et al. 2022) and historical evidence from World War 2 (Collingham 2013), but government policies could expedite redirection in abrupt crisis situations to prevent starvation.

Rapidly increasing animal slaughter and meat preservation infrastructure in response to a large disruption would be useful, but could prove challenging due to the high integration of the meat supply chain (Whitehead and Kim 2022). Immediate drastic reductions in breeding while maintaining the existing slaughter capacity would be easier to implement in order to reduce animal populations to levels that could be sustained without using food crops as feed. Logistical analysis would be needed to first move the maximum number of grazing animals from feedlots to pasture, then determine optimum slaughter rates based on facilities to process and store the meat. Trials could be done to determine the labor and capital productivity of switching an employee of one type of animal slaughter to a different type of animal. Pilot tests could be done to see how fast breeding could be stopped and slaughter could be scaled up in existing facilities.

A potential downside to this solution could be a lower availability of nutrient-rich foods, unless other nutrient-rich foods are introduced as a replacement (e.g., soybeans that otherwise would have been fed to cattle, single cell proteins, grass-fed cattle milk and meat, meat from other cellulose-digesting animals, or seafood). This is because animal products generally contain more bioavailable levels of essential minerals and vitamins than crops, such as vitamin B12, riboflavin, vitamin A, vitamin E, iron, zinc, calcium, and vitamin D (Turk 2014). This is not a major concern when nutritional alternatives are available, as in general, vegetarians and vegans are healthier than meat eaters (Segovia-Siapco and Sabaté 2019). In addition, there are methods to process vegetable crops to increase their nutritional density to levels similar or higher than animal products with an overall higher conversion efficiency, from traditional foods like tofu or tempeh to modern plant-based animal product substitutes seeking to emulate functional properties like meat texture, taste and appearance (Wang et al. 2023).

Redirection of crops used in biofuel production for human consumption

There is also the possibility of redirecting crops currently used in biofuel production for human consumption. The U.S. is the major producer, and corn is the primary crop used in biofuels, in the form of ethanol. The amount of corn that was used for biofuels in the U.S. in 2022 (~5.2 billion bushels of grain) was approximately equivalent to the caloric intake of 600 million people (USDA 2024). Biodiesel is another potential source for redirection as it can be made from rapeseed, palm, and soybean oils, all of which can be used as ingredients for food products. The amount of soybean oil that was produced for biodiesel in the U.S. in 2022

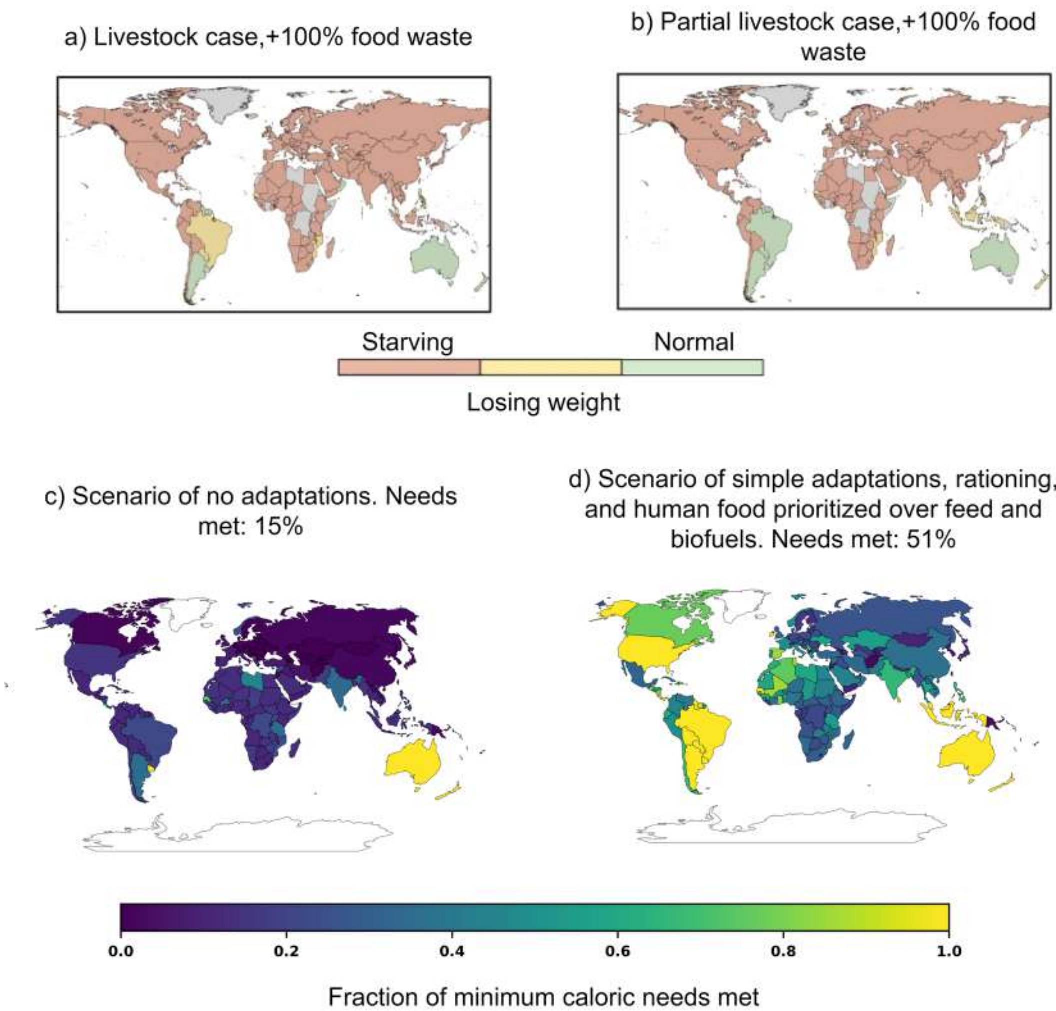


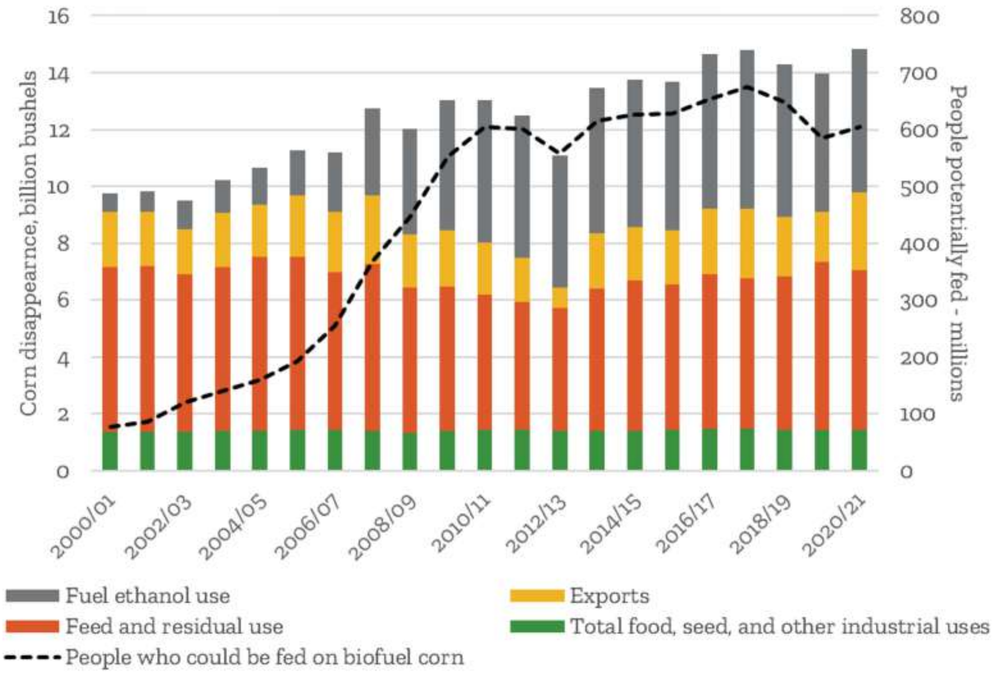
Figure 3. Maps of national food availability without food trade in a 150 Tg scenario. From (Xia et al. 2022) there are figures a) and b), respectively representing the calorie intake status of maintaining current livestock versus maintaining it only partially (Partial Livestock case implies 50% of livestock feed used for human food and the other 50% still used to feed livestock. +100% waste represents all household waste added to food consumption.) Material adapted from: Lili Xia, Alan Robock, Kim Scherrer, Cheryl S. Harrison, Benjamin Leon Bodirsky, Isabelle Weindl, Jonas Jägermeyr, Charles G. Bardeen, Owen B. Toon & Ryan Heneghan, Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection, *Nature Food*, published 2022 by Springer Nature (CC BY 4.0 license, minor changes made). From (Rivers et al. 2024) there are figures c) and d), respectively representing the share of caloric requirements fulfilled in a scenario of no adaptations versus a scenario including the adaptations of rapid redirection of feed and biofuel crops for food, rationing, optimized food stock management and food waste reduction. Material adapted from: Morgan Rivers, Michael Hinge, Kevin Rassool, Simon Blouin, Florian U. Jehn, Juan B. García Martínez, Vasco Amaral Grilo, Victor Jaeck, Ross J. Tieman, James Mulhall, Talib E. Butt & David C. Denkenberger, Food System Adaptation and Maintaining Trade Could Mitigate Global Famine in Abrupt Sunlight Reduction Scenarios, (CC BY 4.0 license, minor changes made). More details about the specific accounting of calories from reducing livestock feed, reducing food waste, and other adaptations, which differs between the two analyses, can be found in the respective sources.

was approximately equivalent to the caloric intake of over 50 million people (USDA 2024). Although fuel sources would be critical in a global catastrophe, biofuels comprise only ~5% of the total energy of petroleum fuels even in the U.S. (EIA 2024), but the crops spent on this equate to twice the daily per capita calorie needs of the U.S. population. Figure 4 shows historical U.S. production of these biofuels and the caloric equivalent of the food spent to obtain them in "people fed" at 2,100 kcal/person/day. Other types of biofuels not based on food crops exist but are a small minority.

Currently, biofuel production mandates in the United States and much of the world are inflexible, meaning a certain volume of crops must be turned into fuels, no matter their availability in a given harvest (Weber 2016). This means in years with an agricultural shortfall, the burden of reduced supply might fall entirely on animal feed and direct food uses. Thus, introducing flexibility in biofuel mandates for crisis situations is an opportunity to generate a "virtual stock" of food, where in the event of very high prices biofuel blending would fall away due to the structure of the policy (via buy outs or other mechanisms). This would free up oilseeds and grains for human consumption in a catastrophe, while still providing a good price for farmers and preserving biofuel policy in typical years.

Reducing food loss and waste

Food loss occurs throughout the food supply chain up to the point of sale, while food waste refers to items discarded by retailers and consumers. In 2022, 13% of global food



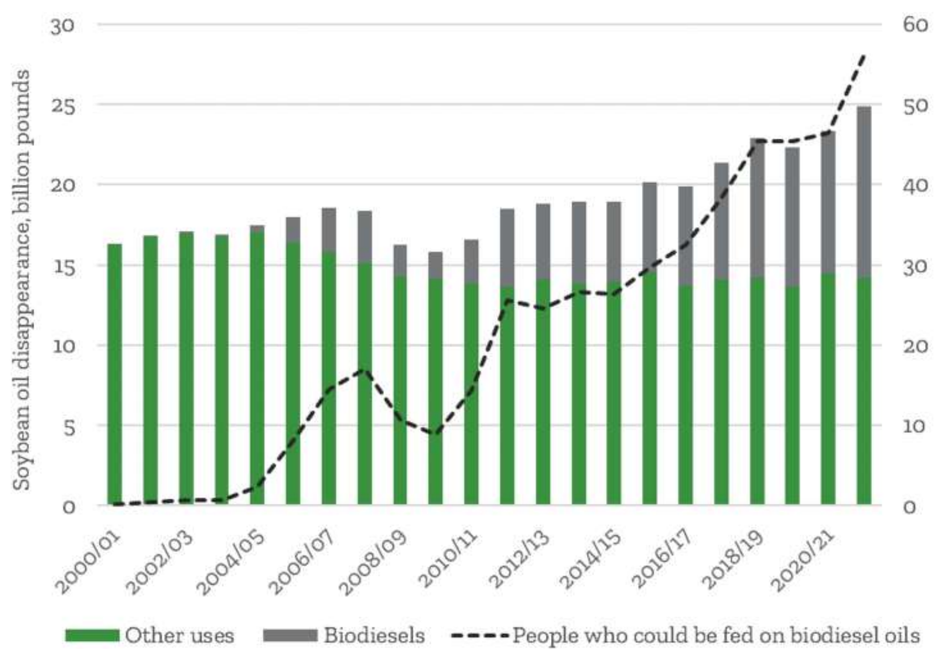


Figure 4. a) U.S. corn usage for bioethanol production and the caloric equivalent - 2000/01–2021/22, b) U.S. soybean oil usage for biodiesel production and the caloric equivalent (USDA 2024).

production was lost before reaching consumers, while an additional 19% was wasted at the retail, food service, and household levels (Nature Food 2024). Harvest loss reduction is complicated by limited data availability obscuring the evaluation of interventions to address it. These include optimizing harvest timing and methods, for example through capacity building for farmers, adopting more precise mechanized harvesting equipment especially in developing countries, deploying protective measures against extreme weather such as field covers or shade nets, and using more resilient crop varieties. Other supply chain losses, stemming from storage, processing, and transportation, are largely a function of the quality of existing storage and transport infrastructure, such as metal silos, hermetic storage, drying equipment, packaging equipment, and cold chains. This makes them difficult to reduce, especially in developing countries with limited infrastructure investment (Nature Food 2024).

Food waste is larger than harvest and distribution losses, with around 60% coming from households, followed by food service and retail. This problem is greater in developed countries, and solutions must be addressed at both the individual and systemic levels, with important regional differences that need to be considered. Strategies have been proposed to reduce food waste, including improved waste management/tracking, improved regulation/quality standards, and reuse/

upcycling (Thi, Kumar, and Lin 2015). Solutions to reuse and upcycle food waste into food sources range from simple interventions like feeding it to animals or reusing sunflower seed pressings and brewer's spent grain processed into flour instead of being used as feed (Aschemann-Witzel et al. 2023), to more complex technologies like fermentation processes to produce single cell proteins and oils from food wastes (Punia Bangar et al. 2024). Municipal collection of food waste to upcycle into food could be implemented by local governments in response to a crisis, but it might require drying at the household level to prevent spoilage.

Trials could be done to study how fast all these interventions could be implemented in combination with rationing schemes. As a result of limited food supply and increased prices during a global catastrophe, industry would likely implement techniques such as these to reduce losses (during harvest, distribution, and retail) in order to maximize their profitability. For example, since the price elasticity of food waste is −1.49 (Landry and Smith 2019), a tripling of food price would be expected to reduce the post-harvest waste from 24–29% to about 6–10% (Verma et al. 2020).

Resilient food solutions

This section discusses the food production options that have been proposed in the literature as resilient against ASRS and/or GCIL, a selection of which is shown in the chart of Figure 5. The resilient food solutions have been divided into three groups of interventions focused on raising the food production baseline to counter catastrophic crop yield reductions. First, land-based solutions (3.1) including grass-fed ruminants, crop relocation, greenhouses, cropland expansion, leaf protein, and mushrooms, followed by water-based solutions (3.2) such as fishing, microalgae production, and farming of seaweed and bivalves, then finally high-tech industrial solutions for the production of food without agriculture or sunlight (3.3). Each of the subsections describes a resilient food intervention following this structure: a brief description of the food production method, an explanation of the reasons why the intervention is particularly useful in a global catastrophe, an overview of current production and cost values and estimates of its production potential and cost during a global catastrophe, whenever available, and a set of key research questions to further characterize its potential and catastrophe readiness.

Land-based solutions

Ruminants fed on grass and agricultural residues

Ruminants (e.g., cows, sheep, goats) can live on plant biomass which humans cannot digest, including grass and agricultural residues (e.g., corn stalks, wheat straw, most leaves). As of 2022, there were 4.3 billion ruminants globally (FAO 2024). There remains, however, uncertainty as to how much of the existing dairy cattle population could be sustained in severe ASRS or GCIL. Modern dairy cattle such as Holstein

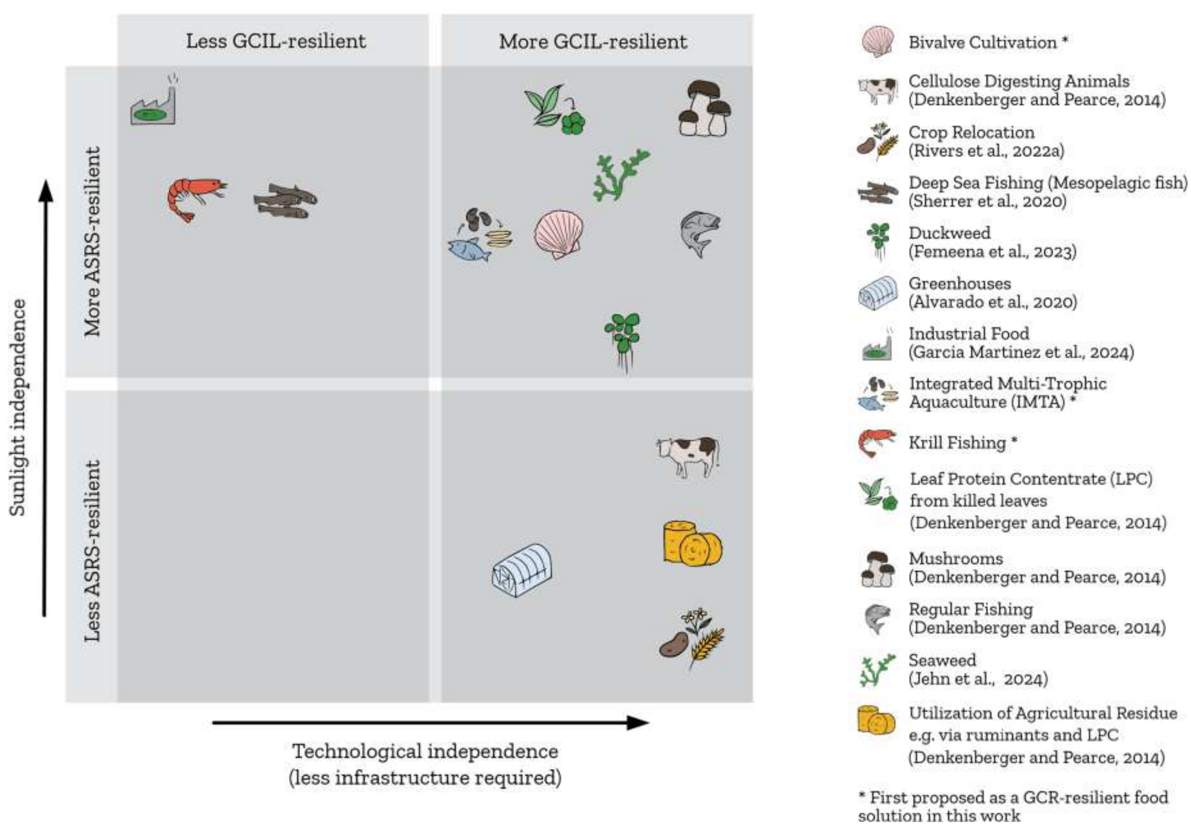


Figure 5. Representation of the space of resilient foods with selected examples based on how resilient the authors consider them to ASRS and GCIL, in terms of how much their production yields would be affected by the different catastrophes. Placements are approximate, as some methods can be done at a wide variety of technological complexity, but the simplest method is generally shown. Note that this graphic does not include fundamental considerations for the potential of these methods for resilient food production, such as production cost, capital intensity, or speed of mass deployment.

cows, which have been optimized to produce as much milk as possible and make up the vast majority of ruminant populations in many regions of the world, are typically fed considerable amounts of grains as part of their diet. Holstein cows can survive on an all-herbage diet, provided they have high-quality forages (Schori and Münger 2021). An important uncertainty is how they would cope in the long-term with diets based on widely available agricultural residues such as from wheat, which is much lower in protein and more fibrous. Future work on feed trials could address this, by giving evidence-based estimates of whether Holsteins provide an efficient way to upcycle widespread agricultural residues with net-positive calorie generation (more energy contained in the milk than in the amount of human edible grains included in their feed). If this was feasible, Rivers et al. estimated that grass-fed milk could provide the equivalent of ~8.5% of the global population's caloric requirements (Rivers et al. 2024). Non-protein nitrogen supplementation could be useful as ruminants can digest moderate amounts (Shen et al. 2023), such as from urea or ammonium salts, which are widely available industrially. Other modern dairy breeds such as Jerseys or Guernseys may be better adapted to cope with these lower-energy diets, but they are less common, and replacing the dominant cattle breeds would take precious time in a global catastrophe. Research on a plan that considers all these factors to optimize the utilization of agricultural residues on a catastrophe would be valuable.

Crop relocation

This solution entails the relocation of cold tolerant crops from the more northern latitudes (where they are often grown) to the regions with a less afflicted climate in an ASRS, in lower latitudes where temperatures would likely remain suitable for their cultivation and where there would be a large amount of arable land in the event of severe reduction in sunlight (Rivers et al. 2024; Wilson et al. 2023). This includes chilling tolerant crops capable of withstanding temperatures between 0–15 °C (e.g., potatoes, rapeseed/canola, and some types of beans)—whose cultivation appears feasible even in the lowest temperature scenarios in vast areas of land mostly in and around the tropics, likely to remain frost-free during the growing season (Coupe et al. 2019)—as well as frost tolerant crops (e.g., wheat, sugar beet, and barley). See tables 2–3 of Wilson, Payne, and Boyd (2023) for examples of promising crops in these categories.

Adaptations to the global distribution of crops have been extensively studied as a solution to ongoing food security challenges, hinting at their potential for response to extreme shocks. Models of reconfiguring crop distribution show it is possible to feed an additional 825 million people using current croplands while also using 12–14% less water (Davis et al. 2017), and that it is possible to palliate expected crop yield losses from climate change by adjusting the crop cultivars being grown (Minoli et al. 2022). The use of traditional local plants has also been proposed as a possible contributor to catastrophic resilience (Winstead, Jacobson, and Di Gioia 2023), although more research is needed to characterize their resilient food potential in terms of scalability, rapid deployment, and cost.

Even in a severe nuclear winter scenario (150 Tg), hundreds of millions of people could be fed by relocating a few cold tolerant crops en masse (Rivers et al. 2024). These crops would then supply a wide range of essential vitamins and minerals as well as have the potential to fulfill most of humanity's nutritional needs following a global catastrophe, if allocated effectively (Rivers et al. 2024). Therefore, by leveraging intensive application of all available fertilizers, in addition to redirecting capital and resources where relevant, the yields of these relocated crops could be supported. Note that in this scenario crop relocation alone often would not be able to feed the population of every single country when considering each country separately, though it could feed significant numbers. Rivers et al. estimated that if international food trade stopped completely, famine would affect 32–85% of the population even with various resilient foods in a severe nuclear winter scenario (Rivers et al. 2024). This highlights the paramount importance of maintaining international as well as intra-national trade and cooperation for saving lives during catastrophes.

It is fundamental to consider which crops can contribute most to nutrition in an ASRS. For example, some legumes such as forage legumes, e.g., alfalfa, show particular promise in terms of cold tolerance (Bhat et al. 2022), but they have not yet been studied in depth for ASRS response, and should be subjected to ASRS yield modeling to evaluate their potential. Another example are frost-resistant crops, which are resilient to the out-of-season frosts that occurred in previous ASRSs such as the "year without summer" caused by Mount Tambora in 1815 (Wilson, Payne, and Boyd 2023). A New Zealand-specific study finds that current production levels of frost resistant crops could not feed all New Zealand citizens following a nuclear war, but expanding their cultivation would suffice (Wilson, Payne, and Boyd 2023), and chilling resistant crops could make significant contributions as well. It is important to note that a crop does not necessarily have to be frost resistant to contribute to nutrition in a 150 Tg nuclear winter, because even in these extreme conditions many tropical and subtropical areas (especially in the Southern Hemisphere) are likely to remain frost-free during the growing season (Coupe et al. 2019). Other areas are unlikely to have significant growing seasons, with some potential exceptions such as New Zealand (Boyd and Wilson 2023a).

Rapeseed is not only an ASRS-resilient source of fats and other key nutrients, it has also been proposed as a potential source of biofuel for maintaining agricultural production in case of diesel shortages due to trade restrictions in fuel-importing regions such as New Zealand during global catastrophes, with wheat being particularly efficient at yielding significant food per unit of fuel spent to cultivate it (Boyd et al. 2024).

There are many challenges behind rapid crop relocation. Firstly, the rapid deployment of cold tolerant seeds to a substantial area of the lower latitudes would need to be done as quickly as possible, which may require the replanting of seeds currently stored for consumption (Rivers et al. 2024). Secondly, support and training would need to be provided on a large scale to farmers to educate them on how to successfully grow crops they may have never cultivated (Rivers et al. 2024). Thirdly, the initiative could require significant international and intra-national cooperation as well as trade agreements for the distribution of seeds, agricultural inputs, and expertise—which could be provided by those in the Northern areas where cultivation is hard or impossible in severe ASRS—along with the land, labor, and local skills from those in the lower latitudes (Rivers et al. 2024). There are exceptions to this for relocation of crops within large countries (e.g., U.S., Brazil, Argentina) which would not require international cooperation. Fourthly, a sufficiently large starting amount of seeds is important to achieve a sufficiently fast deployment.

This solution would benefit from pilot testing. For example, there is a need for testing the deployment of relevant crops under simulated ASRS conditions to validate crop growth models, such as in growth chambers or specialized outdoor locations (perhaps using a mesh to simulate lower solar irradiation and temperature in cool, dry areas, or a cool greenhouse). Furthermore, it would be valuable to test the capacity of farmers to rapidly switch en masse to crop varieties they are unfamiliar with, to better understand how feasible it is and how it might impact yields. Finally, emergency crop saving strategies already used to prevent frost damage in critical stages of growth can be explored for ASRS that include active control methods like heating with fuel or electricity, sprinkling, wind machines, and agricultural plastic tenting (Poling 2007).

Greenhouses

Going one step further than temporary protective tenting, to supplement crop relocation, the rapid deployment of simple polymer-cover greenhouses could enable the cultivation of additional crops with a temperature-improved climate. This would improve the yield per hectare of crops that are temperature sensitive and enable the cultivation of crops in areas where they would not otherwise be able to be grown due to the climate. Greenhouses trap heat from sunlight to create a warmer environment for crop growth (Alvarado et al. 2020). They are widely used in many different regions around the world and on various scales from shed-sized to massive industrial agriculture buildings. Globally, over 1.3 million hectares were used to produce food in greenhouses by 2019 (Tong et al. 2024).

There exist low-tech open-source greenhouse designs based on plastic sheets and simple wooden or plastic structures (Alvarado et al. 2020). Similar greenhouses have been deployed at a large scale (von Zabeltitz 2011). Simple greenhouses that have historically been used in many regions are large-area, made of wood and plastic, and passively ventilated (Vanthoor et al. 2012). There also exist low-cost, open-source, automatic irrigation systems which could be used in these greenhouses (Wiggert et al. 2019). If the necessary processes to ramp up greenhouse development and deployment can be successfully executed in a catastrophe, then they could potentially provide ~30% of the global food requirements after the first year, although there would be challenges such as limited polymer extrusion capacity (Alvarado et al. 2020).

This intervention needs further research, and pilots should be performed since mass fast deployment of greenhouse technology has not yet been tested and there may not be sufficient infrastructure for it. This should include all steps of the production chain, such as sawnwood, construction steel, and plastic film and sheet. Furthermore, alternative ways of scaling low-tech greenhouses could be investigated further, such as polymer tube framing, and household scale lumber production. Structural analysis could be performed to find the most suitable designs, given the potential risks from adverse meteorological conditions such as strong rain, snowfall, hail or wind. The economically optimized selection of construction materials for all adapted greenhouses is very location dependent (Rana et al. 2023), so the structural engineering of appropriate designs will need to be run with all the available materials. In addition, research could look into retrofitting existing structures with plastic sheeting on the sides to create simple greenhouses, such as the rapidly emerging agrivoltaic arrays (Vandewetering, Hayibo, and Pearce 2022), including wood-based fixed and variable tilt arrays as well as most traditional not tracking racking with semi-transparent modules. There are also research directions to assess the extent to which the current large-scale plowing, planting, harvesting and irrigation method of open-air agriculture could be adapted to greenhouses. For instance, one could evaluate whether center pivot or other large-scale irrigation methods could be adapted for greenhouses and whether surface and localized irrigation could continue in an ASRS. To maximize yields and diet variety, a useful research topic would be determining, for each region, the most suitable crops and cultivars to be grown in such greenhouses in an ASRS. In turn, this would require more detailed modeling of the environmental conditions inside greenhouses in an ASRS, and further investigation of irrigation and nutrient requirements by crop, cultivar, and region. Other uncertainties requiring further research include: whether the temperature will be sufficiently raised with just the polymer cover as an insulator or if supplemental heating is needed, and whether the plastic cover would reduce the solar radiation so much as to make the plants grow improperly in severe ASRS, since they require a balance of temperature and sunlight for proper growth.

Expansion of planted crop area

There is a vast amount of cropland which is not actually harvested for agricultural use for numerous reasons (Everest, Sungur, and Özcan 2021). In the U.S. alone, 22 million acres are enrolled under the conservation reserve scheme (Pratt 2023), but these could be put into agricultural use at short notice if needed during a global catastrophe. Government financial support could help make cropland that is currently too cost prohibitive to use become economically viable and convert new areas into profitable croplands (Zheng et al. 2023). Leveraging cropland that is used for non-food crops could free up considerable amounts of land for food production globally, for example cotton alone takes 33 million hectares or 2% of the global cultivated area, and there are many others taking several million hectares such as rubber, tobacco, or flax, as well as non-essential beverage crops such as coffee and tea (Ritchie and Roser 2024). A significant portion of pasture land used to grow forage crops for livestock production could be converted into cropland. 26% of global forest area (~10 million km²) has a slope less than 26% and trees younger than 20 years, making it suitable for agriculture. In less than a year, cropland could potentially be doubled (Monteiro et al. 2024). In addition, more food could be produced using conventional urban or near-urban agriculture methods as long as industry is maintained (Meyer et al. 2021; Boyd and Wilson 2024)—these can sometimes achieve higher yields than commercial agriculture (Payen et al. 2022), make more complete use of the crop, and may provide psychological reassurance around food security in a crisis.

The main technologies required to expand cropland include construction equipment to level the land and remove debris, as well as forestry equipment for tree removal. The main bottleneck for rapid mass expansion would probably be the availability of this machinery, especially in regions where it is not commonly in use. One way to address this could be different countries sharing equipment to expedite planted area expansion as a resilient food response to ASRS, especially sharing the machinery located in regions unable to obtain significant crop yields in an ASRS, as could be the case of many Northern Hemisphere regions. Research is needed for cataloging and planning for such equipment transfers.

Further research with additional crop models is required to better assess the production potential of crop area expansion. Prioritizing the land to clear based on economic return could more accurately predict the expansion of food supply. This would also allow comparative economics with other resilient food sources. In addition, more research is warranted on market incentives and other policies to encourage food production, particularly in the land currently used for crops detrimental to public health, such as tobacco.

Though expanding planted area is a mature technology, there are still valuable pilots to be done. For instance, some areas which currently only support isolated shrubs or arid vegetation could become arable in ASRS. These areas that are currently too dry to cultivate may become viable in ASRS if the crops' evapotranspiration is reduced due to lower temperatures and higher relative humidity, despite the reduction in rainfall—though this remains speculative and water stress could worsen in some areas in an ASRS. A tantalizing precedent is the Sahara desert being relatively green during the past glaciation (Tierney, Pausata, and deMenocal 2017). Therefore, simulating nuclear winter conditions with an air-conditioned greenhouse in some of these promising areas could be valuable to assess the viability in actual soil conditions. Finally, research into rapid redirection of water and irrigation implementation to new cultivation areas would be valuable. Planting crops with higher calorie to irrigation ratios could limit water demand in places where that would remain a bottleneck.

Leaf protein concentrate (LPC)

LPC is a protein-rich, nutrient-dense food made using the nontoxic non-woody parts of plants (Anoop et al. 2023). Producing LPC is a relatively simple process consisting of: 1) mechanical pressing (leaf grinding/pulping), 2) protein precipitation (e.g., by heating, acidification, or other means), and 3) protein concentration (separation and drying) (Santamaría-Fernández and Lübeck 2020). LPC can be consumed in a variety of forms, such as protein powder or concentrate, and is currently consumed by both people and animals.

LPC has been produced on both household and small industrial scales (Nagy et al. 1978), with several industrial plants producing feed and food ingredients in Europe (Santamaría-Fernández and Lübeck 2020), and is now gaining traction as an alternative protein source (Anoop et al. 2023), but LPC has yet to be mass produced globally for human consumption. Companies such as Leaft Foods and Rubisco Foods are working on the mass commercialization of alfalfa-based leaf proteins for use in plant-based protein foods. Other LPC food companies include Grassa and The Leaf Protein Co. Large-scale production of LPC is often used as a replacement for soybean meal protein in animal feed (Ayyat et al. 2021).

Small scale production of LPC has been done in developing countries as a food source for arid and malnourished areas (Rathore 2010). Small scale LPC production can be done relatively easily with limited training, but with lower yields compared to industrial operations (Santamaría-Fernández and Lübeck 2020). A simple open-source LPC press that can be 3-D printed has been developed (Wentworth 2019), and far more sophisticated planetary roller screw designs for other food processing could be used for LPC and also are readily amenable to mass-scale distributed manufacturing. LPC has potential to bridge nutritional deficits including protein and fiber and contains vitamins, minerals, and a combination of essential amino acids, making them a suitable alternative to animal foods. The simplicity of the process, accessibility of plant matter in most locations, and its many other qualities make LPC a highly resilient food option during a catastrophe such as an ASRS or GCIL. It should be pointed out that the general LPC bitter, grassy taste and especially its labor-intensity could be considerable barriers to widespread adoption (Cox et al. 1993). These issues could be bypassed by using the LPC as animal feed, although at notably lower overall food production efficiency.

In just Nigeria alone, it is estimated that the application of LPC technologies to agricultural residues could produce between 3.0–13.8 million Gcal/year through direct consumption and animal feed uses, equivalent to the caloric requirement of an estimated 3.9 to 18.1 million people, covering a large share of Nigeria's food deficit (Ugwoke et al. 2023)—though this is probably an upper bound of the potential, requiring LPC toxicity testing to confirm. The application of LPC was estimated to extract up to 5 times more food than the status quo of mostly feeding it directly to ruminants (Ugwoke et al. 2023). Figure 6 shows the case of higher end of potential yield (13.8 million Gcal) through a Sankey diagram of the Nigeria analysis assuming LPC-enhanced residue utilization and optimal efficiencies.

In an ASRS, a considerable number of leaves would die from the lack of sunlight, including from plants that are not

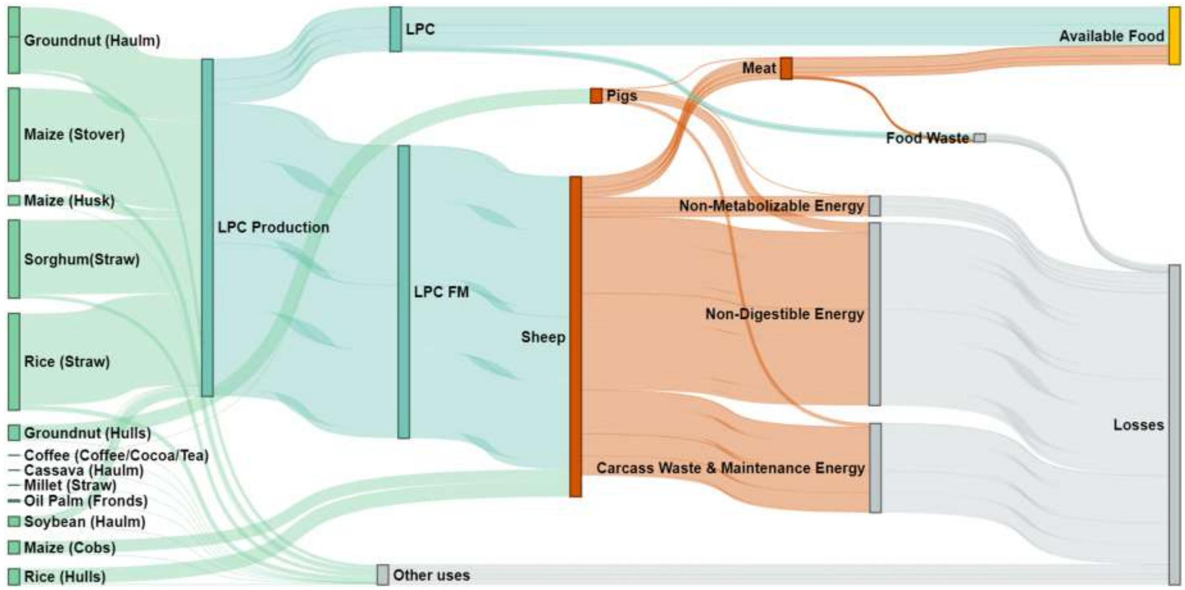


Figure 6. Energy flow diagram showing the potential of leveraging LPC from agricultural residues to improve food security in Nigeria, showing the case of improved residue utilization assuming optimistic efficiencies (energy flows per year), resulting in ~5 times more calories extracted than just feeding the residues to ruminants. Material adapted from: Blessing Ugwoke, Ross Tieman, Aron Mill, David Denkenberger and Joshua M. Pearce, Quantifying Alternative Food Potential of Agricultural Residue in Rural Communities of Sub-Saharan Africa, *Biomass*, published 2023 by MDPI (CC BY 4.0 license, no changes made).

of agricultural origin, and this stock of "killed leaves" has been proposed as a significant source of nutrition which could serve as a "stopgap" food while other interventions are in the deployment stage (Denkenberger and Pearce 2014), but the gathering of these leaves could prove economically challenging. This is in contrast with the LPC utilization of the agricultural residues that could be generated during the ASRS, such as wheat leaves from relocated crops.

Creating a publicly available database of proven safe to eat LPCs is a key opportunity for making LPC more commercially viable, to address the challenge of most leaves not being practical for LPC production. In addition, some leaves commonly used for LPC have anti-nutritional factors (Hussein et al. 1999). Creating such a database could be achieved by using an open-source liquid chromatography coupled mass spectrometry (LC-MS) toxicity testing pipeline (J. Pearce, Khaksari, and Denkenberger 2019) to quickly assess regionally applicable LPC input sources obtained by a network of locally owned production facilities around the world. There has been some screening of toxins done in various LPCs which indicates that it is safe for human consumption, provided that good practices such as improved residue harvesting and processing methods which reduce mold growth and presence of mycotoxins such as Aflatoxin B1 are used (Meyer et al. 2023), but further validation would be beneficial. Efforts to map the distribution of relevant forest classes and leaf biomass for LPC are important, but more work is needed (Fist et al. 2021). Low tech processing and toxin analysis of common North American coniferous trees indicated potential for consumption (Mottaghi et al. 2023), though harvesting of significant leafy biomass may only be viable in conjunction with harvesting main tree body for other uses, such as fuel or lignocellulosic sugar production (see Section "Food without agriculture: high-tech food solutions for ASRS").

Mushrooms

Mushrooms can be grown both outdoors in the natural environment or, more relevant to a global catastrophic scenario, indoors under dark, cool, and slightly damp conditions. They are relatively fast growing as a food source, enabling a quick ramp up to meet a significant fraction of the global caloric needs (Denkenberger and Pearce 2014). It is estimated that in 2021, however, the global mushroom production was 44 million tonnes (FAO 2024), which works out to only about 0.2% of the minimum recommended caloric intake for the global population, as the vast majority of the mushroom mass is water (typically ~85–95%).

The major benefits of mushrooms are that they are easy to grow, can be grown almost anywhere, even on decomposing wood and landfills, can be scaled up quickly as each one produces around a billion spores (Dressaire et al. 2016), and do not require sunlight, making them a promising food source in the event of ASRS. If treated with ultraviolet light, they can be a good source of vitamin D, an essential nutrient which would be difficult to obtain in an ASRS, due to the reduction in sunlight availability for one's skin to absorb it naturally, and the potential risk of trying to do so if the ozone layer is damaged in the ASRS (Pham et al. 2022). This would be especially important if one's diet contains few animal or microbial foods, the only other dietary sources of vitamin D. In addition, the waste from mushroom cultivation could be used as a feed source for organisms such as ruminants that are able to digest cellulose (Denkenberger et al. 2017).

Although mushrooms can convert indigestible plant biomass into food, they are not able to do it as efficiently or at as low of a cost as other food production methods as they have high economic and energy costs per calorie produced (Denkenberger et al. 2019; Salehi et al. 2014). Mushrooms can make significant micronutritional contributions to the diet, however, and automation has been proposed as a means to significantly reduce production cost through reduction of their intensive labor cost. Pilot research to assess the feasibility of individuals growing a large percentage of their calories from mushrooms, perhaps in basements with limited training and electricity, could be relevant for combined ASRS and GCIL scenarios. In addition, work in co-locating mushrooms, which produce carbon dioxide, with photosynthetic forms of indoor growing, like greenhouses, could be valuable to optimize yield per area.

Water-based solutions

Low-tech microalgae cultivation

Microalgae are microscopic forms of algal biomass which grow in water by fixing CO_2 through photosynthesis using sunlight or other sources of light energy. They are highly nutritious and have a long history of being used for food by people, such as in Chad and Mexico. Microalgae are commercially cultivated in: 1) high-tech photobioreactors using artificial light; 2) translucent photobioreactors (e.g., made of plastic) using sunlight; 3) indoor raceway ponds covered by a temperature-controlled greenhouse; and 4) open air raceway ponds which are a simple way to grow large quantities of biomass at lower cost, but which result in lower yields due to minimal control over growing conditions (García Martínez, Behr, and Denkenberger 2024). Current photobioreactor technology is not resilient to GCIL scenarios and is considerably more energy-intensive and costly when using artificial light compared to other resilient foods for ASRS response, with state of the art microalgae systems having ~2% conversion efficiency of electricity to calories compared to hydrogenotrophic bacteria at over 10% (García Martínez, Behr, and Denkenberger 2024), so only the other methods are considered potentially relevant here. Cost estimates of microalgae production in open ponds indicate promise, for example, a final slurry product containing 20% mass content of microalgae could be obtained at a cost of ~$0.70 per dry kg, although producing a food grade and/or dried product could result in much higher costs. However, it has been estimated that using the top 5% most suitable areas near 20 km of the coast for microalgae cultivation could produce 588 megatonne/year, more than the global protein demand projected for 2050 (Greene et al., 2022). More discussion of microalgae can be found in a partner study (García Martínez, Behr, and Denkenberger 2024). Economic and scale-up models are needed to characterize the potential of microalgae in ponds or simple sunlight-based bioreactors as a resilient food source for global catastrophes.

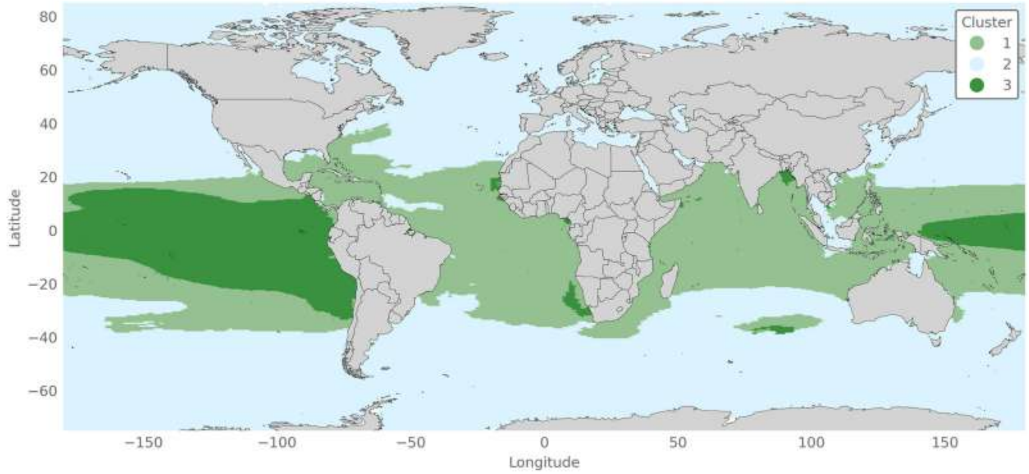
Seaweed

There is considerable underutilized potential for production of seaweed in the ocean, which can be used in a variety of foods consumed directly, or for animal feeds. Cultivation of seaweed can be fairly simple, using minimal technological resources including little more than ropes, buoys, anchors, and boats—although these systems are very labor-intensive, especially when compared with more high-tech automated systems. Seaweed can also be deployed relatively fast without experienced labor using longline systems (Tullberg, Nguyen, and Wang 2022). By increasing seaweed production, there could be numerous benefits toward nutrition, employment, and mitigation of CO_2 emissions, especially through cattle feed (Duarte, Bruhn, and Krause-Jensen 2021).

Seaweed cultivation in the ocean has been performed for centuries in many regions, particularly around East and Southeast Asia, starting in the 1600s in Korea using simple bamboo structures (Hwang et al. 2020), but historically remained fairly small in scale. Cultivation of seaweed has grown tremendously in the past 70 years, reaching 35 million tonnes (wet mass) in 2019 (Cai et al. 2021). At an increased 14% per year growth rate of cultivation, seaweed would yield approximately 500 million tonnes (dry weight) by 2050, which would increase the current world's food supply by about 10%, by taking up only ~0.03% of the ocean surface (World Bank Group 2016). Globally 20–48 million km^2 are estimated to be suitable for seaweed production with yields of 900–3,300 tonnes (dry)/km^2/year (Jehn, Dingal, et al. 2024), implying this area has the potential to produce the equivalent of the global population's calorie requirement many times over.

Research by Jehn et al. indicates that, in less than a year, global seaweed production could be increased to create an equivalent of 45% of the global calorie demand, see Figure 7 (Jehn, Dingal, et al. 2024), although such a degree of scaleup would require scaling up other industries required for the cultivation infrastructure such as rope production. Scaling up the seaweed species currently cultivated as a response to a global catastrophe would increase the availability of food for consumers and feedstock for biochemicals, biofuels or other bioproducts, if needed. The popular but more expensive species of seaweed could be switched to other species with faster growth rates or higher nutritional contents to serve as a quick and scalable addition to people's diets in the event of an ASRS (Jehn, Dingal, et al. 2024). Achieving this is relatively straightforward as different established species of seaweed usually have similar equipment needs and cultivation techniques (Taelman et al. 2015). Most seaweed cultivation is nearshore in wave-sheltered or semi-sheltered waters (Visch et al. 2023).

Seaweed production is not only resilient and capable of generating very large amounts of food, but is also cost-effective in ASRS. Hinge et al. estimated that in an ASRS up to ~250 million tonnes/year of dry seaweed could be produced at $0.50/kg or less, covering ~10% of direct human food needs on a caloric basis, or ~750 million tonnes/year at $1/kg or less. Roughly half of this cost originates from cultivation and the other half from drying. Seaweed could be produced in significant quantities even using just shallow waters close to ports in a few key areas in the tropics. The countries with the highest production potential in ASRS at low costs are Indonesia, Nigeria, India, Angola, Philippines, Peru, and Mexico (Hinge et al. 2024). Figure 7 shows how the Pacific cold tongue has a vast area of high yield potential, but it would be hard to exploit economically given the deep water and great distance from



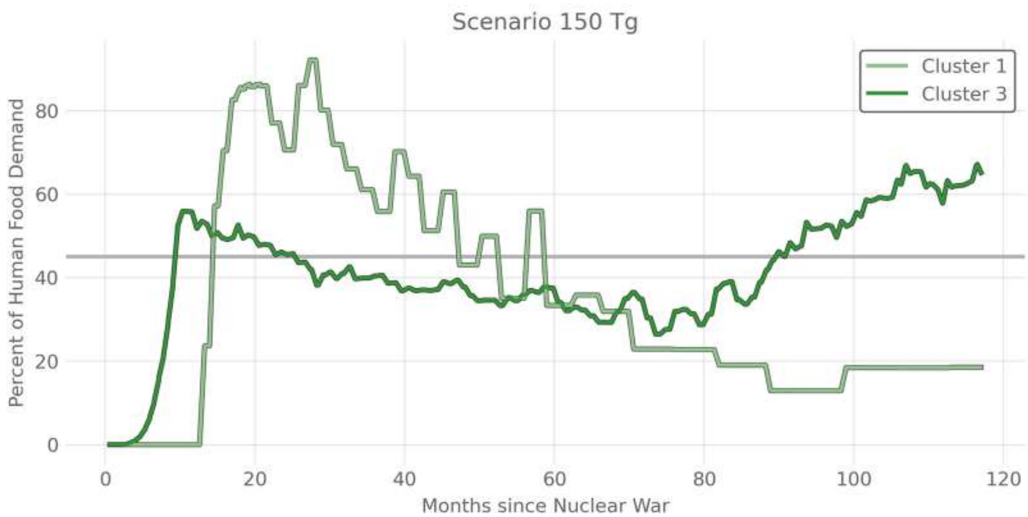


Figure 7. a) Global locations of seaweed (*Gracilaria tikvahiae*) growth regime clusters for a 150 Tg nuclear war scenario (3 is high growth, 1 is moderate growth); b) Seaweed production as percent of human food demand for suitable seaweed growth clusters (150 Tg nuclear war scenario and 30% per day as optimal growth rate). This is optimized for meeting an equivalent of 45% of the global human food demand on average for the whole 10 years (gray line), so cluster 1 requires much more area. Material adapted from: Florian Ulrich Jehn, Farrah Jasmine Dingal, Aron Mill, Cheryl Harrison, Ekaterina Ilin, Michael Y. Roleda, Scott C. James, David Denkenberger, Seaweed as a Resilient Food Solution After a Nuclear War, *Earth's Future*, published 2024 by AGU Publications (CC BY 4.0 license, no changes made).

shore. Perhaps ways to exploit that potential during an ASRS could be found; for example, combining seaweed growth with fishing operations in the area might help.

There is a limit to the amount of seaweed that people could eat due to its high iodine and other mineral content (Jehn, Dingal, et al. 2024), but there are seaweed treatment methods that address this effectively (Zava and Zava 2011). In addition, not all populations can digest seaweed as efficiently. For example, East Asian populations generally have better gut flora for seaweed digestion (Pudlo et al. 2022).

Future work to develop the potential of seaweed to prevent global famine in catastrophes should analyze the scale up of the infrastructure needed for seaweed cultivation and processing, especially drying which can make up a significant share of the final product cost. Pilot testing of rapid seaweed deployment at scale should be done to determine its feasibility for rapid food catastrophe response. Drafting a fast deployment plan to quickly ramp up seaweed cultivation in the event of a global catastrophe could help ensure its success as a resilient food source. This may include rapid tooling (e.g., fiber and rope production, rope twisting) and supply chain risk management (e.g., import and/or export of spores/fragments) as well as personnel deployment planning. Research could be undertaken on the topic of increasing the digestibility of seaweed—especially for populations that have not historically consumed significant quantities and thus may possess suboptimal gut flora—including methods for seaweed processing and extraction of seaweed nutrients, as well as supplements (e.g., probiota) to overcome the challenge of gut flora to aid digestion.

Seaweed cultivation is already commercialized on land in large pools by companies like Acadian Seaplants and could be scaled considerably to provide food during a catastrophe. Future work is needed to assess the potential of onland seaweed cultivation in emergencies at the industrial scale as well as potentially on the community scale by converting hot tubs and pools into seaweed farms. Open-source control systems for photobioreactors could be developed to accelerate both of these potential sources of resilient food.

Regular fishing

Fish would continue to be a useful food source even in the event of a global catastrophe since they could continue to be harvested normally, as long as the relevant infrastructure is operational (e.g., liquid fuel production, spare parts for fishing vessels, refrigeration technology, port facilities, navigation and sonar equipment, weather forecasting), but even with very limited infrastructure some low-tech fishing could be maintained. The world catches approximately 178 million tonnes (live weight) of aquatic animals (excluding mammals) annually (FAO 2022b). Fishing currently contributes ~35 kcal/person/day to the average diet, equivalent to only ~1.7% of the global human caloric requirement (though it is a considerable ~7% of the protein requirement) (FAO 2020). The amount available in ASRS is uncertain due to conflicting factors, but models point to some reduction in availability. For example, recent physical ocean models suggest that the reduced light and cooler ocean temperatures that would occur during an ASRS would negatively impact fish populations, e.g., with global biomass and catch expected to fall by up to 18 ± 3% and 29 ± 7% in a 150 Tg nuclear winter scenario (Harrison et al. 2022; Scherrer et al. 2020), see Figure 8 for various possible scenarios. In an ASRS the increased cooling of the upper layers of the ocean could increase upwelling thus bringing more nutrients to the ocean surface, but models indicate an overall negative effect. (Denkenberger et al. 2017) have also proposed that fertilizing the ocean with macronutrients such as nitrate and phosphate may help maintain fish densities in an ASRS, which could be useful in scenarios where land agriculture is decimated but significant fertilizer production remains. More research is needed on these uncertainties.

The collapse of food webs in a severe ASRS scenario would likely cause a mass extinction event both on land and in the ocean, regardless of the success or failure of resilient food interventions. Impacts on ocean biodiversity and the long term livelihoods of fishers may be reduced in an ASRS by focusing on other resilient food solutions for fulfilling the population's protein requirement. In addition, implementing effective fisheries management and expansion of marine reserves prior to a catastrophe would increase the oceans' potential contribution during a global food emergency (Scherrer et al. 2020), while likely reducing the risk of mass ocean collapse resulting from it as well as producing more food in normal conditions.

The likely limiting factor for expanding fishing would be the availability and capacity of fishing boats. Military, shipping, and personal craft boats could, however, potentially be repurposed as fishing vessels and larger boats could be leveraged for ship-to ship cargo transfer to minimize travel distance (Denkenberger and Pearce 2014), and this could warrant pilot testing. One important piece of future work is incorporating nutrients from river runoff into existing fisheries and ocean ASRS models (Harrison et al. 2022; Scherrer et al. 2020).

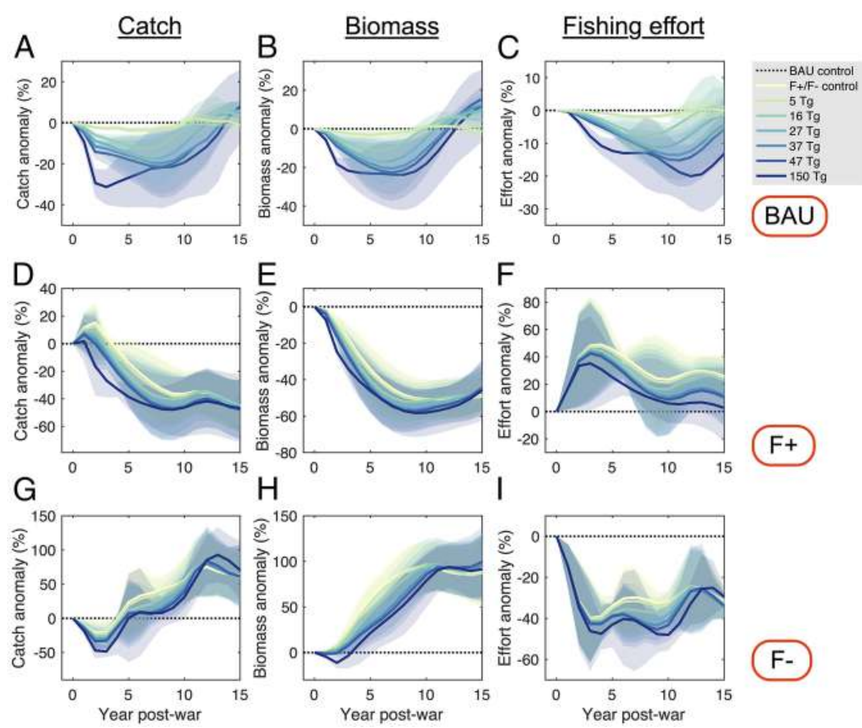


Figure 8. Global fishery developments postwar. Panels show the percent anomaly from the BAU control scenario (dashed line) for all soot inputs (solid lines). Upper row (A–C) shows trajectories of catch, biomass, and fishing effort under BAU fishing, middle row (D–F) shows trajectories under the intensified fishing scenario F+, and lower row (G–I) shows trajectories under the decreased fishing scenarios F−. The shaded areas show SD for the five parameter ensemble runs, while the solid lines are the ensemble mean. The light yellow lines in D–I show the F + and F − responses in the absence of a climatic perturbation, i.e., the F + or F − control. Material adapted from: Kim J. N. Scherrer, Cheryl S. Harrison, Ryan F. Heneghan, Eric Galbraith, Charles G. Bardeen, Joshua Coupe, Jonas Jägermeyr, Nicole S. Lovenduski, August Luna, Alan Robock, Jessica Stevens, Samantha Stevenson, Owen B. Toon, and Lili Xia, Marine wild-capture fisheries after nuclear war, *PNAS*, published 2020 by National Academy of Sciences of the US (CC BY-NC-ND 4.0 license, no changes made).

Deep sea fishing (mesopelagic fish)

In the mesopelagic region of the deep sea, there are numerous species of fish which are suitable for human consumption. It has been estimated that there are 10 billion tonnes of mesopelagic fish biomass, likely dominating the world's total fish biomass (Irigoien et al. 2014). This total mass, assuming an average calorie content of ~1,500 kcal/kg based on (Alvheim et al. 2020), equates to just over twice the yearly caloric requirement of the global population. Very limited fishing in this region is done, however, as the harvesting season is short and the ventures are not always profitable (Fjeld et al. 2023). Between 2015 to 2019, deep sea fishing of 26 vessels in the North-East Atlantic amassed on the order of magnitude of 10^5 tons per year (spending a combined total of ~30,000 h per year fishing) (Paoletti et al. 2021).

Many species of fish found in the mesopelagic region are high in omega-3 fatty acids and other key micronutrients (Alvheim et al. 2020). Deep sea fishing could make significant contributions during an ASRS as it is currently underexploited and could be a reliable source of fish when regular fish populations decline, as suggested by Scherrer et al. (2020). Specialized shipping vessels for deep sea fishing are likely not required, but the vessels should be capable of capturing various different species of fish (Fjeld et al. 2023). Although deep sea fishing has the potential to be profitable, in some locations the catch per ship would be too low, with high bycatch (Paoletti et al. 2021). Preliminary analysis is needed to characterize the potential, cost, and feasibility of rapid mass deployment of mesopelagic fishing technologies for ASRS and GCIL response. This should look at the potential for converting bycatch to food and any technical improvements to be made to make deep-sea fishing economic. If the potential was high, a pilot demonstration of repurposing ships into fishing vessels would be valuable.

Krill fishing

Krill, a well-known type of mesopelagic crustacean, are a common food source for many marine animals, but they are also suitable for direct human consumption. It is one of the most numerous animals on Earth, with an estimated biomass of at least 379 million tonnes (wet) around the poles (Atkinson et al. 2009). Primarily Antarctic krill (*E. superba*) are fished in the Southwest Atlantic using trawlers, as well as North Pacific krill (*E. pacifica*), with a total annual catch of 450,000 tonnes (Cappell, MacFadyen, and ConsTable 2022). From a nutritional perspective, krill is an excellent protein, containing every essential amino acid, and is high in antioxidants and omega-3, calcium, phosphate, magnesium, and vitamins A and E (Tou, Jaczynski, and Chen 2007).

The low availability of infrastructure and knowledge to catch krill is a critical limitation for krill fishing as a resilient food intervention. Other limitations include a better understanding of krill population management and more accurate population monitoring technology (Nicol, Foster, and Kawaguchi 2012). Preliminary analysis is needed to characterize the potential, cost, and feasibility of rapid mass deployment of krill fishing technologies for ASRS and GCIL response. It is likely that existing trawling fishing vessels and personnel could be utilized to increase krill catch (Nicol, Foster, and Kawaguchi 2012), and this could be tested as a catastrophe preparedness pilot experiment. Future research could also investigate low-cost industrial and distributed means to manufacture the fine mesh nets needed for harvesting krill.

Bivalve cultivation

Bivalves, including clams, oysters, cockles, mussels, and scallops, can be grown similar to seaweed, on ropes suspended in the water from a long line supported by buoys, and feed on widely available phytoplankton. Global bivalve production was on average ~15 million tonnes per annum between 2010–2015, with 89% of that coming from aquaculture (Wijsman et al. 2019). Bivalve production yields vary considerably depending on the species and environment, but reported values for mussels are high, ranging between 6,000–59,400 tonne/km^2/year (Gren 2019), or roughly 1,300-13,000 tonnes (dry)/km^2/year. Within the exclusive economic zones of suitable countries, 31 million km^2 are estimated to be environmentally suitable for molluscs (Oyinlola et al. 2018), a fraction of which would suffice to cover the equivalent of the global population's caloric requirement even at the lower end of yield—which is probably more representative of a farming style not requiring external nutrient addition. Considering only the coastlines, where production would be most economical, the potential of bivalve mariculture has been estimated at 592 megatonne (Willer, Nicholls, and Aldridge 2021), which at 80% water content would cover ~7% of the global food requirement.

What makes bivalves a promising resilient food technology is their simple cultivation (Helm and Bourne 2004), high nutritional value, existence of a developed industry, and resilience to sunlight reduction—their primary substrate (phytoplankton) is less affected by changes in sunlight than land crops (Harrison et al. 2022; Xia et al. 2022). 50–70% of the calorie content of bivalves comes from protein, and they provide complete proteins, are a great source of sodium, potassium, calcium, magnesium, iron, zinc, copper, and chromium, and are rich in polyunsaturated fatty acids with high levels of DHA and EPA (Karnjanapratum et al. 2013), unlike many other resilient foods which are poor in omega-3 fatty acids. The cost of producing bivalves is between $1–4/kg (wet) (Wijsman et al. 2019), which at 80% water content translates to $5–20/kg (dry) or $2.50-10.00 to fulfill a person's daily caloric requirement, higher than other resilient foods. This translates to a cost per unit of protein of ~$7–40/kg protein, or $0.40-2.40 for a daily protein requirement of 60 grams.

Further research is needed to characterize the potential, cost, and feasibility of rapid mass deployment of bivalve cultivation technologies for ASRS and GCIL response. Other relevant questions include: how bivalves would be affected by reduced phytoplankton productivity during a nuclear winter, where they could be grown, and whether they could be co-produced with seaweed effectively during ASRS.

Integrated multi-trophic aquaculture (IMTA)

IMTA comprises the cultivation of fed species of sea animals (such as finfish or shrimp) along with extractive species, such as suspension-feeding (e.g., mussels and oysters) as well as deposit-feeding (e.g., sea-cucumbers and sea-urchins) invertebrates, and seaweed that are fertilized by the organic and inorganic waste from the fed species (Buck et al. 2018). The fed species are kept in enclosed netted areas, the suspension-feeding invertebrates and macroalgae are grown on moored submerged longlines, and the deposit-feeding invertebrates are kept in cages on the seafloor (Tzachor, Richards, and Holt 2021).

IMTA can be implemented in temperate waters and has been demonstrated in the waters of Canada, Chile, China, France, Ireland, Norway, Portugal, Spain, South Africa, the United Kingdom (mostly Scotland), and the U.S. (Barrington, Chopin, and Robinson 2009). It has potential for wide-scale use since between 25 million and 31 million km^2 of the ocean are considered to be environmentally suitable for both finfish and molluscs (Oyinlola et al. 2018). The pioneering IMTA system in Sanggou Bay, China, boasts a biomass production yield of 2,400 tonne/km^2/year (Fang et al. 2016)—even at a fraction of this yield, an area of 25 million km^2 should suffice to cover global calorie requirements, although production may only be economic in the subset of this area closest to the coast. During an ASRS, water temperatures would change, so the coasts of the tropics could become more temperate, making it a more viable option for IMTA. Small scale implementations of near shore versions of IMTA systems are relatively simple to construct (Parappurathu et al. 2023), and progress is being made toward making IMTA relatively effective, low-investment, and low-maintenance (Resende et al. 2021). Presently, China is the world leader in IMTA, generating more than 40% of its mariculture production of 14 million tonnes (including shells) of shellfish and 25 million tonnes (wet weight) of seaweeds (FAO 2022a). Incentives for developing IMTA are lacking, but changes to current regulations and policies, such as requiring aquaculture operations to internalize nutrient discharge costs, would incentivize the development of IMTA from the pilot scale to the commercial scale in new regions (Chopin 2013). Future research on the potential, cost, and feasibility of rapid mass deployment of bivalve and seaweed cultivation in ASRS and GCIL should include IMTA.

Food without agriculture: high-tech food solutions for ASRS

Modern industrial technologies such as fermentation, biosynthesis, and chemical synthesis enable enormous potential for the production of food virtually independent of environmental conditions, using CO_2, biomass, or hydrocarbons as raw materials. Developed in the last century, these methods can not only produce all 3 macronutrients (see Figure 9), but also key micronutrients such as vitamins, essential amino acids and essential fatty acids, especially through precision fermentation. These technologies and their application for food production, especially in conditions of extreme agricultural catastrophe such as an ASRS, are discussed in-depth in the review article complementing the current one by (García Martínez, Behr, and Denkenberger 2024).

Further research is needed on most of these technologies, but at least two of these are particularly promising for helping prevent a global catastrophic food failure: 1) the production of single cell protein from methane (e.g., in natural gas or biogas) can be an affordable, widespread, high-quality source of proteins and even some fats and carbohydrates in catastrophic scenarios (García Martínez et al. 2022); and 2) the conversion of lignocellulosic biomass to sugar (Throup et al. 2022). The latter could be used not only as an affordable caloric contribution in ASRS—especially when obtained through rapid repurposing of paper mills and second generation biorefineries—but also as a platform for precision fermentation to obtain all kinds of essential nutrients fundamental for human health, to prevent malnutrition. Of note is the capacity to produce micronutrients which could be scarce in an ASRS, such as essential fatty acids and certain vitamins. Vitamin C is already produced industrially at 140,000 tonnes/year, and lysine at 2.2 million tonnes/year (García Martínez, Behr, and Denkenberger 2024).

In an agricultural catastrophe, these technologies could serve multiple purposes: 1) to be used as food ingredients to counter agricultural yield reduction if needed such as in major crisis scenarios (e.g., ASRS); 2) to secure the animal feed supply required to keep animal agriculture sectors afloat; and 3) as an intermediate for strategic production, for example, cellulosic sugar could be used as a fermentation platform for strategic production of nutrients (vitamins, omega fats, etc.) or even biofuels if a fuel shortage is involved. For example, converting the entire global production of roundwood and agricultural residues to sugars could produce an amount of calories equivalent to the entire global population's caloric requirement, at an estimated cost of $0.43-0.91 to provide a person's daily caloric requirement (Throup et al. 2022). Converting the entire global production of natural gas to food through single cell protein production results in nearly 3 times the caloric requirement of the global population, or 9–15 times the protein requirement, with models indicating that fulfilling the global protein requirement using this technology could be done in a few years—at an estimated cost of $1.65-2.81 to provide a person's daily caloric requirement or $0.15-0.25 for the daily protein requirement (García Martínez et al. 2022). Paraffins derived from oil could be converted into synthetic fats to produce 8–17% of the global caloric requirements at an estimated cost of $0.74-2.71 to provide a person's daily caloric requirement (García Martínez, Alvarado, and Denkenberger 2022; García Martínez, Behr, and Denkenberger 2024). Other methods of this kind are discussed in Appendix B.

To increase agricultural catastrophe resilience and technology deployment speed, investments can be made in non-agricultural resilient foods, including constructing a fast pilot (24/7 construction) methane single cell protein (García Martínez et al. 2022) and lignocellulosic sugar production plant, and pilot repurposing facilities like paper factories for sugar conversion (Throup et al. 2022). Further repurposing potential analyses should be done for other industries and high-tech industrial foods, such as for repurposing breweries

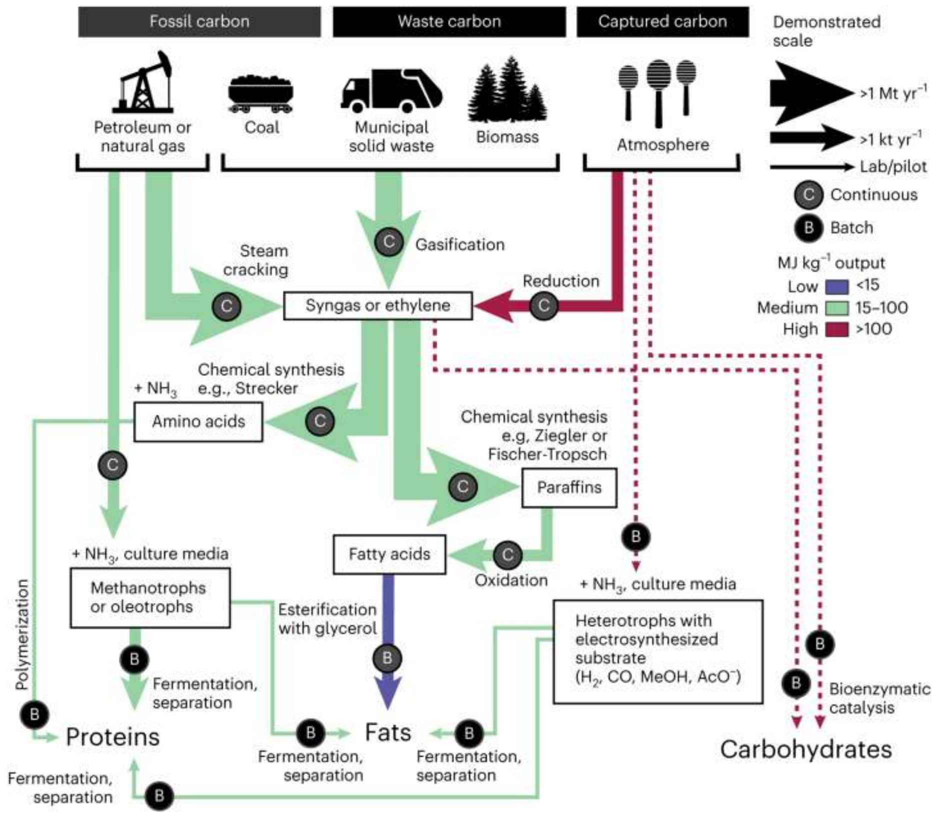


Figure 9. Schematic of selected pathways to synthesize food without agriculture. Material reprinted from: Steven Davis, Kathleen Alexander, Juan Moreno-Cruz, Chaopeng Hong, Matthew Shaner, Ken Caldeira & Ian McKay, Food without agriculture, *Nature Sustainability*, published 2023 by Springer Nature (CC BY 4.0 license, no changes made). Other relevant pathways (not pictured) include the conversion of biomass to carbohydrates through methods other than gasification, the conversion of those sugars to proteins, fats, and essential micronutrients through fermentation, or the cultivation of photosynthetic microorganisms.

to SCP production. Future research could also focus on process development, food safety, and product development research on converting other widespread nonagricultural inputs into food, and establishing safety and quality standards. Finally, forming public-private partnerships with pioneering companies could offer insights into scaling up production effectively, and leveraging current commercial trials in various feed markets to potentially achieve economies of production scale similar to the learning curves seen in renewable energy (García Martínez, Behr, and Denkenberger 2024). Lastly, for each type of high-tech solution efforts can be made to make open-source small-scale systems that can be mass replicated to provide distributed resilient food production.

Policy work on resilient food solutions and related interventions

In 2021, the United Nations Secretary General made a call for “defining, identifying, assessing and managing existential risks” as part of the UN Common Agenda. These risks may comprise the majority of the risk threatening modern societies, but they are rarely considered as such in governmental risk management policies (Boyd and Wilson 2023b). Addressing tail risks of food systems is a neglected priority of our time in line with this thinking, and public policy must be applied in tandem with resilient food technology research and development to mitigate global catastrophic risk and existential risk related to food systems. Various groups are currently working to produce such policies.

Reports scoping out national risk preparedness plans to prevent a food failure in case of an ASRS have been produced for several countries, such as for Argentina (Ulloa Ruiz et al. 2024), by the Alliance to Feed the Earth in Disasters (ALLFED) and the Observatorio de Riesgos Catastróficos Globales (ORCG), and for New Zealand (Boyd, Payne, et al. 2023). There is historical precedent for this type of risk preparedness plans against other high-impact low-probability hazards, both natural (e.g., tsunamis) and anthropogenic (e.g., nuclear plant accidents). These efforts have called for establishing the national capability to deploy the resilient food interventions described in the current work, as well as complementary ASRS interventions to maintain equitable food access (rationing, producer subsidies, price controls, food vouchers), and highlighting the importance of international cooperation, water management, flexible legislation to reduce food-based biofuel production quotas, and food waste reduction in ASRS. Figure 10 shows the estimated increase in food production in Argentina for increasing levels of implementation of disaster response policies including resilient foods, demonstrating how they could not only potentially avoid a national famine but vastly increase food production in the region (Ulloa Ruiz et al. 2024), reducing the risk of conflict and refugee crises.

(Boyd, Payne, et al. 2023) have presented an extensive set of recommendations for New Zealand to be used as the

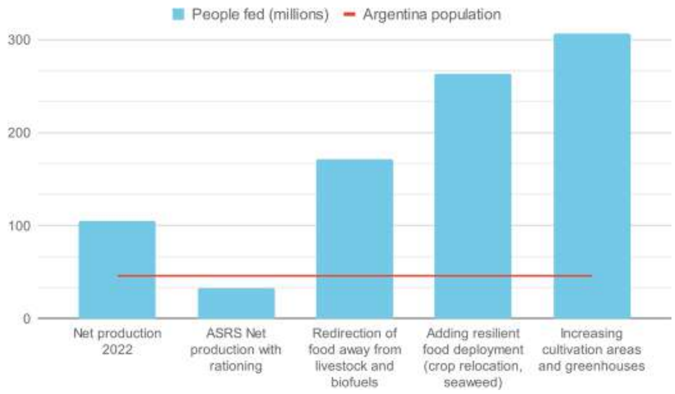


Figure 10. Estimated increase in food production in Argentina in terms of people fed for increasing levels of implementation of relevant disaster response policies, including resilient foods. The first bar is current net food production, and the rest represent 150 Tg ASRS conditions with increasing adaptations from left to right—meaning the last column includes not just increased area and greenhouses but also rationing, redirection, and resilient food deployment. Material reprinted from: Mónica A. Ulloa Ruiz, Jorge A. Torres Celis, Morgan Rivers, David C. Denkenberger, Juan B. García Martínez, Soluciones alimentarias resilientes para evitar la hambruna masiva durante un invierno nuclear en Argentina, published 2024 by *Revista de Estudios Latinoamericanos sobre Reducción del Riesgo de Desastres REDER*, (CC BY-NC 4.0 license, translated, minor edits).

basis of a plan to weather a nuclear war between foreign powers, discussing not only how to prevent a nuclear winter-induced food failure in the region but also focusing on maintaining provision of other critical infrastructure needs (energy, water, transport, communications) in the face of other extreme consequences that may arise in the scenario, such as a loss of international trade and coordination. Among these, the report contains many which are applicable to any other country: development of a National Food Security Strategy that includes these shocks (vulnerability assessments, quantification and supply of food, water and energy needs, infrastructure needs), development of plans for fuel management in catastrophe (supply, rationing, and deployment of fuel alternatives like biofuel), targeted investments (strategic stockpiles of seeds, agricultural inputs, and critical parts for machinery, information infrastructure for dissemination of contingency plans, biorefining capacity), establishing collaboration agreements with neighboring nations in case of global food crises, and assessment of the local cost-effectiveness of these resilience options.

Finally, Glomseth has called for ASRS preparedness in Norway, suggesting a cross-sectoral collaboration between the Norwegian food and trade ministries, civil protection agency, and Nuclear Safety Authority (Glomseth 2024).

National contingency plans can be developed to maintain the population's basic needs even in the case of a GCIL, incorporating a "reverse roadmap" that describes how to temporarily return to less advanced agriculture, water provision and energy systems. These could draw from historical case studies such as the example of Cuba in the post-Soviet Collapse, as highlighted by Boyd, Payne, et al. (2023), whose numerous recommendations for contingency planning are also relevant to GCIL planning. Agronomic research in current subsistence agricultural production systems could also be relevant to this effort. It should be noted that no historical case studies provide quite the necessary context for this work, which is a challenge of this type of extrapolative research.

Discussion and future work

Deep uncertainty and scenario characterization work

The field of research on resilient foods deals with mitigating the impact of a range of extreme catastrophic scenarios with limited historical precedents. While scenario characterization is not the focus of the current work, it is important to clarify the presence of fundamental uncertainties involved. There remains significant uncertainty on the risk distribution and degrees of severity to be expected, both for ASRS and GCIL, as well as the probability of the scenarios materializing from different hazards (Denkenberger et al. 2021; Denkenberger et al. 2022). For example, the risk distribution of ASRS scenarios is not well studied, with milder scenarios more likely than more severe scenarios, and with varying degrees of severity and probability depending on origin (volcanic, nuclear, or asteroid/comet). Another example is how, for nuclear ASRS, uncertainty remains in myriad factors such as the probability distribution of the number of nuclear weapons likely to be used in the conflict, the types of targets and their flammability, and the likelihood of generated sunlight-blocking particles reaching the stratosphere (Hess 2021; Pinsent and Tan 2024), to name some. For GCIL, there also remains uncertainty as to how likely the related hazards are (e.g., HEMP, solar storms, cyberattacks, pandemics) and what degree of supply chain disruption they would entail (Denkenberger et al. 2021; Denkenberger et al. 2022). For both ASRS and GCIL, a considerable uncertainty is to what degree reduced coordination and cooperation may hinder food responses regardless of prior preparation, and how much the development and knowledge of resilient foods can prevent these instabilities from becoming unmanageable. In other words: is there a degree of shock at which societal systems collapse no matter how much preparation is in place, perhaps due to breakdown of social order? Or can a sufficiently fast and effective response prevent this?

All of these considerations and more are fundamental to mounting an effective catastrophe response. The degree and type of the shock determines which of the interventions should be prioritized. Consider different types of scenarios: 1) a mild ASRS with minimal supply disruption, in which the best move is probably to prioritize interventions aimed at maintaining food trade and increasing food conservation, such as redirecting crops away from animal agriculture and biofuel production; 2) a severe nuclear winter, which would require a much more comprehensive food resilience response with varying degrees of deployment of many or all of the foods described in this work across all levels of technological sophistication; 3) a scenario with both severe ASRS and GCIL which would severely constrain the response to food conservation and ASRS-resilient foods based on simple technologies (see the top right quadrant of Figure 5, and for more discussion of this scenario see (Denkenberger et al. 2017)).

This is why it is important to have a portfolio of resilient foods ready to be deployed, allowing people to respond and provide enough food given the large variety of possible future shocks—this variety of options, known as response diversity, is the basis for adaptive behavior (Walker et al. 2023). In addition, further research is needed to bound these risks, which would inform both which interventions are the most important for response across all hazards, and what level of resilience investment is warranted to insure people against them. Finally, uncertainties around the flexibility of markets and nations to redirect resources and engage in response interventions inside and outside of their borders warrant future work on resource distribution such as integrated models (Rivers et al. 2024) and economic analyses of resilient foods responses in a variety of scenarios.

Future work on resilient food research and development

A long list of future research and development areas have been proposed in the sections of each food production method. This section focuses on summarizing at a high level and discussing additional ideas not focused on one particular food.

Basic research work is still needed on food production methods, production ramp-up, and technology deployment, as well as research on the nutrition and safety of some of the more novel foods. For example, some resilient foods would benefit from conducting food safety and nutritional studies which verify that the novel foods created from these technologies are safe and nutritional for human consumption in the long term, such as the different types of leaf protein concentrate, some seaweeds, or some novel industrial foods. In addition, basic analysis of key metrics to characterize the potential of various food production methods (cost, speed, and feasibility of mass scale deployment in catastrophe conditions) is still missing, such as for expanding planted area, krill fishing, bivalve cultivation, IMTA, leaf protein concentrates, duckweed, foraged resources, and various technologies for industrial production of food without agriculture. A technical readiness level analysis of all resilient foods could be made for both industrial and small-distributed scale. For those with a lower technology readiness level, optimizing existing production processes may yet be needed. Research on decentralized food production would also be beneficial, including the production of open-source engineering designs for food production equipment, and the study of the potential of ramping up urban agriculture.

More ambitiously, a large plant breeding or genetic engineering program could be launched to try to enhance ASRS resilience traits in staple crops, such as tolerance to frost, drought, and lower sunlight. However, the multigenic nature of these traits could make it technically challenging to achieve considerable improvements while maintaining high yields. If ASRS-resilient but lower yielding staple crops were developed, they would not replace regular high-yielding varieties in global agriculture. In this case, stockpiles of ASRS resilient seeds could be maintained as a backup, but they would need to be of considerable size in order to deploy at sufficient speed to counter ASRS-induced losses, requiring significant investment. Considerable uncertainty remains on this option, requiring further research.

Finally, and most importantly, further development and piloting of resilient food technologies would be conducive to a faster response, through rapid deployment including fast construction and repurposing, as described throughout Section "Resilient food solutions". Future research will focus on analyzing in more depth the technology readiness level of resilient food solutions and what research and development is needed to improve it.

Future work on critical infrastructure resilience for GCRs

There is a long list of research projects that would support food resilience and other critical infrastructure resilience against global catastrophic risks such as an ASRS or GCIL. From (Boyd, Payne, et al. 2023) several items for further research in the field are clear, which could be applied to any region of the world for food resilience, perhaps funded by the local government. These include: 1) determining logistics of supplying minimal fuel for agricultural equipment, and minimal agricultural inputs (especially if these are normally imported), 2) quantifying current food production and distribution under nuclear winter and zero trade/scarce fuel conditions, and 3) investigating the possibility of rapidly switching from diesel to electrification or biofuels for agriculture and supply chains in nations dependent on imported fuel to respond to a trade breakdown. Denkenberger et al. have proposed research on rapid deployment of many interventions for resilience to GCIL, including: 1) burning wood from landfills to provide an alternative to synthetic fertilizer; 2) rapid deployment of nitrogen fixing crops including legumes (peas, beans, etc.); 3) nonindustrial pest control; 4) low-tech alternatives to current fuels in supply chains, such as biomass gasifier systems (Nelson, Turchin, and Denkenberger 2024; Vennard, Pearce, and Denkenberger 2024) or retrofitting appropriate vessels to use wind power; 5) retrofitting widespread technology such as household ovens for space heating (Jose et al. 2024); and 6) alternative communication systems such as EMP-hardened satellites or a network of shortwave radios (Denkenberger et al. 2017; Denkenberger et al. 2021). Backup energy generation plans for ASRS scenarios should be researched, considering increased future renewable energy penetration (e.g., rapid solar photovoltaic deployments underway), since a severe ASRS could reduce combined wind and solar energy generation by up to 59% (Varne et al. 2024). Interventions for providing other critical needs such as water distribution, sewage treatment, and healthcare should be studied. Finally, investing in satellite monitoring capabilities for soot or particulate emissions would help characterize the magnitude of shocks and expedite resilient food responses when needed.

Future work on GCR policy

At the national level, every government can develop a comprehensive National Food Security Strategy that tackles risks impacting food supply and corresponding resilience measures (Rivers et al. 2024; Boyd, Payne, et al. 2023; Ulloa Ruiz et al. 2024). They can also implement legislation for in-depth analysis of GCRs such as the Global Catastrophic Risk Mitigation Act of the USA (Sepasspour 2023), incorporate global agricultural catastrophes to their national risk assessments (Boyd and Wilson 2023b), develop government protocols that facilitate rapid adaptation of the food system and efficient scaling-up of resilient food solutions (i.e., response plans), and stimulate investment in the research and development of mitigation interventions as described in this work. This would all be done most effectively through an all-hazards policy approach (Sepasspour 2023; Boyd, Payne, et al. 2023). An impactful first step would be the formation of a national committee or task force to make recommendations on improving preparedness and response to global agricultural catastrophes, and identifying national food system vulnerabilities. Community consultations (surveys, citizen assemblies, Polis-type engagement) may also be useful (Boyd, Payne, et al. 2023).

At the international level, work could involve advocacy on multilateral resolutions that increase resilience to global catastrophic food failures, for example: UN proposals on how countries ought to collaborate and maintain trade in a catastrophe, share intellectual property in areas of resilient food, or make adjustments to international rules. Jehn et al. estimated that the unequally distributed food production disruptions in ASRS would require radical changes in trading partners, with most countries losing 50–100% of their imports (Jehn, Gajewski, et al. 2024). This transition could be eased through pre-catastrophe international trade agreements, but national actions may differ from international agreements in such crisis situations, especially in the absence of enforcement mechanisms (Hoffman et al. 2022), which complicates multilateral advocacy.

Concluding remarks

Catastrophes such as nuclear war or volcanic eruption could trigger a breakdown in the environmental conditions on which global food production depends (sunlight, temperature, precipitation), potentially reducing it by up to 90%. A collapse of critical global infrastructures, perhaps triggered by nuclear electromagnetic pulse, solar storm or extreme pandemic, could reduce crop production by 35–48% due to lack of agricultural inputs. Future developments in AI might facilitate similar catastrophes through coordinated cyber-attacks, or biotechnological development of new highly contagious and deadly viruses or new plant pathogens. At present, the world is ill-equipped to deal with these scenarios: food reserves could be depleted in a matter of months.

This work reviews the field of resilient food adaptations to these global catastrophic food shock scenarios, divided in four categories: 1) food conservation solutions (prioritizing crops away from animal feed and biofuels for human food, reducing food waste); 2) land-based solutions such as optimizing grass- and plant-residue–fed animal agriculture, relocating resilient crops, greenhouses, expanding cropland, and producing leaf protein; 3) water-based solutions (duckweed, algae, fishing, bivalves); and 4) high-tech industrial solutions for the production of food without agriculture. Included are both novel foods selected for their resilience and affordability in the face of catastrophe (single cell proteins, lignocellulosic sugar, leaf protein, etc.), as well as mature food production methods whose scalability is well known: crop relocation, ruminants, greenhouses, seaweed, fishing, bivalves, and mushrooms. Extensive recommendations for future research and development include rapid deployment trials and 24/7 construction pilots, production ramp-up and economic analyses, and food safety studies. The policy literature advocates for integrating these interventions into disaster preparedness. Recommendations include incorporating global catastrophes into national risk assessments and food strategies, developing national preparedness plans, forming task forces for global catastrophe resilience, and investing in rapid response capabilities.

Deep uncertainty, however, remains regarding the risk distribution of these hazards. Effective catastrophe response depends on the specific scenario, with varying strategies needed depending on its severity and specifics. Thus, developing a diverse portfolio of resilience interventions and a better understanding of the risks is crucial for ensuring food security in the face of global catastrophes.

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Abbreviations

ASRS	Abrupt sunlight reduction scenario
AI	Artificial intelligence

GCIL	Global catastrophic infrastructure loss
GCR	Global catastrophic risk
IMTA	Integrated multi-trophic aquaculture
LPC	Leaf protein concentrate
SCP	Single cell protein
HEMP	High-altitude electromagnetic pulse

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Appendix A: Other minor resilient foods

A.1 Other cellulose-digesting animals, e.g., insects and shipworms

Some insects (i.e., certain beetle and fly larvae, as well as termites) can also live on grass or agricultural residues (Martin et al. 1997; Ramzy et al. 2022). Some mollusks, such as shipworms—which have historically been consumed in some regions—can live on wood, much like termites. Insects reproduce extremely quickly, can be densely packed, and are amenable to decentralized food production from household food waste (Denkenberger and Pearce 2014). However, to the best of our knowledge there exist no sizable farming operations of insects fed on lignocellulosic biomass yet, and the shipworm farming industry is still under development (Willer and Aldridge 2020). On the other hand, ruminants are widespread and have been an established food source since prehistoric times. The advantage of insects is they have somewhat more efficient feed ratios than mammals, but their challenges include the low societal acceptance of their consumption in some cultures (Ros-Baró et al. 2022). There is also a difficulty to scale up to meet significant production (Denkenberger and Pearce 2014) in a cost-effective way (Denkenberger et al. 2019), since current methods for mass production remain expensive (Morales-Ramos et al. 2020).

For example, mealworms (*Tenebrio Molitor* larvae), a type of insect commonly studied for mass production operations, are being sold on the market by various companies at prices around ~$8/kg dry, equivalent to ~$4 to fulfill a person's daily caloric requirement. They have some capacity to digest cellulose (Li et al. 2016), but do not have the right microbiota to produce the cellulase enzyme that allows other animals such as ruminants and xylophages (wood eaters, e.g., termites, shipworms, gribbles) to break down cellulose into carbohydrates. Mealworms are comparable to poultry in terms of cost and feed efficiency, both having typical values of around 1.5-2.5 kg of weight gained per kg of feed consumed (Cassidy et al. 2013; Bordiean et al. 2020). Work on automation of insect production may reduce costs to an acceptable level, but highly automated systems could be harder to deploy in an ASRS, or impossible in a GCIL.

Considerable uncertainty thus remains on the potential of these animals as a resilient food source. Some research exists on rearing or harvesting termites or shipworms, but the literature does not have in-depth analyses of the feasibility and cost of producing food-grade products at scale, which could be addressed by future research. Trials on feeding agricultural residues to insects, similar to those proposed in the previous section for dairy cattle, would be useful to see if they would outperform ruminants in terms of calories in versus calories out. The usefulness of this research for catastrophe response is limited by the existence of potentially better options for mass deployment in this class, however, such as certain types of ruminants for ASRS and GCIL response, or single cell proteins for ASRS, which can be produced without consuming any human edible food at lower cost and are also high in protein (García Martínez et al. 2022).

A.2 Foraging

Many foods grow in the wild, including garlic, nettle, fungi, seaweed, fruits, and nuts, which can help feed the population in a global catastrophe. Tropical wild edible plants that are traditionally foraged have been proposed as viable for foraging following an ASRS, for both immediate consumption through foraging and for cultivation, such as konjac, wild cassava, vegetable amaranths, and safou (Winstead and Jacobson 2022).

Earthworms are another potentially foraged food which can be obtained through either simple manual means (e.g., charming/grunting) or through more complex means such as mechanical sieving, chemical expellants, or electroshocking (Miller et al. 2024). Earthworm density is extremely high in various regions of the world (Phillips et al. 2019), and the doubling time of an earthworm population is 60–70 days (Sinha 2009). The extraction of earthworms is very labor intensive, however, taking a median 6 h to obtain a person's daily protein needs, making it too expensive in regions without a very high earthworm density. The median cost to fulfill a person's daily calorie requirement is $185, but could be as low as $32 in regions with high earthworm density and low labor costs (Miller et al. 2024), which is still much less affordable than the most promising resilient foods. Another concern with foraging earthworms is that in the event of an ASRS, colder soil temperatures and reduced precipitation may make foraging more difficult. In addition, processing earthworms to be safe for human consumption is technologically intensive (Miller et al. 2024).

Although only a small percentage of the global population still forage for food, the availability of forageable food is still accessible evidenced by the prevalence of the modern foraging movement (Rickard 2022). A downside to foraging is that it requires knowledge of what foods are edible and which are not (or are poisonous) in order to be practical, and this knowledge is quite rare. There has been extensive development of smartphone applications that enable identification of plants which could be used to improve foraging potential, but this still involves risk. More analysis is needed to ascertain the potential of foraging and the means to leverage it as a catastrophe resilience intervention.

A.3 Freshwater pond plants, e.g., duckweed

Lemnaceae are the smallest flowering plants on Earth, and could constitute another water-based resilient food. More commonly referred to as duckweeds or water lentils, they grow in small freshwater bodies and float on the surface. Due to their fast growth rate and nutritional composition, duckweeds are used in numerous sectors including food, pharmaceuticals, and phytoremediation (Baek, Saeed, and Choi 2021). Duckweed is rich in protein (20–35%) and omega 3 fatty acids, and has been historically consumed as food in some South East Asian countries (Appenroth et al., 2017). It has also been approved as a novel food by the European Food Safety Authority (Turck et al. 2023). The global duckweed market is estimated to currently be worth $76 million USD and is projected to grow to $195.4 million by 2033 (Choudhury 2023). Another freshwater pond plant called *Azolla* has been suggested as a potential resilient food for similar reasons and potential advantages over duckweed (Winstead et al. 2024), such as lower nitrogen requirement through nitrogen fixation and higher cold and temperature tolerance, but they are not currently produced in significant quantities.

Duckweed grows exceptionally fast, producing up to 10,000 tonnes dry matter per km^2 (Cao, Fourounjian, and Wang 2018). Rubisco, a protein that can be derived in large quantities from duckweed, is highly digestible, has a complete nutritional profile, and has numerous beneficial culinary properties (F. G. Pearce and Brunke 2023). For these reasons, companies such as Plantible, Rubisco Proteins, Rubisco Foods, DryGro, Urban Tiller, Sustainable Panet, and Microterra are working on the mass commercialization of Rubisco proteins from duckweed for use in plant-based foods. Freshwater pond plants can be grown on raceway ponds, either outdoors (lower capital requirement), indoors (more control over cultivation conditions), or a combination of both.

Duckweed is resilient to a variety of severe environmental conditions, and it shows promise for extreme food catastrophe resilience thanks to its capacity to grow in low light conditions (i.e., below 25 μmol $m^{-2}s^{-1}$) (Femeena, Roman, and Brennan 2023)—which is even lower than those in a severe ASRS—as well as for its simplicity to cultivate which is relevant to GCIL scenarios. The growth of some species is hindered at temperatures lower than 17 °C, but in general they can grow in temperatures as low as 1–3 °C and some "even continue to grow during the winter months" (Vymazal 2008). Although under very low light and temperature conditions (below 5 °C and 25 μmol $m^{-2}s^{-1}$) the growth of *Lemna minor* was reported to be minimal, good growth rates were achieved at 15 °C (Femeena, Roman, and Brennan 2023). The shorter growing seasons in ASRS would complicate duckweed cultivation, but greenhouse systems would alleviate this.

Key challenges of duckweed production are that large biomass volumes are required, the extraction and fractionation processes are inefficient, and purification can be costly (F. G. Pearce and Brunke 2023). Other challenges include: design of cultivation structures, determination of operational conditions, choice of medium type, selection of the duckweed species and lineage, manipulation of the microbiome, and development of harvesting technologies (Coughlan et al. 2022). Economic and scale-up models are needed to characterize the potential of duckweed as a resilient food source for global catastrophes.

Appendix B: Notable interventions not included as resilient foods

There are some notable food production methods that have been discussed in the relevant literature, but which were not included in the list of resilient foods. One notable example are non-cellulose digesting animals, which currently make a considerable contribution to diets globally, mostly in the form of grain-fed pigs and chickens. (Denkenberger and Pearce 2014) discussed the possibility of rearing small, quickly reproducing animals such as chickens, rabbits, rats, detritivorous arthropods and fish whose production could be scaled quickly given the right feeds. As described in Section "Ruminants fed on grass and agricultural residues", however, these are generally dependent on human-edible crops that may be better directly consumed by humans in a catastrophe, and thus cannot be considered as a truly resilient primary food source. Although rats and pigs have some capacity to partially digest cellulose through their internal microbiota and rabbits are monogastric hindgut fermenters that can survive on fresh grass only, majority grass feeds are not used in commercial operations because these animals are not efficient enough at digesting lignocellulose. There may, however, be cases where it is locally efficient to do this as a form of upcycling low nutrition crops, food waste, or partially decomposed leaves into highly nutritious meats. Rabbits are already harvested at scale in many countries and can be more feed-efficient than chicken meat production—but not egg production (Meyer et al. 2021).

Another notable example is the application of artificial light, including technologies such as vertical farming of vegetables, or growing microalgae in photobioreactors, which is the most efficient artificial light option (Alvarado et al. 2021). While it may at first appear to be a reasonable alternative in scenarios like ASRS where photosynthetic crops are severely affected, it is generally prohibitively expensive compared to alternatives, at a cost of hundreds of dollars to fulfill a person's daily calorie requirement (Denkenberger et al. 2019). There exist technologies for the production of food that are significantly more efficient at converting electricity into calories, such as single cell proteins obtained through water electrolysis using CO2 (García Martínez, Behr, and Denkenberger 2024). There may, however, be some uses of artificial light which might make economic sense on the margin in the framework of a resilient food response to ASRS, such as the strategic application of some artificial light in greenhouses to improve overall yields (Alvarado et al. 2020). There may also be some catastrophic scenarios warranting the application of artificial light for food production locally, such as high latitude regions with large electricity production in ASRS if international trade is not possible. As indoor growing becomes more efficient, future research may be warranted in the economic viability of this pathway.

There exist myriad other processes to produce food independently of sunlight and other environmental conditions through industrial technologies in addition to those highlighted in section "Policy work on resilient food solutions and related interventions", which have not been included here due to uncertainties in their potential as a resilient food technology compared with alternatives, including single cell proteins from hydrogen feedstock produced by electrolysis or biomass gasification (García Martínez, Egbejimba, et al. 2021), or from other feedstocks such as peat, methanol, paraffins, gas oil, and plastics; as well as methods to produce food involving microbial electrosynthesis (García Martínez, Brown, et al. 2021), *in vitro* BioTransformation, or chemical synthesis of carbohydrates and carboxylic acids (García Martínez, Behr, and Denkenberger 2024). Production of lignocellulosic sugar, which is promising at a large scale for ASRS response, can also be successfully done at a small household scale (Siva and Anderson 2023; Siva and Anderson 2024). It may not, however, be practicable due to the complexity of sourcing sufficient enzymes for efficient sugar extraction, although cellulase-producing fungal species might help realize this at a community level. In addition, the household process would need to demonstrate its food safety, for example, with sufficiently low levels of toxins such as furfural.

It is also worth noting that several interventions for mitigation of a global catastrophic food failure were not included because they are outside of the scope of this work. One example are speculative geoengineering response interventions that have been proposed for mitigation of ASRS, such as interventions that may prevent or mollify supervolcanic eruptions (Denkenberger and Blair 2018), or intentional release of fluorinated gasses (Xu et al. 2023). Another example are policy efforts for GCR prevention, such as nuclear diplomacy, because of this article's focus on response and resilience. Prevention of a nuclear war or other types of attacks (e.g., digital, biological) leading to a global catastrophe is unambiguously the best outcome and should continue to be pursued in parallel to food resilience efforts.

It’s time to consider global catastrophic food failures

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Abstract

Food systems today face interconnected, systemic risks that could culminate in widespread disruptions triggering extreme global famine, in addition to neglected extreme risks. This paper introduces the concept of Global Catastrophic Food Failure (GCFF) to describe such scenarios; where food shortages overwhelm response capacities of governments and private sectors, necessitating extraordinary interventions. While the exact likelihood of GCFFs is uncertain, consequences would be profound. Currently, GCFF is a blind spot requiring research and policy efforts to strengthen food systems' resilience and capacity to sustain humanity.

Main

History is full of examples where catastrophic events like war, disease or climate shifts led to local disruptions of the food system. This in turn triggered famine and often a collapse of local population numbers[1]. Today's food security is strongly reliant on global food and energy trade, as many countries are net food importers[2,3]. This means that many events that would impact humanity's food system today could be felt globally. The recent COVID-19 pandemic and geopolitical tensions like the Russia-Ukraine conflict have underscored the vulnerability of global food systems[3,4]. The current global food system is precariously balanced, prone to major disruptions that could trigger catastrophic food shortages greater than 5% of global calorie supply. Reliance on intensive industrial methods and global supply-chains has locked the food system into unstable self-undermining dynamics that disrupt yields and supply chains[5,6]. Dependence on global supply chains means disruptions in one region can cascade, impacting food availability and prices elsewhere. Current research on the food system has mostly focused on specific risks separately (e.g., climate change or trade shock), so we propose a new concept to integrate different types of risk in an interconnected manner.

We introduce the term 'Global Catastrophic Food Failure' (GCFF) as a type of global catastrophic risk, to help bring together different strands of research that are all focused on ensuring food availability on a global scale. The benefits of adopting this new term include:

- Highlighting worst-case scenarios: GCFF emphasizes the need for robust contingency planning by considering catastrophic events that could drastically reduce global food production and supply
- Catalyzing proactive risk management: GCFF shifts the focus from reactive crisis management to anticipatory resilience-building by identifying vulnerabilities and implementing risk reduction measures, including through policymaking.

What is a Global Catastrophic Food Failure?

We define a Global Catastrophic Food Failure (GCFF) as an extreme, widespread food supply shortage beyond the capacity of national governments, international institutions, and the private sector to manage through ordinary means. The shortage occurs in a few years or less, triggered, either by an exceptional natural or human-caused event such as a volcanic eruption or a nuclear attack, or by a more gradual systemic crisis.

A GCFF is characterized by a severe reduction in the availability of staple foods such as grains, legumes, and vegetables, leading to a caloric deficit of at least 5% of global food supply or access. A GCFF would be identified by a combination of factors, such as: rapid and sustained increase in global food prices, widespread reports of food shortages and hunger across multiple regions, depletion of strategic food reserves without prospects for replenishment, breakdown of normal food supply chains and distribution networks, and inadequacy of emergency food assistance to meet the scale of need. Without effective and timely intervention, a GCFF could result in widespread starvation, causing tremendous suffering, loss of life, and severe disruptions to national governments, international relations, and social and global security.

Defining Characteristics and Elements of GCFF

The catastrophic nature of a GCFF is defined by the extreme severity of its effects. In the following we outline a range of criteria which we think cover this severity:

Rapid Onset: a GCFF would occur suddenly and with little warning. This is important to differentiate a GCFF from catastrophes that allow for significant time to implement adaptations within regular coping capacity, or could be mostly resolved by using existing food stocks. A GCFF would, in expectation, be triggered by abrupt events and exacerbated by an abrupt shock or stressor event that triggers a rapid onset cascade of failures across multiple components of the system.

Extended Duration: While abruptness is a key factor in the onset of a GCFF, the longevity of the crisis is equally crucial. Short-term shocks lasting less than a year might be buffered by global trade and food stockpiles. However, a GCFF is characterized by its potential to persist for multiple years, severely testing humanity's limited resilience to prolonged periods of low food production.

Limited Resilience: Chronic food security issues, while serious, often allow for some level of adaptation and resilience-building over time. Communities and nations can implement long-term strategies to mitigate chronic food shortages. In contrast, the abrupt, extreme, and protracted nature of GCFFs leaves little room for preparation or adaptation, making them much harder to address effectively.

Extreme Magnitude: GCFFs are defined by their extreme and unparalleled magnitude. Since the industrial revolution we have not seen a global drop in globally available food on such a scale. These events have the potential to affect not just one region or a particular group of people, but to have global repercussions. The scale of food scarcity and its impact on populations worldwide is significantly greater in a GCFF compared to chronic food security issues.

High Humanitarian Impact: GCFFs result in an immediate and profound humanitarian crisis. They can lead to widespread famine, malnutrition, and death on a massive scale. The urgency of responding to prevent such a crisis is paramount due to the potential loss of life and suffering it entails.

Global Interconnectedness: In today's interconnected world, disruptions in one part of the globe can quickly affect others[8]. GCFFs can arise when a global catastrophe triggers a domino effect, impacting supply chains, economies, and geopolitical stability, further exacerbating their acute nature. The global food trade system seems to be especially vulnerable to such systemic risks.

Our emphasis on GCFF does not diminish the importance of addressing other food disasters that do not meet the scale and severity level of GCFF. More common events including localized droughts, floods or conflicts can have significant and far-reaching impacts, warranting robust scientific, agricultural, and societal attention. Instead, we strive to bring increased focus to extraordinary risks that have received insufficient study and action despite their potential harm to humanity.

Causal dynamics of a GCFF

Figure 1 presents an event tree diagram that maps out potential cascading impacts and feedback loops that could arise from a large-scale volcanic eruption, leading to a Global Catastrophic Food Failure (GCFF).

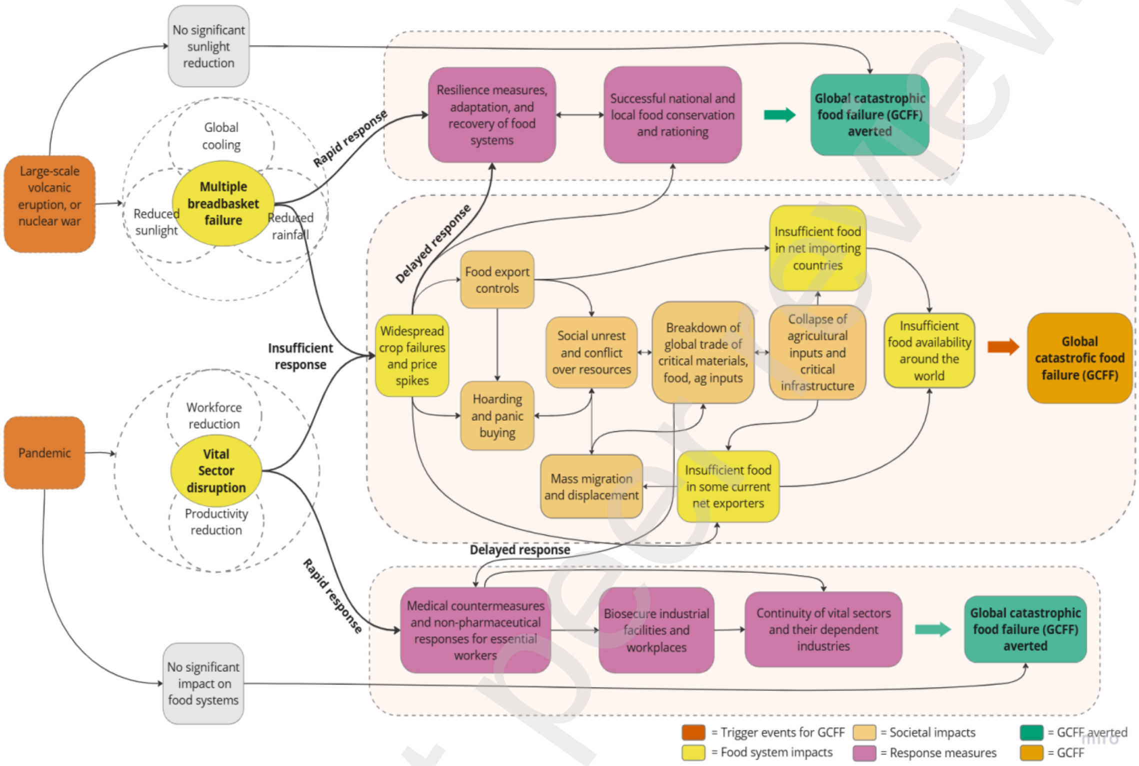


Figure 1. Event-tree causality for a GCFF based on two potential mechanisms.

The diagram illustrates how an abrupt climate change event could lead to a multiple breadbasket failure, which could cause a breakdown of global food trade or the continuation of trade with adaptations. A breakdown in trade could result in widespread food shortages and price spikes, which might trigger hoarding and panic buying behaviors that further exacerbate the crisis as feedback loops. Ultimately, this could lead to a breakdown of the food system structures and GCFF.

Potential GCFF scenarios

While it is heartening to note that large-scale famines have been decreasing over time due to advances in agricultural science, international aid, and improved global food distribution[1], it is essential to recognize that the specter of famine has not been banished from reality. The following scenarios provide examples of triggers that could generate such food system failures leading to famine:

Abrupt Sunlight Reduction Scenarios (ASRSs)

Abrupt Sunlight Reduction Scenarios represent a subset of the most extreme food catastrophes, where a sudden catastrophic event leads to a massive release of aerosol materials, such as sulfates or black carbon (soot), into the stratosphere. This, in turn, causes an abrupt reduction in absorbed solar radiation reaching Earth's surface, global temperatures, and precipitation levels, which could swiftly trigger near-total global agricultural collapse and push billions of people into starvation if proper planning and preparedness are lacking[9].

Three potential mechanisms for ASRSs have been identified in the literature:

Volcanic Winter: A large volcanic eruption can inject a substantial amount of aerosols into the stratosphere, leading to a volcanic winter scenario. While the triggering of such winter scenarios is rare, volcanic eruptions of this magnitude occur every 400-600 years[10], and have had devastating consequences for global agriculture[11].

Asteroid or Comet Impact Winter: An exceptionally large asteroid or comet impact can also propel significant amounts of aerosols into the stratosphere, causing a sudden reduction in sunlight. Although the likelihood of such impacts is exceedingly low, their potential impact is catastrophic[12].

Nuclear Winter: A nuclear winter could be triggered by a large-scale nuclear war, particularly one in which numerous cities are targeted. The subsequent firestorms could inject substantial soot into the stratosphere, prolonging the nuclear winter for years[13].

Historical Case-study: Tambora Eruption of 1815

In April 1815, Mount Tambora in Indonesia erupted in one of the most significant volcanic events in recorded history. The eruption was so massive that it injected an enormous amount of ash and sulfur dioxide into the atmosphere (estimated to be 50-70 megatons of sulfur dioxide)[14]. The subsequent cooling of the Earth's climate resulted in widespread crop failures, food shortages, and famines in many parts of the world[11]. The year 1816 became known as the "Year Without a Summer," as the Northern Hemisphere experienced unusually cold and harsh weather conditions during the summer months. The consequences of the Tambora eruption underscore the potential impact of extreme volcanic events on global food security.

A GCFF may also emerge as a consequence of more gradual systemic crises. These include, but are not limited to: extreme weather-induced crop failures and yield reductions, loss of pollinators, collapse of critical infrastructures supporting food production and distribution, and breakdown of international trade and cooperation. Thus GCFF mitigation could particularly benefit from methodologies and insights at the intersection of global catastrophic risk studies and systemic risk studies

Trade Disruption Scenarios

Trade disturbances would directly affect populations dependent on food imports, which have grown substantially in recent decades[2]. Domestic food production reliant on imported agricultural inputs such as fertilizers, pesticides, feeds, and machinery would also be severely impacted[5]. Under a scenario of a 50% shock to the supply of key inputs like fertilizers, pesticides and machinery, global maize and wheat production could decrease by up to 26% and 21% respectively, with high-yielding food production areas hit the hardest[15].

Several potential mechanisms could trigger such devastating trade disturbances, including pandemics and the containment measures imposed by governments, wars and conflicts that disrupt supply chains and trade routes, and blockages of critical trade chokepoints like the Suez Canal incident in 2021. While certain disruption events alone may not cause a GCFF, compounding risk and cascades may lead to it, given the deeply interconnected nature of the global food system.

As a result of the framing provided herein, the following scenario examples would not be considered GCFFs:

Slowly falling yields per hectare due to changing temperature and other climatic patterns. Anthropogenic climate change is a major risk to humanity and ecosystems. However, given its gradual nature, it does not seem likely to cause a loss of yield that fits the needed-definition of severity and abruptness of a GCFF. One possible mechanism for climate change to result in a GCFF is through extreme weather events and regional climate changes linked by teleconnections that trigger Multiple Breadbasket Failures in the >10% range of yield losses[40]. Climate change has likely already caused a ~1% reduction in global production of ten crops at 1 degree celsius of warming[41].

Even accounting for this however, this average production figure would need to account for regional and adaptations over the coming decades, such as cultivar shifts and enhancements, which may mitigate impacts by a few percentage points[42]. Overall, given the uncertainty of this relationship, the significant time for adaptation, and also the fact that past yield shocks (see Figure 1) were mitigated through production and market-responsivity/balancing, we are not confident enough to classify chronic climate change as a GCFF trigger at this time. Nonetheless, climate change is a threat multiplier that further underscores the importance of taking a systemic perspective to GCFFs.

A volcanic "autumn" that temporarily and abruptly changes the climate but only causes a small variation in production that does not result in increased food insecurity. Total production shortfalls would need to be extreme enough to severely affect availability and/or affordability of food for societies around the world. The world has seen many volcanic eruptions that have even caused abruptly but mild cooler temperatures and drought effects (e.g. the Pinatubo eruption[43]), but rarely generate global consequences.

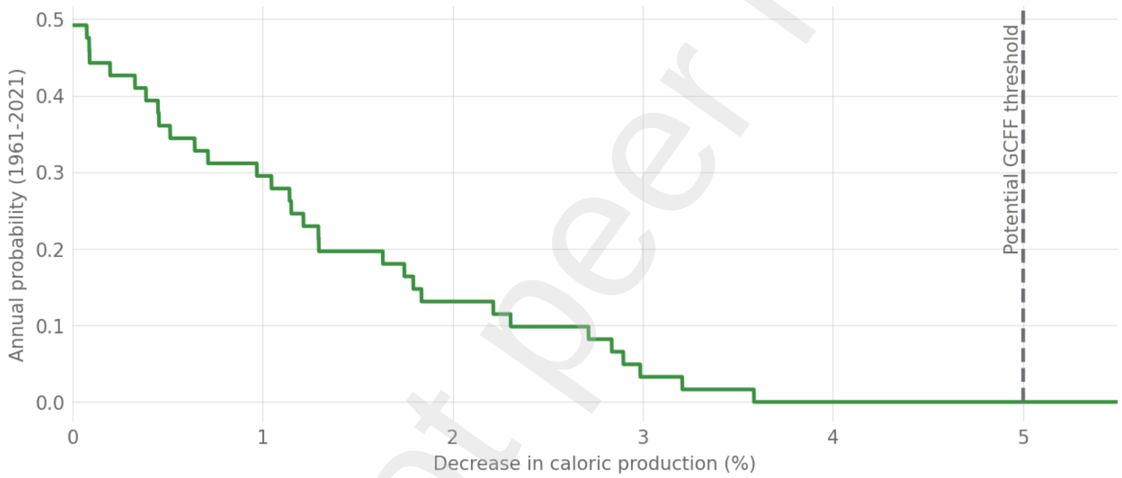
The Irish Potato Famine (1845–1852) was a significant food crisis in Ireland caused by a potato blight that devastated the potato crop, which was a staple food for many Irish people at the time. The blight resulted in widespread potato crop failures and led to a severe shortage of food. The situation was also exacerbated by British policy toward Ireland at time time, which is relevant for considering the role of policy in contributing to food failure. The famine had devastating consequences on the Irish population, with millions of people suffering from malnutrition and disease, and hundreds of thousands emigrating to escape the dire conditions. This coincided with wider potato blight in Europe, known historically as the "Hungry Forties"[1]. This famine illustrates how dependence on a single crop and vulnerability to plant diseases can lead to catastrophic food failure on a regional and even continental scale. However, it did not affect the global supply of food significantly, so cannot be considered a GCFF based on level of severity.

Estimates of GCFF Likelihood

Estimates regarding the likelihood of food shocks that significantly reduce global food production vary. One climate modeling study indicates an approximately 80% probability of a food shock resulting in a 10% reduction in global food production within this century, emphasizing the persistent risk[44]. A visualization of past food shocks (Figure 1) shows that a 5 % global loss at some point seems likely, especially given that the reliable data for global yields only exists from 1961 onwards. These food shocks since 1961 do not represent any major climatic disruptive events like large magnitude eruptions, but recent research suggests that an eruption with global climatic consequences is likely to occur in the next few hundred years, with historical records indicating a frequency of 1 in 6 per century[45].

These forecasts underscore the importance of recognizing and preparing for the potential occurrence of these catastrophic events, which could lead to GCFF on an unprecedented scale.

Figure 1: Occurrence frequency of global decreases in the supply of calories from 11 major crops over the period 1961-2021.



[The line traces the frequency of shocks greater than the value given by the horizontal axis. For example, a decrease of caloric production greater than 2.5% is recorded for ~10% of years. The caloric supply for each year is estimated from FAO yield data[46] for barley, cassava, cotton, maize, millet, palm fruit, potatoes, rapeseed, rice, sorghum, soybeans, sugar beet, sugar cane, and wheat. For each crop, yearly fluctuations were calculated by subtracting a baseline trend from the actual yield time series. This baseline trend was calculated by applying a first-order Savitzky-Golay filter (window length of 15 years) to the original data. For each crop, decreases were then identified as years where the yield time series drops below the smoothed baseline. The data for all crops were then aggregated by summing for each year between 1961 and 2021 the increases and decreases for the 11 crops, weighting the contribution of each crop by its relative contribution to the global supply of calories.[47]]

The need for awareness and foresight

There may be a risk of action-paralysis occurring when dealing with such high impact, high uncertainty events. We believe the opposite should be true. High uncertainty in this context means that gaining additional information provides a significant boost in our understanding. This is our motivation for raising awareness of GCFF.

It is essential to note that the likelihood of a GCFF is influenced by numerous interconnected factors, and these arguments represent different perspectives within a complex and evolving field of research. Pursuing a diverse, collaborative research agenda across these areas is essential to fill knowledge gaps, deepen understanding and guide policy to transform food systems. However, realizing this potential will depend on significant expansions in research and scientific cooperation locally and globally. Resilience to GCFF requires bold ideas and unprecedented collaboration across borders, sectors, and disciplines. By raising awareness of GCFF, we hope to start a critical conversation that helps galvanize action towards food systems that are robust, equitable, and capable of sustaining humanity in all potential risk scenarios.

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Conflicts of Interest

The authors declare no conflict of interest.

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