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Food System Adaptation and Maintaining Trade Greatly Mitigate Global Famine in Abrupt Sunlight Reduction Scenarios

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Abstract

After a nuclear war, volcanic eruption or asteroid or comet impact that causes an abrupt sunlight reduction scenario, agricultural yields would plummet. Global society is currently unprepared for such an event, implying an urgent need for evaluation and prioritization of solutions. We analyzed a nuclear winter scenario involving the injection of 150 Tg of soot in the stratosphere using a linear optimization model by-country and at a global scale. We investigated the effects of loss of trade, some simple adaptations, rationing and storage of excess food for the coldest years, and rapid, large-scale deployment of *resilient foods* including cold tolerant crops, methane single cell protein, lignocellulosic sugar, greenhouse crops, and seaweed. We calculate 191% of caloric needs met post-waste in the 2020 baseline. In comparison, found that global macronutrient availability increased from a no adaptation case of approximately 19% of global needs to approximately 146% with all adaptations and trade. However, insufficient preparation beforehand, post-disaster conflict, or economic collapse would worsen these outcomes and reduce the likelihood of international trade and effective adaptation.

1 Main

Global food production is vulnerable to catastrophic events which cause a widespread and rapid reduction in sunlight reaching the surface of the Earth. We summarize those types of events under the label *abrupt sunlight reduction scenarios* (ASRS). At least three mechanisms for ASRS have been identified in the literature: extreme volcanic eruption, large bolide (asteroid/comet) impact, and nuclear war[1]. In these scenarios, an enormous sudden injection of aerosol material such as sulfates or soot (black carbon) can occur, causing multi-year reductions in global temperature, solar irradiation, and precipitation, leading to a global catastrophic food shock (GCFS). Large bolide impact is estimated at a likelihood of ~0.0001% per year, supervolcano eruption at a likelihood of ~0.01% per year[2], and though more uncertain, nuclear war has been estimated at a likelihood of ~1% per year[3,4].

In the event of a full-scale Russia-US nuclear exchange, starting in the month of May with 4,400 cities each bombed with a 100 kT (kilotonnes of TNT equivalent) detonation, the subsequent

firestorms could cause 150 Tg of soot to be injected into the stratosphere, causing a nuclear winter[5]. This is considered a worst-case plausible shock to the global climate due to nuclear war. By the end of the second year, average global reductions over croplands would decrease in temperature by 16°C, solar radiation by 85%, and precipitation by 68%. Xia et al. (2022)[5] have estimated an 89% reduction in global crop reduction and a global fatality rate of 75% due to starvation in the 150 Tg nuclear winter. The primary difference between the 150 Tg nuclear winter ("the nuclear winter") and a comparable volcanic eruption is the higher-altitude lofting in the stratosphere of soot emanating from firestorms induced from the nuclear blast, which prolongs the nuclear winter to 15 years[6].

Prevention of a nuclear winter is unambiguously the best outcome. However, according to the "three layers of defense" model of existential risk, a comprehensive strategy should include prevention, response and resilience[7]. In this paper we investigate the feasibility of response and resilience approaches to an extreme nuclear winter, in line with the recent United Nations calls for "defining, identifying, assessing and managing existential risks"[8].

There exists no research which comprehensively assesses the effectiveness of global food system adaptations over a wide range of assumptions in an ASRS. In this paper we assess both food system alterations (conventional sectors of the food system used efficiently) and resilient foods (major new sectors of food production to compensate for reductions in conventional food production). Food system alterations include the prevention of a breakdown in international food trade, global storage and rationing for the coldest years, the halting of animal feed and biofuels, the reduction of food waste, and the culling of livestock. We also assess resilient foods, including cold tolerant crops, methane single cell protein (SCP), lignocellulosic sugar, greenhouse crops, and seaweed, finding them to produce large quantities of nutritionally adequate[9] food in the nuclear winter. We perform these assessments using data from estimated crop, marine fish, and grassland reductions in conjunction with publicly available data on the food system in 2020. We then run a series of simulations with a global and a country-by-country linear optimization model which estimates month-by-month macronutrient (calories, fat, and protein) production and losses in the first 6 years of the nuclear winter.

2 Results

A linear optimization is used to determine the quantity and timing of the consumption of available food resources over the duration of the nuclear winter. The linear optimization is run once for the globe if international food trade continues (***trade***), and once for each country and for the EU27+UK trading bloc in the case of minimal ***trade***. The caloric needs met reported below indicate the expected percentage of the population under consideration that could be fed the minimum recommended caloric consumption of 2,100 Kcals per capita per day[10], with all others in that population receiving no food. Due to this paper's exclusive focus on food production and food losses with and without trade, deaths from direct effects of the blasts, infrastructure loss, continuing conflict and food riots, migration, hoarding, and economic

collapse were not incorporated into the estimate. These factors would likely mean the reported percentage of needs met should be considered an upper bound on the population that would survive the famine, especially in the case of minimal ***trade***.

Nine adaptations to the nuclear winter are considered: ***trade***, ***simple_adaptations***, ***storage***, ***culling***, ***cold_crops***, ***seaweed***, ***cellulosic_sugar***, ***methane_scp***, and ***greenhouse_crops*** (see Table 1). We construct each scenario by adding some number of these adaptations to the scenario with no adaptations.

Table 1. Food system adaptations

Nine feasible adaptations have been identified to mitigate famine by increasing the likelihood that sufficient macronutrients would be available to meet human needs. Resilient foods have been selected for their potential to scale quickly, be affordable, and provide sufficient calories, fat, and protein. While all adaptations listed are plausible, some require international preparation by governments and global agribusiness, increased government regulation, continued economic functioning such as a stable dollar and functioning banks and financial institutions, or sufficient institutional capacity to support new sectors of the economy.

Category	**Adaptation**	**Definition**
Food System Alterations (conventional sectors of the food system used more efficiently)	***trade***	The prevention of a loss of international food trade outside EU 27 + UK.
	simple_adaptations	Prioritization of grasses, fodder crops, and residues for dairy cattle due to dairy production’s greater efficiency versus meat production; redirection of human edible foodstuffs from biofuels to humans 2 months after onset and redirection of human edible animal feed to humans 3 months after onset; immediate reduction in postharvest food waste (which includes human “overconsumption” beyond minimum healthy levels) from between 24 and 29% to between 6 and 10% of production due to an assumed tripling of global food prices.
	storage	Rationing of food stocks and early food production so that they are stored until their consumption in the coldest years of the nuclear winter.
	culling	Slaughter and storage of existing livestock populations for the coldest years of the nuclear winter. Preservation via e.g. drying/salting/canning of meat would be necessary.
Resilient Foods (major new sectors of food	***cold_crops***	Altering crop rotations to have more cold tolerant crops, and redirecting fertilizer to high productivity tropical cropland.

production to compensate for reductions in conventional food production)	***seaweed***	Rapidly scaling the seaweed industry to approximately 70 times present-day farm area and production quantities.
	cellulosic_sugar	Rapidly repurposing paper and pulp factories to produce sugars from lignocellulosic biomass (an "industrial food").
	methane_scp	Rapidly establishing and deploying methane single cell protein (SCP) factories[11] from natural gas (an "industrial food").
	greenhouse_crops	Rapidly constructing 62.5 million hectares of low-tech greenhouses in the tropics[12].

2.1 Minimal International Food Trade

In light of historical precedent for trade restriction in lesser shocks, most international food trade could halt after the onset of the nuclear winter, without establishing international agreements to maintain it beforehand. To simplify the analysis, all scenarios assume continued trade within countries. The EU27+UK was allowed to trade due to having few internal borders, a common market for goods and services, and a highly integrated agricultural supply chain.

The overall global caloric needs with minimal ***trade*** were determined using a mathematical mean over all trading blocs of the percentage of caloric needs met in a trading bloc (capped at 100%) weighted by that trading bloc's population. Under these assumptions, a scenario with no adaptations and with minimal ***trade*** showed only 19% of the population's global caloric needs could be met (Figure 1 top left).

A scenario with no adaptation could be characterized by a popular distrust in future cooling effects, a failure to reduce meat consumption by the global rich despite rising prices, extremely slow changes in biofuel legislation, and the majority of existing livestock herds failing to be slaughtered and consumed due to unprepared slaughter and meatpacking industries.

Adding ***simple_adaptations*** to the scenario improves needs met to 23% while ***culling*** improves needs met to 34%.

If ***storage*** is assumed, all accessible stocks are used in the nuclear winter. In a typical year, the combined stocks will never quite all be used, as some buffer is left over in case the harvest is low that year. Using only stocks down to the typical buffer from levels at the beginning of May 2020 was found to increase caloric needs met by about 26 percentage points globally to 59%. If all stocks are used (***storage***) the needs met increase to 64%.

We will refer to this scenario, with minimal ***trade***, but with ***simple_adaptations***, ***culling***, and ***storage,*** as the "Example Scenario". By comparison, 93% were able to meet their caloric needs with baseline 2020 crop production, with minimal ***trade***, and with ***simple_adaptations***, ***culling***, and ***storage***. However, including fat requirements reduced this to an estimated 87% (protein was not estimated to be a significant limitation).

The incorporation of all resilient foods into the "Example Scenario" provided an additional 20 percentage points of caloric needs met for a total of 85%, with each resilient food allowing for approximately 4-6 more percentage points of the population to meet their caloric needs (Figure 1 right hand side). Resilient foods are more important if ***storage*** is not assumed, providing an additional 29 percentage points of needs rather than 20. Industrial foods provided the most food for non-tropical trading blocs which largely could not grow their own food in the nuclear winter due to ground freezing, while crop relocation, seaweed, and greenhouses fed the most people in tropical countries. See Figure 2 for a time resolved depiction of the monthly caloric contribution of each food source in the top 5 population trading blocs.

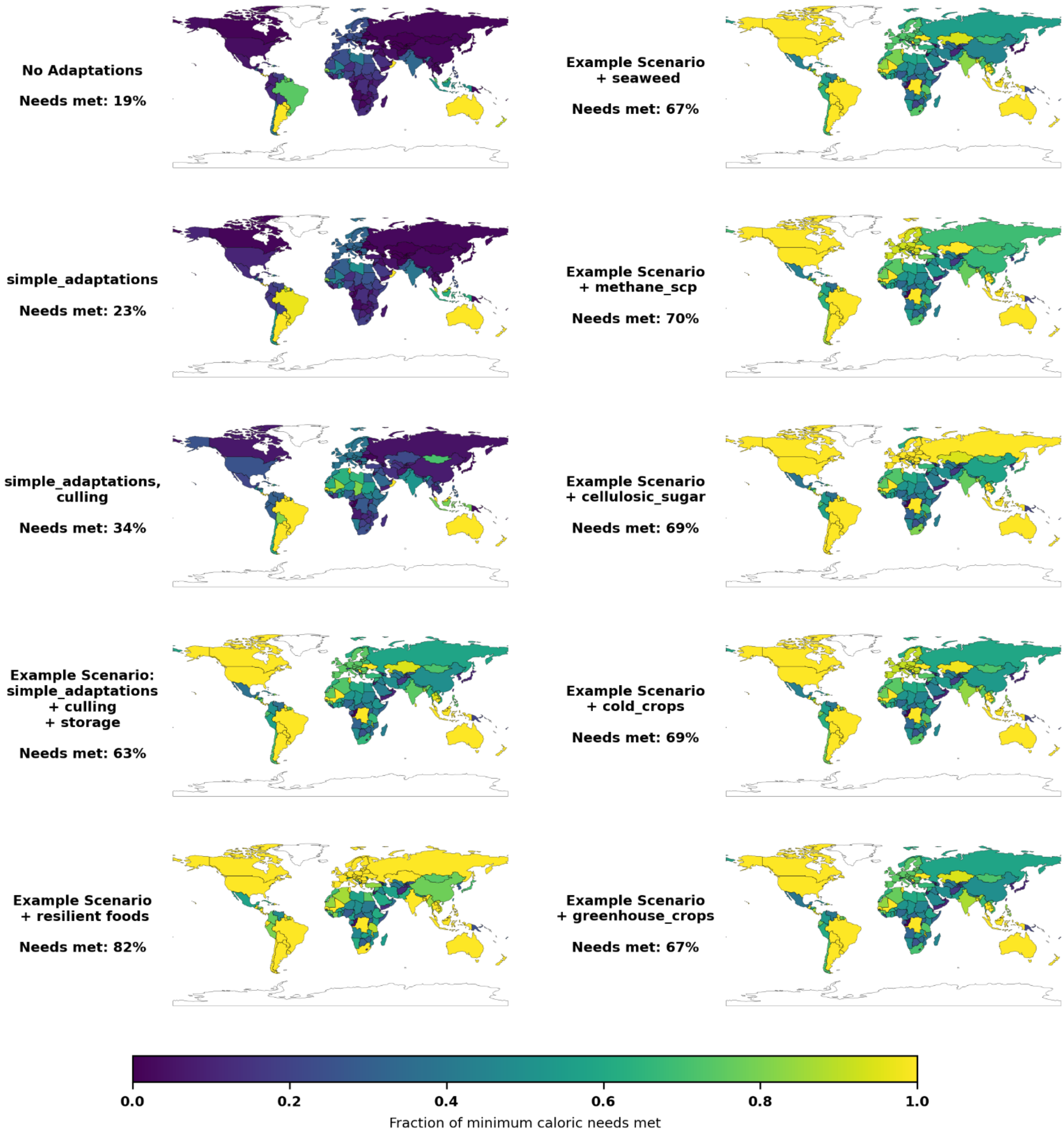

Fig. 1| Caloric needs met, minimal international food trade, all trading blocs. We show the minimum percentage of needs met in any month of the nuclear winter for all countries and with minimal ***trade***. If ***trade*** is not assumed, there remain several adaptations that can greatly increase the percentage of caloric needs met. Enforcing minimum recommended dietary fat shows 5-20 percentage points lower needs met than calories alone, although health effects from deficient dietary fat is not likely to be the decisive factor for starvation in such extreme shortages. Protein deficiency was small compared to caloric or fat deficiency. (**left**) A series of scenarios with different adaptations applied. The scenario on the top left may not represent a true worst case, due to the possibility that non-food trade would halt, conflict would continue, or soaring food prices would price out the global poor. (**right**) The "Example Scenario" with each resilient food added individually. We found ***methane_scp*** and ***cold_crops*** made up for most fat deficiency (mostly fat from increased rapeseed production).

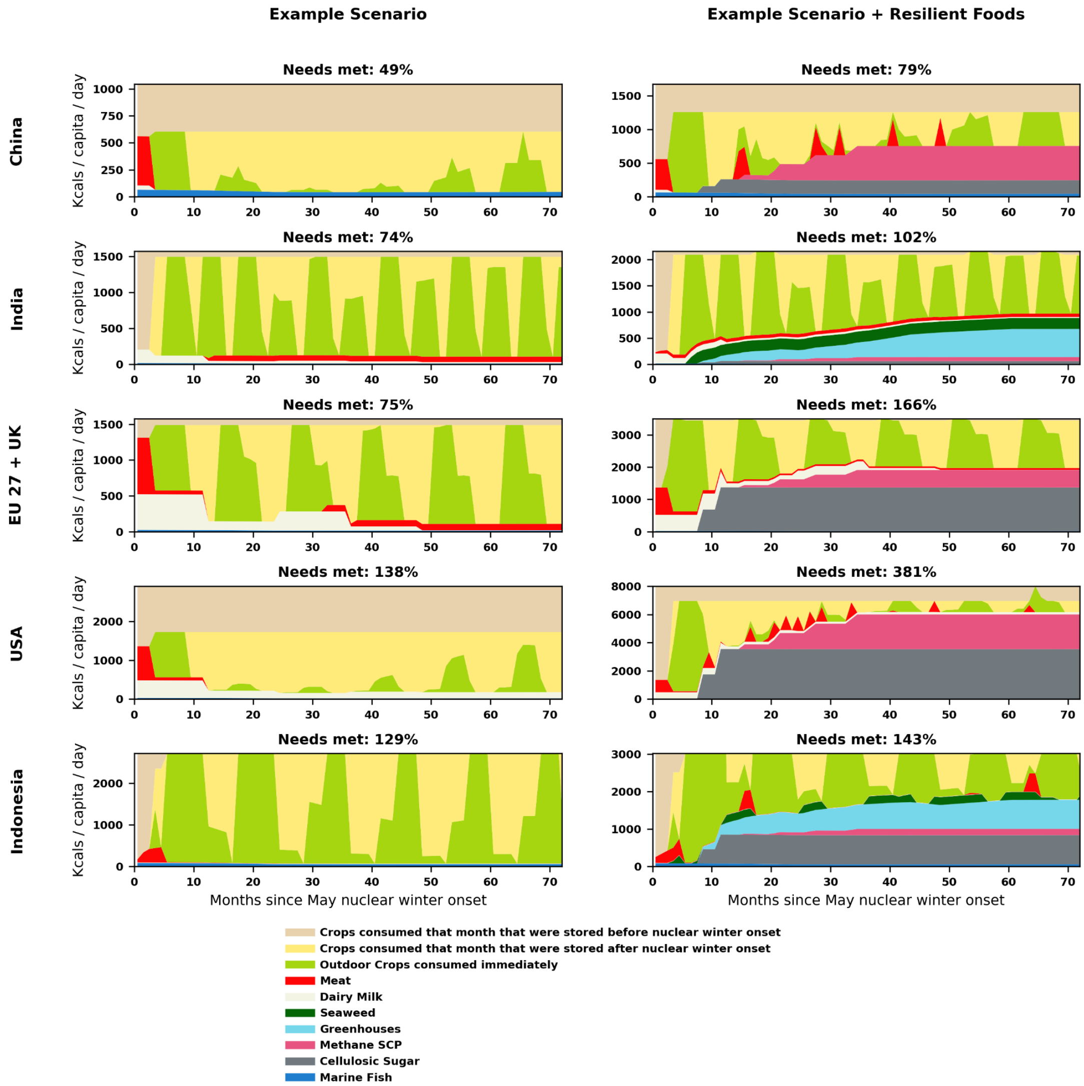

Fig. 2 | Caloric needs met over time, top 5 population trading blocs, minimal international food trade. Expected food production is shown over the full 72 months of the simulation in each trading bloc. Approximately half the world's population is represented. Available food production after losses is shown for each food source, represented with the height of each layer in the stackplot. Feed and biofuels have been subtracted from stored food plus outdoor crops. By-country results are less accurate than global numbers due to increased data source inaccuracy on the country scale. **a.** We show each trading bloc's expected food production and relative contributions from different traditional food sources over time in the "Example Scenario": ***simple_adaptations, storage,*** and ***culling***. **b.** The same as **a**, with the addition that resilient foods have been deployed at scale (***cold_crops***, ***seaweed***, ***cellulosic_sugar***, ***methane_scp***, and ***greenhouse_crops***). Each of the top 5 population trading blocs are shown to increase global caloric needs by at least 15 percentage points due to the deployment of resilient foods. Research and and pilots for resilient foods have been shown to be highly cost effective per life saved on expectation in other work.[13,14]

Individual trading blocs differed greatly in per capita production of food resources and in available food stocks. In general, higher population trading blocs fared better in the model while smaller population trading blocs faced issues with insufficient agricultural production and food stores. For example, in Indonesia, which has a late growing season, food storage limitations and a low estimate for slaughter capacity was the limiting factor for maximizing calories to humans in the worst months. Although not considered due to simplifications with the model, China would in reality be able to produce 10% of its calories from ***seaweed*** within the first year. Even with production past 100% of needs, increased food prices could price out the global poor. However, this could be offset by a number of interventions, including international subsidies and transfers from richer countries, or rationing similar to policies adopted in World War II. See the discussion section. The top 5 countries could generally meet from ½ to ⅔ of their fat requirement, except Indonesia which could meet less than half of its minimum recommended protein in the first year.

2.2 Continued International Food Trade

While we generally expect widespread food export bans in the nuclear winter, economic trade incentives to trade for countries with a surplus, unenforceable bans, and neutral countries with non-problematic bilateral relationships may also allow much food trade to continue. We display global scenarios assuming ***trade*** in Figure 3.

With mostly continuing ***trade***, increased access to markets would likely drive biofuel and feed prices up much higher in countries where animal feed and biofuels are produced, making ***simple_adaptations*** much more likely. As trade implies functioning markets, ***simple_adaptations*** were assumed. A scenario with ***trade*** and ***simple_adaptations*** shows only 30% of minimum global caloric needs could be met.

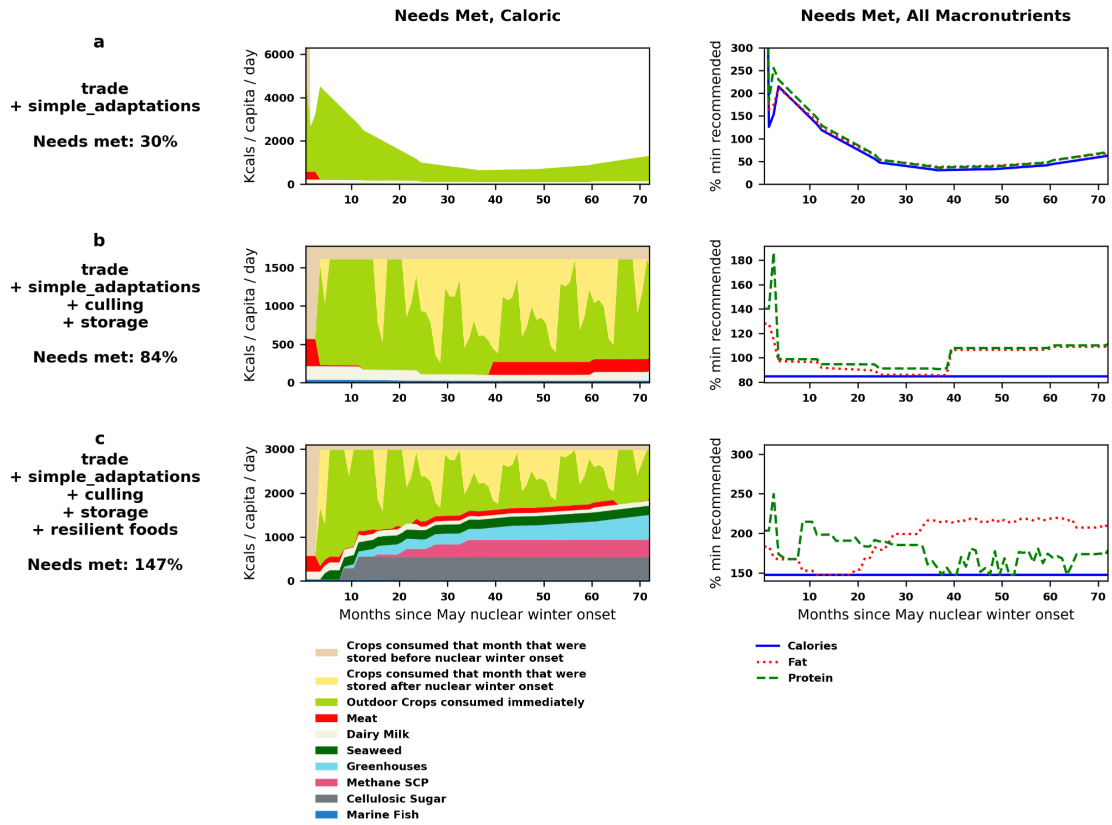

Fig. 3 | Needs met with continued international food trade. (**left**) The height of each layer of the stackplot shows the caloric contribution of each food to the total needs met globally for the first 6 years of the nuclear winter. (**right**) The percentage of needs met from each macronutrient over the 6 year duration. **a.** ***trade*** continues and ***simple_adaptations*** take place. If ***storage*** is not added in the model, seasonality is not incorporated and a linear interpolation of the annual crop reduction is used to estimate crop production in each month. **b**. Storage and culling make up for deficiencies in later years of the catastrophe. **c.** In addition to the successful adaptations in **a** and **b** above, \$30-\$300 million in technical preparations and preparedness plans are assumed to enable a reasonably successful scale-up of resilient foods[14], although the full potential of macronutrient production from resilient foods has not been assumed here.

Including ***culling*** and ***storage*** on a global scale greatly increases caloric needs met to 83% of needs. The inclusion of resilient foods with ***trade*** drastically improves the situation, with 146% of minimum caloric needs met. The models indicate that sufficient fat and protein would be available to meet the needs of those who could obtain enough calories with a mixed diet. In summary, we find that international action to prevent the loss of ***trade*** and to coordinate deployment of these foods would greatly mitigate famine in all areas able to trade and receive food.

3 Discussion

Food security relies on a sufficient production of nutritious and affordable foods.[15] However, modern food systems thinking has challenged its centrality, instead highlighting food allocation and access as more important[16]. In the last 100 years, global food production shortfalls have only been a few percent lower than expected production[17] and are well above minimum human needs. By contrast, in the 150 Tg nuclear winter, we find 16% of the global population would be left without food, even in an optimistic scenario outcome with ***trade***, ***simple_adaptations***, ***storage***, ***culling***, and ample international subsidies for the global poor to allow them to afford food throughout the nuclear winter. We focus on ensuring sufficient low cost food production and on efficiencies to mitigate losses in the food system as our primary topic of analysis in this paper. Still, while availability of low cost food production above human macronutrient needs after subtracting waste, feed, and biofuels is necessary to mitigate widespread starvation, it is not sufficient. Broader factors such as equitable food allocation and distribution in both ASRS and other food shocks are also vitally important[16].

Key work to prevent global famine from lack of production in any ASRS includes 1) research on food production methods, production ramp-up and technology deployment, as well as research on the nutritional qualities of the foods, 2) further development/piloting of technologies and techniques conducive to a faster response such as fast construction and rapid repurposing, and 3) policy outcomes such as the creation and distribution of effective disaster response plans.

The resilient foods assessed were selected for their amenability to rapid production ramp-up and low cost, as affordability is a key factor for adequate access to food during an ASRS, just as it is today[18]. Resilient food production estimates for scenarios involving resilient foods are expected to require $30 million to $300 million spent on researching technology deployment and constructing technology demonstration pilots before the ASRS[14]. Arguably, these areas of work can also inform preparedness and resilience against less-extreme global catastrophic food risks, such as a multiple bread-basket failure due to concurrent weather shocks or crop diseases and pests. We assess the feasibility of scaling resilient foods below.

Low-tech marine seaweed farm designs hold the potential to be a low-cost, rapidly scaleable, and nutritious food source. As an example of their potential for scalability, the farmed area of the seaweed industry in the south China sea increased by 12,000-fold, from 0.13 hectares in 2000 to 1,500 hectares in 2011[19]. Seaweed also tolerates low sunlight conditions and cold temperatures[20].

Several challenges would need to be overcome to scale seaweed to close to 10% of human caloric intake. The two primary challenges are twisting sufficient synthetic fiber and the feasibility of drying the seaweed in a humid, cold ASRS, as ASRS are colder and more humid than baseline climate. At 2,100 km^2 of seaweed per day, seaweed farms would require approximately 70,000 tonnes of rope from synthetic fiber per day. Production was only 223.5 tonnes per day in 2016[21]. Scale-up in an ASRS would require a factor of approximately 300 increase in industrial production of synthetic rope. Despite these challenges, other promising

aspects of seaweed production and historical precedent in famines point towards it being a promising resilient food. More information on seaweed can be found in the methods section.

Greenhouses present their own challenges to scaling. While 250 million hectares of greenhouse area over a period of 36 months are estimated to be technically feasible[12], the relatively high cost of greenhouses per unit of production may slow the growth due to lower demand for costlier foods. Consequently, greenhouse construction was estimated at ¼ of the expected maximum technically feasible construction rate, at 62.5 million hectares. The complexity and relatively high upfront cost to some industrial foods may prohibit their successful adoption in some regions. Industrial responses would likely develop in parallel at different paces and with varying degrees of success, as happened during the COVID-19 pandemic[22], potentially including others not considered in this model such as foods from CO_2[23] (other SCPs, carbohydrates, or electrosynthesized foods) or synthetic fats[24], although the potential for these other foods was not modeled.

Relocated crops present their own barriers to success. While nitrogen, water, temperature, and sunlight stress were assessed in these models, little work has been done to assess the reduction in yields due to UV radiation in nuclear winter. Other major uncertainties include the reduced yields due to farmers planting crops they are not accustomed to farming, and the possibility that a loss of trade would extend to seeds, fertilizer, and pesticides. However, we expect the existence of cold tolerant crops in higher elevation regions already in warm regions and the economic incentive to trade seeds for future food to counteract this.

Another key challenge to adaptation is the likely loss of most global food trade without pre-existing international agreements. Export bans have been introduced by a number of countries following much less extreme situations than a nuclear winter, including in 2007/2008 across rice markets, early in 2020 due to the threat of COVID, and in 2022 due to rising energy prices and agricultural market disruptions following Russia's invasion of Ukraine. It thus seems likely that the pressure to reassure domestic populations will lead to widespread export bans post disaster, especially among countries that have imposed such bans in the past or where they are deficient domestically.

However, there are also reasons to be hopeful that some food trade will continue. In particular, we found a number of countries still able to produce a significant domestic surplus of foods post disaster in all nutrients. Even for more extreme scenarios, a single nutrient such as fat or protein was in surplus in one country but not in countries in neighboring regions, implying an incentive to trade. In addition, countries may have the incentive to trade temporally, for example if they start with high stocks but will struggle to produce in subsequent years, a trade agreement could be reached to send food and support early in the disaster in exchange for future reciprocal flows. Finally, countries with abundant coastlines are expected to quickly exceed their own domestic ability to consume seaweed at 10% of their caloric intake, and would have an incentive to trade the surplus inland.

Furthermore, several adaptations could occur with no planning on national or international levels. The majority of biofuel usage should halt quickly in most countries, due to the rapid

expected rise in food prices relative to fuels. Because continuing to feed livestock at present-day levels would mean fewer animals would starve than humans, and economic incentives would increase the cost of feed, the majority of human-edible feed currently fed to animals would be redirected back to humans (most of the animal feed is soybeans and field maize[25], which are currently consumed by humans as edamame and ground maize in products such as tortillas[26]). As the disaster progressed and feed prices rose, livestock would likely become a key source of macronutrients, as most livestock would be consumed or stored as meat for the coldest years. Finally, in part due to soaring food prices, waste would be sharply reduced.

During World War II several countries increased domestic outputs of foodstuffs and key industrial goods at short notice across the globe. Pre-war trade flows were disrupted by blockades across the world. Meanwhile, output fell due to conflict, as well as labor and inputs being diverted to wartime uses. In response, farmers adjusted from cash crops and animal cultivation to staple crops, and prioritized milk over meat, similar to the recommendations made above. This was combined with a rapid introduction of rationing and price controls to ensure access to foods. Nutritional access for the poorest in the United Kingdom actually improved over the period, as rationing provided better access to foods compared to their pre-war diet[27].

The global food system is complex and will exhibit nonlinear dynamics as system variables change[28]. Complex systems often exhibit tipping points – thresholds which, once surpassed, result in a conformational change of the system to another state through positive feedback loops[29]. Failure of electrical grids, transportation infrastructure, telecommunications, or other infrastructure destruction due to the nuclear war is not considered, although infrastructure could be affected such that countries may no longer be able to communicate and trade internally or externally after the GCFS[30], demonstrating that ASRS such as nuclear war pose a risk for large-scale societal collapse.

There are many benefits to preparation for an ASRS in addition to mitigating resulting famine. Increasing the usage of methane SCP for fish food would lessen the environmental burden on fisheries, and reducing overfishing would increase marine fish populations in times of global production shortfalls[31]. Similarly, expanding use of seaweed as a food and feed[32] today could directly draw down CO_2 concentrations in the atmosphere, and reduce cattle methane emissions by feeding the seaweed to cattle[32]. As a low cost nutritious food, seaweed could improve food security around the world today[33].

Several topics remain untouched by this paper and are left for future research. Hoarding is an economically stratified effect which would likely raise food prices in the first year, although without a dedicated economic analysis, the overall effect in terms of food availability on starvation in the coldest years remains uncertain given the increased level of personal stores for the cold years if hoarding occurs. Food riots could disrupt continuity of government creating further stress on the food supply chain. Mass migration could overwhelm already strained food systems, or perhaps mitigate distribution issues from food export bans. Continuing conflict and a failure of non-food trade would reduce the functioning of critical infrastructure as well as

change population levels and hence demand for food. The effects from soaring food prices, the possibility for international subsidies for the global poor, and changes in global income distributions would be influential in determining the fraction of the population that could afford the food being produced. The complexity of substantially mitigating famine in a GCFS highlights the need for more preparedness work at local, national and international levels.

As demonstrated by the many reasons for pessimism regarding global food security in the nuclear winter discussed in this paper, there is an urgent and well-established need for large-scale global nuclear arms reduction[34]. We encourage work on the prevention of nuclear war, in parallel with ongoing research and preparations to mitigate global famine during a nuclear winter or other ASRS should they occur. We also recommend that business continuity managers and decision makers working in disaster risk management promote the creation of GCFS preparedness and response plans, as has been done for other high-impact low-probability risks, both natural (e.g., tsunamis[35]) and anthropogenic (e.g., nuclear plant accidents[36]). Regional preparedness plans could complement the international "emergency platform" proposed by the UN Secretary-General for responding to global catastrophic risks[8].

4 Methods

All results in this paper were created with a software model that simulates food production with and without resilient foods on a global or country-by-country scale (Figure 4). The analysis optimizes for macronutrition in scenarios with the optional addition of any number of the 9 adaptations detailed in Table 1. All results are run either for the 150 Tg nuclear winter, or the baseline climate in 2020.

To assess food system adaptations to the nuclear winter, we combine estimated reductions from traditional food production with previously published estimates of meat and dairy, livestock populations, waste, feed, biofuel usage, stored food, and the scaling of resilient foods. We use this to determine the caloric, fat, and protein production in each country or trade bloc on a monthly basis over 72 months (6 years), covering the years of lowest crop production.

Xia et al[5] reported estimates for the country-by-country reduction of maize, rice, soybean, and spring wheat, a global estimate of reductions in commercial marine fish catch, as well as country-by-country reductions in grass production for ruminants in the nuclear winter. We combine the reductions in each of the four crops and grass to create a country-by-country estimate of reduced crop yields and reduced meat and dairy production, and use the results from the fishery model to estimate reductions in seafood. Variations in food resources and food consumption within trading blocks were not considered.

Separate modules each estimate macronutrient resources and usages from each part of the food system before optimization, including separate modules for cellulosic sugar, meat and dairy, seaweed, feed and biofuels, methane SCP, stored food, outdoor crops, and greenhouse crops.

The optimization objective maximizes the minimum ratio of human nutritional needs to minimum recommended calories, fat, and protein in any month of the scenario, or only calories if fat and protein are not included as constraints. A secondary optimization is also run to smooth fluctuations in utilized food resources, although it does not change the minimum percentage of needs reported. The optimization determines the optimal timing of the harvesting for further vegetative growth versus consumption of seaweed if ***seaweed*** is added, the optimal timing of the consumption of culled meat if ***culling*** is added, and the optimal allocation of stored food from outdoor crops and stocks at the onset of the nuclear winter if ***storage*** is added. Feed and biofuel nutrient usage was reduced to a maximum nutrient usage of the nutrients available from stored food plus outdoor crops on a monthly basis. See Figure 4 for a visualization of the logical flow of the model execution.

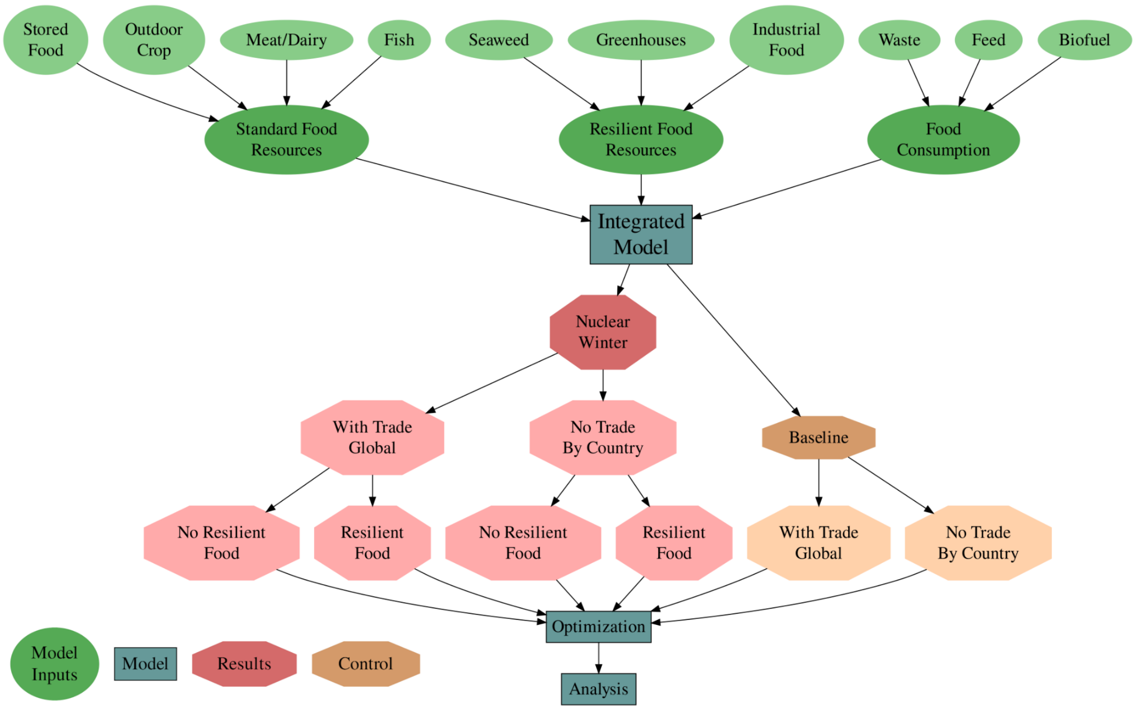

Fig. 4 | Workflow of model set-up and scenario selection. The integrated model considers standard food resources (stored food, outdoor crops, meat and dairy, fish), resilient foods (seaweed, greenhouses, industrial food) and nonhuman food consumption (waste, feed, biofuel). Depending on continued or ceased trade, the optimization was run either globally or country by country. The output from the optimization model estimated the food availability and food macronutrients for each scenario. Results are shown in pink, while "Baseline" "With Trade Global" is used as validation (Supplemental Information Section I), and the caloric needs met without ***trade*** have been previously reported in the results. Colors indicate different steps of the process. Lighter versions of the same color indicate that those are substeps.

4.1 Food System Model

Initial food stocks and crop years were taken from the USDA PSD (United States Department of Agriculture Production, Supply and Distribution) database[15]. Stocks are based on the crop year ending stocks and adjusted to the crop years of each trading bloc (see Supplemental

Information II for food stocks details). We assumed a four-month harvest period, beginning in the first month of the crop year, with stocks building up over harvests then being drawn down to the crop year end total based on monthly consumption. Annual consumption was split over the 12 months evenly. Crop years have been used to adjust annual yields to a monthly basis, again assuming production is split over a four-month harvest period. The average seasonality of production in the tropics (±24° latitude in this case) was used as a proxy for monthly variation in global production because it is expected that the majority of crop production in the nuclear winter would come from tropical areas[5].

By-country population in 2020 was obtained from the World Bank[37]. Deaths or reduction in livestock populations from the nuclear detonations or fallout are not incorporated into the model. FAOSTAT data[38] on a by-country basis were used to estimate animal stocks for culled meat and grasslands for grazing, nutrition of outdoor crops, food consumption from waste, feed, biofuels, and standard food resources (outdoor crops, meat, dairy, and seafood). Summary statistics and a model validation for the baseline scenario are described in Supplemental Information Section I. All data used for the simulations can be found in the repository of this paper[39].

4.1.1 Nutrition

The minimum recommended daily intake of energy and macronutrients is 2,100 Kcals, 51 grams of protein, and 47 grams of fat per capita for an average weight adult (62 kg). This is in line with previous assessments of GCFS[10,15–17]. Quality of protein (the full complement of amino acids in sufficient proportions) and quality of fat (sufficient unsaturated fat, and omega-3 and omega-6 fatty acids) are beyond the scope of this paper, although combinations of the same resilient foods as discussed in this paper have been calculated to provide a protein-complete diet[9]. Resilient food diets appear to be able to largely meet key macronutrient and micronutrient requirements at a population scale with adequate nutritional planning[9]. Therefore, meeting specified daily quantities of macronutrients is considered nutritionally sufficient under each scenario.

4.1.3 Marine Fish

The catch of marine fish could continue at a reduced rate during the nuclear winter[5]. Half of current aquatic caloric production (mostly marine fish) was considered as a calorie source. The month-by-month global reduction in fish catch was applied to this caloric production in the nuclear winter. The other half of aquaculture systems typically uses human edible fish food, so it does not contribute net positive calories. The loss in calories and differences in macronutrients from seafood fed with human edible food was not considered, as it contributes less than 1% of baseline crop caloric production.

4.2 Food System Alterations

4.2.1 Simple Adaptations

Waste

Baseline post-harvest waste in 2020 was 24-29% of production depending on the commodity. If ***simple_adaptations*** are added***,*** we estimate retail waste would fall sharply assuming a tripling of prices – globally, post-harvest waste estimates combining household, retail and distribution would fall to 6-10% of production in the nuclear winter, depending on the commodity[43]. No delay was applied to the change in waste. Based on current waste and an estimated tripling of food prices, an estimated price elasticity of food waste of -1.49[44] (implying each doubling of prices reduces waste by 64% from its previous value) was used to determine how much increasing prices would reduce waste in each trading bloc. See Supplemental Information Section III for details.

Human inedible foods fed to animals

If ***simple_adaptations*** are not assumed, the ratio of dairy cattle to total cattle[45] is used for allocating feed to milk and meat. Otherwise, if global dairy production hits the current production levels, additional edible feed would go to producing beef. Similarly, human edible feed first went to feeding cattle, unless it already reached the current dairy production limit. Once the dairy production limit is met with human edible feed, any additional food goes to chicken and pork production, then finally to produce beef if chicken and pork exceed baseline levels. As some beef would be produced from dairy cattle at the end of their productive life, and some beef would likely be available from culling, we expect little human edible feed would be used for beef.

Total output of inedible feed (grasses, crop residues and fodder crops) was taken from the results presented in the Global Livestock Environmental Assessment Model (GLEAM) database[45], which also provided global average feed conversion ratios for edible and inedible feeds to meat and milk, depending on the animal and the feed system under consideration.

If ***simple_adaptations*** are added to the scenario, total inedible feed was reduced by the decline in grass yields for grasslands and the average decline in crop yields for fodder crops and crop residues. Grasses were all reduced by the grass yield loss on an annual basis, while residues and fodder were reduced by the average crop yield reduction per year. Total inedible feed was then assigned to milk production first, at a ratio of 1.44 dry caloric tonnes of feed per tonne of milk produced[46] (1 dry caloric tonne = 4 million kcals), up to the present day whole milk output of 879 million tonnes. Any surplus inedible feed after milk was maximized was assigned to meat at the ratio assumed in the GLEAM database of 92.6 dry caloric tonnes per wet tonne of meat, via the following formulas:

$$milk \ = \ min(inedible\_feed \ / \ 1.44, \ milk\_baseline) \tag{1}$$

$$meat \ = \ max(0, \ inedible\_feed \ - \ milk\_prewar \ * \ 1.44) \ / \ 92.6 \tag{2}$$

Human edible foods fed to animals

If ***simple_adaptations*** are added, before human edible feed ("edible feed") is shut off, the feed is used to produce further animal products. It first goes to higher efficiency monogastric (single stomach) animals up to their present day levels, followed by ruminants if there is any feed remaining. The assumed ratio of human edible feed dry caloric tonnes to tonnes meat chicken/pork monogastric systems is averaged at 4.8, once again taken from GLEAM. This has a maximum of 250 million tonnes of meat output, based on 2019 FAOSTAT figures for pork and chicken combined.

The ratio of edible feed dry caloric tonnes to tonnes of cattle meat is 9.8. This includes the production of some small ruminants such as sheep and absorbs any remaining edible feed surplus.

The formula for feedlot meat production from edible feed is summarized below:

$$meat\_feedlots = min(edible\_feed / 4.8,\ monogastric\_meat\_baseline) + max(0,\ edible\_feed - monogastric\_meat\_baseline * 4.8) / 9.8 \quad (3)$$

See Supplemental Information Section IV for more details on meat and dairy assumptions.

Feed and biofuels

Feed and biofuels from human edible sources are assumed to use only the combination of stored food and outdoor crops. If nutrient usage is more than any macronutrient that could be supplied by stored food and outdoor crops, feed and biofuel usage are both reduced by a constant factor over the entire duration of the simulation to meet nutrient availability. Feed and biofuels from human edible sources are always set to zero after 12 months if ***storage*** is not added to the scenario. This accounts for greatly increased human edible crop prices in year 2 onward in those scenarios.

4.2.3 Storage and Culling

Without ***storage*** enabled, only the first 12 months were allowed to optimize with stored food. If ***storage*** was added to the scenario, stored food was allowed to be used in any of the 72 months to maximize the objective. Furthermore, excess monthly crop production could be stored for later years if ***storage*** was added to the scenario. Crop production seasonality was only considered with ***storage*** enabled.

Slaughter rate of meat from ***culling*** was limited to present day annualized levels of meat slaughter per month in each trading bloc, or globally for the global analysis. Global slaughter monthly is about 5% of herd size[45]. No growth in herd size is assumed, even if feed continues at

current rates. No constraints on storage duration or storage capacity were assumed. The minimum expected maintained meat in any month was subtracted from available culled meat.

4.3 Resilient Foods

All resilient food production methods evaluated here have been deployed at a large scale. Low-cost foods are included preferentially. Resilient foods were selected according to anticipated resource constraints (e.g., industrial capacity, availability of production inputs) and the value of the food output – roughly macronutrient content (calories, fat, protein) per unit cost. The scenarios with resilient foods account for greatly increased food resources from ***greenhouse_crops***, ***seaweed***, ***cold_crops***, and industrial foods (***methane_scp*** and ***cellulosic_sugar***).

4.3.1 Seaweed

We selected *Gracilaria tikvahiae* as a representative example for its cold tolerance and high growth rate. A one month delay of seaweed farm construction starting was assumed.

Due to concerns around digestibility[47] and excessive iodine consumption, ***seaweed*** was capped at a maximum of 10% of calories for humans and restricted to countries with capital cities between ±30° latitude, though in practice much larger production levels could probably be achieved. Experts suggest 1-2 mg is a safe level of iodine, although, empirically, higher consumption does not typically cause health issues[48]. Boiling and washing the seaweed has also been shown to reduce iodine content in similar seaweeds[49]. Many large countries with capitals outside of ±30° have long coastlines within ±30°, providing a further degree of pessimism in the estimate of the potential for seaweed as a resilient food source. Most countries with seaweed available achieve the 10% cap of calories from seaweed within a year.

When ***seaweed*** was added to the model, the following set of constraints were applied for each trading bloc *b* and month *m.* Harvests were allowed at the end of each month.

$$wet\_on\_farm_{b,m=0} = initial\_seaweed_{b} \tag{4}$$

$$area_{b,m=0} = initial\_farm\_area_{b}$$

$$for\ all\ trading\ blocs\ b,\ months\ 0 < m \leq 72 \tag{5}$$

$$\begin{aligned} area_{b,m} &= area_{b,m-1} + monthly\_area\_built_{b} \\ wet\_on\_farm_{b,m} &= wet\_on\_farm_{b,m-1} * monthly\_growth \\ &\quad - (area_{b,m} - area_{b,m-1}) * min\_density * harvest\_loss \\ &\quad - seaweed\_produced_{b,m} \\ seaweed\_produced_{b,m} &\leq 10\%\ monthly\_caloric\_needs \end{aligned}$$

The total food produced per month from seaweed was determined from the *seaweed_produced*$_{c,m}$ variable. *wet_on_farm* refers to the mass of seaweed in the ocean before harvest. Initial seaweed production estimates were taken from FAOSTAT. Harvesting was assumed to happen only once a month. The harvest process and natural losses such as from grazing fish are dependent on seaweed species and other factors. We estimated *harvest_loss* as a factor of 0.85[50]. Minimum wet-on-farm density of the stock (*min_density*) was estimated at 0.4 kg/m^2 , while maximum wet-on-farm density after harvest (*max_density*) was estimated as 4 kg/m^2, based on harvests of the species *Gracilaria tikvahiae*[51]. The initial area (*area*) was selected at only 10 km^2 because much of the current seaweed area would no longer be suitable for seaweed cultivation. We assumed that 2,100 hectares of new seaweed farms could be built daily, limited to a maximum global total of 1 million km^2.

The seaweed daily growth rate is determined based on the daily growth rates as a percentage of mass for a variety of seaweed species. Growth rates observed in current aquaculture vary between 9 and 12% growth per day[52] so 10% growth per day was assumed, compounded to a factor of 17.5 wet mass monthly. The main factor for reduced growth is likely insufficient phosphorus[53]. Growth can further be inhibited by a temperature below 13 °C[54].

The starting seaweed stock in each trading bloc was loaded from FAOSTAT[38], but each trading bloc with a coast was assumed to start with at least 500 kg wet mass. Initial farm area and max area built was calculated based on the fraction of ocean coastline in each trading bloc out of the global total (taken from The World Factbook[55]).

4.3.2 Crop Relocation (***cold_crops***)

Crop production would fall to much lower percentages of baseline production in the nuclear winter without relocated cold-tolerant crops grown in the tropics. Sugar beets and potatoes produced the most calories per hectare, rapeseed produced the most fat per hectare, and wheat produced the most protein per hectare. While these crops would not be the only crops able to be grown outdoors in the nuclear winter, they represent a reasonable high yield, cold-tolerant rotation for macronutrients, which would be likely combined alongside some ongoing cultivation of maize, rice, pulses and vegetables where possible. Expanding arable land would in principle be feasible over the course of the nuclear winter, but was not included in the analysis.

Improvements from crop relocation in the nuclear winter were applied after an assumed 10-month delay (2 months before a planting of different crop rotations begins plus 8 months until the altered rotations affect yields). The improvement was calculated by taking the remaining fraction of crop caloric output produced in each year of the nuclear winter to the power of 0.80, although crop production in any years where crop yields improved in a trading bloc due to the nuclear winter were left unchanged. The power law was selected in order to ensure that the mean change in the coldest year would be a factor of 1.54 (11% of yields improved to 17% of yields in the coldest year) while ensuring that regions with zero crops

would remain zero, and that improvements would never cause the crop growth in nuclear winter to be equal to or more than in baseline climate. The cold tolerant crops were estimated as having 165% of the fat and 111% of the protein per unit calorie. See Supplemental Information Section V for details on how these improvements were determined.

4.3.3 Greenhouse Crops (***greenhouse_crops***)

While greenhouses today produce a small percentage of global calories, low-tech polymer-based greenhouses have been estimated to provide a large fraction of calories as a resilient food source in the nuclear winter at an affordable price in past work[12]. While these low-tech greenhouses reduce the CO_2 levels, air circulation, and incoming photosynthetically active radiation (PAR) for crops, they increase the average temperature, humidity, and thus increase available *growing degree days* (GDDs). Greenhouses may also allow for growth in some regions which would otherwise be unable to grow significant quantities of food. Greenhouse yields were restricted to countries with capital cities within ±23° latitude. The maximum percentage of area covered by greenhouses in each country was set to be proportional to the existing percentage of crop area in the tropics. To avoid overly optimistic outcomes, a 2-month delay before construction was assumed. Newly constructed greenhouses would be built only on viable outdoor growing cropland area[38] in the nuclear winter. This fraction of area was subtracted from outdoor cropland in the tropics, reducing the yield estimated from outdoor crop production. While 250 million hectares of greenhouse area over a period of 36 months are estimated to be technically feasible[12], only 62.5 million hectares are assumed, to account for the higher prices of crops grown in greenhouses.

Yield improvements for greenhouse crops were estimated assuming yields are directly proportional to GDDs. Manaus (Brazil) was considered for being representative of tropical regions, and the base temperature was set to 7.2°C and 4.4°C for potatoes and wheat, respectively. To calculate the yearly GDDs, the base temperature was subtracted from the mean monthly average temperature, and the difference multiplied by 365.25 days. Altering the average 12.5°C on-land tropical reduction in the nuclear winter at the end of year 2 to an estimated 9.0°C reduction in greenhouses led to increases in yields of 36% and 51 % for potatoes and wheat, respectively. Overall, we estimate greenhouses would have approximately the average of the two improvements, at 144% of the non-greenhouse yield. This improvement was applied in addition to the estimated improvement in yield from cold tolerant crop rotations and improved nitrogen application for all greenhouse crops.

4.3.4 Industrial Foods (***methane_scp***, ***cellulosic_sugar***)

The ramp-up of industrial resilient food production in the nuclear winter was modeled as a combination of the two options with highest technology readiness at the current time of writing. The first one is sugars from lignocellulosic biomass, assuming rapid repurposing of pulp

and paper mills to sugar biorefineries[56]. The second one is single cell protein (SCP) production from natural gas based on fast construction of large-scale fermentation facilities[11]. We assume a 3-month delay of industrial food conversion or construction.

The growth of industrial foods in the current model was assigned a pre-set monthly growth profile using previously published estimates[11,56]. First, a large wave of paper factory repurposing is assumed (approximately two thirds of the current global pulp and paper capacity), from then onwards the available industrial resources are assumed to be invested in methane SCP production. SCP can serve as a useful food product due to its high-quality protein content and micronutrient profile, despite the higher resource intensity and unit costs compared to lignocellulosic sugar. Fast repurposing for sugar production can help bridge the sudden gap in food production, but after the most promising facilities have been repurposed, a switch to more nutritionally rich products was assumed.

The global repurposing rate of existing pulp and paper factories to lignocellulosic sugar factories and the global ramp up of new methane SCP factories were estimated using the previously published growth rate model results, based on the capital expenditure of chemical and related industries[11,56]. These data are available on a regional basis. Where country level data are not available, the regional totals for relevant capital investments were divided by the share of fixed capital accumulation of each country in the region[37]. The ***cellulosic_sugar*** produced in each trading bloc was estimated by dividing the trading bloc's wood pulp processing share by the global total[38], while ***methane_scp*** produced in each bloc was estimated from the share of industrial capital in each bloc.

Data Availability

The Supplemental Information includes more detail on methodology, while the supplemental spreadsheet data and production for all countries and more combinations of adaptation assumptions can be located in the repository of the paper[39] . The spreadsheet and reports with more results can be found in the Zenodo data repository https://zenodo.org/record/7039924. Crop relocation data are available on request.

5 Code Availability

The model code as well as all data imported for the simulations are available at https://github.com/allfed/allfed-integrated-model. The citable version of the code published with this paper is available at https://zenodo.org/record/7039906[39].

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Ethics Declarations

Competing interests

The authors declare no competing interests.

Food System Adaptation and Maintaining Trade Greatly Mitigate Global Famine in Abrupt Sunlight Reduction Scenarios

Supplemental Information

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I. Model validation with 2020 food production

For the food resources, net stock movements were set to mimic crop year ending 2020 levels in order to reproduce 2020 consumption. Production and consumption are for the 2020 global population of 7.72 billion, and a linear projection of food utilization statistics from 2014 through 2018[1].

We set the global annual outdoor crop production at 3898 million dry caloric tonnes, global meat and dairy at 1203 million dry caloric tonnes (74 million for beef production, 250 million for chicken and pork production, 879 million dry caloric tonnes for dairy production), and marine fish at 28 million dry caloric tonnes (1 dry caloric tonne = 4 million kcals). Feed and biofuel nutrient usage on the global level annually were set to 1447 million dry caloric tons and 623 million dry caloric tonnes in 2020. These numbers were used as the initial properties of the global food system for scenarios with trade. The food resources in the scenarios with no food trade were obtained on a country-by-country basis[1].

Outdoor crop production in the simulation used the average global seasonal production variation based on crop years listed in the USDA PSD (United States Department of Agriculture Production, Supply and Distribution) database[2], assuming a 4 month average harvest period.

For meat and dairy production, human inedible feeds were used when available, and human edible feeds were assumed to be fed to animals only once human caloric needs have been met.

The diet calculation incorporates all the food resources and food consumptions, assuming 2020 levels for the animal feed and biofuels. We set waste to 2020 levels (see Methods Waste section in the main text). The diet composition for this 2020 baseline is shown in Figure S1b.

We define primary food production as any food production which results in net-positive creation of calories amenable to human consumption (and is not converted to another source of food). This definition excludes animal products, eggs, fish farms, and dairy milk that are not based on inedible inputs, i.e. grazing and agricultural residues. Total primary food availability of foodstuffs suitable for human consumption aggregate to approximately 5600 kcals per capita daily, excluding retail and distribution waste but including production losses, and amounts to 191% of minimum needs after incorporating baseline waste (including “overconsumption”). This is significantly higher than human needs because foods go to uses other than direct consumption, such as animal feed and biofuels (which account for around 2,000 and 800 kcals per capita per day respectively). In particular, foods such as meat, dairy, and eggs based upon human edible feeds consume more calories than they produce in aggregate, due to energy losses inherent in their production.

A plot of the diet in 2020 from the model is shown below, which accounts for the satisfaction of global dietary and macronutrient consumption. The baseline daily intake of human macronutrition was estimated as 2100 kcal, 61 g of protein and 59.5 g of fat per capita. Distribution waste, retail waste (including household), and overconsumption, leave approximately 2015 calories, 72 grams of protein, and 60 grams of fat. These discrepancies could be due to a myriad of factors, including limited protein digestibility, inaccurate estimates of nutrition usage by feed, errors in estimating dairy production, rounding errors, or input data inaccuracy. A 1.5% adjustment upwards of stocks and outdoor crop caloric production, an 8% increase in fat, and a 6% decrease in outdoor crop protein were applied to all scenarios compared to FAOSTAT data to increase accuracy of the final percent needs met.

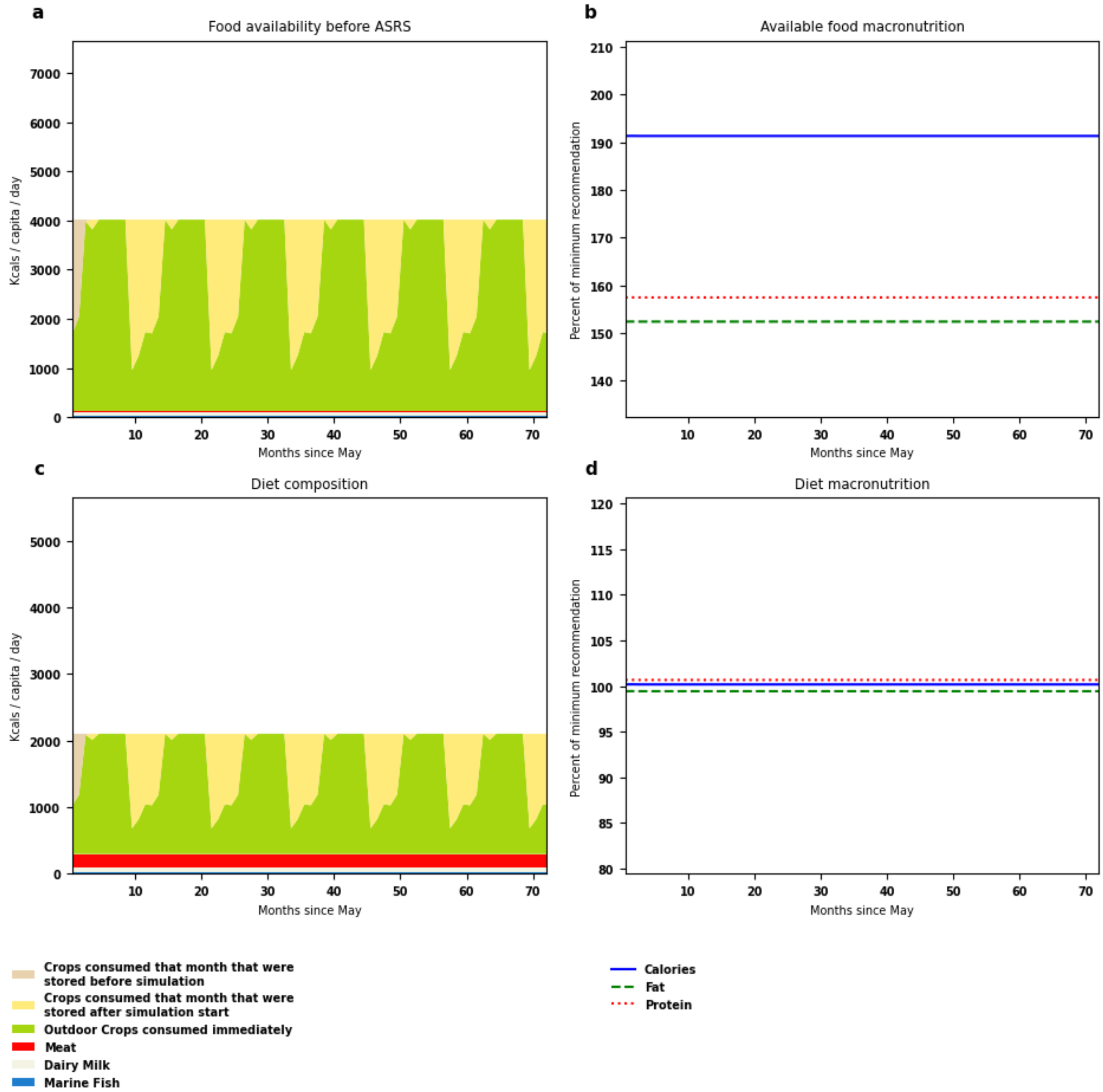

Figure S1 | Production in 2020: a Year 2020 agricultural primary food availability by source **b** Macronutrition of primary production **c** Dietary composition, excess calories are fed to livestock and used for biofuels at 2020 levels **d** Macronutrition of average 2020 diet.

Additional validation with previously published results from Xia et al[3] has found similar values under assumptions mimicking their model for the case of no food trade and baseline climate, and the case of a nuclear winter with "worst case" no adaptations. Reproducing the model also required setting feed reduction proportional to the climate reduction and continuing feeding animals and biofuels throughout the nuclear winter.

II. Details on global food stocks modeling

The global stored food considered includes private commercial and government stores, but does not consider food in transit or food in consumer homes, warehouses, or retail establishments.

The USDA PSD database[2] presents detailed estimates of crop year ending stocks by country. We set global stored food to 1.5 billion dry caloric tonnes at the beginning of the month of May (12 months of global population fed on the 2100 Kcals per capita per day requirement before waste). May is the month of the nuclear winter onset in the climate model.

Stocks were taken for all key grains (wheat, barley, rice and maize), centrifugal sugar, oilseeds (primarily soybeans) and vegetable oils, for the period 2014-2018. Data on storage for fruits, vegetables and tubers are not available; however, these are likely to be small in caloric terms by comparison, and their exclusion will not significantly bias our total stock estimations downwards.

Crop years refer to the cycle of harvest, stock buildups (where stored food rises around harvests), consumption and stock drawdowns (where stocks fall during the off crop periods) which characterize agricultural markets, with the crop year end referring to the last month before harvests begin. Because of this, crop year end values represent the minimum level stocks reached before harvests/processing begins again, and do not line up with a standard calendar year unless harvests begin in January. As a result, simply adding crop year end stocks will give a significant under estimate of total global stocks in a given month, as harvests and therefore crop year ends do not align.

To correct for this, crop years have been downloaded for each crop and each country globally (also reported in the PSD database). We have assumed that harvests start at the beginning of their crop year, last 4 months, and stocks build over this period based upon reported production. Meanwhile consumption/exports/other disappearance is flat month to month, with crops drawn down to their crop year end value reported in the database. On a country-by-country basis this may not hold, as for example key exporters may see higher shipments in the months during and just after harvest. However, on a global basis, this methodology will average out any seasonality between importers and exporters.

By carrying out this analysis for all crops and all countries by month, we calculated an estimate of total stocks for each crop by month. This total volume was then multiplied by the nutritional values for each crop/product as reported by the FAO, in order to convert them into a total calorie, protein and fat basis.

Stores in transit were not considered in the model. Bulk shipment times between Asia and Europe average around 15 days via the Suez canal, and Europe to the US East Coast averages around 8-10 days, depending upon the ports[4]. We assumed two months total stores considering handling, processing, logistics to and from the port and other factors, which is likely an overestimate of the storage that cannot be depleted, making the number of people who could be fed on storage an underestimate.

III. Details on Estimating Waste

Waste was determined primarily using the FAOSTAT Supply Utilization Accounts database, based upon data taken from 2014 to 2018[1]. Agricultural waste consists of harvest losses, distribution losses, and retail/household waste. Harvest losses are already accounted for in the estimates of current-day agricultural production and were not adjusted in the ASRS, which is likely an underestimate of waste as there would be effort to reduce harvest losses given the higher prices. Distribution losses refer to losses in processing, transit and storage, post-farm but before they are delivered to the retail level. Distribution losses are largely a function of existing quality of storage and transport infrastructure[2], and are assumed to be maintained. Distribution losses vary widely by crop/food variety, and so the percentage loss appropriate for each agricultural category in FAOSTAT is assumed to continue[1].

Meanwhile, retail/household waste refers to food damaged or not consumed at the retail level onwards, such as shops rejecting or failing to sell products or households discarding food once purchased. Base levels of waste have been estimated based upon Verma et al 2020[5].

IV. Details on calculating animal products

While crop yields would be severely reduced in an ASRS, efficient allocation of agricultural residues could be used to maintain a significant amount of dairy production. Prioritizing maintenance of dairy, if ***simple_adaptations*** are added to the scenario, is justified by the favorable feed and protein conversion efficiency of dairy as compared to beef[6], with around 400 kcal and 21 g of protein per kg of inedible feed for milk and 22 kcal and 2 g of protein per kg of inedible feed for beef.

It was estimated that livestock was reduced to levels that could be maintained by a combination of grasslands, agricultural residues, fodder crops and excess stored food and outdoor crops for the 150 Tg scenario. This ignores the potential of any stored cellulosic material such as hay, and any material killed by the catastrophes such as tree leaves, which makes it an underestimate of the livestock production.

In order to model total meat and dairy output post disaster, we have split systems into those based on human inedible feeds (grasses, crop residues and some fodder crops such as alfalfa), and those based on human edible feeds (primarily grains, oilseeds and oilseed meals). Eggs are ignored as they are less than 1% of global food production. Human edible feeds are only fed to animals in calculations where the model is estimating the diet nutritional profile. Post disaster, it is always optimal to make use of human inedible feeds when available. A few months after the disaster onset, human edible feeds are assumed to be fed to animals, but only once human caloric needs have been met. Edible feeds were assumed to only be redirected from the outputs of outdoor growing and stored food, even in the case of resilient food deployment. We have included edible organs in our analysis, all under the title of meats.

Animal products for trading blocs have been calculated using the same logic as for the global system, adjusted to the total area under pastures and croplands for each country (to provide estimates of grasses, fodder and residue availability).

V. Details on Estimating Outdoor Crop Yields

Present-day crop yields were determined from FAOSTAT yield data for the years 2014-2018, and due to data unavailability in 2019 and 2020 for calories, fat, and protein, a linear trend was extrapolated to the year 2020. Present-day production used the average global seasonal production variation based on crop years listed in the USDA PSD database[2], assuming a 4 month average harvest period. The no resilient foods ASRS case was estimated by scaling down year 2020 production by the annual reduction in yields for a 150 Tg scenario from the analysis of Xia et al[3]. Because their analysis concludes that the majority of crop production in an ASRS would come from currently tropical areas, the seasonality of production in the tropics (here between +/-24° latitude) was used as a proxy for monthly variation in global production throughout an ASRS.

Improvements in crop rotations were determined using a single run of the DSSAT based MINK global gridded model[9]. The crop model was run for one year averaging over many runs of a random weather generator using the climate average of 1994-2016, centered on 2005, and run with 400 ppm atmospheric CO_2[10]. The model was then run again but was modified to reflect the worst year of the ASRS period which starts 36 months after onset, with a 60 percentage point reduction in photosynthetically active radiation (PAR), reduction in average overland daily highs of 14°C, reductions in average overland daily lows of 12°C, and 68 percentage point reduction in average rainfall overland. Planting dates were selected such that emergence would occur no later than 30 days after planting and maturity would occur no later than 241 days after planting. If non-food trade continues, then due to the reduced arable land in a nuclear winter, we would expect higher nitrogen available per hectare. Application of 100 kg/ha elemental nitrogen equivalent was modeled in all cropped areas to simulate the increase in available fertilizer per hectare of viable cropland in an ASRS assuming continued present-day fertilizer production. This equals the nitrogen application rate in India in 2017[1]. Yields were determined for maize, paddy rice, wheat, soybeans, barley, rapeseed, potatoes, sorghum, sugar beet, sunflower seed, and chickpeas, which account for 63% of cropland and approximately 80% of the caloric production in 2005.

Calculation of relocation yield improvements were determined using a crop simulation with and without the nuclear winter, using 2005 weather conditions. In the nuclear winter, the yield of the crop was estimated as the total production if planted uniformly over all current cropland, divided by the total area of all cropland. The crop rotation percentage for each crop was then multiplied by the yield of that crop if planted on all considered crop areas to determine total production of that crop. Double or triple cropping was not considered. The relative crop production determined by this method was then used as a reduction factor for 3 years after the onset of the ASRS. The nutritional content was assumed to remain constant for each crop after the ASRS.

Even with the full 100 kg/ha of nitrogen, the estimated reduction for the crops considered was approximately 6 percentage points higher than the estimate from Xia et al, which used an estimate of present-day nitrogen in its crop model. We expect nitrogen did not greatly increase yields because nitrogen stress is not a key limiting factor for yields in the nuclear winter, unless relocation is used to grow more appropriate crops for the climate conditions[11]. Other factors which may account for the difference include the lack of time-dependent temperature reductions in our crop model and our simplification of uniform climate alterations in the 150 Tg nuclear winter averaged over all land area in the tropics.

For the relocated case and for the limited crops considered, sugar beets and potatoes produced the most calories, rapeseed produced the most fat, and wheat produced the most protein. These four crops were considered “important” and prioritized in allocating relocated cropland. In current global food cropland, these crops consist of approximately 34% of cropland area. The average caloric production in the nuclear winter scenario involved approximately a 50% reduction in planting area of unimportant crops, which was selected as the median scenario for our analysis. Important crops were wheat, potatoes, rapeseed and sugar beet. Wheat was increased from 17.5% of area to 20.7% of cropland area, rapeseed from 2.5% to 7% of cropland area, potatoes from 1.7% to 14% of cropland area, and sugar beet from 0.5% to 1% of cropland area. Other crops were reduced in area proportionally. Because the crop model attempted planting in all current cropland, many planted areas did not produce any yield. The alterations in crop area percentages due to this effect were not considered in the analysis. Furthermore, a lower bound for planting as a function of crop yield was not considered.

Detailed calculations are in the associated spreadsheet tab “Crop_Model_Relocation_Estimate'' in the Supplemental Data spreadsheet.

The varieties and types of relocated crops were very important in meeting fat and protein requirements. Protein from rapeseed meal was not included as a food, as more research as to the safety of consumption of rapeseed meal for human consumption needs to be performed[12]. Wheat was the largest contributor of protein per hectare in the relocated crop model, closely followed by soybean. However, soybean produced much fewer calories per hectare in the relocated case and was reduced to allow for other crops to be grown.

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