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Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection

Lili Xia¹✉, Alan Robock¹, Kim Scherrer^{2,3}, Cheryl S. Harrison⁴, Benjamin Leon Bodirsky^{5,6}, Isabelle Weindl⁵, Jonas Jägermeyr^{5,7,8}, Charles G. Bardeen⁹, Owen B. Toon¹⁰ and Ryan Heneghan¹¹

Atmospheric soot loadings from nuclear weapon detonation would cause disruptions to the Earth's climate, limiting terrestrial and aquatic food production. Here, we use climate, crop and fishery models to estimate the impacts arising from six scenarios of stratospheric soot injection, predicting the total food calories available in each nation post-war after stored food is consumed. In quantifying impacts away from target areas, we demonstrate that soot injections larger than 5 Tg would lead to mass food shortages, and livestock and aquatic food production would be unable to compensate for reduced crop output, in almost all countries. Adaptation measures such as food waste reduction would have limited impact on increasing available calories. We estimate more than 2 billion people could die from nuclear war between India and Pakistan, and more than 5 billion could die from a war between the United States and Russia—underlining the importance of global cooperation in preventing nuclear war.

Extraordinary events such as large volcanic eruptions or nuclear war could cause sudden global climate disruptions and affect food security. Global volcanic cooling caused by sulfuric acid aerosols in the stratosphere has resulted in severe famines and political instability, for example, after the 1783 Laki eruption in Iceland¹ or the 1815 Tambora eruption in Indonesia^{2,3}. For a nuclear war, the global cooling would depend on the yields of the weapons, the number of weapons and the targets, among other atmospheric and geographic factors. In a nuclear war, bombs targeted on cities and industrial areas would start firestorms, injecting large amounts of soot into the upper atmosphere, which would spread globally and rapidly cool the planet^{4–6}. Such soot loadings would cause decadal disruptions in Earth's climate^{7–9}, which would impact food production systems on land and in the oceans. In the 1980s, there were investigations of nuclear winter impacts on global agricultural production¹⁰ and food availability¹¹ for 15 nations, but new information now allows us to update those estimates. Several studies have recently analysed changes of major grain crops^{12–14} and marine wild catch fisheries¹⁵ for different scenarios of regional nuclear war using climate, crop and fishery models. A war between India and Pakistan, which recently are accumulating more nuclear weapons with higher yield¹⁶, could produce a stratospheric loading of 5–47 Tg of soot. A war between the United States, its allies and Russia—who possess more than 90% of the global nuclear arsenal—could produce more than 150 Tg of soot and a nuclear winter^{4–9}. While amounts of soot injection into the stratosphere from the use of fewer nuclear

weapons would have smaller global impacts¹⁷, once a nuclear war starts, it may be very difficult to limit escalation¹⁸.

The scenarios we studied are listed in Table 1. Each scenario assumes a nuclear war lasting one week, resulting in the number and yield of nuclear weapons shown in the table and producing different amounts of soot in the stratosphere. There are many war scenarios that could result in similar amounts of smoke and thus similar climate shocks, including wars involving the other nuclear-armed nations (China, France, United Kingdom, North Korea and Israel).

Recent catastrophic forest fires in Canada in 2017¹⁹ and Australia in 2019 and 2020^{20,21} produced 0.3–1 Tg of smoke (0.006–0.02 Tg soot), which was subsequently heated by sunlight and lofted high in the stratosphere. The smoke was transported around the world and lasted for many months. This adds confidence to our simulations that predict the same process would occur after nuclear war.

Nuclear war would primarily contaminate soil and water close to where nuclear weapons were used²². Soot disperses globally once it reaches the upper atmosphere; thus, our results are globally relevant regardless of the warring nations. Here, we focus on the climate disruption from nuclear war, which would impact global food production systems on land and in the oceans. So far, an integrated estimate of the impacts of the entire range of war scenarios on both land- and ocean-based food production is missing. We examine the impacts of six war scenarios, generating 5 Tg to 150 Tg of soot, on the food supply (Table 1). We use model simulations of major crops and wild-caught marine fish together with estimated changes in

¹Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, USA. ²Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain. ³Department of Biological Sciences, University of Bergen, Bergen, Norway. ⁴Department of Ocean and Coastal Science, Center for Computation and Technology, Louisiana State University, Baton Rouge, LA, USA. ⁵Potsdam Institute for Climate Impact Research, Potsdam, Germany. ⁶World Vegetable Center, Tainan, Taiwan. ⁷NASA Goddard Institute for Space Studies, New York, NY, USA. ⁸Center for Climate Systems Research, Columbia University, New York, NY, USA. ⁹National Center for Atmospheric Research, Boulder, CO, USA. ¹⁰Laboratory for Atmospheric and Space Physics, Department of Atmospheric and Ocean Sciences, University of Colorado, Boulder, CO, USA. ¹¹School of Mathematical Sciences, Queensland University of Technology, Brisbane, Queensland, Australia. ✉e-mail: lilixia@envsci.rutgers.edu

Table 1 | Number of weapons on urban targets, yields, direct fatalities from the bomb blasts and resulting number of people in danger of death due to famine for the different scenarios we studied

Soot (Tg)	Number of weapons	Yield (kt)	Number of direct fatalities	Number of people without food at the end of Year 2
5	100	15	27,000,000	255,000,000
16	250	15	52,000,000	926,000,000
27	250	50	97,000,000	1,426,000,000
37	250	100	127,000,000	2,081,000,000
47	500	100	164,000,000	2,512,000,000
150	4,400	100	360,000,000	5,341,000,000
150	4,400	100	360,000,000	*5,081,000,000

The 5 Tg case scenario is from ref.¹⁶ for an India–Pakistan war taking place in 2008; the 16–47 Tg cases are from ref.¹⁸ for an India–Pakistan war taking place in 2025; and the 150 Tg case is from ref.⁵¹, which assumes attacks on France, Germany, Japan, United Kingdom, United States, Russia and China. The last column is the number of people who would starve by the end of Year 2 when the rest of the population is provided with the minimum amount of food needed to survive, assumed to be a calorie intake of 1,911 kcal per capita per day, and allowing for no international trade; from Supplemental Information, Supplementary Table 5, the Partial Livestock case, in which 50% of livestock grain feed is used for human consumption, and 50% of livestock grain feed is used to raise livestock, using the latest complete data available for the year 2010. For 2010, the total population of the nations used in this study was 6,700,000,000. There are many other scenarios in which these amounts of soot could be produced by a nuclear war, and the scenarios we use are only meant to be illustrative examples. The last column is the case with the fewest number of deaths without international trade, and other cases are available in the Supplementary Information. *Assuming total household waste is added to food consumption.

other food and livestock production to assess the impacts on global calorie supply.

Results

Impacts on crops and fish catch productivity. Using climate, crop and fishery models (Methods), we calculate calorie production for different food groups, for each year after a range of six different stratospheric soot injections. The climatic impacts would last for about a decade but would peak in the first few years (Fig. 1).

Global average calorie production from the crops we simulated decreased 7% in years 1–5 after the war even under the smallest, 5 Tg soot scenario (Fig. 2a; comparable to previous multi-model results¹⁴, Supplementary Fig. 2) and up to 50% under the 47 Tg scenario. In the 150 Tg soot case, global average calorie production from crops would decrease by around 90% 3–4 years after the nuclear war. The changes would induce a catastrophic disruption of global food markets, as even a 7% global yield decline compared with the control simulation would exceed the largest anomaly ever recorded since the beginning of Food and Agricultural Organization (FAO) observational records in 1961¹⁴.

Fish are another important food resource, especially in terms of protein supply. Nuclear war would reduce the wild fish catch¹⁵, but the reduction would be less than for land agriculture (Fig. 2b), because reduction in oceanic net primary productivity—the base of the marine food web—is moderate (from 3% in 5 Tg to 37% in 150 Tg), and ocean temperature changes are less pronounced (Fig. 1). Terrestrial crop production dominates the total calorie change of crops and fisheries combined (Fig. 2c), because global crop production is 24 times higher than wild fisheries in terms of dry matter, and staple crops contain around five times more calories than fish per unit retail mass^{23,24}. In total, marine wild capture fisheries contribute 0.5% of total calories but 3.5% of global average protein supply (Fig. 3 and Supplementary Fig. 3).

Cooling from nuclear wars causes temperature limitations for crops, leading to delayed physiological maturity and additional

cold stress¹⁴. Calorie reduction from agriculture and marine fisheries shows regional differences (Supplementary Fig. 4), with the strongest percentage reductions over high latitudes in the Northern Hemisphere. Even for the India–Pakistan case, many regions become unsuitable for agriculture for multiple years. For example, in the 27 Tg case, mid- to high latitudes of the Northern Hemisphere show reductions in crop calorie production greater than 50%, along with fish catch reductions of 20–30%. The nuclear-armed nations in mid- to high latitude regions (China, Russia, United States, France, North Korea and United Kingdom) show calorie reductions from 30% to 86%, and in lower latitudes (India, Pakistan and Israel), the reduction is less than 10% (Supplementary Tables 1 and 2). Impacts in warring nations are likely to be dominated by local problems, such as infrastructure destruction, radioactive contamination and supply chain disruptions, so the results here apply only to indirect effects from soot injection in remote locations.

Impacts on total human calorie intake. To estimate the effect on the total food calories available for human consumption, we consider diet composition, calorie content of different food types, crop usage and changes in food production that we did not directly model (Methods). In 2010, FAO²³ reported that 51% of global calorie availability came from cereals, 31% from vegetables, fruit, roots, tubers and nuts and 18% from animal and related products, of which fish contributed 7%, with marine wild catch contributing 3% (Fig. 3a). The crops and fish we simulated provide almost half of these calories and 40% of the protein. Further, only portions of the simulated food production are available for human consumption. Many crops (for example, maize and soybean) are used mainly for non-food uses such as livestock feed (Fig. 3c).

In addition, the total number of calories available as food is highly dependent on human reactions to nuclear wars. We assume that international trade in food is suspended as food-exporting nations halt exports in response to declining food production (Methods). Furthermore, we considered three societal responses, *Livestock*, *Partial Livestock* and *No Livestock* (Supplementary Table 3). For the *Livestock* response scenario, representing a minimal adaptation to the climate-driven reduction in food production, people continue to maintain livestock and fish as normal. Although harvesting a larger share of crop residues for feed or adding new feed such as insect-based supplements may increase the potential livestock feed, we assume that no new feed supplements are added and the ratio of agricultural grains, residues and grazed biomass to livestock feed is the same. Calories from all crops are reduced by the average reduction in our four simulated crops, and calorie changes from marine wild-caught fish are calculated with business-as-usual fishing behaviour. The *No Livestock* response represents a scenario where livestock (including dairy and eggs) and aquaculture production are not maintained after the first year, and the national fractions of crop production previously used as feed are now available to feed humans. In addition, fishing pressure intensifies, simulated through a fivefold increase in fish price¹⁵. Similar responses took place in New England in the ‘year without a summer’ after the 1815 Tambora volcanic eruption². Even though the temperature changes were smaller than modelled in any of the nuclear war scenarios here, crop failures forced farmers to sell their livestock because they could not feed them³, and previously unpalatable fish were added to their diet^{2,3,25}. We test a full range (0–100%) of the fraction of food-competing feed²⁶ that could be used by humans and select 50% as an example in some plots and tables. Between the *Livestock* and *No Livestock* cases, we also consider a *Partial Livestock* case, in which the remaining portion of livestock grain feed after converting to human consumption would be used for raising livestock.

Final biofuel products (biodiesel and ethanol) only count for 0.5% of the plant-based products²⁷, which could be repurposed as food in the form of plant oil (~1.8% of total food calories) and

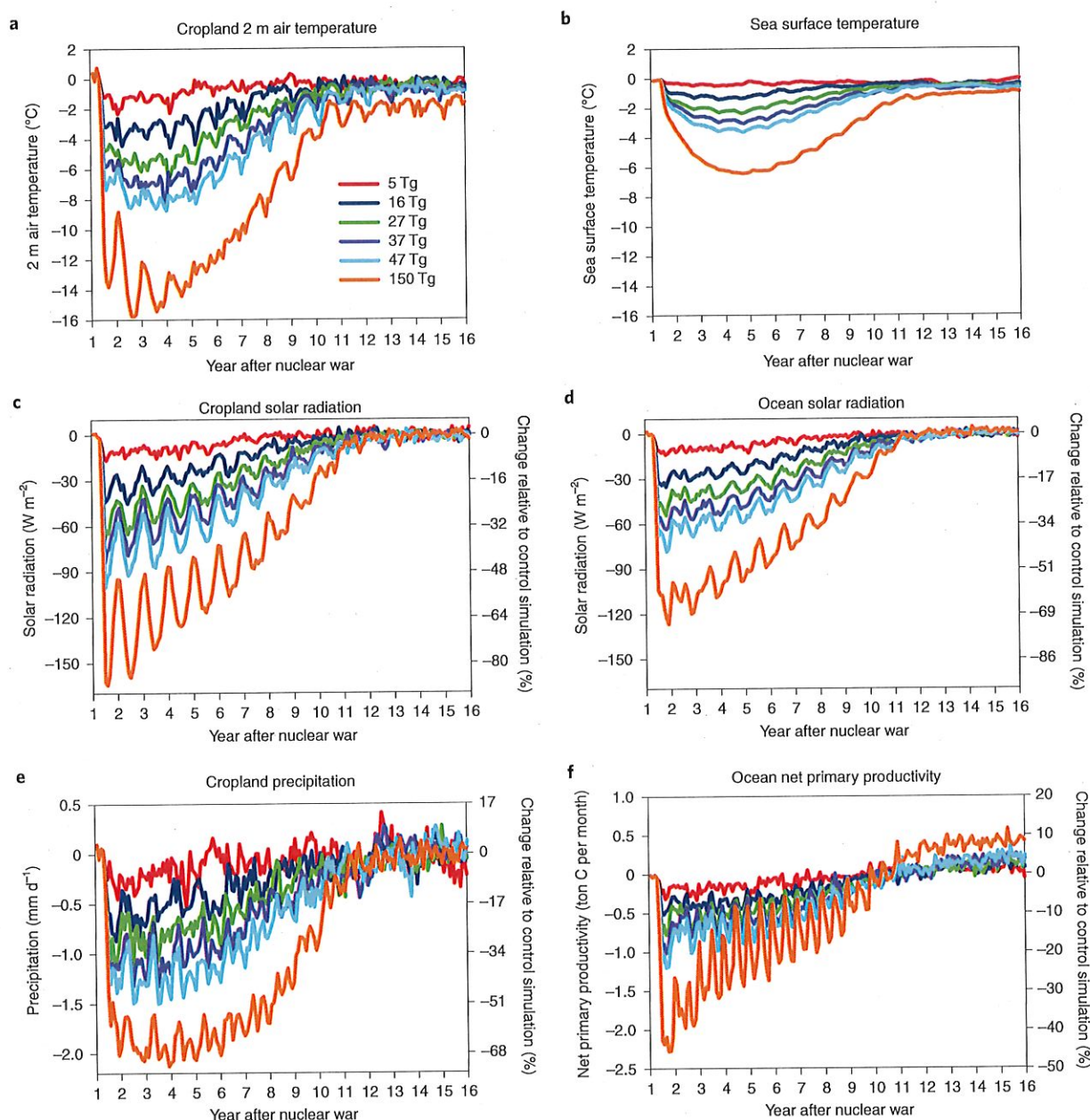


Fig. 1 | Climatic impacts by year after different nuclear war soot injections. a–f, Changes in surface temperature (a), solar radiation (c) and precipitation (e) averaged over global crop regions of 2000 (Supplementary Fig. 1) and sea surface temperature (b), solar radiation (d) and net primary productivity (f) over the oceans following the six stratospheric soot-loading scenarios studied here for 15 years following a nuclear war, derived from simulations in ref. ¹⁸. These variables are the direct climate forcing for the crop and fishery models. The left y axes are the anomalies of monthly climate variables from simulated nuclear war minus the climatology of the control simulation, which is the average of 45 years of simulation. The right y axes are the percentage change relative to the control simulation. The wars take place on 15 May of Year 1, and the year labels are on 1 January of each year. For comparison, during the last Ice Age 20,000 years ago, global average surface temperatures were about 5 °C cooler than present. Ocean temperatures decline less than for crops because of the ocean's large heat capacity. Ocean solar radiation loss is less than for crops because most ocean is in the Southern Hemisphere, where slightly less smoke is present.

alcohol (3.4% of total food calories). Byproducts of biofuel have been added to livestock feed and waste²⁷. Therefore, we add only the calories from the final product of biofuel in our calculations. Global averaged household waste is around 20% (ref. ²⁸). If we assume that after a nuclear war there would be 50% less or 100% less household waste, these extra calories would become available.

National consequences of calorie loss depend on the amount of fallow cropland, regional climate impacts, population levels and assuming a complete halt of international food trade (Methods;

Fig. 4). Here, we focus on two calorie intake levels in nations: calorie intake to maintain normal physical activity and calorie intake lower than the basal metabolic rate (also known as the resting energy expenditure)²⁹. The two levels vary in countries depending on the composition and physical activity of the population. Food consumption of less than the first level would not allow a person to maintain their normal physical activity and keep their weight at the same time, and less than the basal metabolic rate would cause fast weight loss even with only sedentary activity and thus would

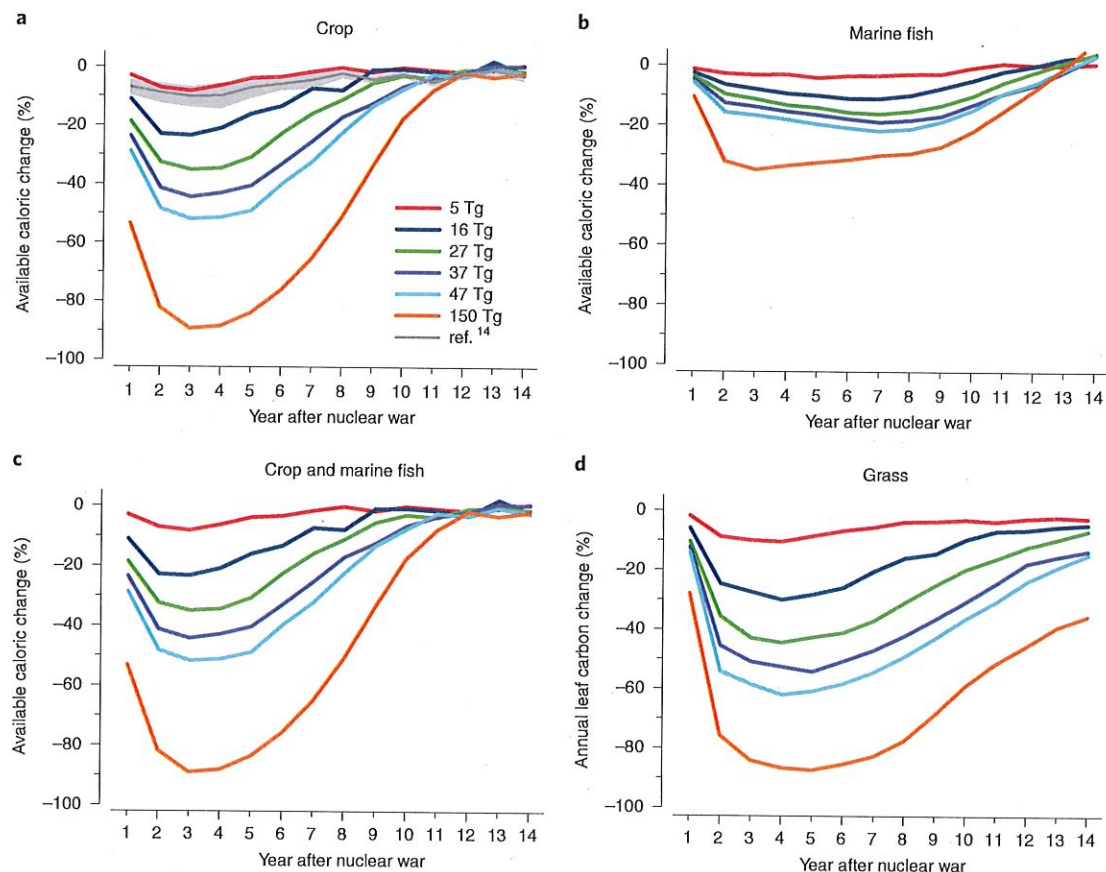


Fig. 2 | Calorie production changes for crops and fish, and accumulated carbon change for grasses following different nuclear war soot injections. **a–c**, Global average annual crop calorie production changes (%; maize, wheat, rice and soybeans, weighted by their observed production (2010) and calorie content; **a**), marine fish production changes (%; **b**) and combined crop and fish calorie production changes (%; **c**) after nuclear war for the different soot-injection scenarios. **d**, Grass leaf carbon is a combination of C3 and C4 grasses, and the change is calculated as annual accumulated carbon. For context, the grey line (and shaded area) in **a** are the average (and standard deviation) of six crop models from the Global Gridded Crop Model Intercomparison (GGCMI, ref. ¹⁴) under the 5 Tg scenario. CLM5crop shows a conservative response to nuclear war compared with the multi-model GGCMI response.

quickly lead to death²⁹. With a 5 Tg injection, most nations show decreasing calorie intake relative to the 2010 level but still sufficient to maintain weight (Fig. 4 and Supplementary Fig. 5). With larger soot-injection cases, severe starvation occurs in most of the mid–high latitude nations under the *Livestock Case*. When 50% of food-competing feed is converted for human consumption in each nation, some nations (such as the United States) would maintain sufficient calorie intake under scenarios with smaller soot injections, but weight loss or even severe starvation would occur under larger soot-injection cases (Fig. 4 and Supplementary Fig. 5).

Under the 150 Tg scenario, most nations would have calorie intake lower than resting energy expenditure²⁹. One exception is Australia. After we turn off international trade, wheat contributes almost 50% of the calorie intake in Australia, and production of rice, maize and soybean in Australia are less than 1% that of wheat^{23,24}. Therefore, the wheat response to simulated nuclear wars largely determines calorie intake in Australia. Because spring wheat is used to represent wheat, and simulated spring wheat there shows increasing or small reductions under nuclear war scenarios in which more favourable temperatures occur for food production, the calorie intake in Australia is more than other nations. However, this analysis is limited by the FAO data, which are collected at national levels. Within each nation, particularly large ones, there may be large regional inequities driven by infrastructure limitations, economic structures and government policies. New Zealand would also

experience smaller impacts than other countries. But if this scenario should actually take place, Australia and New Zealand would probably see an influx of refugees from Asia and other countries experiencing food insecurity.

The global average calorie supply post-war (Fig. 5a) implies that extreme regional reductions (Fig. 4) could be overcome to some extent through trade—but equal distribution of food globally would probably be a major challenge. Under the *Livestock* case, if food were evenly distributed over the world and household waste were 20% as in 2010²⁸, there would be enough food for everyone under the 5 Tg scenario to support their normal physical activity; if household waste were reduced from 20% to 10%, extra calories would support everyone under the 16 Tg scenario; and if there were no household waste, even under the 27 Tg case, everyone would consume sufficient calories for survival. With the most optimistic case—100% livestock crop feed to humans, no household waste and equitable global food distribution—there would be enough food production for everyone under the 47 Tg case. Assuming international trade ceased and food was distributed optimally within each country¹¹, such that the maximum number of people were given the calorie intake to maintain their weight and normal physical activity²⁸, the percentage of population that could be supported can be calculated (Fig. 5b and Supplementary Fig. 6b). Under the 150 Tg case, most countries would have less than 25% of the population survive by the end of Year 2 (Supplementary Fig. 7). In 2020, 720 million–811 million

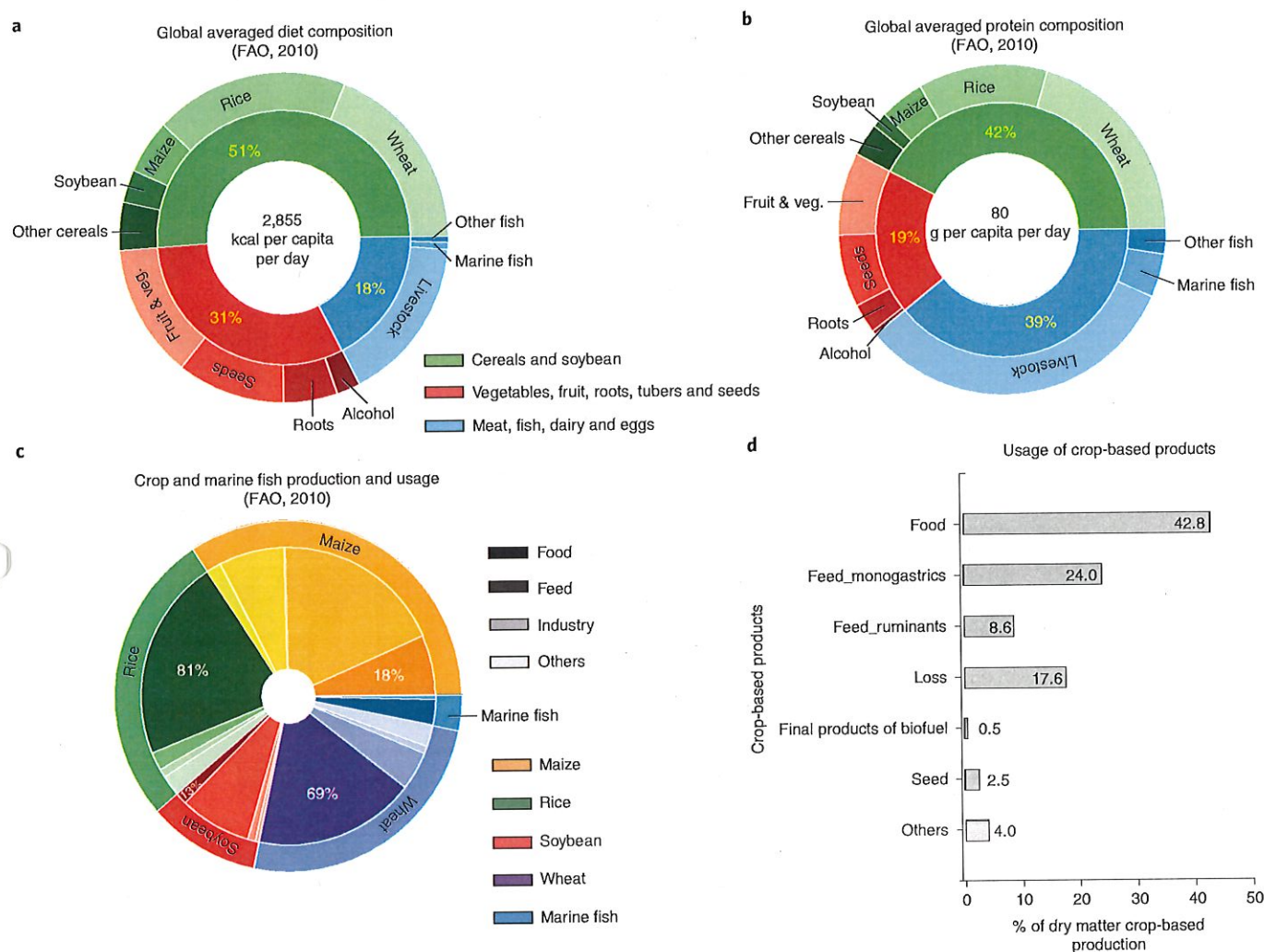


Fig. 3 | Global average human diet and protein composition and usage of crop-based products. **a**, Global average human diet composition²³. Percentages are % of available calories. Veg. is vegetables. **b**, Global average human protein diet composition²³. Marine wild capture contributes 75% of marine fish⁴⁶. Percentages are % of dry matter production. **c**, Distribution of four major cereal crops and marine fish between human food and other uses^{24,47}. Percentages are % of dry matter production. **d**, Usage of crop-based products in 2010 (% of dry matter crop-based production)²⁶. The colour gradient legend in grey in **c** illustrates the usage of different crops and fish in colours. While humans consume most of the wheat and rice grown, most maize and soybeans are used for livestock feed.

people suffered from undernutrition worldwide³⁰, despite food production being more than sufficient to nourish a larger world population. Thus, it is likely that food distribution would be inequitable both between and within countries.

Discussion

Using state-of-the-art climate, crop and fishery models, we calculate how the availability of food supplies could change globally under various nuclear war scenarios. We combine crops and marine fish and also consider whether livestock and animal products continue to be an important food source.

For a regional nuclear war, large parts of the world may suffer famine—even given the compensating behaviours considered in this paper. Using crops fed to livestock as human food could offset food losses locally but would make limited impacts on the total amount of food available globally, especially with large atmospheric soot injections when the growth of feed crops and pastures would be severely impaired by the resulting climate perturbation. Reducing household food waste could help in the small nuclear war cases but not in the larger nuclear wars due to the large climate-driven

reduction in overall production. We find particularly severe crop declines in major exporting countries such as Russia and the United States, which could easily trigger export restrictions and cause severe disruptions in import-dependent countries²⁴. Our no-trade response illustrates this risk—showing that African and Middle Eastern countries would be severely affected.

Our analysis of the potential impacts of nuclear war on the food system does not address some aspects of the problem, leaving them for future research. In all the responses, we do not consider reduced human populations due to direct or indirect mortality and possible reduced birth rate. The total number and composition of population changes would affect available labour, calorie production and distribution. Also, we do not consider farm-management adaptations such as changes in cultivar selection, switching to more cold-tolerating crops or greenhouses³¹ and alternative food sources such as mushrooms, seaweed, methane single cell protein, insects³², hydrogen single cell protein³³ and cellulosic sugar³⁴. Although farmer adaptation³⁵ and alternative food sources could reduce the negative impact from a simulated nuclear war, it would be challenging to make all the shifts in time to affect food availability in Year 2,

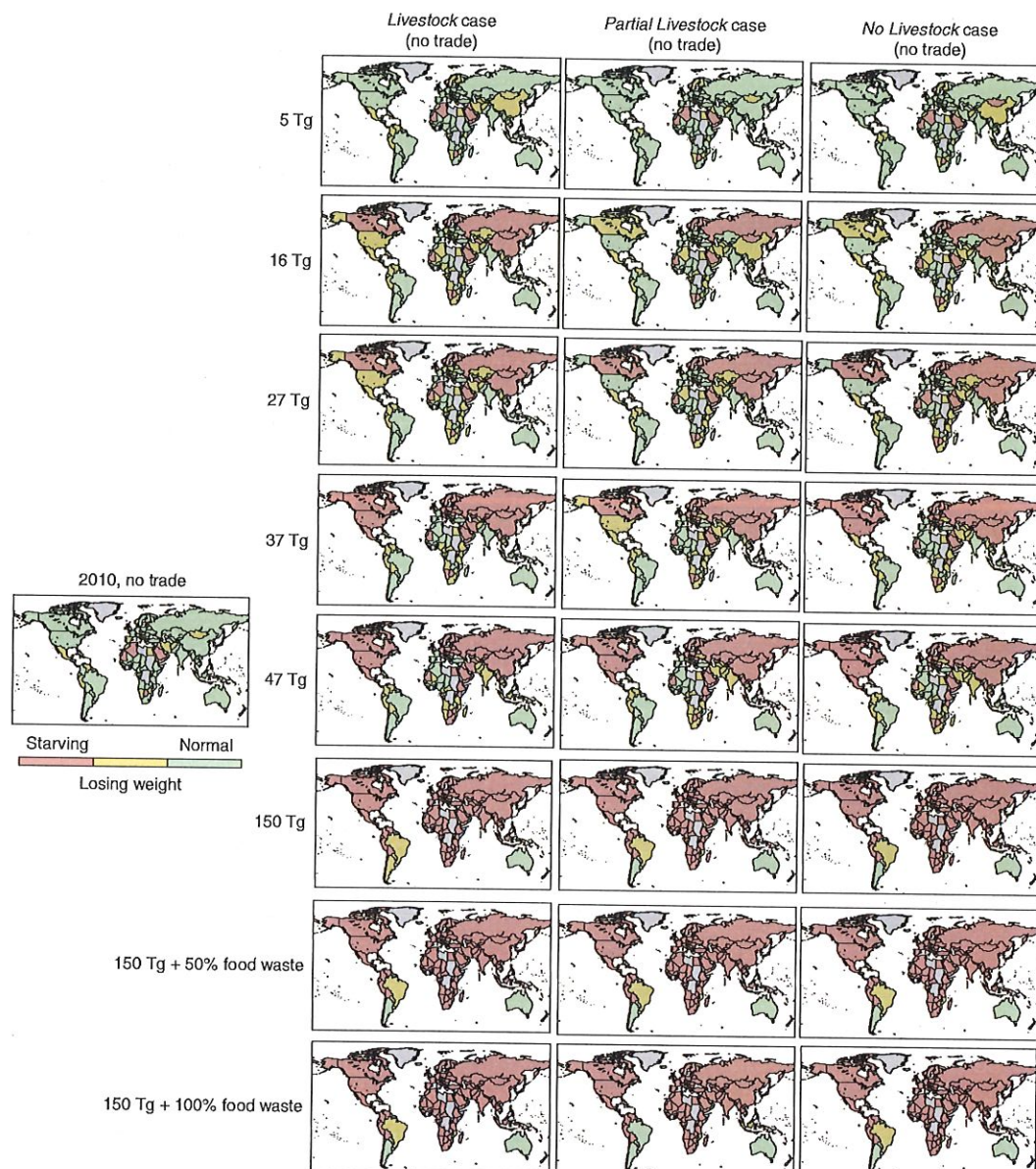


Fig. 4 | Food intake (kcal per capita per day) in Year 2 after different nuclear war soot injections. The left map is the calorie intake status in 2010 with no international trade; the left column is the *Livestock case*; the middle column is the *Partial Livestock case*, with 50% of livestock feed used for human food and the other 50% still used to feed livestock; and the right column is the *No Livestock case*, with 50% of livestock feed used for human food. All maps assume no international trade and that the total calories are evenly distributed within each nation. Regions in green mean food consumption can support the current physical activity in that country; regions in yellow are calorie intake that would cause people to lose weight, and only sedentary physical activity would be supported; and regions in red indicate that daily calorie intake would be less than needed to maintain a basal metabolic rate (also called resting energy expenditure) and thus would lead to death after an individual exhausted their body energy reserves in stored fat and expendable muscle²⁸. 150 Tg + 50% waste is half of the household waste added to food consumption, and 150 Tg + 100% waste is all household waste added to food consumption.

and further work should be done on these interventions. Current food storage can alleviate the shortage in Year 1 (ref. ¹⁴) but would have less impact on Year 2 unless it were rationed by governments or by the market. Expanding or shifting cropping land to favourable climate regions would increase crop production. Further studies on adaptation and the impacts on short-term food availability are needed, but those topics are beyond the scope of this study. Adaptation in fisheries is also not considered, such as changes in the use of discarded bycatch and offal in fisheries. These include reduced availability of fuel, fertilizer and infrastructure for food production after a war, the effects of elevated ultraviolet radiation³⁶ on food production and radioactive contamination³⁷. While this analysis focuses on calories, humans would also need proteins and

micronutrients to survive the ensuing years of food deficiency (we estimate the impact on protein supply in Supplementary Fig. 3). Large-scale use of alternative foods, requiring little-to-no light to grow in a cold environment³⁸, has not been considered but could be a lifesaving source of emergency food if such production systems were operational.

In conclusion, the reduced light, global cooling and likely trade restrictions after nuclear wars would be a global catastrophe for food security. The negative impact of climate perturbations on the total crop production can generally not be offset by livestock and aquatic food (Fig. 5a). More than 2 billion people could die from a nuclear war between India and Pakistan, and more than 5 billion could die from a war between the United States and Russia (Table 1).

Table 2 | Changes in food calorie availability (%) in Year 2 after a nuclear war for the nations with nuclear weapons and global average assuming no trade after simulated nuclear wars under the *Livestock* case, the *Partial Livestock* case and the *No Livestock* case with 50% livestock feed to human consumption

Nations	5 g	16 Tg	27 Tg	37 Tg	47 Tg	150 Tg	150 Tg + hw	150 Tg + tw
Livestock case								
China	-14.1	-47.4	-64.0	-77.7	-83.5	-99.5	-99.5	-99.4
France	1.6	-13.0	-17.2	-26.0	-29.4	-98.3	-97.9	-97.6
India	-4.6	-4.7	-2.0	-9.4	-21.6	-66.8	-64.1	-61.4
Israel	25.4	-5.0	-1.9	-4.5	3.8	-63.3	-55.2	-46.9
North Korea	-18.1	-88.7	-90.7	-98.3	-99.2	-99.9	-99.9	-99.9
Pakistan	-0.9	15.9	18.5	-13.8	-19.9	-85.3	-84.1	-82.8
Russia	1.3	-62.3	-83.1	-89.6	-90.9	-99.0	-98.9	-98.7
United Kingdom	1.2	-29.7	-40.5	-56.9	-72.2	-89.0	-87.1	-85.2
United States	-11.2	-45.8	-62.0	-75.7	-86.3	-98.8	-98.5	-98.3
Global	-8.2	-23.8	-33.4	-42.1	-49.2	-81.3	-78.8	-76.5
Partial Livestock case (50% livestock feed to human consumption, 50% livestock feed to livestock)								
China	-2.1	-40.6	-59.8	-75.2	-81.5	-99.6	-99.5	-99.5
France	58.8	33.2	28.2	16.3	10.8	-99.0	-98.8	-98.6
India	-1.4	-0.2	2.7	-4.7	-17.8	-65.0	-62.1	-59.2
Israel	16.7	0.3	-1.1	-3.8	-8.1	-75.5	-70.0	-64.5
North Korea	-13.3	-88.7	-90.9	-98.8	-99.5	-99.9	-99.9	-99.9
Pakistan	-1.4	20.8	21.6	-11.9	-16.0	-83.6	-82.2	-80.8
Russia	25.3	-56.1	-80.6	-88.0	-88.7	-99.0	-98.9	-98.7
United Kingdom	30.7	-12.5	-27.0	-50.7	-72.1	-94.4	-93.4	-92.5
United States	70.8	-0.5	-32.7	-60.4	-78.9	-99.1	-98.9	-98.7
Global	13.5	-5.7	-17.4	-28.1	-36.7	-77.1	-74.0	-71.2
No Livestock case (50% livestock feed to human consumption)								
China	-11.4	-46.6	-64.0	-77.9	-83.5	-99.7	-99.6	-99.5
France	45.2	20.5	16.6	6.6	1.4	-99.8	-99.7	-99.7
India	-5.4	-3.1	-0.2	-7.0	-20.0	-65.8	-63.0	-60.1
Israel	-24.7	-26.7	-30.6	-32.4	-44.3	-91.5	-89.5	-87.7
North Korea	-16.0	-89.6	-91.8	-99.4	-99.8	-99.9	-99.9	-99.9
Pakistan	-12.1	12.7	11.8	-19.4	-21.2	-83.7	-82.4	-81.0
Russia	16.4	-60.7	-82.6	-89.0	-89.2	-99.0	-98.9	-98.8
United Kingdom	15.9	-24.2	-37.3	-59.7	-79.7	-99.8	-99.8	-99.8
United States	60.3	-8.1	-38.6	-65.1	-81.8	-99.5	-99.4	-99.3
Global	5.9	-12.1	-22.9	-32.9	-40.8	-79.0	-76.3	-73.7

The total calorie reduction is referenced to the observed food calorie availability in 2010. China here includes Mainland China, Hong Kong and Macao. 150 Tg + hw is half of the household waste added to food consumption, and 150 Tg + tw is total household waste added to food consumption. Bold is used for headings and global averages.

we label Year 2 should be relabelled Year 3. However, since the severe climate and food impacts last for more than 5 years (Figs. 1 and 2), the same conclusions apply to a world after a nuclear war.

Direct climate model output use. Because climate models have biases, it is typical to bias correct model output before using it as input for crop models. There are various techniques that attempt to use past observational data to address changes in the mean and variance, but none are perfect and all are limited by assumptions that future relations between model output and crop model input can be based on the recent past. A common method¹⁴ is the delta method in which an observational reanalysis weather dataset is used and monthly means of temperature, precipitation and insolation are modified according to the climate model simulations. This comes with the advantage of realistic internal variability important for crop modelling^{12–14} but does not adjust changes in variance, which might be an unrealistic assumption under higher emission scenarios, such as the 150 Tg case. Here, because we are using a crop model that has already been calibrated with the same climate model that we are using, we use raw climate model output ($1.9^\circ \times 2.5^\circ$) to force the crop model, and this allows variance to change too.

Crop model. Crop simulation uses the Community Land Model version 5 crop (CLM5crop)^{11–13} in the Community Earth System Model version 2 (CESM2). Dynamic vegetation is not turned on. CLM5crop has six active crops, maize,

rice, soybeans, spring wheat, sugar cane and cotton, and also simulates natural vegetation, such as grasses. In this study, we used the output of the cereals (maize, rice, soybeans and spring wheat) and grasses. Although CLM5crop does not simulate winter wheat, we assume winter wheat production is changed by the same amount as spring wheat, which has been found in other studies¹⁴; however, this may underestimate the winter wheat response, because winter wheat would experience colder temperatures during its growing period that would be more likely to cross critical thresholds¹⁴. Surface ozone and downward ultraviolet radiation would also be impacted by nuclear war³⁶, but CLM5crop is not able to consider those impacts, which might exacerbate the losses. In addition, the crop model does not consider the availability of pollinators, killing frost and alternative seeds. The model simulates rainfed crops and irrigated crops separately, and all results presented here refer to the total production of rainfed and irrigated crops. Irrigated crops are simulated under the assumption that freshwater availability is not limiting⁴³. Although evaporation is reduced with cooling, it is possible that our result may underestimate the negative impact from precipitation reduction, especially for the large injection cases.

CLM5crop was evaluated¹¹ using FAO observations (average of 1991–2010), and it does a reasonable job of reproducing observed spatial pattern of maize, rice, soybean and spring wheat yield. Also, time series of crop yields simulated by CLM5crop compare with FAO data from 2006 to 2018, and CLM5crop reasonably represents global total production and average yields of maize, rice, soybean and spring wheat¹².

CLM5crop is spun up for 1,060 years by repeating the past 10 years of the CESM control to reach the equilibrium of four soil carbon pools. The crop simulations are at the same resolution as CESM simulations ($1.9^\circ \times 2.5^\circ$). The crop planting date is determined by growing degree days, and the location of cropland is fixed for all crops.

Fishery model. Fish and fisheries responses are simulated with the BioEconomic mArine Trophic Size-spectrum (BOATS) model^{15,44,45}. BOATS was used to calculate the size-structured biomass of commercially targeted fish based on gridded (1° horizontal resolution) inputs of sea surface temperature and oceanic net primary production from CESM. The model also interactively simulates fishing effort and fish catch through a bioeconomic component that depends on fish price, cost of fishing, catchability and fisheries regulation¹⁵. Details are found in ref. ¹⁵ and references therein.

Combining crop and marine fish data. Supplementary Table 1 shows the total calorie reductions for each of the nine nuclear states from just the simulated crops and marine fish. Data for countries can be found in Supplementary Table 2.

To calculate nation-level calories available from simulated crops and fish, we weight the production by the calorie content of each type of food. We use data from FAO^{23,24,46,47}. Nation-level calorie reduction (%) from total production of maize, rice, soybean, wheat and marine fish is thus calculated as:

$$w_{iy} = \frac{P_i c_i R_{iy}}{\sum_{i=1}^5 P_i c_i R_{iy}} \quad (1)$$

and

$$R_y = \sum_{i=1}^5 R_{iy} w_{iy} \quad (2)$$

where index i is maize, rice, soybean, wheat or marine fish wild catch, w_{iy} is the calorie weight of each commodity per country each year, P_i is the national production of item i in FAO-Food Balance Sheet (FBS)^{23,24}, c_i is calories per 100 g dry mass for each item²³, R_{iy} is national production reduction (%) of each item in year y after the nuclear wars and R_y is nation-averaged calorie reduction (%) of the five items in year y after the nuclear wars.

Effects on other food types. Other crops. National averaged calorie reduction (%) of the four simulated crops is applied to the total calories of all crops in 2010 to estimate simulated nuclear war impacts on this category.

Livestock and aquaculture. We assume these two types of food share a similar response to simulated nuclear war as they involve feeding animals in a relatively controlled environment. For global calculations for livestock, we assume that 46% are fed by pasture and 54% are fed by crops and processed products⁴⁸ and use national-level data²⁶ to calculate reduction of livestock feed from pasture and crop-based products. We assume that livestock production is linearly correlated with the feed. Annual leaf carbon of grasses (both C3 and C4) is used to estimate pasture changes, and reduction of the four simulated crops is used for crop feed changes. For aquaculture, the feed is only from crops and processed products, and the production is also correlated with the amount of feed fish receive. Direct climate change impacts on livestock and fish are not considered.

Inland fish capture is not considered in this study. Because inland fish contribute only 7% of total fish production⁴⁶, adding inland fisheries would not change the main conclusions of this study.

International trade. All food commodity trade calculations are based on the 2010 FAO Commodity Balance Sheet (FAO-CBS), FAO-FBS and processed data from previous studies^{24,27,28,47}. This dataset provides the production and usage of each food and non-food agricultural product for each country and imports and exports and thus allows the calculation on a national basis of food usage and calorie availability.

Domestic availability of a food in each country comes from domestic production and reserves, reduced by exports and increased by imports. We calculate no international trade by applying the ratio of domestic production and domestic supply to each food category and the food production in different usages:

$$C_{\text{food-notrade}} = C_{\text{food}} \times \frac{P_{\text{dp}}}{P_{\text{ds}}} \quad (3)$$

where C_{food} is national-level calorie supply from different food types^{26,46}, $C_{\text{food-notrade}}$ is national-level calorie supply from different food types with the assumption of no international trade, P_{dp} is national-level domestic production for each type of food in FAO-CBS and P_{ds} is national-level domestic supply for each type of food in FAO-CBS. Domestic supply is the available food on the market, including domestic production, export and import.

Food usage of maize, soybean, rice and wheat is calculated from FAO-CBS. In FAO-CBS, maize products are maize and byproduct maize germ oil, soybean

products are soybean and byproducts soybean oil and soybean cake, rice products are rice and byproduct rice bran oil and wheat product is wheat. Products for food purposes are the sum of food supply in each category and the processing product minus the total byproducts (the difference includes processing for the purpose of alcohol or sugar).

Calorie calculations. For the *Livestock* case, national-level available calories are calculated by

$$\begin{aligned} C_L = & C_{\text{plantbased}} \times (1 - R_{cy}) + C_{\text{livestock-ruminant}} \times (1 - R_{\text{grass}}) \\ & + C_{\text{livestock-monogastric}} \times (1 - R_{cy}) + C_{\text{livestock-monogastric}} \\ & \times R_{\text{grass}} \times (1 - R_{cy}) \times \frac{F_{\text{ruminant-cropfeed}}}{F_{\text{monogastric-cropfeed}}} \\ & + C_{\text{aquaculture}} \times (1 - R_{cy}) + C_{\text{marine-catch}} \times (1 - R_{\text{marine-catch-y}}) \\ & + (1 - R_{cy}) \times C_{\text{plantbased}} \times \frac{f_{\text{final-product-biofuel}}}{f_{\text{food}}} \end{aligned} \quad (4)$$

where C_L is calories available in each nation L (kcal per capita per day) under the *Livestock* case, $C_{\text{plantbased}}$, $C_{\text{livestock-ruminant}}$ and $C_{\text{livestock-monogastric}}$ are calories available from plant-based products, ruminants and monogastrics²⁷ and $C_{\text{aquaculture}}$ and $C_{\text{marine-catch}}$ are calculated by calorie availability from fish²⁷ multiplied by the ratio of aquaculture and catch⁴⁶. R_{grass} is grass production change, and $R_{\text{marine-catch-y}}$ is marine capture change. $F_{\text{ruminant-cropfeed}}$ is the fraction of crop feed for ruminant, and $F_{\text{monogastric-cropfeed}}$ is the fraction of crop feed for monogastrics²⁶. R_{cy} is crop production change calculated as:

$$w_{iy} = \frac{P_i c_i R_{iy}}{\sum_{i=1}^4 P_i c_i R_{iy}} \quad (5)$$

and

$$R_{cy} = \sum_{i=1}^4 R_{iy} w_{iy} \quad (6)$$

where index i is maize, rice, soybean or wheat, w_{iy} is the calorie weight of each commodity per country each year, P_i is the national production of item i in FAO-CBS⁴⁹, c_i is calories per 100 g retail weight for each item²³ and R_{iy} is national production change (%) of each item in year y after the nuclear wars. $f_{\text{final-product-biofuel}}$ is the fraction of final product of biofuel in plant-based product, and f_{food} is the fraction of food in plant-based product.

For the *No Livestock* case, national-level available calories are calculated by

$$\begin{aligned} C_{NL} = & C_{\text{plantbased}} \times (1 - R_{cy}) + C_{\text{marine-catch}} \times (1 - R_{\text{marine-catch-y}}) \\ & + C_{\text{plantbased}} \times f_{\text{feed-to-food}} \times (1 - R_{cy}) \times p_{\text{feed-for-human}} \\ & + (1 - R_{cy}) \times C_{\text{plantbased}} \times \frac{f_{\text{final-product-biofuel}}}{f_{\text{food}}} \end{aligned} \quad (7)$$

C_{NL} is national-level available calories in the *No Livestock* case. $f_{\text{feed-to-food}}$ is the fraction of food crops that are used as feed relative to their usage as food, calculated based on their calorie content²⁶. $p_{\text{feed-for-human}}$ is the percentage of livestock grain feed used for human consumption. We tested 0%, 20%, 40%, 50%, 60%, 80% and 100% and used 50% for Table 2 and Fig. 4.

For the *Partial Livestock* case, national-level available calories are calculated by

$$\begin{aligned} C_{PL} = & C_{\text{plantbased}} \times (1 - R_{cy}) + C_{\text{marine-catch}} \times (1 - R_{\text{marine-catch-y}}) \\ & + C_{\text{plantbased}} \times f_{\text{feed-to-food}} \times (1 - R_{cy}) \times p_{\text{feed-for-human}} \\ & + (1 - p_{\text{feed-for-human}}) \times (C_{\text{livestock-ruminant}} \times (1 - R_{\text{grass}}) \\ & + C_{\text{livestock-monogastric}} \times (1 - R_{cy}) \\ & + C_{\text{livestock-monogastric}} \times R_{\text{grass}} \times (1 - R_{cy}) \times \frac{F_{\text{ruminant-cropfeed}}}{F_{\text{monogastric-cropfeed}}}) \\ & + (1 - R_{cy}) \times C_{\text{plantbased}} \times \frac{f_{\text{final-product-biofuel}}}{f_{\text{food}}} \end{aligned} \quad (8)$$

C_{PL} is national-level available calorie in *Partial Livestock* case. On the basis of the assumed percentage of livestock crop feed to convert to human consumption, instead of wasting the remaining portion of livestock crop feed as in *No Livestock* case, here we use the remaining livestock crop feed to raise livestock.

The percentage of national household waste is calculated by

$$P_{\text{waste}} = 100\% \times \frac{C_{\text{available}} - C_{\text{intake}}}{C_{\text{available}}} \quad (9)$$

P_{waste} is the percentage of national household waste of food calorie availability in 2010, $C_{\text{available}}$ is the food calorie availability per day per person in each country and C_{intake} is the national calorie intake per day per person²⁷.

Calorie requirements. The population percentage supported by available calories calculated for the *Livestock*, *Partial Livestock* and *No Livestock* responses indicates the macro-level consequences for food security (Fig. 4). The current average human available calorie supply is 2,855 kcal per capita per day, including food intake and food waste (Fig. 3). Calorie requirements vary significantly with age, gender, size, climate, level of activity and underlying medical conditions. Ref. ²⁷ estimated the national-level calorie availability, calorie intake, calorie from plant-based product, livestock and fish and also calculated the calorie intake of an underweight population with current physical activity of an underweight population with sedentary physical activity and calorie intake lower than the basal metabolic rate. We assume that the calorie intake of an underweight population with current physical activity is needed to support life and regular labour activity.

Uncertainties. This work was done with one Earth system model, with only one ensemble member for all the cases with soot injections >5 Tg, only one crop model and only one fishery model. For the 5 Tg case and the control, there are three ensemble members, but only the ensemble averages are used. The three ensemble members for the 5 Tg case are very similar (Supplementary Fig. 8), so climate variability for the larger forcings would be much smaller than the signal.

CESM is a state-of-the-art climate model, and its simulations of the impacts of nuclear war have been almost identical to simulations with other models for the 5 Tg (refs. ^{49,50}) and 150 Tg (ref. ⁹) cases. However, further developments in climate models, such as including organic carbon in fire emissions, and better simulating aerosol growth and interactions with the surrounding environment, may improve climate prediction after a nuclear war.

CLM5crop and BOATS are also state-of-the-art models, but future simulations with different models would certainly be useful. CLM5crop compares well with other crop models in response to nuclear war forcing⁴⁴ (Supplementary Fig. 2). If anything, CLM5crop underestimates the crop response to nuclear war (Fig. 2 and Supplementary Fig. 2). Because most crop models were developed for the current or warmer climates, further research is needed to understand how crops react to a suddenly cold environment. Our study is the first step to reveal national food security after nuclear wars, but crops may not respond uniformly to the same forcing in each nation, given different farming practices. In addition, multi-model assessment will be essential to fully investigate this problem, and crop model developments are important to understand impacts from surface ozone, ultraviolet radiation and freshwater availability. Furthermore, local radioactive contamination and climate change from nuclear war would impact the insect community. The influence on pests, pollinators and other insects is unclear, and hence further studies are needed.

Some assumptions in this study could be examined in future work. For example, to turn off international trade, the ratio of local production to domestic supply is applied on a national level. Also, to calculate national calorie intake after nuclear wars, we assume that food is evenly distributed in each country. Economic models will be necessary to further understand the contributions of trade and local food distribution systems to human calorie intake after nuclear wars.

This study uses calorie intake from ref. ²⁷, and food loss from harvesting is not considered. If human behaviour and the food industry would change substantially, this would affect our conclusions.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Data of crop yield, grass production, national livestock feed, national calorie and national plant product usage are available at <https://osf.io/YRBSE/>. Additional data that support the findings of this study are available from the corresponding author upon request.

Code availability

The source code for the CESM(WACCM) model used in this study is freely available at https://www.cesm.ucar.edu/working_groups/Whole-Atmosphere/code-release.html, and the code for CLM5 is available at <https://www.cesm.ucar.edu/models/cesm2/land/>.

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Author contributions

L.X., A.R., K.S. and C.S.H. designed the study. C.G.B. conducted the climate model simulations, L.X. conducted the crop simulations and K.S. and R.H. conducted the fishery simulations. J.J. provided GGCMI crop model simulations. B.L.B. and I.W. provided national livestock feed and national calorie intake data. L.X. analysed the data with contributions from all the authors. A.R. and L.X. wrote the first draft, and all authors contributed to editing and revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Lili Xia.

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Data of crop yield, grass production, national livestock feed, national calorie, and national plant product usage are available at <https://osf.io/YRBSE/>. Additional data that support the findings of this study are available from the corresponding author upon request.