Global Famine after Nuclear War

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**Recommended Citation**

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Article

Keywords: global famine, nuclear war, climate impact

DOI: https://doi.org/10.21203/rs.3.rs-830419/v1

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Global Famine after Nuclear War

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Submitted as an Article to Nature Food

August, 2021
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\textsuperscript{1,2,3}. The soot loadings would cause decadal disruptions in Earth’s climate\textsuperscript{4,5,6}, which would impact food production systems on land and in the oceans. In 1980s, investigations of nuclear winter impacts on global agricultural production\textsuperscript{7} and food availability\textsuperscript{8} for 15 nations, but new information now allows us to update those estimates. Recently, several studies analyzed changes of major grain crops\textsuperscript{9,10,11} and marine wild-catch fisheries\textsuperscript{12} for different scenarios of regional nuclear war using sophisticated models. However, the impact on the total food supply available to humans is more complex. Here we show that considering all food sources and potential adaptation measures, such as using animal feed directly for humans, famine would result for most of Earth even from a war between India and Pakistan using less than 3\% of the global nuclear arsenal. We look at the climate impacts from a range of scales from regional to global nuclear war, and estimate the total amount of food calories available in each nation, including crops, livestock, and fisheries, for each year following a nuclear holocaust. Our findings quantify the global indirect impacts of nuclear war away from target areas, and demonstrate the need to prevent any scale of nuclear war.

Extraordinary events such as large volcanic eruptions or nuclear war could cause sudden global climate disruptions. Global volcanic cooling from sulfates has resulted in severe famines and political instability, for example after the 1783 Laki eruption in Iceland\textsuperscript{13} or the 1815 Tambora eruption in Indonesia\textsuperscript{14,15}. 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. A war between India and Pakistan could produce a stratospheric loading of 5-47 Tg of
soot\textsuperscript{16,17} and 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\textsuperscript{1-6}. Recent catastrophic forest fires in Canada in 2017\textsuperscript{18} and Australia in 2019 and 2020\textsuperscript{19,20} 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, adding confidence to nuclear war simulations that predict the same process will occur after nuclear war.

Climate disruption from nuclear war would impact food production systems on land and in the oceans, but 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. Here, we examine the impacts of six war scenarios, generating 5 to 150 Tg of soot, on the food supply. We use model simulations of major crops and wild-caught marine fish together with estimated changes in other food and livestock productivity to assess the impacts on global calorie supply.

Because soot disperses globally once it reaches the upper atmosphere, our results apply regardless of the warring nations. 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, the UK, North Korea, and Israel).

**Impacts on crops, and fish catch productivity**

Using climate, crop, and fishery models (Methods), we calculate the supply of food, in terms of daily energy per person, for each year after a range of six different stratospheric soot injections. The climatic impacts would last for about a decade, but peak in the first few years (Figure 1).

Global averaged calories from the crops we simulated decreased 7% in years 1-5 after the conflict even under the smallest, 5 Tg soot scenario (Figure 2a; comparable to previous multi-
model results\textsuperscript{11}, Figure S1) and up to 50\% under the 47 Tg scenario. In the 150 Tg soot case, global average calories from crops would decrease by around 90\% 3-4 years after the nuclear conflict. The changes would induce a catastrophic disruption of global food markets, as even a 7\% global yield decline would exceed the largest anomaly ever recorded since the beginning of the FAO observational records in 1961\textsuperscript{11}.

Fish are another important food resource, especially in terms of protein supply. Nuclear war would reduce the wild fish catch\textsuperscript{12}, but the reduction would be less than for land agriculture (Figure 2b), since 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 temperature changes are less pronounced (Figure 1). Terrestrial agricultural production dominates the total calorie change of crops and fisheries combined (Figure 2c), since global crop production is 24 times that of wild fisheries and staple crops contain around five times more calories than fish per unit mass\textsuperscript{21,22}. In total, marine wild capture contributes 0.5\% of total calories, but 3.5\% of global average protein supply (Figures 3 and S2).

Calorie reduction from agriculture and marine fisheries shows regional differences (Figure S3), with the strongest percentage reductions over high latitudes in the Northern Hemisphere. Cooling from nuclear conflicts causes temperature limitations for crops, leading to delayed physiological maturity and additional cold stress\textsuperscript{11}. 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 crop reductions > 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 reduction from 30\% to 86\%, and in lower latitudes (India, Pakistan and Israel) the reduction is less than 10\% (Tables S1 and S2).
We underline that impacts in warring nations are likely to be dominated by local problems, like infrastructure destruction and radioactive contamination, 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 energy available for human consumption, we consider diet composition, energy content of different food types, crop usage, and changes in foods that we did not directly model (Methods). In 2013, the Food and Agriculture Organization\textsuperscript{21,22} reported that 51% of global calorie intake was from cereal, 31% from vegetables, fruit, roots, tubers, and nuts, and 18% from meat and related products, of which fish contributed 7%, with marine wild catch contributing 3% (Figure 3a). The crops and fish we simulated provide almost half of these calories and 40% of the protein. Further, only portions of the simulated foods are consumed by humans. Many crops (e.g., maize and soybean) are used mainly for livestock feed and biofuel (Figure 3c).

In addition, the total number of calories available as food is highly dependent on human reactions to nuclear conflicts. 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 two societal responses, *Livestock* and *No Livestock*, two contrasting extreme scenarios (see Table S3), in between which the complex societal reactions would be likely to fall. For the *Livestock* response scenario, representing a minimal adaptation to the climate-driven reduction in food supply, people continue to maintain livestock and fish as normal. Calories from all cereals, vegetables, fruit and nuts are reduced by the average reduction in our four simulated crops, and caloric changes from marine wild-caught fish are calculated with business-as-usual fishing behavior. Grass leaf carbon (Figure 2d) is used to estimate pasture change, and simulated
crop production change is used to estimate animal feed from grains. Average animal feed has ratio of 46% grass to 54% crops\textsuperscript{23}. 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 through a five-fold increase in fish price\textsuperscript{12}. Similar responses took place in New England in the “Year Without a Summer” after the 1815 Tambora volcanic eruption. Even though the temperature changes were smaller than modeled in any of the nuclear war scenarios here, crop failures forced farmers to sell their livestock because they could not feed them\textsuperscript{15} and previously unpalatable fish were added to their diet\textsuperscript{14,15,24}. Since all livestock feed from crops is not easily adaptable for human consumption, we test a full range (0%-100%) of the fraction of animal feed that could be used by humans, and use 50% as an example in some plots and tables. In all responses, we do not consider reduced human populations due to direct or indirect mortality or farmer adaptations such as changes in planting dates, cultivar selection, or switching to more cold-tolerating crops.

National consequences of calorie loss depend on fallow cropland, regional climate impacts, population levels, and assuming a complete halt of international food trade (Methods; Figure 4). Here, we focus on two calorie intake levels: 2200 kcal/capita/day and 1600 kcal/capita/day. Food consumption of less than 2200 kcal/capita/day would not allow a person to maintain their weight, and less than 1600 kcal/capita/day would be less than needed to maintain a basal metabolic rate (also known as the resting energy expenditure), and thus would quickly lead to death\textsuperscript{24}. With a 5 Tg injection, most nations show decreasing calorie intake relative to the 2013 level (Table S4), but still sufficient to maintain weight (Figure 4). With larger soot injection cases, severe starvation occurs in most of the mid-high latitude nations under the Livestock Case. When 50% of livestock
feed is converted for human consumption in each nation, some nations (such as U.S.) 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 (Figure 4, Table S5). Under the 150 Tg scenario, most nations would have calorie intake lower than resting energy expenditure\textsuperscript{24} except for Australia (see Figure 4 caption). However, this analysis is limited by the Food and Agriculture Organization 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.

The global average caloric supply post-war (Figure 5a) implies that extreme regional reductions (Figure 4) could be overcome to some extent through trade, but equal distribution of food is likely to be a major challenge. One could make the assumption of optimal food distribution within each country\textsuperscript{8}, in which the maximum number of people are given the 2200 kcal/capita/day needed to maintain their weight and level of activity and calculate the percentage of population that could be supported this way (Figure 5b). Under the 150 Tg case, most countries will have less than 25% of the population survive by the end of Year 2 (Figure S4). However, people and surviving governments would react in more complex ways, and that is a subject for future research. For example, if some favored people get more than the minimum, then more people would die.

**Discussion and conclusions**

Using state-of-the-art climate, crop, and fishery models, we calculate how the availability of food would change in the world under various nuclear war scenarios. We combined crops and marine fish, and also consider whether livestock, including dairy and eggs, continues to be an important food source.
Even for a regional nuclear war, large parts of the world would have famine. Using livestock feed as human food could offset food losses locally, but does not make much difference in the total amount of food available globally, especially at large soot injections when the growth of feed crops and pastures is severely impaired by the climate perturbation. We find particularly severe crop declines in major exporting countries like Russia, U.S., and China, which could easily trigger export restrictions and then cause severe disruptions in import dependent countries\textsuperscript{25}. Our no-trade response illustrates this risk, and shows 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. These include reduced availability of fuel and infrastructure for food production after a war, the effect of elevated UV on food production, and radioactive contamination\textsuperscript{26}. We also underline that while this analysis focuses on calories, humans would also need proteins and micronutrients to survive the ensuing years of food deficiency, and we estimate the impact on protein supply in Figure S2. Large-scale use of alternative foods requiring little-to-no light to grow in a cold environment\textsuperscript{27}, if possible, has not been considered.

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 (Figure 5a). The results here provide further support to the 1985 statement by U.S. President Ronald Reagan and Soviet General Secretary Mikhail Gorbachev, and restated by Presidents Biden and 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 scenario (Table 1, ref. 17). 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 cereal 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 Figure 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 (Figures 1b and 1d), with resulting changes in lower trophic level marine primary productivity. We applied local changes at every grid cell to the crop and fish models.

Climate model

All nuclear war scenarios$^{6,17}$ are simulated using the Community Earth System Model (CESM)$^{28}$. This model includes interactive atmosphere, land, ocean, and sea ice. Both atmosphere
and land have a horizontal resolution of 1.9°x2.5°, and the ocean has a horizontal resolution of 1°. The atmospheric model is the Whole Atmosphere Community Climate Model version 4\textsuperscript{29}. The land model is the Community Land Model version 4 with the carbon-nitrogen cycle. CESM output at 1- and 3-hourly resolution, including 2 m air temperature, precipitation, humidity, and downward longwave radiation and solar radiation (direct and diffuse radiation) are 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 5 Tg case, and one simulation for each other nuclear war scenario.

**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 as well as 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 method\textsuperscript{11} 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 modeling\textsuperscript{9-11}, 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°x2.5°) to force the crop model, and this allows variance to change, too.
Crop simulation is conducted by the Community Land Model version 5 crop (CLM5crop)\textsuperscript{30,31} 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 of 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\textsuperscript{11}, 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\textsuperscript{11}. Surface ozone and downward ultraviolet radiation would also be impacted by nuclear war\textsuperscript{32}, 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 fresh water availability is not limiting. Irrigation water is from the nearby runoff or the ocean\textsuperscript{33}. 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 is spun up for 1060 years by repeating the last 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°x2.5°). 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\textsuperscript{12,34,35}. 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 simulated fishing effort and fish catch through a bioeconomic component that depends on fish price, cost of fishing, catchability and fisheries regulation\textsuperscript{34,36}. Details are found in ref. 12 and references therein.

Combining crop and marine fish data

Table S1 shows the total calorie reductions for each of the nine nuclear states from just the simulated crops and marine fish. Data for all the countries in the world can be found in Table S2.

To calculate nation-level calories available from simulated crops and fish, we weight the production by the caloric content of each type of food. We use data from the Food and Agricultural Organization\textsuperscript{21,22}. Nation-level calorie reduction (%) from total production of maize, rice, soybean, wheat and marine fish is thus calculated as:

\begin{equation}
    w_{yi} = \frac{P_i c_i R_{iy}}{\sum_{i=1}^{5} P_i c_i R_{iy}}
\end{equation}

\begin{equation}
    R_y = \sum_{i=1}^{5} R_{iy} w_i
\end{equation}

Where index \( i \) is maize, rice, soybean, wheat, or marine fish wild catch, \( w_{iy} \) is the caloric weight of each commodity per country each year, \( P_i \) is the national production of item \( i \) in FAO- Food Balance Sheet (FBS)\textsuperscript{21,22}, \( c_i \) is calories per 100 g dry mass for each item\textsuperscript{21}, \( R_{iy} \) is national production reduction (%) of each item in year \( y \) after the nuclear conflicts, and \( R_y \) is nation-averaged calorie reduction (%) of the five items in year \( y \) after the nuclear conflicts.
Effects on other food types

*Other cereal, vegetables, fruit, roots, tubers and nuts.* National averaged calorie reduction (% of the four simulated crops) is applied to the total calories of other cereals, vegetables, fruit, roots, tubers and nuts in 2013 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 livestock we assume that 46% are fed by pasture, and 54% are fed by crops and processed products. Livestock production is linearly correlated with the feed. Annual leaf carbon of grass (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 linearly correlated with the amount of feed they receive. Direct climate change impacts on livestock and fish are not considered.

*Inland fish capture* is not considered in this study. Since inland fish only contributes to 7% of total fish production, adding inland fishery will not significantly change the main conclusions of this study.

**International trade**

All food commodity trade calculations are based on the 2013 Food and Agriculture Organization (FAO) data Commodity Balance Sheet (FAO-CBS) and FAO-FBS. This data set also provides the production and consumption of each food type and non-food type for each country, as well as the imports and exports, and thus allows the calculation on a national basis of diet consumption and food usage.

Domestic availability of a food commodity 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 (element code 5511 in FAO-FBS),
and domestic supply (element code 5301 in FAO-FBS) to each food category, and the food
production in different usages:

\[ C_{food-notrade} = C_{food} \times \frac{P_{dp}}{P_{ds}} \]  
\[ P_{usage-notrade} = P_{usage} \times \frac{P_{dp}}{P_{ds}} \]

where \( C_{food} \) is national level calorie supply from different food types in FAO-FBS, \( C_{food-notrade} \) is
national level calorie supply from different food types in FAO-FBS with the assumption of no
international trade, \( P_{dp} \) is national level domestic production for each type of food in FAO-FBS,
and \( P_{ds} \) is national level domestic supply for each type of food in FAO-FBS. Domestic supply is
the available food on the market, including domestic production, export, import and changes in
stocks and \( P_{usage} \) is the national level food usage. Food usage includes food, feed, seed, losses,
processing, residuals, tourist consumption and other use (non-food). For a detailed description,
see Definitions and Standards in FAO-NFB. \( P_{usage-notrade} \) is the national level food usage with the
assumption of no international trade.

Food usage of maize, soybean, rice and wheat is calculated from FAO-CBS. In FAO-CBS,
maize products are maize and by-product maize germ oil, soybean products are soybean, and by-
products soybean oil and soybean cake, rice products are rice and by-product rice bran oil, and
wheat product is wheat. Products for food purposes is the sum of food supply in each category,
and also the processing product minus the total by-products (the difference includes processing for
the purpose of alcohol or sugar).
Caloric requirements

The population percentage supported by available calories calculated for the Livestock and No Livestock responses indicate the macro-level consequences for food security (Figure 4). The current average human caloric intake is 2844 kcal/capita/day (Figure 3). Caloric requirements vary significantly with age, gender, size, climate, level of activity, and underlying medical conditions. The consumption of less than 2200 kcal/capita/day would not allow an average person to maintain their weight\(^{24}\). 1600 kcal/day is the resting energy expenditure for an average person and a sustained diet less than that would be life threatening in someone who did not have substantial stores of body fat\(^{24}\). We assume 2200 kcal/capita/day is needed to support life and regular labor activity, which means that in Year 2 after the six nuclear scenarios, there are billions of people threatened by food insufficiency (Figure 4).

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 (Figure S5), 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\(^{38, 39}\) and 150 Tg\(^{6}\) 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 forcing\textsuperscript{11} (Figure S1). If anything, CLM5crop underestimates the crop response to nuclear war (Figures 2, S1). 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 conflicts, but crops may not respond uniformly 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, UV and freshwater availability.

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 conflicts.

This study uses calorie intake from FAO data, and food loss and waste are not considered, which account for around 1/3 of the world’s food. If human behavior and the food industry would change substantially, this would affect our conclusions.

Data 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](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/. The crop yield and grass production data are available at https://osf.io/YRBSE/. Additional data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This study was supported by the Open Philanthropy Project, with partial support from the European Research Council under the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement 682602. Alan Robock and Lili Xia were supported by National Science Foundation grants AGS-2017113 and ENG-2028541. We thank Ira Helfand and Benjamin Bodirsky for valuable suggestions on the work.

Author Contributions

L.X., A.R., K.S., and C.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. L.X. analyzed 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.
Table 1. Computed calorie changes (%) in Year 2 after a nuclear conflict for the nations with nuclear weapons and global average assuming no trade after simulated nuclear conflicts under both the Livestock Case and the No Livestock Case, with 50% livestock feed to human consumption. The total calorie reduction is referenced to the observed production in 2013.

<table>
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<th>Nations</th>
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<th>27 Tg</th>
<th>37 Tg</th>
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Figure 1. Change in surface temperature, solar radiation, and precipitation averaged over global crop regions, and sea surface temperature, solar radiation, and net primary productivity over the oceans following the six stratospheric soot loading scenarios studied here, for 15 years following a nuclear war, derived from simulations in ref. 13. The anomalies are monthly climate variables from simulated nuclear war minus the climatology of the control simulation, which is the average of 45 years of 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.
Figure 2. (a) Global average annual crop calorie change (%) (maize, wheat, rice, and soy, weighted by their observed production (2018) and calorie content), (b) marine fish calorie changes (%) after nuclear war, for the different soot injection scenarios, and (c) combined impact of crops and marine fish on available caloric input. Grass leaf carbon is a combination of C3 and C4 grass and the change is calculated as annual accumulated carbon. The gray line in (a) is the average of six crop models from ref. 11 under the 5 Tg scenario, and the light gray envelope in (a) is the standard deviation of the six crop models. If anything, CLM5 underestimates the crop response to nuclear war.
Figure 3. (a) Global average human diet composition. (b) Global average human protein diet composition. Marine wild capture contributes 75% of marine fish. (c) Distribution of four major cereal crops and marine fish between human food and other uses. The color gradient legend in gray in (c) illustrates the usage of different crops and fish in colors. While humans consume most of the wheat and rice grown, most maize and soybeans is used for livestock feed.
Figure 4. Food availability (Kcal/Capita/Day) in Year 2 after different nuclear war soot injections. The left two maps are the caloric intake status in 2013 with international trade on and off, the middle column is the Livestock Case, and the right column is the No Livestock Case with 50% of livestock feed used for human food. All assume no international trade and that the total calories
are evenly distributed within each nation. Food consumption of less than 2200 Kcal/Capita/Day would not allow an average seized adult to maintain their weight, and less than 1600 Kcal/Capita/Day would be less than needed to maintain a basal metabolic rate (also called resting energy expenditure)\textsuperscript{24}, and thus would lead to death after an individual exhausted their body energy reserves in stored fat and expendable muscle. Australia is the only nation with enough calorie intake under the 150 Tg scenario, but it may be greatly overestimated. 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\textsuperscript{22}. Therefore, the wheat response to simulated nuclear wars largely determines calorie intake in Australia. Since we use spring wheat to represent wheat, and simulated spring wheat in Australia shows increasing or small reductions under nuclear war scenarios in which more favorable temperatures occur for food production, the calorie intake in Australia is more than other nations.
Figure 5. Overview of global calorie intake and sensitivity to livestock and trade assumptions. (a) The global average change in caloric intake per person per day in year 2 post-war under the *Livestock* case (yellow bars), in which all food sources except livestock are reduced for the different soot injections averaged, and for the *No Livestock* case (red bars), in which also there are no meat, dairy, or eggs. For the *No 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). Critical food intake levels are marked in the right margin. (b) Without international trade, the global population (%) that could be supported by domestic food production at the end of Year 2 after a nuclear war if they receive 2200 Kcal/Capita/Day and the rest population would receive no food, under the *Livestock* and *No Livestock* cases. National data are calculated first (Figure S6), and then aggregated to global data.
References


   https://doi.org/10.1038/s43016-020-00211-7


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Supplementary Files

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- NatureFoodNW13Supplementary.pdf