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

Lili Xia, Alan Robock, Kim Scherrer, Cheryl S. Harrison, Benjamin Leon Bodirsky, Isabelle Weindl, Jonas Jägermeyr, Charles G. Bardeen, Owen B. Toon and Ryan Heneghan

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.
cold stress\textsuperscript{44}. 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, FAO\textsuperscript{14} 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 price\textsuperscript{15}. Similar responses took place in New England in the ‘year without a summer’ after the 1815 Tambora volcanic eruption\textsuperscript{3}. 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 them, and previously unpalatable fish were added to their diet\textsuperscript{5,32}. We test a full range (0–100%) of the fraction of food-competing feed\textsuperscript{26} 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 products\textsuperscript{27}, which could be repurposed as food in the form of plant oil (~1.8% of total food calories) and

| 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 |

\textsuperscript{1}The 5 Tg case scenario is from ref. 30 for an India–Pakistan war taking place in 2008; the 16–47 Tg cases are from ref. 31 for an India–Pakistan war taking place in 2025; and the 150 Tg case is from ref. 32, 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 1971 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 Supplemental Information. *Assuming total household waste is added to food consumption.
alcohol (3.4% of total food calories). Byproducts of biofuel have been added to livestock feed and waste. 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. 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.
quickly lead to death. 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 expenditure. 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. 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 2010, 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 country, such that the maximum number of people were given the calorie intake to maintain their weight and normal physical activity, 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
people suffered from undernutrition worldwide⁴⁵, 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 greenhouses⁴⁵ and alternative food sources such as mushrooms, seaweed, methane single cell protein, insects⁴⁶, hydrogen single cell protein ³³ and cellulosic sugar ³⁴. Although farmer adaptation ³⁵ 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,

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**Fig. 3 | Global average human diet and protein composition and usage of crop-based products.**

- **a**, Global average human diet composition ²³. Percentages are % of available calories. Veg. is vegetables.
- **b**, Global average human protein diet composition ²³. Marine wild capture contributes 75% of marine fish ⁴⁶. 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.
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 favorable 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 radiation on food production and radioactive contamination. 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 environment, 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).

**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 muscle. 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.
The results here provide further support to the 1985 statement by US President Ronald Reagan and Soviet General Secretary Mikhail Gorbachev and restated by US President Joe Biden and Russian President Vladimir Putin in 2021 that ‘a nuclear war cannot be won and must never be fought’.

Methods
We use a state-of-the-art global climate model to calculate the climatic and biogeochemical changes caused by a range of stratospheric soot injections, each associated with a nuclear war scenario9,18 (Tables 1 and 2). Simulated changes in surface air temperature, precipitation and downward direct and diffuse solar radiation are used to force a state-of-the-art crop model to estimate how the productivity of the major crops (maize, rice, spring wheat and soybean) would be affected globally, and changes in oceanic net primary production and sea surface temperature are used to force a global marine fisheries model. We combine these results with assumptions about how other crop production, livestock production, fish production and food trade could change and calculate the amount of food that would be available for each country in the world after a nuclear war.

The simulated surface climate disruptions due to the nuclear war scenarios are summarized in Fig. 1. Averaged over the current crop regions, surface downwelling solar radiation reduces by 10 W m\(^{-2}\) (5 Tg soot injection) to 130 W m\(^{-2}\) (150 Tg soot injection). With less energy received, the maximum average 2 m air temperature reductions range from 1.5°C (5 Tg soot injection) to 14.8°C (150 Tg soot injection), peaking within 1–2 years after the war, with temperature reduction lasting for more than 10 years. The cooling also reduces precipitation over summer monsoon regions. Similar but smaller reductions of solar radiation and temperature are projected in marine regions (Fig. 1b,d), with resulting changes in upper trophic-level marine primary productivity. We applied local changes at every grid cell to the crop and fish models.

Climate model. All nuclear war scenarios9,18 are simulated using the Community Earth System Model (CESM)19. This model includes interactive atmosphere, land, ocean and sea ice. Both atmosphere and land have a horizontal resolution of 1.9°×2.5°, and the ocean has a horizontal resolution of 1°. The atmospheric model is the Whole Atmosphere Community Climate Model version 4 (ref. 20). The land model is the Community Land Model version 4 with the carbon–nitrogen cycle. CESM output at 1- and 3-hour resolution, including 2 m air temperature, precipitation, specific humidity and downward longwave radiation and solar radiation (separated into direct and diffuse radiation), is used to drive the offline crop model simulations. There are three ensemble members of the control simulation, which repeats the climate forcing of 2000 for 15 years, three ensemble members of the control case (yellow bars) and for the Partial Livestock case (red bars), assuming that all food and waste is evenly distributed. For the Partial Livestock case, additional calories potentially available by human consumption of animal feed, mainly maize and soybeans, are plotted for various portions of converted animal feed (pink tick marks), and the remaining livestock crop feed is used for raising livestock. Critical food intake levels are marked in the right margin. (remaining livestock grain feed is used for livestock)

Calories from crops, vegetables, fruit and marine fishery (fishing effort is business as usual) Portions of calories from livestock and aquaculture

Calories from livestock feed added to human consumption Tickets from bottom to top are 0%, 20%, 40%, 60%, 80% and 100%

The remaining livestock crop feed is for raising livestock

Calories from food waste; ticks are 50% and 100%

Fig. 5 | Overview of global calorie intake and sensitivity to livestock and food waste assumptions. a. Global average change in calorie intake per person per day in Year 2 post-war under the Livestock case (yellow bars) and for the Partial Livestock case (red bars), assuming that all food and waste is evenly distributed. For the Partial Livestock case, additional calories potentially available by human consumption of animal feed, mainly maize and soybeans, are plotted for various portions of converted animal feed (pink tick marks), and the remaining livestock crop feed is used for raising livestock. Critical food intake levels are marked in the right margin. b. Without international trade, the global population (%) that could be supported, although underweight, by domestic food production at the end of Year 2 after a nuclear war if they receive the calories supporting their regular physical activity21 and the rest of the population would receive no food, under the Livestock and Partial Livestock cases. The blue line in b shows the percentage of population that can be supported by current food production when food production does not change but international trade is stopped. National data are calculated first (Supplementary Tables 4 and 5 and Supplementary Fig. 5) and then aggregated to global data.
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 observational input can be based on the recent past. A common method 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, 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° × 2.5°) 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) 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 studies; 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 thresholds. Surface ozone and downward ultraviolet radiation would also be impacted by nuclear war, 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.

| 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  | −92.9       | −92.6       |
| 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       |
| United Kingdom| 16.4 | −60.7 | −82.6 | −89.0 | −89.2 | −99.0  | −98.9       | −98.8       |
| United States | 15.9 | −24.2 | −37.3 | −59.7 | −79.7 | −99.8  | −99.8       | −99.8       |
| **Global**    | 60.3 | −8.1  | −38.6 | −65.1 | −81.8 | −99.5  | −99.4       | −99.3       |
| **Total food calorie reduction (%) in Year 2 after a nuclear war** | | | | | | |       | |

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.
CLMaScrop 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° x 2.5°). 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\[^{11,12}\]. 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 regulation\[^{11}\]. Details are found in ref. \(^{[11]}\) 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 Food Balance Sheet (FBS)\[^{23,24}\], Nation-level calorie reduction (%) from total production of maize, rice, soybean, wheat and marine fish is thus calculated as:

$$w_y = \frac{p \times r_y}{\sum_{i=1}^{5} p_i \times r_{iy}}$$

where index \(i\) is maize, rice, soybean, wheat or marine fish, \(w_y\) 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 item\[^{23}\], \(R_y\) 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 products\[^{30}\] and use national-level data\[^{31}\] 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 production\[^{31}\], 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\[^{26,27}\]. 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:

$$C_{food\text{-domestic}} = C_{food} \times \frac{P_{dom}}{P_{da}}$$

where \(C_{food\text{-domestic}}\) is national-level calorie supply from different food types\[^{26}\], \(C_{food}\) is national-level calorie supply from different food types with the assumption of no international trade, \(P_{dom}\) is national-level domestic supply for each type of food in FAO-CBS and \(P_{da}\) 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

\[
C_L = C_{planthand} \times (1 - R_y) + C_{monogastric} \times (1 - R_y) + C_{ruminant} \times (1 - R_y)
\]

where \(C_{planthand}\) is calories available in each nation \(L\) (kcal per capita per day) under the Livestock case, \(C_{monogastric}\) and \(C_{ruminant}\) are calories available from plant-based products, ruminants and monogastrics\[^{36}\] and \(C_{feed}\) is the fraction of crop feed for monogastrics\[^{36}\]. \(R_y\) is crop production change calculated as:

\[
w_y = \frac{P_{c} \times R_{iy}}{\sum_{i=1}^{5} P_{c} \times R_{iy}}
\]

\[
R_y = \frac{1}{5} \sum_{i=1}^{5} R_{iy}
\]

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

\[
C_{NL} = C_{planthand} \times (1 - R_y) + C_{monogastric} \times (1 - R_y) + C_{ruminant} \times (1 - R_y)
\]

where \(C_{NL}\) is national-level available calories in the No Livestock case. \(R_{y}\) is the fraction of crop feed that are used as feed relative to their usage as food, calculated based on their calorie content\[^{37}\]. \(R_{y}^{\text{feed-to-food}}\) 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

\[
C_{PL} = C_{planthand} \times (1 - R_y) + C_{monogastric} \times (1 - R_y) + C_{ruminant} \times (1 - R_y)
\]

where \(C_{PL}\) is national-level available calories 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

\[
P_{waste} = 100\% \times \frac{C_{available} - C_{intake}}{C_{available}}\]

\(P_{waste}\) is the percentage of national household waste of food calorie availability in 2010, \(C_{available}\) is the food calorie availability per day per person in each country and \(C_{intake}\) is the national calorie intake per day per person\[^{38}\].

The percentage of food calories available from domestic production for each type of food is applied to the total calories of all crops in 2010 to estimate domestic production change.
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10. This study uses calorie intake from ref. 3, and food loss from harvesting is not considered. If human behaviour and the food industry would change substantially, this would affect our conclusions.

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

12. Data availability. Data of crop yield, grass production, national livestock feed, national calorie and national plant product usage are available at https://ou.osa/YBISW. Additional data that support the findings of this study are available from the corresponding author upon request.

13. Code availability. The source code for the CSM(WACC) model used in this study is freely available at https://www.cesm.ucar.edu/models/cesm1.Model/cesm-release.html, and the code for CLM5 is available at https://www.cesm.ucar.edu/models/cesm2/land/. Received: 24 August 2021; Accepted: 14 July 2022; Published online: 15 August 2022

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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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|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Research sample                                                                   | We used one climate model, forced by six different scenarios, and one crop model.                                               |
| Sampling strategy                                                                 | We used all the data we had.                                                                                                   |
| Data collection                                                                   | N/A                                                                                                                               |
| Timing and spatial scale                                                          | N/A                                                                                                                               |
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