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

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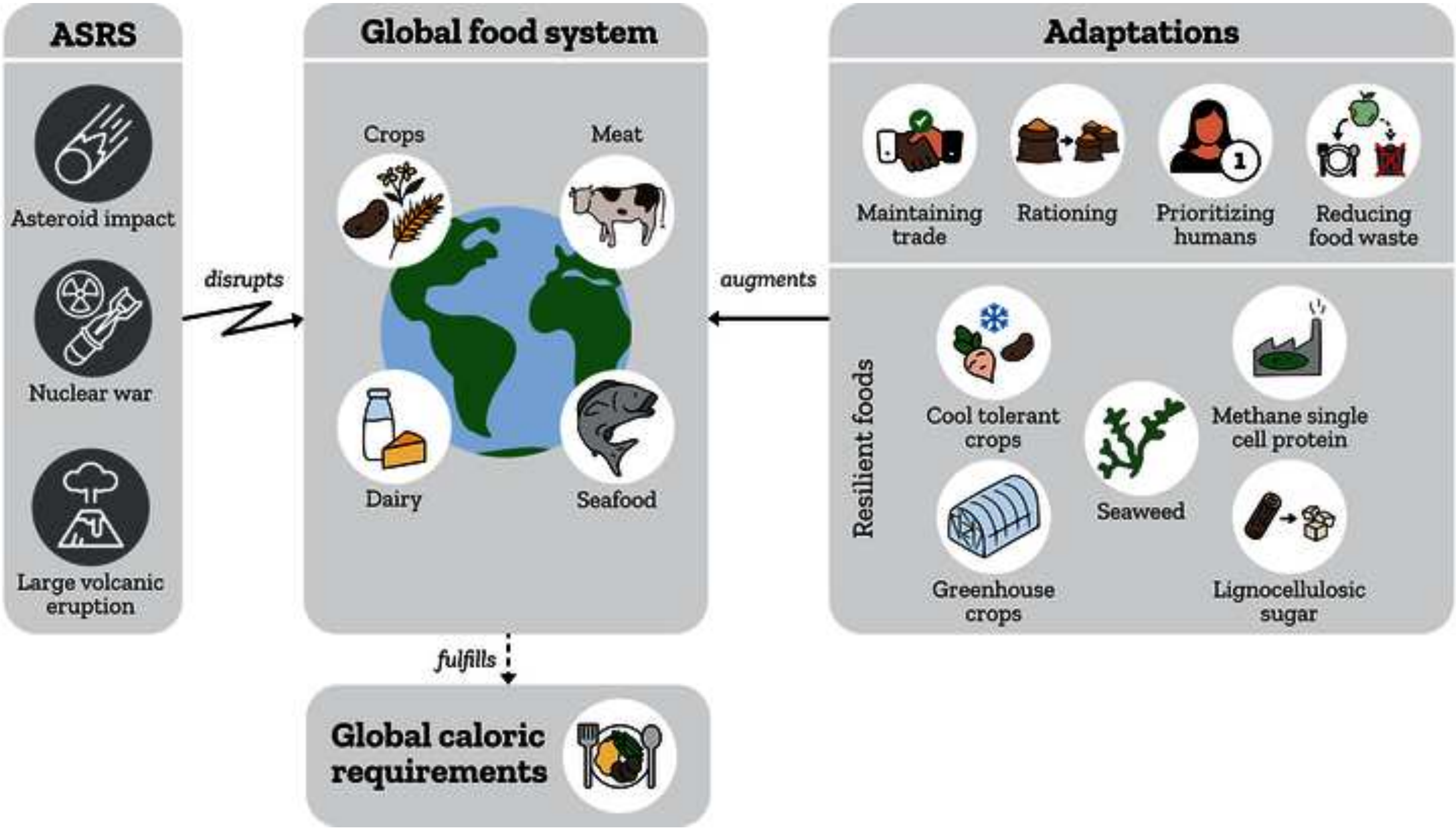
ASRS
Asteroid impact
Nuclear war
Large volcanic eruption
disrupts
Global food system
Crops
Meat
Dairy
Seafood
augments
Adaptations
Maintaining trade
Rationing
Prioritizing humans
Reducing food waste
Resilient foods
Cool tolerant crops
Methane single cell protein
Seaweed
Greenhouse crops
Lignocellulosic sugar
fulfills
Global caloric requirements

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

Abstract

After a major nuclear war, volcanic eruption or asteroid or comet impact that causes an abrupt sunlight reduction scenario, agricultural yields would plummet. We analyzed a nuclear winter scenario involving the injection of 150 Tg of soot in the stratosphere using a linear optimization model with and without global food trade. We investigated the effects of loss of global trade, some simple adaptations like rationing and storage of excess food for the coldest years, and rapid, large-scale deployment of food sources which are less dependent on present day climate (so called resilient foods) including cool tolerant crops, methane single cell protein, lignocellulosic sugar, greenhouse crops, and seaweed. In the worst case of no global trade and no adaptations, the model predicts a global famine. However, scaling up resilient foods quickly could mitigate this for many countries. Maintaining global trade would further alleviate pressure on local food systems, unlocking the potential to feed the entire global population. However, insufficient preparation, post-disaster conflict, or economic collapse would worsen outcomes and hinder adaptation.

1 Introduction

Global food production is vulnerable to catastrophic events which cause a widespread and rapid reduction in sunlight reaching the surface of the Earth. We label these *abrupt sunlight reduction scenarios* (ASRSs). At least three mechanisms for ASRS have been identified: extreme volcanic eruption[1,2], large bolide (asteroid/comet) impact[3,4], and nuclear war[5,6]. 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 failure. Large bolide impact is estimated at a likelihood of ~0.0001% per year[7], supervolcano eruption at a likelihood of ~0.01% per year[8], and though more uncertain, nuclear war has been estimated at a likelihood of ~1% per year[9–11].

In the event of a full-scale Russia-US nuclear war, starting in the month of May with 4,400 non-overlapping detonations of 100 kT (kilotonnes of TNT equivalent) over cities, the subsequent firestorms could cause 150 Tg of soot to be injected into the stratosphere, causing a nuclear winter[12]. This is considered a worst-case plausible shock to the global climate due to nuclear war[5]. By the end of the second year, average global reductions over croplands would be 16°C, solar radiation by 85%, and precipitation by 68%[5,12]. Xia et al. (2022)[12] have estimated an 89% reduction in global crop production 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 up to 10-15 years[13].

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[14]. In this paper we investigate the feasibility of response and resilience approaches to an extreme nuclear winter, in line with "Our Common Agenda" outlined by the United Nations, calling for "defining, identifying, assessing and managing existential risks"[15].

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 conservation solutions (conventional sectors of the food system used efficiently) and resilient foods (major new sectors of food production which are resilient to the colder climate after a nuclear war, to compensate for reductions in conventional food production). Food conservation solutions include the prevention of a breakdown in international food trade, rationing of stored food for the coldest years, the halting of animal feed and biofuel production, the reduction of food waste, and halting livestock breeding for meat. We also model resilient foods, including cool tolerant crops, methane single cell protein (SCP)[16], lignocellulosic sugar[17], greenhouse crops[18], and seaweed[19], finding them to produce large quantities of nutritionally adequate[20] food in the nuclear winter scenario. 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 linear optimization model simulations for each country and globally (in the case of continued food trade), which estimates month-by-month caloric production and losses in the first 10 years of the nuclear winter.

Scope and Limitations

We specifically model nuclear winter in this work, but results are generally applicable to other ASRSs, like a volcanic winter. The model focuses on the food system only and does not account for other possible effects of a nuclear war like breakdown of international financial systems, loss of non-food trade (including agricultural inputs such as fertilizer and seeds), loss of solar dependent energy (photovoltaics, wind power, etc), freezing of infrastructure (e.g. water and sewer pipes), or political effects, which are left for upcoming research. We model a variety of adaptations to nuclear winter both with and without food trade. The purpose of this study is to determine whether sufficient food system adaptation is possible in an ASRS in principle, even if global food trade were to halt entirely. Results indicate that producing enough food to prevent global famine is unlikely if food trade breaks down but plausible if it remains, as long as resilient food adaptations are deployed en masse. This investigation provides a foundational scenario to examine political and economic implications in future research.

2 Results

A set of linear optimizations is used in each scenario to determine the quantity and timing of the consumption of available food resources over the duration of the nuclear winter, reducing starvation while prioritizing preferred foods to humans, and increasing production as the next priority. These linear optimizations are run once for the globe if international food trade continues (***trade***), and once for each country in the case of no food 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[21], 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 likely mean that 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 no food ***trade***.

We list adaptations considered in 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. While all adaptations listed are plausible, some require international preparation by governments and global agribusiness, increased government regulation, continued economic functioning such stable currencies and functioning banks and financial institutions, or sufficient institutional capacity to support new sectors of the economy. Therefore, this analysis can be seen as a best case response to ASRSs.

Category	Adaptation	Definition
Food Conservation Solutions (conventional sectors of the food system used more efficiently)	***trade***	The prevention of a loss of international food trade.
	simple adaptations	Redirection of human edible foodstuffs from biofuels to humans 6 months after onset and redirection of human edible animal feed to humans 12 months after onset; immediate reduction in food waste from between 24 and 29% to between 6 and 10% of production due to an assumed tripling of global food prices, and a sharp reduction in retail waste.
	rationing	Rationing of food stocks carried into the disaster, early food production, and meat so that they are stored until their consumption in the coldest years of the nuclear winter. Preservation of meat, e.g. through drying, salting, or canning, would be necessary.
	humans prioritized	Human edible feed is restricted from being fed to animals and used for biofuels if it would result in human caloric intake to be below 2,100 kcals per day in any month. Human

		edible feed is allowed to go to milk producing animals in this scenario.
Resilient Foods (major new sectors of food production to compensate for reductions in conventional food production)	***cool tolerant crops***	Altering crop rotations to have more cool tolerant crops, and redirecting fertilizer to tropical cropland.
	seaweed	Shifting the geographic distribution of seaweed farming and scaling up the overall production considerably[19].
	lignocellulosic sugar	Rapidly repurposing pulp and paper factories, etc to produce sugars from lignocellulosic biomass (a “non-agricultural food”)[17].
	methane SCP	Rapidly establishing and deploying methane single cell protein (SCP) factories[16] from natural gas (a “non-agricultural food”).
	greenhouse crops	Rapidly constructing 190 million hectares of low-tech greenhouses[18].

2.1 No International Food Trade

In light of historical precedent for trade restriction in lesser shocks[22–24], 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 overall global caloric needs with no food ***trade*** were determined using a mathematical mean over all countries of the percentage of caloric needs met in a country (capped at 100%) weighted by that country’s population. More data for all 10 years run may be found in the Data Availability section.

No adaptations

Under these assumptions, a scenario with no adaptations and with no food ***trade*** shows only 15% of the population’s global caloric needs could be met (Figure 1 top left) which is similar to the results of Xia et al. of 19% under similar assumptions[12]. In order to represent a reasonable worst case scenario, in the case of no adaptations a minimal amount (10%) of each country’s minimum human caloric demand is satisfied before calories are allocated to animal feed and biofuels. Any remaining food after baseline feed and biofuel demands are satisfied is allocated as much as possible to humans. This prioritization of only 10% of people is in place unless the ***humans prioritized*** adaptation is included, which enforces that 100% of the human minimum caloric demand (2,100 kcals per person per day) is met before nonhuman consumption is satisfied.

Simple adaptations, Rationing, Humans Prioritized

Adding ***simple adaptations*** to the scenario improves needs met from 15% to 29%, while ***rationing*** improves needs met to 37%.

If ***rationing*** is assumed, all accessible stocks are used in the nuclear winter. However, 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 in the next year. If only the typical levels of stored food are used (leaving the buffer normally in reserve unused), the **simple adaptations** improve the scenario from 15% to 23%, and ***rationing*** improves needs met to 28%. We find stored food can still reduce starvation without ***rationing***. This is because some countries still have a minimum caloric availability in the first 12 months. Stored food and stored meat consumption is restricted to the first 12 months without ***rationing*** and so the increased stored food from removing the buffer reduces starvation during this time.

We will refer to the scenario with no food ***trade***, but with ***simple adaptations***, ***rationing***, and ***humans prioritized***, as the "Example Scenario". In this scenario, 51% of global caloric requirements are fulfilled. By comparison, 94% of global caloric requirements are fulfilled with baseline 2020 crop production, with no food ***trade***, and with ***simple adaptations***, ***rationing***, and ***humans prioritized***. Globally in present day conditions, our model indicates approximately 116% of global caloric requirements are fulfilled (see Supplemental Information Section II).

Resilient food adaptations

The incorporation of all resilient foods into the "Example Scenario" provided an additional 17 percentage points of caloric needs met for a total of 68%, with each resilient food allowing for between 2-6 more percentage points of the population to meet their caloric needs (Figure 1 right hand side). Without ***rationing***, resilient foods only provide 11, rather than 17 percentage points. Non-agricultural foods provided the most food for non-tropical countries 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 various large countries.

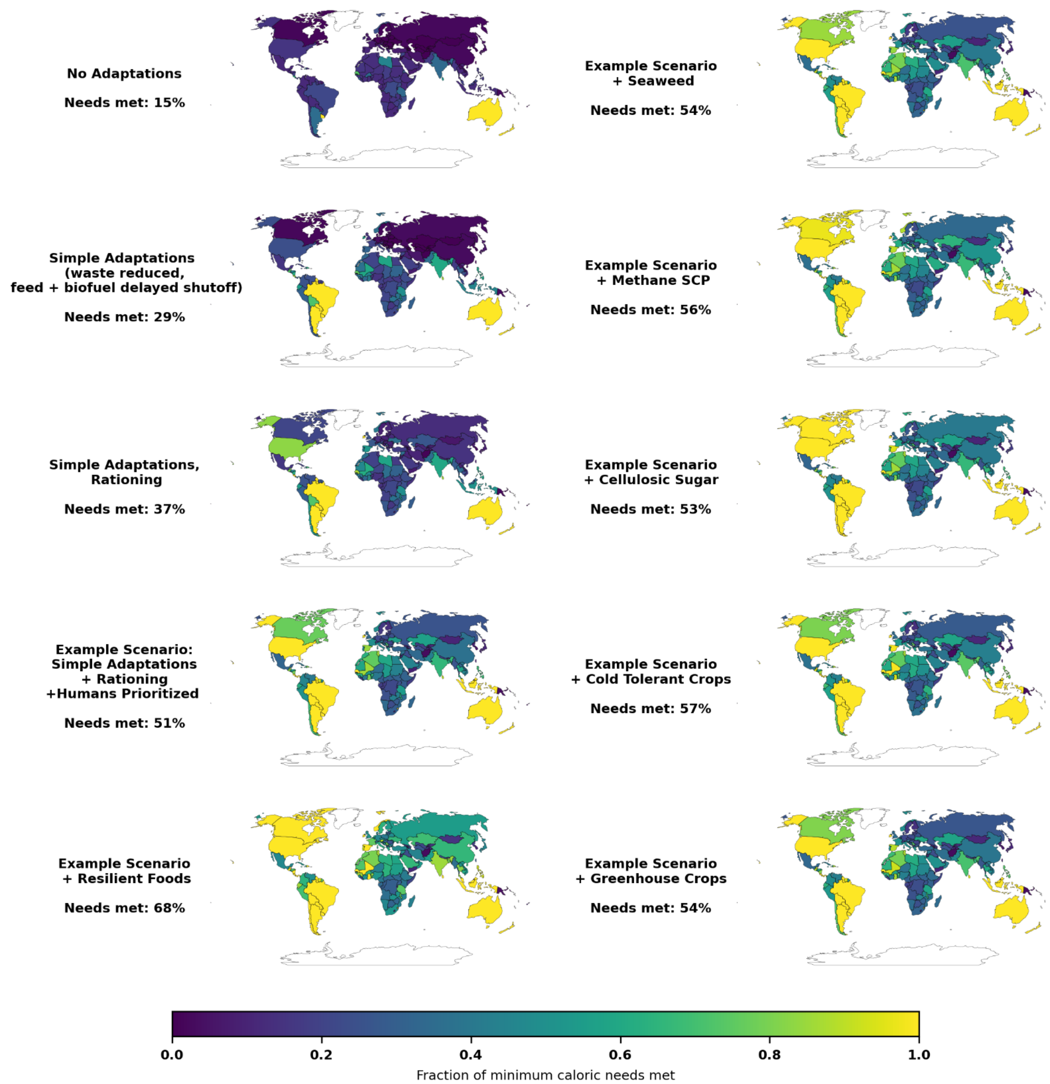

Fig. 1| Caloric needs met, no international food trade, all countries. We show the minimum percentage of caloric needs met in any month of the nuclear winter for all countries and with no food ***trade***. If ***trade*** is not assumed, there remain several adaptations that can greatly increase the percentage of caloric needs met. (**left**) A series of scenarios with different adaptations applied. The scenario on the top left may not represent the absolute 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.

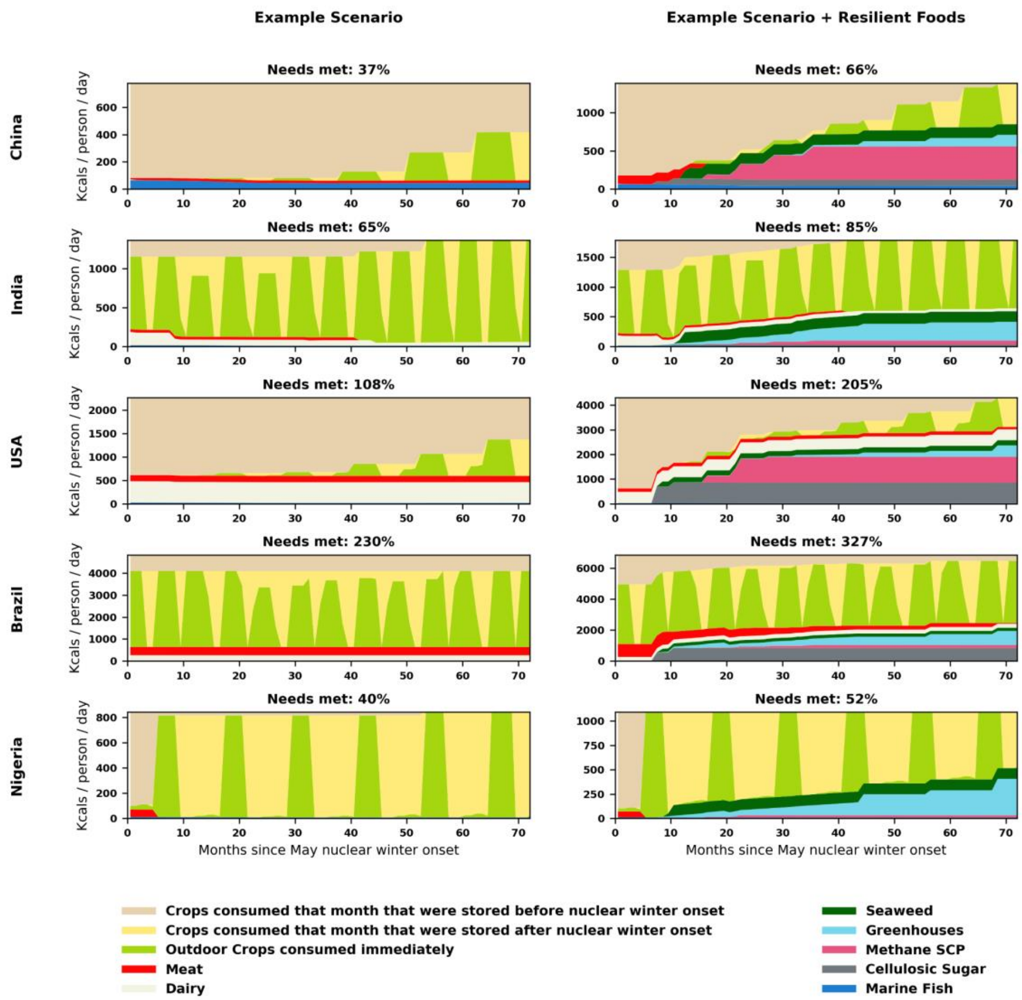

Fig. 2 | Caloric needs met over time, various large countries, no international food trade. Expected food consumption is shown over the first 72 months of the simulation in each country. Approximately half the world's population is represented. Available food consumption after losses is shown for each food source, represented with the height of each layer in the stackplot. Feed and biofuels have been subtracted from stored food plus outdoor crops only. By-country results are less accurate than global numbers due to increased data source inaccuracy on the country scale. **a.** We show each country's expected food production and relative contributions from different traditional food sources over time in the "Example Scenario": ***simple adaptations, rationing****, and* ***humans prioritized***. **b.** The same as **a**, with the addition that resilient foods have been deployed at scale (***cool tolerant crops***, ***seaweed***, **lignocellulosic *sugar***, ***methane SCP***, and ***greenhouse crops***). Research and pilots for resilient foods have been shown to be highly cost effective per life saved in expectation in other work.[25,26]

In general, higher population countries fared better in the model while smaller population countries faced issues with insufficient agricultural production and food stores. However, individual countries differed greatly in per capita production of food resources and in available food stocks. In Nigeria, which has a late growing season, limited domestic stored food supplies and reduced crop production due to the cooling effects were similarly important bottlenecks for supplying calories to humans in the first six months, so with no ***trade***, the late-arriving resilient foods had a limited utility in preventing starvation.

2.2 Continued International Food Trade

Simple Adaptations

With mostly continuing ***trade***, access to world 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. A scenario with ***trade*** and ***simple adaptations*** shows 52% of minimum global caloric needs could be met. Including ***rationing*** and ***humans prioritized*** on a global scale increases caloric needs met to 69% of needs.

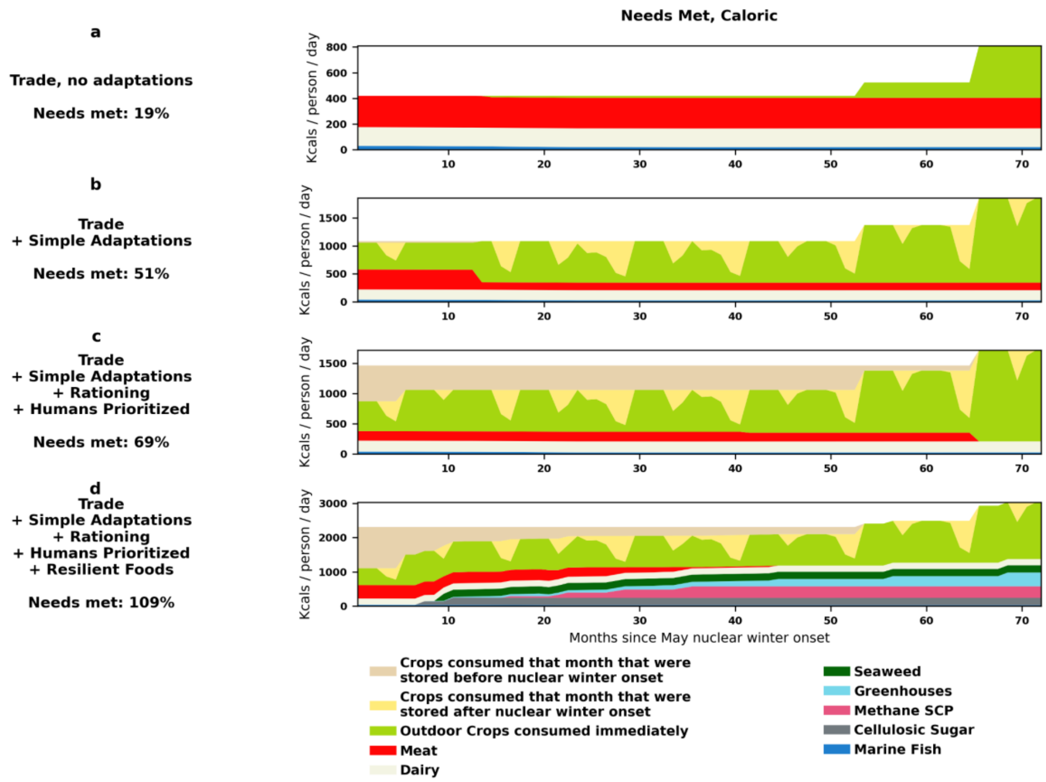

Fig. 3 | Needs met with continued international food trade. The height of each layer of the stackplot shows the caloric contribution of each food to the total needs met globally for the first 6 years of the nuclear winter. Although the full 10 years have been calculated, we only show the first 6 years as they are more critical for human survival. **a. trade** continues, otherwise no adaptations adopted **b. *trade*** continues and ***simple adaptations*** take place. **c**. ***rationing*** and ***humans prioritized*** reduce the calories directed to feed and biofuels and allow for stored food to be used throughout the scenario. **d.** In addition to the successful adaptations in **b** and **c** above, $30-$300 million in technical preparations and preparedness plans are assumed to enable a reasonably successful scale-up of resilient foods[26]. With ***trade**,* relocated crops provide approximately 350 additional kcals per person per day of crop production after waste globally, averaged over the first 53 months when food supply is minimum in this scenario.

Resilient food adaptations

The inclusion of resilient foods with ***trade*** drastically improves the situation, with 109% of minimum caloric needs met. 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. Since countries are more likely to export food if they can produce more food, awareness of and preparedness for resilient food production would likely increase the chance of continued international trade.

3 Discussion

Food security relies on a sufficient production of nutritious and affordable foods.[27] In the last 100 years, global food production shortfalls have only been a few percent lower than expected production[28] and were well above minimum human needs, in contrast to nuclear winter. We focus on ensuring sufficient low-cost food production and on efficiencies to mitigate losses in the food system. Still, while total availability of low-cost food for humans 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[29].

3.1 Technical challenges for resilient foods

The two primary challenges to scale seaweed to close to 10% of human caloric intake are twisting sufficient synthetic fiber and the feasibility of drying the seaweed in a humid, cold ASRS. At 2,100 km^2 per day, seaweed farm construction would require approximately 70,000 tonnes of rope from synthetic fiber per day. Production was only 223.5 tonnes per day in 2016[30]. Scale-up in an ASRS would require approximately a 300 fold increase in industrial production of synthetic rope, though it could be done with current polymer production.

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 from 0.13 hectares in 2000 to 1,500 hectares in 2011[30]. Seaweed also tolerates low sunlight and temperatures[31].

Other promising aspects of seaweed production and historical precedent in famines point towards it being a promising resilient food.

For greenhouses, while 250 million hectares of greenhouse area over a period of 36 months are estimated to be technically feasible[18], the relatively high cost of greenhouses per unit of production may slow construction due to lower demand for costlier foods. The complexity and relatively high upfront cost to some non-agricultural foods may prohibit their adoption in poorer regions.

Industrial responses would likely develop in parallel at different paces and with varying degrees of success, as happened during the COVID-19 pandemic[32], not necessarily limited to lignocellulosic sugar or methane SCP. These may include the production of other non-agricultural foods not considered in the modelling, such as chemosynthetic, biosynthetic, or electrosynthetic foods from biomass, hydrogen[33], CO_2[34], and hydrocarbons,[16,35] such as various other SCPs and synthetic carbohydrates, fats[35] and micronutrients. The potential for these other foods, expanding planted crop area[36], mushrooms[37], insects[38], rabbits[39], earthworms, or leaf protein concentrate[40] were not modeled.

While nitrogen, water, temperature, and sunlight stress were assessed in the crop models for relocated crops, 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. Missing such inputs can lead to massive reductions in yield[41]. However, we expect existing cool tolerant crops at higher elevation regions in the tropics, and the economic incentive to trade seeds for future food, to counteract this.

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 a nuclear winter, just as it is today[27]. Resilient food production estimates shown in this paper are expected to require $30 million to $300 million spent on researching technology deployment and constructing technology demonstration pilots before the ASRS[10]. Arguably, these areas of work can also inform preparedness and resilience against less-extreme catastrophic events, such as a multiple bread-basket failure due to concurrent weather shocks or crop diseases and pests[42].

3.2 Global cooperation and trade after a nuclear war

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[22], early in 2020 due to the threat of COVID[24], and in 2022 due to rising energy prices and agricultural market disruptions following Russia's invasion of Ukraine[23]. It thus seems likely that the pressure to reassure domestic populations will lead to widespread export bans post-disaster, especially among countries deficient domestically or with a history of export bans. It may only take a few of the main exporting countries implementing bans to cascade into the majority of countries having bans.[43]

However, some food trade may continue. A number of countries (like Australia or Argentina) are able to produce a significant domestic surplus of foodstuffs post disaster. In addition, countries may 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 domestic ability to consume seaweed, incentivizing increased trading of the surplus inland.

The global food system is a complex system, and will exhibit nonlinear dynamics as system variables change[43]. 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[44]. In a nuclear winter, such a conformational change could apply to critical infrastructure on a global scale. In this work, failure of electrical grids, transportation infrastructure, telecommunications, or other infrastructure destruction due to the nuclear war is not considered, but could have massive impacts on yields[41]. In addition, infrastructure could be affected such that countries may no longer be able to communicate and trade internally or externally after the catastrophe.[45]

3.3 Preparations on a national level

Furthermore, several adaptations could occur with no planning on national or international levels. These ***simple adaptations*** were assumed for most scenarios in the model.

One likely outcome is that 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 likely be redirected to humans (most of the animal feed is soybeans and field maize[46], which are currently consumed by humans in various forms such as soy flour and ground maize in products such as tortillas[47]). As the disaster progresses and feed prices rise, livestock may become a key source of macronutrients, as most livestock would likely be consumed or stored as meat for the coldest years. Finally, in part due to soaring food prices, waste would likely be sharply reduced. However, a rapid reduction in feed or biofuels, such as before 6-12 months, may not be economically advantageous, implying the ***humans prioritized*** adaptation could fail without preparatory legislation initiatives.

During World War II several countries increased domestic outputs of foodstuffs and key industrial goods at short notice[48]. 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 in countries such as the United Kingdom, Belgium, and the Netherlands adjusted from cash crops and animal cultivation to staple crops, and prioritized milk over meat.[49] Such a switch is also likely after a nuclear war[50]. This was combined with a rapid introduction of rationing and price controls to ensure access to foods[51]. While 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[51], increased imports of meat may also have improved diets of the poor[52].

There are many benefits to preparation for an ASRS unrelated to 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[53]. Similarly, expanding use of seaweed as a food and feed[54] today could directly draw down CO_2 concentrations in the atmosphere, and reduce cattle methane emissions[54]. As a low-cost nutritious food, seaweed can improve food security around the world today[55].

3.4 Outlook

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 reduce population and thus food demand. The effects from soaring food prices, the possibility for international subsidies for the global poor, and changes in global income distributions would influence people's ability to afford food. The complexity of preventing famine in an ASRS 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[56]. We encourage work on the prevention of nuclear war, in parallel with ongoing research and preparations to mitigate global famine during an ASRS. 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 (e.g. paper factories into lignocellulosic sugar factories), and 3) policy outcomes including the distribution of effective disaster response plans. We also recommend that business continuity managers and decision makers working in disaster risk management promote the creation of ASRS preparedness and response plans, as has been done for other high-impact low-probability hazards, both natural (e.g., tsunamis[57]) and anthropogenic (e.g., nuclear plant accidents[58]). Regional preparedness plans could complement supranational initiatives such as the international "emergency platform" proposed by the UN Secretary-General for responding to global catastrophic risks[15]. In summary, there are ample opportunities for work to increase the chance that ASRS-induced global catastrophic food failure is avoided.

4 Methods

All results 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 caloric sufficiency in scenarios with the 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 production in each country on a monthly basis over 120 months (10 years), covering the years of lowest crop production.

Xia et al.[12] 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 countries were not considered.

Separate modules each estimate macronutrient resources and usages from each part of the food system before optimization as detailed in Figure 4. See Supplemental Information section I for details on the software optimization methodology.

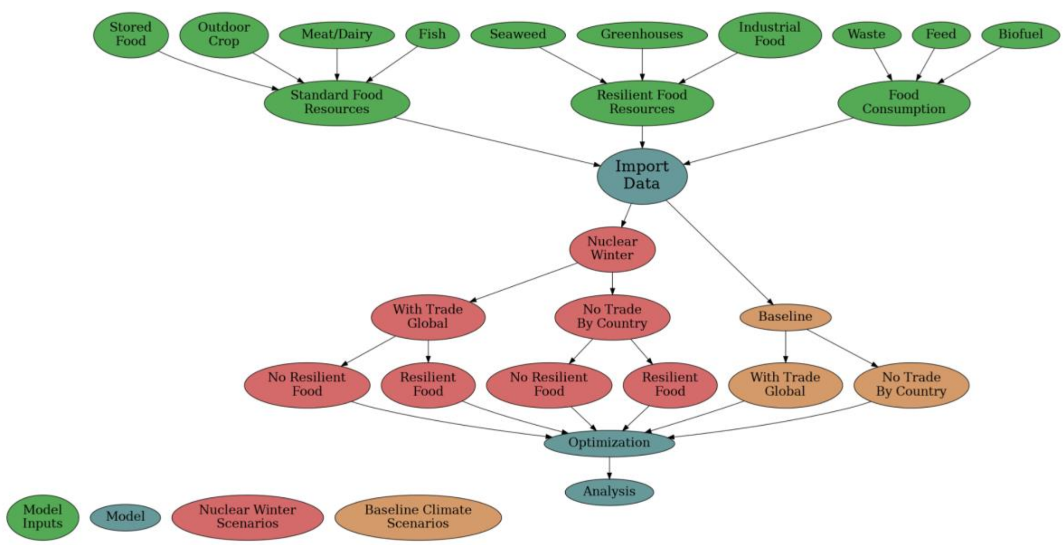

Fig. 4 | Workflow of model set-up and scenario selection. The integrated model considers standard food resources (stored food, outdoor crops, meat and dairy, fish), resilient foods (seaweed, greenhouses, crop relocation, non-agricultural food) and nonhuman food consumption (waste, feed, biofuel). Depending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

4.1 Food System Model

Initial food stocks and crop years were taken from the USDA PSD database[27]. Stocks are based on the crop year ending stocks and adjusted to the crop years of each country (see Supplemental Information III 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[12].

By-country population in 2020 was obtained from the World Bank[59]. Deaths or reduction in livestock populations from the nuclear detonations or fallout are not incorporated into the model. FAOSTAT data[60] on a country-by-country basis were used to estimate animal stocks for 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 II.

The minimum recommended daily intake of energy is set to 2,100 kcals per person per day in the model. Fat and protein are not modeled, although resilient food diets appear to be able to largely meet key macronutrient and micronutrient requirements at a population scale with nutritional planning[20]. Therefore, meeting caloric needs is considered nutritionally sufficient under each scenario.

In all scenarios, inedible feed was reduced by the same percent of decline in grass yields for grasslands on an annual basis and the same percentage as average decline in crop yields for fodder crops and crop residues. Total output of inedible feed (grasses, crop residues and fodder crops) was taken from the results presented in the GLEAM database[61], 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.

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

4.2 Resilient Foods

Resilient foods were chosen based on resource constraints, cost-effectiveness, and technical feasibility. The scenarios with resilient foods account for greatly increased food resources from ***greenhouse crops***, ***seaweed***, ***cool tolerant crops***, and non-agricultural foods. Low-cost foods are included preferentially. Details on modelling of more conventional food system adaptations can be found in Supplementary Information Section IX.

4.2.1 Seaweed

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

Seaweed was limited to 10% of human caloric intake due to digestibility and iodine concerns.[62] Experts suggest 1-2 mg is a safe daily intake of iodine, although, empirically, higher consumption does not typically cause health issues[63]. Boiling and washing the seaweed has also been shown to reduce iodine content in similar seaweeds[64].

The seaweed daily growth rate is determined by using monthly growth rates from Jehn et al.[19] and aggregating them by the exclusive economic zones of the countries. The starting seaweed stock in each country was loaded from FAOSTAT[60], but each country with a coast was assumed to start with at least 500 kg wet mass. Initial farm area and maximum area built was calculated based on the fraction of ocean coastline in each country out of the global total[65]. See Supplemental Information section VI for more details on seaweed modeling.

4.2.2 Crop Relocation (***cool tolerant crops***)

Crop production would fall to much lower percentages of baseline production in the nuclear winter without relocated cool-tolerant crops grown in the tropics. On a per hectare basis, sugar beets and potatoes produced the most calories, rapeseed the most fat, and wheat the most protein. While these crops would not be the only crops viable outdoors in the nuclear winter, they represent a high yield, cool-tolerant crop rotation for macronutrients, which would be likely combined alongside continued cultivation of maize, rice, pulses and vegetables where possible.

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, and leaving fractions greater than 1 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 still have zero production. See Supplemental Information Section VII for details on how these improvements were determined.

4.2.3 Greenhouse Crops (***greenhouse crops***)

Low-tech polymer-covered greenhouses could affordably boost calorie production during nuclear winters despite currently low global contributions.[18] 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 could enable crop growth in otherwise infertile regions. To avoid overly optimistic outcomes, a 2-month delay before construction of greenhouses was assumed. New greenhouses are constructed only on viable croplands[60]. The maximum ratio of area covered by greenhouses in each country was set to 190 million hectares divided by the total global cropland in 2020 of 1.43 billion hectares (a maximum percentage of 13.3% of each country's cropland). Outdoor cropland in the tropics was in turn reduced by 13.3%.

See Supplemental Information Section VIII for more greenhouse yield details.

4.2.4 Non-agricultural foods (***methane SCP***, **lignocellulosic *sugar***)

Non-agricultural food production during nuclear winter includes rapidly converting paper mills to sugar biorefineries[17] for lignocellulosic biomass and constructing large-scale fermentation facilities for SCP from natural gas.[16] Both are currently at high technological readiness. We assume a 2-month delay of non-agricultural food repurposing or construction. Although it is technically feasible to continue SCP factory construction past month 33, we assume construction halts due to high capital intensity needing to be spread over sufficient number of years of production.

Growth profiles for non-agricultural foods were based on previously published estimates,[16,17] starting with repurposing two-thirds of global paper mills for sugar, with remaining industrial resources invested in 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. Sugar production quickly addresses immediate food shortages, while SCP is slower to come online but more nutritious.

Global conversion rates of paper mills to sugar factories and SCP facility setups were estimated from previously published growth rate models and the capital expenditures of chemical and related industries.[16,17] 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[59]. The **lignocellulosic *sugar*** produced in each country was estimated by dividing the country's wood pulp processing share by the global total[60], while ***methane SCP*** produced in each country was estimated using the share of industrial capital in each country.

Data and Code Availability

The supplemental spreadsheet data is located in the code repository for the paper. Monthly caloric availability, feed and biofuel consumption, and animal slaughter and populations for all 10 years for all countries and all scenarios in Figure 1 is located at https://zenodo.org/records/10950464[66]. Crop relocation data are available on request. All code for this paper is available at https://github.com/allfed/allfed-integrated-model/tree/1.3.

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Ethics Declarations

Competing interests

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

Supplemental Information

I. Details on software optimization methodology

There are several linear optimizations performed for each scenario. When no feed or biofuel is used, only one round of linear optimizations is performed. With feed or biofuels, there are two additional rounds. The first additional optimization round enforces humans are fed at least 2,100 kcals per person per day if possible, with food given to humans prioritized in descending order of fish, meat, dairy, greenhouse crops, outdoor crops, stored food, methane SCP, lignocellulosic sugar, and seaweed. Any remaining feed and biofuels are then allocated to animals. The last round uses the feed allocated from the second round to estimate meat consumption for humans.

Each round has a set of optimizations: first, we maximize the minimum ratio of human nutritional needs to minimum recommended calories in any month of the scenario. A secondary optimization is then run to prioritize consumption of outdoor crops and stored food by humans, and a tertiary optimization is run to reduce fluctuations in utilized food resources and maximize food production (even if it doesn't change the calories consumed in the minimum month).

Each linear 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 slaughtered meat, the preference of reduced changes in caloric production amongst optimized foods, the maximization of calories available (even if not altering months where calories are at a minimum), and the optimal allocation of stored food from stocks at the onset of the nuclear winter if rationing is added. It also enforces maximal nutritional constraints for humans and animals (see Supplemental Information Section V, "Details on calculating animal products"). Feed and biofuel were restricted to only consume stored food or outdoor crops.

II. 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 (1 dry caloric tonne = 4 million kcals), human inedible grasses for feed at 4206 million dry caloric tonnes energy equivalent, and marine fish at 28 million dry caloric tonnes. Feed and biofuel nutrient usage on the global level annually were set to 1447 million dry caloric tons and 623 million dry caloric tonnes, respectively, 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 four 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 IV Waste section below). The diet composition for this 2020 baseline is shown in Figure S1.

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. 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. In most cases, the ratio is high, with an approximate average ratio of 6 calories to 1 calorie for eggs and dairy, and over 30 for beef in the US for example[3].

A plot of the diet in 2020 from the model is shown below, which accounts for the satisfaction of global caloric consumption. The food supply at the retail/household level was estimated at around 2930 kcals per person per day, with waste. Losses and waste at the household/retail level due to is estimated at around 700 kcals per person per day, leaving approximately 2230 kcals per capita. The model indicates approximately 2440 kcals. Given the many uncertainties in production and waste in the global food system, this level of consumption was deemed plausible and left unchanged in the model.

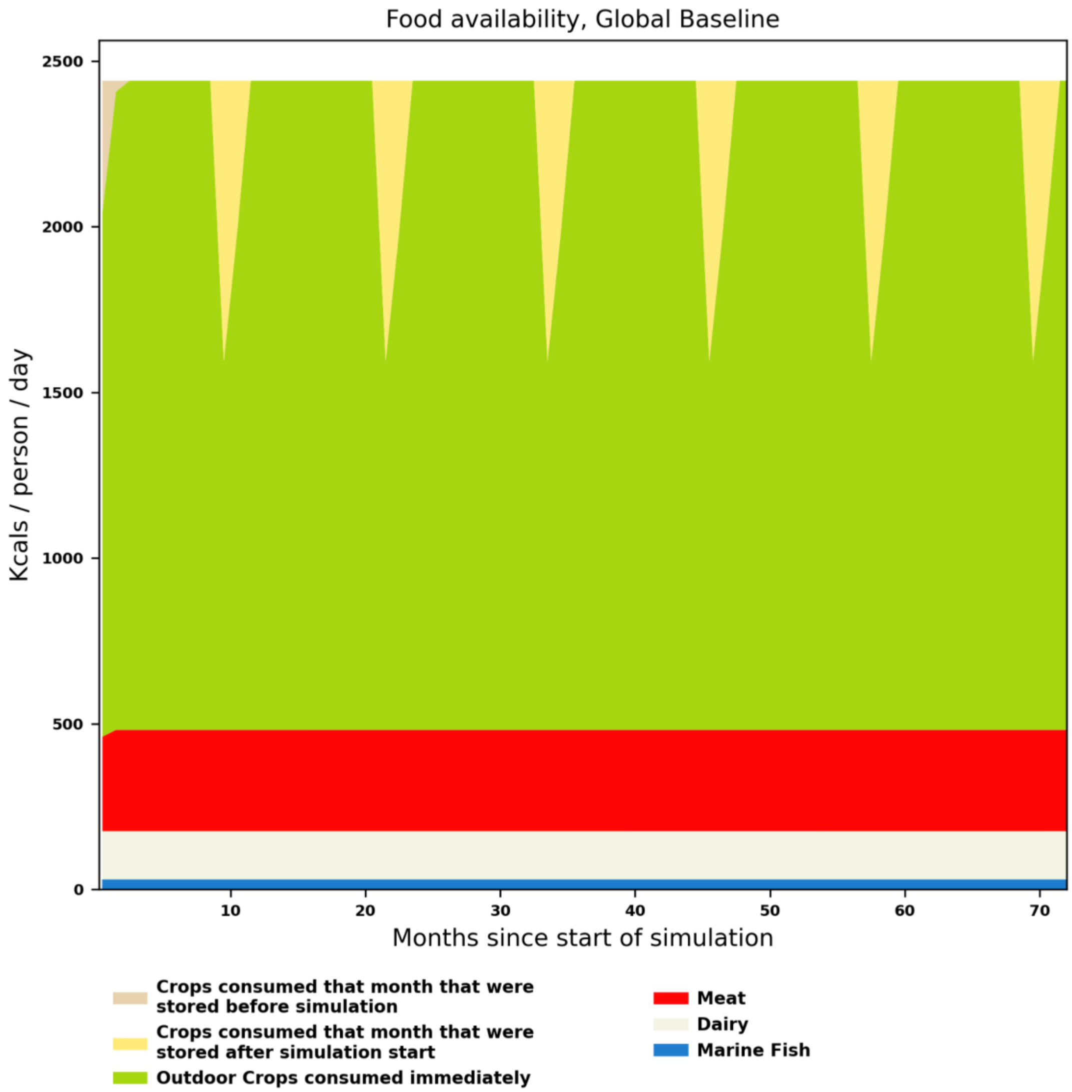

Figure S1 | Production in 2020: Dietary composition, excess calories are fed to livestock and used for biofuels at 2020 levels

Additional validation with previously published results from Xia et al[4] 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 no adaptations. Reproducing the model also required setting feed reduction proportional to the yield reduction and continuing feeding animals and biofuels throughout the nuclear winter.

III. 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 found that the global stored food is 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 war 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 harvest 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[5]. 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.

IV. Details on Estimating 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[6]. We expect prices would more than triple, but we conservatively chose to limit price increase when calculating waste to ensure we did not overestimate the overall reduction in waste. 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[6] (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 country.

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 nuclear winter. As most likely there would be an effort to reduce harvest losses given the higher food prices, harvest waste would likely be lower in reality than in the model. 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[6].

V. Details on calculating animal products

While crop yields would be severely reduced in a nuclear winter, efficient allocation of agricultural residues could be used to maintain a significant amount of dairy production. Prioritizing maintenance of dairy is justified by the favorable feed and protein conversion efficiency of dairy as compared to beef[7], 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 dry 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. Edible feeds were assumed to only be redirected from the outputs of outdoor growing, stored food, methane SCP (at max 43% of feed, no restriction for the percent of biofuel demand), cellulosic sugar (at max 10% of feed, no restriction for the percent of biofuel demand), or seaweed (at max 10% of feed and 10% of biofuel demand). 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).

VI. Details on estimating seaweed production

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

$$wet\quad m_{b,m=0} = initial_{seawee}d_b \qquad (4)$$
$$area_{b,m=0} = initial\quad a_b$$

$$forallcountriesc, months 0 < m \leq 120 \qquad (5)$$
$$area_{c,m} = area_{c,m-1} + monthly\quad t_b$$
$$wet\quad m_{c,m} = wet\quad m_{c,m-1} * monthly_{growth^{c,m}}$$
$$-(area_{c,m} - area_{c,m-1}) * min_{density} * harvest_{fraction}$$
$$-seaweed_{produce}d_{c,m}$$
$$seaweed_{produce}d_{c,m} \leq 10\% monthly$$

$$\text{wet\_on\_farm}_{b,m=0} = \text{initial\_seaweed}_b \qquad (4)$$
$$area_{b,m=0} = \text{initial\_farm\_area}_b$$

$$\text{For all countries } b\text{, months } 0 < m \leq 72: \qquad (5)$$
$$area_{b,m} = area_{b,m-1} + \text{monthly\_area\_built}_{b,m}$$
$$\text{wet\_on\_farm}_{b,m} = \text{wet\_on\_farm}_{b,m-1} * \text{monthly\_growth}$$
$$-\left(area_{b,m} - area_{b,m-1}\right) * \text{min\_density} * \text{harvest\_fraction}$$
$$-\text{seaweed\_produced}_{b,m}$$
$$\text{seaweed\_produced}_{b,m} \leq 10\% \text{ monthly\_caloric\_needs}_b$$

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 are from FAOSTAT. Harvesting happens 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_fraction* as a factor of 0.85[8]. Minimum wet-on-farm density of the stock (*min_density*) was estimated at 1.2 kg/m^2, while maximum wet-on-farm density after harvest (*max_density*) was estimated as 3.6 kg/m^2, based on harvests of the species *Gracilaria tikvahiae*[9]. The initial area (*area*) was selected at only 10 km^2 because most current seaweed area would no longer be suitable for seaweed cultivation. From rope availability, we assumed that 63,000 km^2 of new seaweed farms could be built monthly (*monthly_area_built*), limited to a maximum of 3 km^2 per km of coast in the region being modeled.

VII. 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 nuclear winter 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[4]. Furthermore, because their analysis concludes that the majority of crop production in a nuclear winter 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 a nuclear winter.

The Xia et al. manuscript gives the reduction in harvest of the first year, but does not distinguish country harvests for May through December of the first year. In our model, Japan, North Korea and South Korea were set to zero harvest yield, South Africa to normal harvest yield, and otherwise the ratio of a normal harvest in the country and the harvest in nuclear winter was used as the estimated harvest in May - December of the first year. Japan, North Korea, and South Korea were set to zero yield as all the harvest in these countries typically occurs on or after the month of May, and they are expected to have a very low yield in the first year. Other than for these countries, the ratio of yield in the third year (December to December) was weighted by the harvest normally occurring in each month of the year of each country. For countries with less than ¼ the harvest after May, the harvest in May-December were left unchanged.

Improvements in crop rotations were determined using a single run of the DSSAT based MINK global gridded model[10]. Results were used only in aggregate over all countries, and yield changes were not evaluated on a by-country basis; instead the global improvements from relocation were applied to all countries equally. 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[11]. The model was then run again but was modified to reflect the worst year of the nuclear winter 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% 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 a nuclear winter 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 nuclear winter. The nutritional content was assumed to remain constant for each crop after the nuclear winter.

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[12]. 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, all per hectare. These four crops were considered “important” for relocation and prioritized in allocating relocated cropland. These crops make up approximately 22% of global food cropland area. Remaining crops considered were deemed “unimportant” for relocation (maize, paddy rice, soybeans, barley, sorghum, sunflower seed, and chickpeas). To model a successful deployment of relocated crops in the nuclear winter scenario, we estimated the increase in calories produced if there were a halving of planted area globally of the “unimportant” crops considered, and an increase in important crop area to make up for the reduced area of the unimportant crops for relocation. Wheat was increased from 17.5% of area to 20.7% of global food cropland area, rapeseed from 2.5% to 7% of global food cropland area, potatoes from 1.7% to 14% of global food cropland area, and sugar beet from 0.5% to 1% of global food cropland area. These increases were selected to balance increasing calories, fat and protein in proportion to our estimates of the approximate severity of their deficit in nuclear winter. Because the crop model attempted planting in all current global food 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 Results" 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[13]. Wheat was the largest contributor of protein per hectare in the relocated crop model, closely followed by soybean. However, soybean produced many fewer calories per hectare in the relocated case and was reduced to allow for other crops to be grown.

VIII. Details on Estimating Greenhouse Crops

Yield improvements for greenhouse crops were estimated assuming yields are directly proportional to *growing degree days* (GDDs). Manaus (Brazil) was considered for being representative of tropical regions where most of the greenhouse crop production occurs. 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.

IX. Food conservation solutions

The integrated food system model can simulate a wide range of food system adaptations to ensure food production during a nuclear winter.

Feed and biofuels delayed shut off

To account for the extremity of the nuclear winter, the simple adaptations of shutting off biofuels based on food crops after 6 months and human edible feed after 12 months in all countries were implemented. This was assumed to occur due to rapidly increasing prices of human edible food and thus a lack of economic viability for continued feed and biofuel usage.

Rationing

Without ***rationing*** enabled, only the first 12 months were allowed to optimize with stored food. If ***rationing*** was added to the scenario, stored food was allowed to be used in any of the 120 months to maximize the objective. No constraints on meat storage duration or storage capacity were assumed with ***rationing*** enabled.

Humans Prioritized

We assume that the speed of animal slaughter can only be improved by around 10% with ***humans prioritized***, as meat processing is highly industrialized and cannot change its output quickly (non-industrial solutions may be feasible, but these are conservatively ignored). As animal populations decline, feed is redirected to human consumption.

The simplest way to reduce the feed consumption is to stop animal breeding for animals consuming human edible feed. If the ***humans prioritized*** adaptation is added to the scenario, breeding is halted for all animals except for milk producing animals, when the catastrophe occurs. Furthermore, feed and biofuels are always reduced to zero if they cause humans to go below 2,100 kcals in any month in the ***humans prioritized*** scenarios. This enforces the priority of survival of all humans over animals in this scenario.

Marine Fish

Marine fish catch could continue at a reduced rate during the nuclear winter[14]. Half of the current catch (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. Aquaculture systems typically use human edible fish food, so it does not contribute net positive calories. The loss in calories from seafood fed with human edible food was not considered, as it contributes less than 1% of baseline crop caloric production.

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