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Global Famine after Nuclear War

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1 **Global Famine after Nuclear War**

2
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32 In a nuclear war, bombs targeted on cities and industrial areas would start firestorms,
33 injecting large amounts of soot into the upper atmosphere, which would spread globally and
34 rapidly cool the planet^{1,2,3}. The soot loadings would cause decadal disruptions in Earth's
35 climate^{4,5,6}, which would impact food production systems on land and in the oceans. In 1980s,
36 investigations of nuclear winter impacts on global agricultural production⁷ and food availability⁸
37 for 15 nations, but new information now allows us to update those estimates. Recently, several
38 studies analyzed changes of major grain crops^{9,10,11} and marine wild-catch fisheries¹² for different
39 scenarios of regional nuclear war using sophisticated models. However, the impact on the total
40 food supply available to humans is more complex. Here we show that considering all food sources
41 and potential adaptation measures, such as using animal feed directly for humans, famine would
42 result for most of Earth even from a war between India and Pakistan using less than 3% of the
43 global nuclear arsenal. We look at the climate impacts from a range of scales from regional to
44 global nuclear war, and estimate the total amount of food calories available in each nation,
45 including crops, livestock, and fisheries, for each year following a nuclear holocaust. Our findings
46 quantify the global indirect impacts of nuclear war away from target areas, and demonstrate the
47 need to prevent any scale of nuclear war.

48

49 Extraordinary events such as large volcanic eruptions or nuclear war could cause sudden
50 global climate disruptions. Global volcanic cooling from sulfates has resulted in severe famines
51 and political instability, for example after the 1783 Laki eruption in Iceland¹³ or the 1815 Tambora
52 eruption in Indonesia^{14,15}. For a nuclear war, the global cooling would depend on the yields of the
53 weapons, the number of weapons, and the targets, among other atmospheric and geographic
54 factors. A war between India and Pakistan could produce a stratospheric loading of 5-47 Tg of

55 soot^{16,17} and a war between the United States, its allies, and Russia, who possess more than 90%
56 of the global nuclear arsenal, could produce more than 150 Tg of soot and a nuclear winter¹⁻⁶.
57 Recent catastrophic forest fires in Canada in 2017¹⁸ and Australia in 2019 and 2020^{19,20} produced
58 0.3-1 Tg of smoke (0.006-0.02 Tg soot), which was subsequently heated by sunlight and lofted
59 high in the stratosphere, adding confidence to nuclear war simulations that predict the same process
60 will occur after nuclear war.

61 Climate disruption from nuclear war would impact food production systems on land and in
62 the oceans, but so far an integrated estimate of the impacts of the entire range of war scenarios on
63 both land- and ocean-based food production is missing. Here, we examine the impacts of six war
64 scenarios, generating 5 to 150 Tg of soot, on the food supply. We use model simulations of major
65 crops and wild-caught marine fish together with estimated changes in other food and livestock
66 productivity to assess the impacts on global calorie supply.

67 Because soot disperses globally once it reaches the upper atmosphere, our results apply
68 regardless of the warring nations. There are many war scenarios that could result in similar
69 amounts of smoke and thus similar climate shocks, including wars involving the other nuclear-
70 armed nations (China, France, the UK, North Korea, and Israel).

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

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

76 Global averaged calories from the crops we simulated decreased 7% in years 1-5 after the
77 conflict even under the smallest, 5 Tg soot scenario (Figure 2a; comparable to previous multi-

78 model results¹¹, Figure S1) and up to 50% under the 47 Tg scenario. In the 150 Tg soot case,
79 global average calories from crops would decrease by around 90% 3-4 years after the nuclear
80 conflict. The changes would induce a catastrophic disruption of global food markets, as even a
81 7% global yield decline would exceed the largest anomaly ever recorded since the beginning of
82 the FAO observational records in 1961¹¹.

83 Fish are another important food resource, especially in terms of protein supply. Nuclear
84 war would reduce the wild fish catch¹², but the reduction would be less than for land agriculture
85 (Figure 2b), since reduction in oceanic net primary productivity – the base of the marine food-
86 web– is moderate (from 3% in 5 Tg to 37% in 150 Tg), and temperature changes are less
87 pronounced (Figure 1). Terrestrial agricultural production dominates the total calorie change of
88 crops and fisheries combined (Figure 2c), since global crop production is 24 times that of wild
89 fisheries and staple crops contain around five times more calories than fish per unit mass^{21, 22}. In
90 total, marine wild capture contributes 0.5% of total calories, but 3.5% of global average protein
91 supply (Figures 3 and S2).

92 Calorie reduction from agriculture and marine fisheries shows regional differences (Figure
93 S3), with the strongest percentage reductions over high latitudes in the Northern Hemisphere.
94 Cooling from nuclear conflicts causes temperature limitations for crops, leading to delayed
95 physiological maturity and additional cold stress¹¹. Even for the India-Pakistan case, many regions
96 become unsuitable for agriculture for multiple years. For example, in the 27 Tg case, mid- to high-
97 latitudes of the Northern Hemisphere show crop reductions > 50%, along with fish catch reductions
98 of 20-30%. The nuclear-armed nations in mid- to high-latitude regions (China, Russia, United
99 States, France, North Korea, and United Kingdom) show calorie reduction from 30% to 86%, and
100 in lower latitudes (India, Pakistan and Israel) the reduction is less than 10% (Tables S1 and S2).

101 We underline that impacts in warring nations are likely to be dominated by local problems, like
102 infrastructure destruction and radioactive contamination, so the results here apply only to indirect
103 effects from soot injection in remote locations.

104 **Impacts on total human calorie intake**

105 To estimate the effect on the total food energy available for human consumption, we
106 consider diet composition, energy content of different food types, crop usage, and changes in foods
107 that we did not directly model (Methods). In 2013, the Food and Agriculture Organization^{21,22}
108 reported that 51% of global calorie intake was from cereal, 31% from vegetables, fruit, roots,
109 tubers, and nuts, and 18% from meat and related products, of which fish contributed 7%, with
110 marine wild catch contributing 3% (Figure 3a). The crops and fish we simulated provide almost
111 half of these calories and 40% of the protein. Further, only portions of the simulated foods are
112 consumed by humans. Many crops (e.g., maize and soybean) are used mainly for livestock feed
113 and biofuel (Figure 3c).

114 In addition, the total number of calories available as food is highly dependent on human
115 reactions to nuclear conflicts. We assume that international trade in food is suspended as food
116 exporting nations halt exports in response to declining food production (Methods). Furthermore,
117 we considered two societal responses, *Livestock* and *No Livestock*, two contrasting extreme
118 scenarios (see Table S3), in between which the complex societal reactions would be likely to fall.
119 For the *Livestock* response scenario, representing a minimal adaptation to the climate-driven
120 reduction in food supply, people continue to maintain livestock and fish as normal. Calories from
121 all cereals, vegetables, fruit and nuts are reduced by the average reduction in our four simulated
122 crops, and caloric changes from marine wild-caught fish are calculated with business-as-usual
123 fishing behavior. Grass leaf carbon (Figure 2d) is used to estimate pasture change, and simulated

124 crop production change is used to estimate animal feed from grains. Average animal feed has ratio
125 of 46% grass to 54% crops²³. The *No Livestock* response represents a scenario where livestock
126 (including dairy and eggs) and aquaculture production are not maintained after the first year, and
127 the national fractions of crop production previously used as feed are now available to feed humans.
128 In addition, fishing pressure intensifies through a five-fold increase in fish price¹². Similar
129 responses took place in New England in the “Year Without a Summer” after the 1815 Tambora
130 volcanic eruption. Even though the temperature changes were smaller than modeled in any of the
131 nuclear war scenarios here, crop failures forced farmers to sell their livestock because they could
132 not feed them¹⁵ and previously unpalatable fish were added to their diet^{14,15,24}. Since all livestock
133 feed from crops is not easily adaptable for human consumption, we test a full range (0%-100%) of
134 the fraction of animal feed that could be used by humans, and use 50% as an example in some
135 plots and tables. In all responses, we do not consider reduced human populations due to direct or
136 indirect mortality or farmer adaptations such as changes in planting dates, cultivar selection, or
137 switching to more cold-tolerating crops.

138 National consequences of calorie loss depend on fallow cropland, regional climate impacts,
139 population levels, and assuming a complete halt of international food trade (Methods; Figure 4).
140 Here, we focus on two calorie intake levels: 2200 kcal/capita/day and 1600 kcal/capita/day. Food
141 consumption of less than 2200 kcal/capita/day would not allow a person to maintain their weight,
142 and less than 1600 kcal/capita/day would be less than needed to maintain a basal metabolic rate
143 (also known as the resting energy expenditure), and thus would quickly lead to death²⁴. With a 5
144 Tg injection, most nations show decreasing calorie intake relative to the 2013 level (Table S4), but
145 still sufficient to maintain weight (Figure 4). With larger soot injection cases, severe starvation
146 occurs in most of the mid-high latitude nations under the *Livestock Case*. When 50% of livestock

147 feed is converted for human consumption in each nation, some nations (such as U.S.) would
148 maintain sufficient calorie intake under scenarios with smaller soot injections, but weight loss or
149 even severe starvation would occur under larger soot injection cases (Figure 4, Table S5). Under
150 the 150 Tg scenario, most nations would have calorie intake lower than resting energy
151 expenditure²⁴ except for Australia (see Figure 4 caption). However, this analysis is limited by the
152 Food and Agriculture Organization data, which are collected at national levels. Within each
153 nation, particularly large ones, there may be large regional inequities driven by infrastructure
154 limitations, economic structures, and government policies.

155 The global average caloric supply post-war (Figure 5a) implies that extreme regional
156 reductions (Figure 4) could be overcome to some extent through trade, but equal distribution of
157 food is likely to be a major challenge. One could make the assumption of optimal food distribution
158 within each country⁸, in which the maximum number of people are given the 2200 kcal/capita/day
159 needed to maintain their weight and level of activity and calculate the percentage of population
160 that could be supported this way (Figure 5b). Under the 150 Tg case, most countries will have less
161 than 25% of the population survive by the end of Year 2 (Figure S4). However, people and
162 surviving governments would react in more complex ways, and that is a subject for future research.
163 For example, if some favored people get more than the minimum, then more people would die.

164 **Discussion and conclusions**

165 Using state-of-the-art climate, crop, and fishery models, we calculate how the availability
166 of food would change in the world under various nuclear war scenarios. We combined crops and
167 marine fish, and also consider whether livestock, including dairy and eggs, continues to be an
168 important food source.

169 Even for a regional nuclear war, large parts of the world would have famine. Using
170 livestock feed as human food could offset food losses locally, but does not make much difference
171 in the total amount of food available globally, especially at large soot injections when the growth
172 of feed crops and pastures is severely impaired by the climate perturbation. We find particularly
173 severe crop declines in major exporting countries like Russia, U.S., and China, which could easily
174 trigger export restrictions and then cause severe disruptions in import dependent countries²⁵. Our
175 no-trade response illustrates this risk, and shows that African and Middle Eastern countries would
176 be severely affected.

177 Our analysis of the potential impacts of nuclear war on the food system does not address
178 some aspects of the problem leaving them for future research. These include reduced availability
179 of fuel and infrastructure for food production after a war, the effect of elevated UV on food
180 production, and radioactive contamination²⁶. We also underline that while this analysis focuses
181 on calories, humans would also need proteins and micronutrients to survive the ensuing years of
182 food deficiency, and we estimate the impact on protein supply in Figure S2. Large-scale use of
183 alternative foods requiring little-to-no light to grow in a cold environment²⁷, if possible, has not
184 been considered.

185 In conclusion, the reduced light, global cooling and likely trade restrictions after nuclear
186 wars would be a global catastrophe for food security. The negative impact of climate perturbations
187 on the total crop production can generally not be offset by livestock and aquatic food (Figure 5a).
188 The results here provide further support to the 1985 statement by U.S. President Ronald Reagan
189 and Soviet General Secretary Mikhail Gorbachev, and restated by Presidents Biden and Putin in
190 2021, that “a nuclear war cannot be won and must never be fought.”

191

192 **Methods**

193 We use a state-of-the-art global climate model to calculate the climatic and biogeochemical
194 changes caused by a range of stratospheric soot injections, each associated with a nuclear war
195 scenario (Table 1, ref. 17). Simulated changes in surface air temperature, precipitation, and
196 downward direct and diffuse solar radiation, are used to force a state-of-the-art crop model to
197 estimate how the productivity of the major cereal crops (maize, rice, spring wheat, and soybean)
198 would be affected globally, and changes in oceanic net primary production and sea surface
199 temperature are used to force a global marine fisheries model. We combine these results with
200 assumptions about how other crop production, livestock production, fish production and food trade
201 could change and calculate the amount of food that would be available for each country in the
202 world after a nuclear war.

203 The simulated surface climate disruptions due to the nuclear war scenarios are summarized
204 in Figure 1. Averaged over the current crop regions, surface downwelling solar radiation reduces
205 by 10 W/m^2 (5 Tg soot injection) to 130 W/m^2 (150 Tg soot injection). With less energy received,
206 the maximum average 2 m air temperature reductions range from 1.5°C (5 Tg soot injection) to
207 14.8°C (150 Tg soot injection) peaking within 1-2 years after the war with temperature reduction
208 lasting for more than 10 years. The cooling also reduces precipitation over summer monsoon
209 regions. Similar but smaller reductions of solar radiation and temperature are projected in marine
210 regions (Figures 1b and 1d), with resulting changes in lower trophic level marine primary
211 productivity. We applied local changes at every grid cell to the crop and fish models.

212 **Climate model**

213 All nuclear war scenarios^{6,17} are simulated using the Community Earth System Model
214 (CESM)²⁸. This model includes interactive atmosphere, land, ocean, and sea ice. Both atmosphere

215 and land have a horizontal resolution of $1.9^{\circ}\times 2.5^{\circ}$, and the ocean has a horizontal resolution of 1° .
216 The atmospheric model is the Whole Atmosphere Community Climate Model version 4²⁹. The
217 land model is the Community Land Model version 4 with the carbon-nitrogen cycle. CESM output
218 at 1- and 3-hourly resolution, including 2 m air temperature, precipitation, humidity, and
219 downward longwave radiation and solar radiation (direct and diffuse radiation) are used to drive
220 the offline crop model simulations. There are three ensemble members of the control simulation,
221 which repeats the climate forcing of 2000 for 15 years, three ensemble members of the 5 Tg case,
222 and one simulation for each other nuclear war scenario.

223 **Direct climate model output use**

224 Because climate models have biases, it is typical to bias-correct model output before using
225 it as input for crop models. There are various techniques that attempt to use past observational
226 data to address changes in the mean as well as variance, but none are perfect and all are limited by
227 assumptions that future relations between model output and crop model input can be based on the
228 recent past. A common method¹¹ is the delta-method, in which an observational reanalysis weather
229 dataset is used and monthly means of temperature, precipitation, and insolation are modified
230 according to the climate model simulations. This comes with the advantage of realistic internal
231 variability important for crop modeling⁹⁻¹¹, but does not adjust changes in variance, which might
232 be an unrealistic assumption under higher emission scenarios, such as the 150 Tg case. Here,
233 because we are using a crop model that has already been calibrated with the same climate model
234 that we are using, we use raw climate model output ($1.9^{\circ}\times 2.5^{\circ}$) to force the crop model, and this
235 allows variance to change, too.

236 Crop model

237 Crop simulation is conducted by the Community Land Model version 5 crop
238 (CLM5crop)^{30,31} in the Community Earth System Model version 2 (CESM2). Dynamic vegetation
239 is not turned on. CLM5crop has six active crops: maize, rice, soybeans, spring wheat, sugar cane,
240 and cotton, and also simulates natural vegetation, such as grasses. In this study, we used the output
241 of the cereals, maize, rice, soybeans, and spring wheat, and of grasses. Although CLM5crop does
242 not simulate winter wheat, we assume winter wheat production is changed by the same amount as
243 spring wheat, which has been found in other studies¹¹, however this may underestimate the winter
244 wheat response, because winter wheat would experience colder temperatures during its growing
245 period that would be more likely to cross critical thresholds¹¹. Surface ozone and downward
246 ultraviolet radiation would also be impacted by nuclear war³², but CLM5crop is not able to
247 consider those impacts, which might exacerbate the losses. In addition, the crop model does not
248 consider the availability of pollinators, killing frost, and alternative seeds. The model simulates
249 rainfed crops and irrigated crops separately, and all results presented here refer to the total
250 production of rainfed and irrigated crops. Irrigated crops are simulated under the assumption that
251 fresh water availability is not limiting. Irrigation water is from the nearby runoff or the ocean³³.
252 Although evaporation is reduced with cooling, it is possible that our result may underestimate the
253 negative impact from precipitation reduction, especially for the large injection cases.

254 CLM5crop is spun up for 1060 years by repeating the last 10 years of the CESM control to
255 reach the equilibrium of four soil carbon pools. The crop simulations are at the same resolution
256 as CESM simulations (1.9°x2.5°). The crop planting date is determined by growing degree days,
257 and the location of cropland is fixed for all crops.

258 **Fishery model**

259 Fish and fisheries responses are simulated with the BiOeconomic mArine Trophic Size-
 260 spectrum (BOATS) model^{12,34,35}. BOATS was used to calculate the size-structured biomass of
 261 commercially targeted fish based on gridded (1° horizontal resolution) inputs of sea surface
 262 temperature and oceanic net primary production from CESM. The model also interactively
 263 simulated fishing effort and fish catch through a bioeconomic component that depends on fish
 264 price, cost of fishing, catchability and fisheries regulation^{34,36}. Details are found in ref. 12 and
 265 references therein.

266 **Combining crop and marine fish data**

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

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

$$273 \quad w_{yi} = \frac{P_i c_i R_{iy}}{\sum_{i=1}^5 P_i c_i R_{iy}} \quad (1)$$

$$274 \quad R_y = \sum_{i=1}^5 R_{iy} w_i \quad (2)$$

275 Where index i is maize, rice, soybean, wheat, or marine fish wild catch, w_{iy} is the caloric weight
 276 of each commodity per country each year, P_i is the national production of item i in FAO- Food
 277 Balance Sheet (FBS)^{21,22}, c_i is calories per 100 g dry mass for each item²¹, R_{iy} is national production
 278 reduction (%) of each item in year y after the nuclear conflicts, and R_y is nation-averaged calorie
 279 reduction (%) of the five items in year y after the nuclear conflicts.

280 **Effects on other food types**

281 *Other cereal, vegetables, fruit, roots, tubers and nuts.* National averaged calorie reduction
282 (%) of the four simulated crops is applied to the total calories of other cereals, vegetables, fruit,
283 roots, tubers and nuts in 2013 to estimate simulated nuclear war impacts on this category.

284 *Livestock and aquaculture.* We assume these two types of food share a similar response
285 to simulated nuclear war as they involve feeding animals in a relatively controlled environment.
286 For livestock we assume that 46% are fed by pasture, and 54% are fed by crops and processed
287 products²³. Livestock production is linearly correlated with the feed. Annual leaf carbon of grass
288 (both C3 and C4) is used to estimate pasture changes, and reduction of the four simulated crops is
289 used for crop feed changes. For aquaculture, the feed is only from crops and processed products,
290 and the production is also linearly correlated with the amount of feed they receive. Direct climate
291 change impacts on livestock and fish are not considered.

292 *Inland fish capture* is not considered in this study. Since inland fish only contributes to 7%
293 of total fish production³⁷, adding inland fishery will not significantly change the main conclusions
294 of this study.

295 **International trade**

296 All food commodity trade calculations are based on the 2013 Food and Agriculture
297 Organization (FAO) data Commodity Balance Sheet (FAO-CBS) and FAO-FBS^{21,22}. This data
298 set also provides the production and consumption of each food type and non-food type for each
299 country, as well as the imports and exports, and thus allows the calculation on a national basis of
300 diet consumption and food usage.

301 Domestic availability of a food commodity in each country comes from domestic
302 production and reserves, reduced by exports and increased by imports. We calculate no

303 international trade by applying the ratio of domestic production (element code 5511 in FAO-FBS),
 304 and domestic supply (element code 5301 in FAO-FBS) to each food category, and the food
 305 production in different usages:

306

$$307 \quad C_{food-notrade} = C_{food} \times \frac{P_{dp}}{P_{ds}} \quad (3)$$

$$308 \quad P_{usage-notrade} = P_{usage} \times \frac{P_{dp}}{P_{ds}} \quad (4)$$

309

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

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

325 Caloric requirements

326 The population percentage supported by available calories calculated for the *Livestock* and
327 *No Livestock* responses indicate the macro-level consequences for food security (Figure 4). The
328 current average human caloric intake is 2844 kcal/capita/day (Figure 3). Caloric requirements
329 vary significantly with age, gender, size, climate, level of activity, and underlying medical
330 conditions. The consumption of less than 2200 kcal/capita/day would not allow an average person
331 to maintain their weight²⁴. 1600 kcal/day is the resting energy expenditure for an average person
332 and a sustained diet less than that would be life threatening in someone who did not have
333 substantial stores of body fat²⁴. We assume 2200 kcal/capita/day is needed to support life and
334 regular labor activity, which means that in Year 2 after the six nuclear scenarios, there are billions
335 of people threatened by food insufficiency (Figure 4).

336 Uncertainties

337 This work was done with one Earth system model, with only one ensemble member for all
338 the cases with soot injections > 5 Tg, only one crop model, and only one fishery model. For the 5
339 Tg case and the control, there are three ensemble members, but only the ensemble averages are
340 used. The three ensemble members for the 5 Tg case are very similar (Figure S5), so climate
341 variability for the larger forcings would be much smaller than the signal.

342 CESM is a state-of-the-art climate model, and its simulations of the impacts of nuclear war
343 have been almost identical to simulations with other models for the 5 Tg^{38,39} and 150 Tg⁶ cases.
344 However, further developments in climate models, such as including organic carbon in fire
345 emissions, and better simulating aerosol growth and interactions with the surrounding
346 environment, may improve climate prediction after a nuclear war.

347 CLM5crop and BOATS are also state-of-the-art models, but future simulations with
348 different models would certainly be useful. CLM5crop compares well with other crop models in
349 response to nuclear war forcing¹¹ (Figure S1). If anything, CLM5crop underestimates the crop
350 response to nuclear war (Figures 2, S1). Because most crop models were developed for the current
351 or warmer climates, further research is needed to understand how crops react to a suddenly cold
352 environment. Our study is the first step to reveal national food security after nuclear conflicts, but
353 crops may not respond uniformly the same forcing in each nation, given different farming
354 practices. In addition, multi-model assessment will be essential to fully investigate this problem,
355 and crop model developments are important to understand impacts from surface ozone, UV and
356 freshwater availability.

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

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

366

367 **Data Availability**

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

370 for CLM5 is available at <https://www.cesm.ucar.edu/models/cesm2/land/>. The crop yield and
371 grass production data are available at <https://osf.io/YRBSE/>. Additional data that support the
372 findings of this study are available from the corresponding author upon reasonable request.

373

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380

381 **Author Contributions**

382 L.X., A.R., K.S., and C.H. designed the study. C.G.B. conducted the climate model simulations,
383 L.X. conducted the crop simulations, and K.S. and R.H. conducted the fishery simulations. L.X.
384 analyzed the data with contributions from all the authors. A.R. and L.X. wrote the first draft and
385 all authors contributed to editing and revising the manuscript.

386

387 **Competing interests**

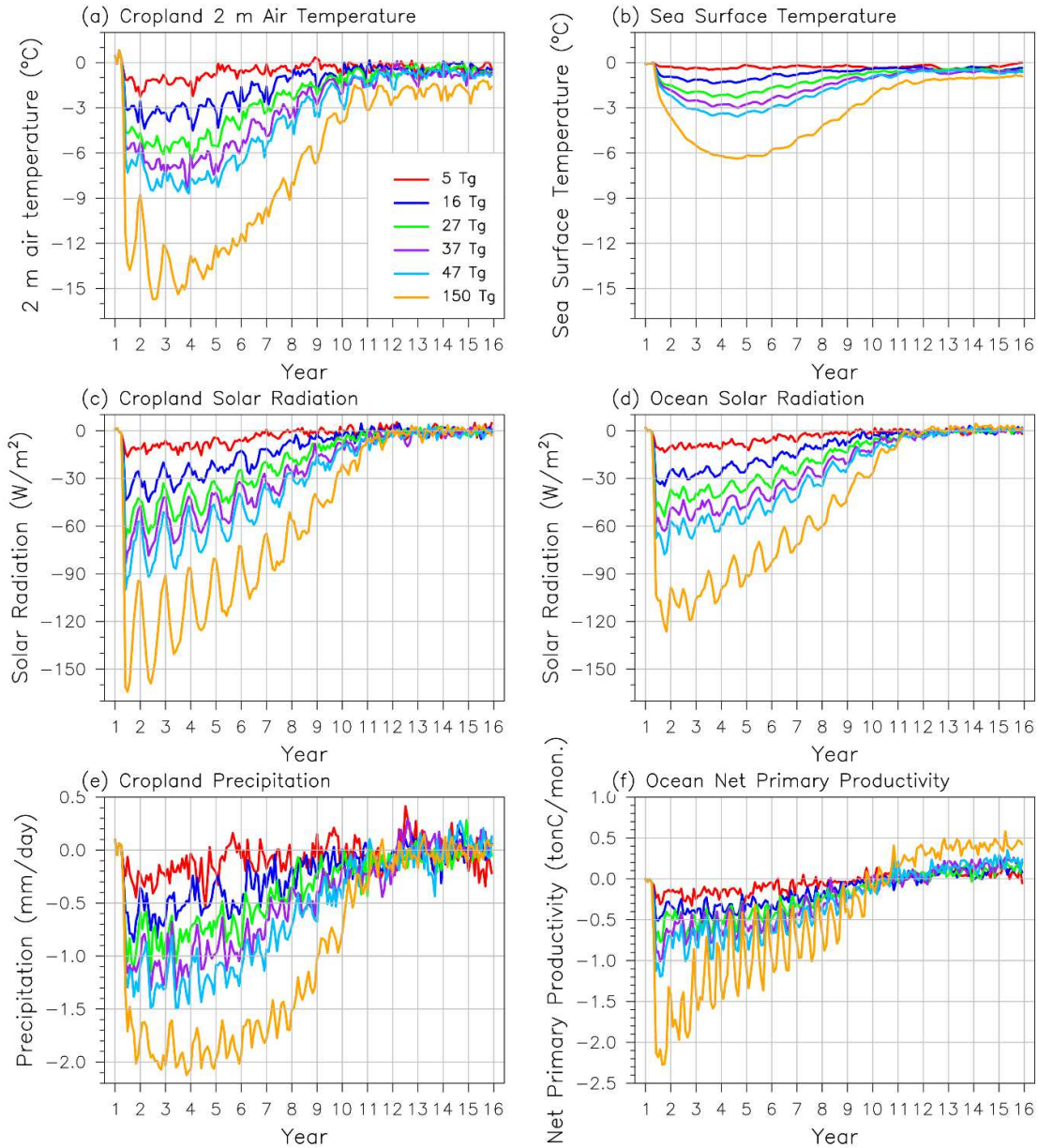
388 The authors declare no competing interests.

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390 **Table 1.** Computed calorie changes (%) in Year 2 after a nuclear conflict for the nations with
 391 nuclear weapons and global average assuming no trade after simulated nuclear conflicts under both
 392 the *Livestock Case* and the *No Livestock Case*, with 50% livestock feed to human consumption.
 393 The total calorie reduction is referenced to the observed production in 2013.
 394

Nations	5 Tg	16 Tg	27 Tg	37 Tg	47 Tg	150 Tg
<i>Livestock Case</i>						
China	-13.2	-47.5	-64.3	-78.1	-84.4	-99.7
France	-5.3	-21.5	-24.4	-31.4	-34.7	-99.4
India	-2.6	-0.7	0.9	-7.5	-21.3	-68.4
Israel	27.3	14.7	11.1	8.3	-2.6	-80.0
North Korea	-12.6	-90.3	-92.4	-98.9	-99.6	-100.0
Pakistan	-1.9	13.7	15.1	-18.2	-23.7	-86.2
Russia	-2.4	-67.5	-86.2	-91.7	-92.2	-99.7
United Kingdom	0.7	-32.7	-43.8	-62.1	-78.5	-95.8
United States	-12.8	-47.3	-63.3	-76.6	-86.9	-98.8
Global	-8.1	-23.7	-33.2	-42.0	-49.0	-81.1
<i>No Livestock Case (50% livestock feed to human consumption)</i>						
China	-12.3	-48.7	-65.5	-79.2	-84.3	-98.3
France	49.0	18.3	14.0	3.3	-1.6	-99.2
India	-8.7	-6.2	-4.7	-11.2	-23.3	-64.3
Israel	7.0	4.6	-0.3	-2.7	-17.8	-77.8
North Korea	-11.4	-91.0	-93.2	-99.8	-99.9	-100.0
Pakistan	-31.3	-15.5	-16.2	-41.1	-42.8	-88.6
Russia	11.8	-64.7	-84.8	-90.6	-90.8	-99.1
United Kingdom	17.9	-22.5	-35.8	-58.3	-78.4	-98.7
United States	62.9	-8.9	-39.1	-64.4	-80.3	-94.7
Global	-5.8	-22.2	-32.0	-41.2	-48.5	-82.2

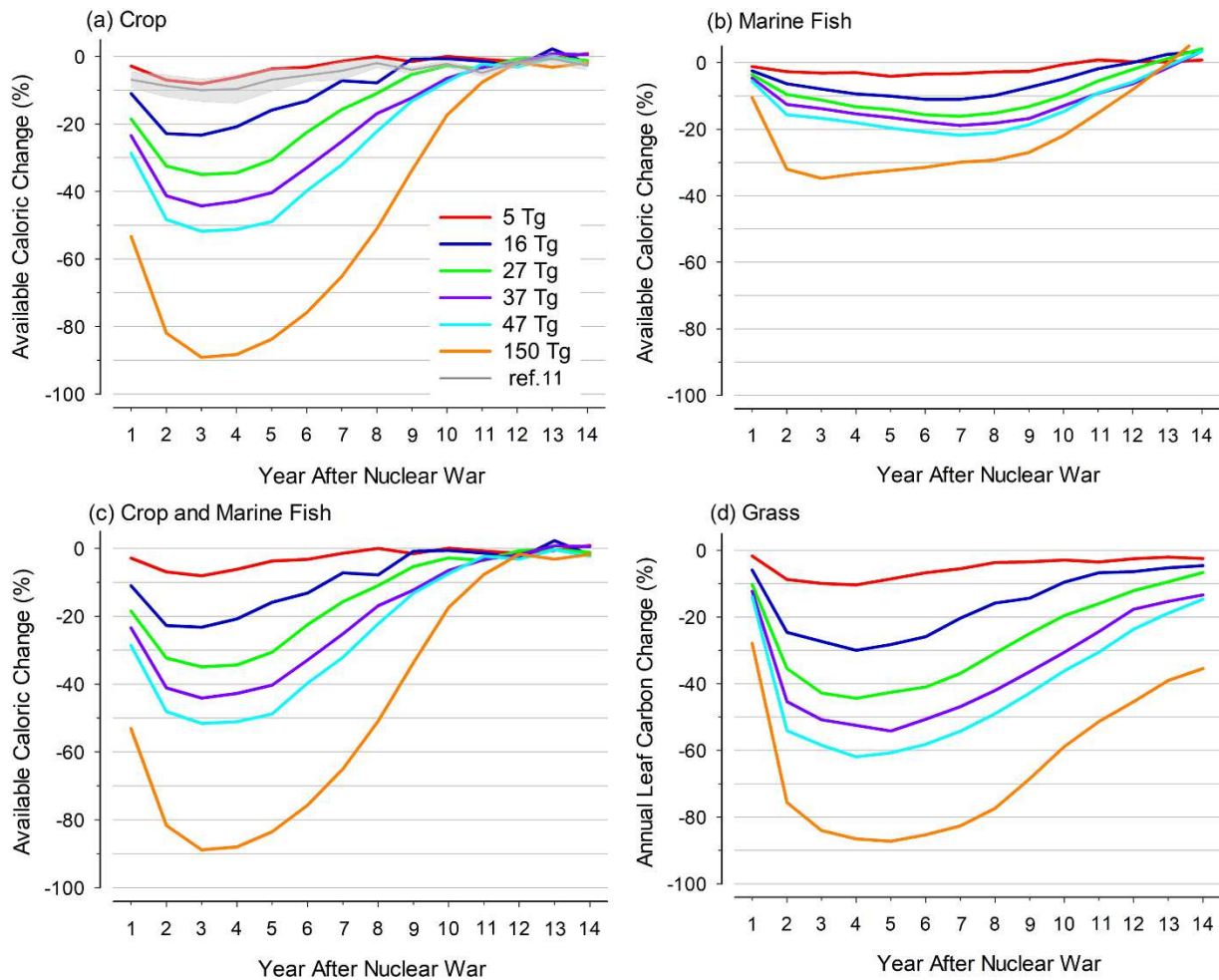
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397 **Figure 1.** Change in surface temperature, solar radiation, and precipitation averaged over global
 398 crop regions, and sea surface temperature, solar radiation, and net primary productivity over the
 399 oceans following the six stratospheric soot loading scenarios studied here, for 15 years following
 400 a nuclear war, derived from simulations in ref. 13. The anomalies are monthly climate variables
 401 from simulated nuclear war minus the climatology of the control simulation, which is the average
 402 of 45 years of simulation. The wars take place on 15 May of Year 1, and the year labels are on 1
 403 January of each year. For comparison, during the last Ice Age 20,000 years ago, global average
 404 surface temperatures were about 5°C cooler than present. Ocean temperatures decline less than
 405 for crops, because of the ocean's large heat capacity. Ocean solar radiation loss is less than for
 406 crops because most ocean is in the Southern Hemisphere, where slightly less smoke is present.

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410 **Figure 2.** (a) Global average annual crop calorie change (%) (maize, wheat, rice, and soy,

411 weighted by their observed production (2018) and calorie content), (b) marine fish calorie changes

412 (%) after nuclear war, for the different soot injection scenarios, and (c) combined impact of crops

413 and marine fish on available caloric input. Grass leaf carbon is a combination of C3 and C4 grass

414 and the change is calculated as annual accumulated carbon. The gray line in (a) is the average of

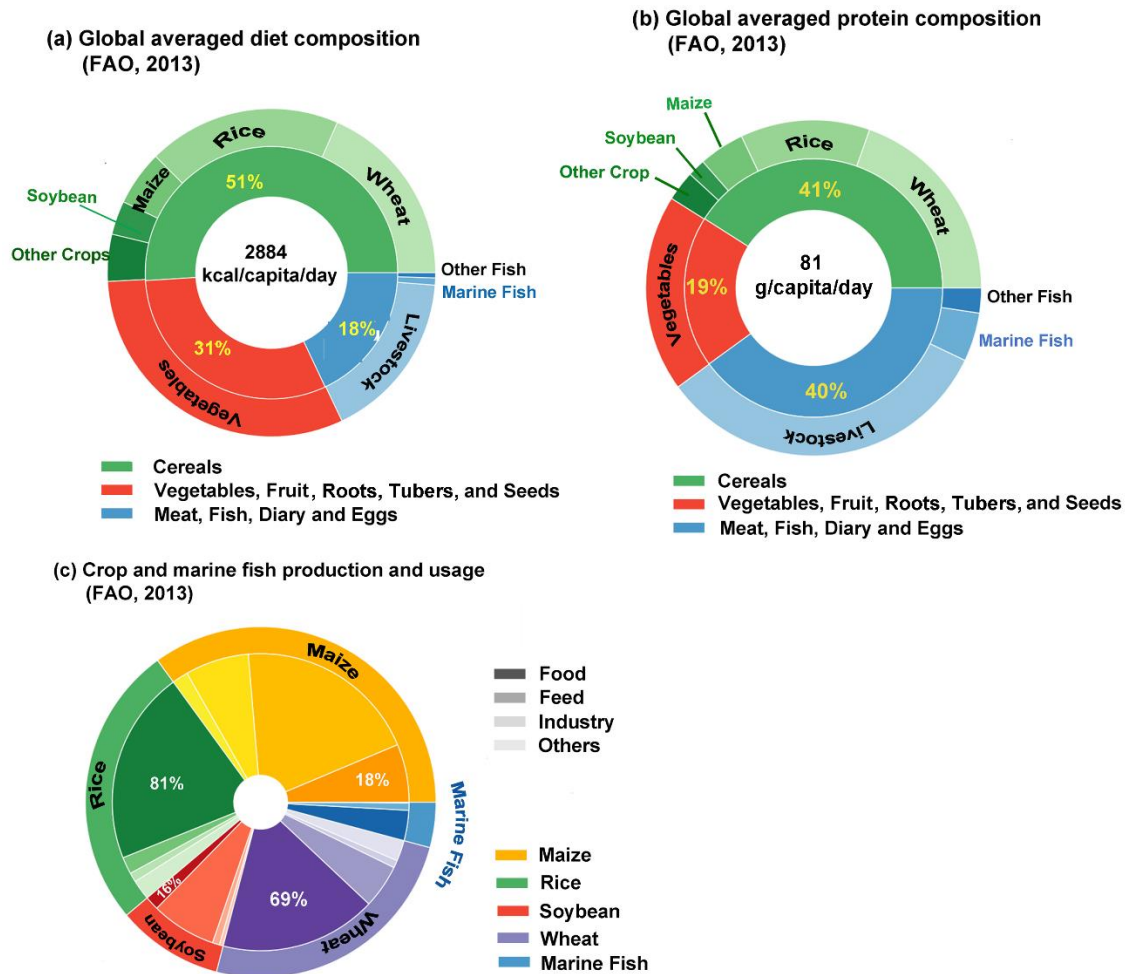
415 six crop models from ref. 11 under the 5 Tg scenario, and the light gray envelope in (a) is the

416 standard deviation of the six crop models. If anything, CLM5 underestimates the crop response to

417 nuclear war.

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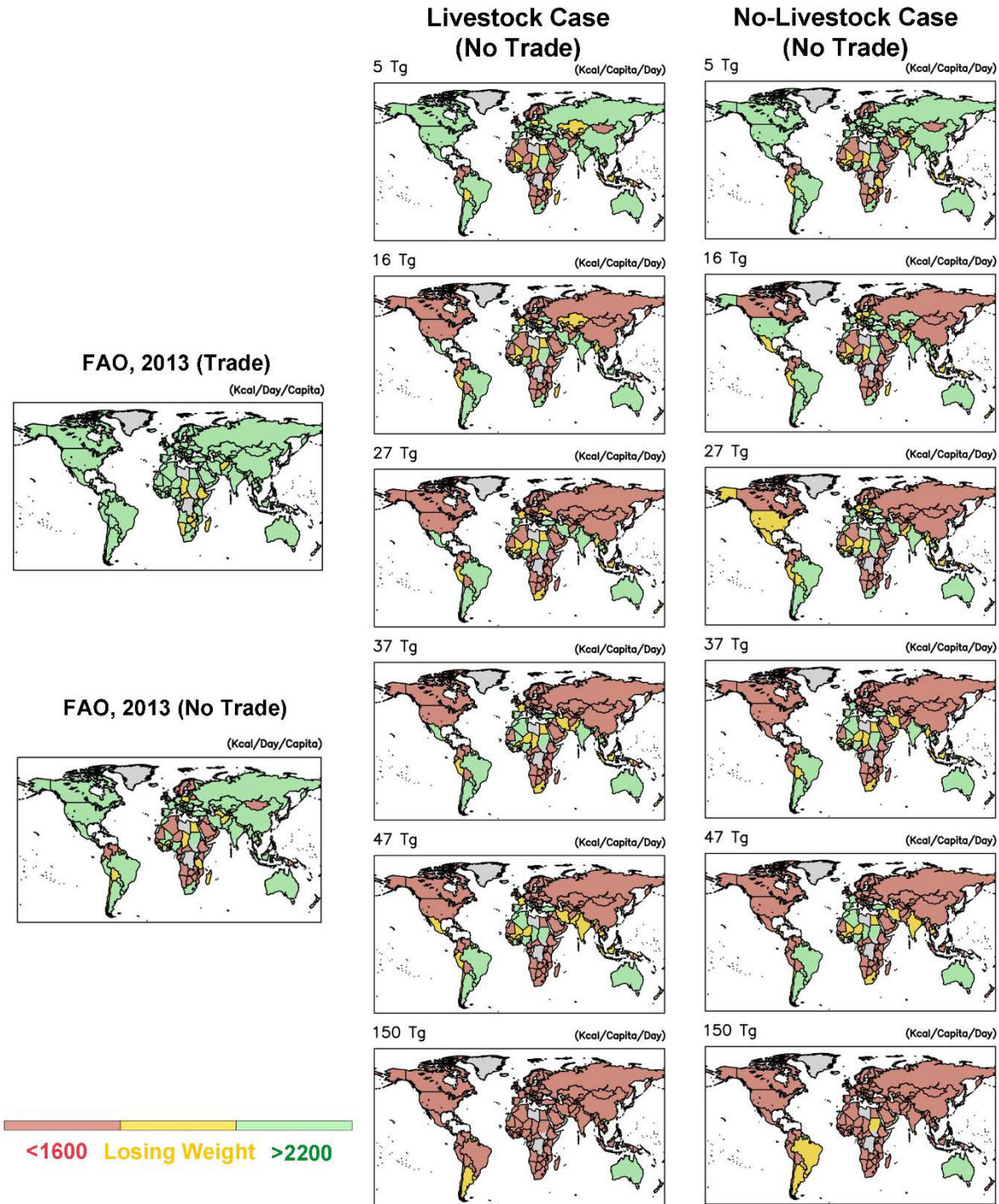
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421 **Figure 3.** (a) Global average human diet composition²². (b) Global average human protein diet422 composition²². Marine wild capture contributes 75% of marine fish⁴⁰. (c) Distribution of four423 major cereal crops and marine fish between human food and other uses^{22,41}. The color gradient

424 legend in gray in (c) illustrates the usage of different crops and fish in colors. While humans

425 consume most of the wheat and rice grown, most maize and soybeans is used for livestock feed.

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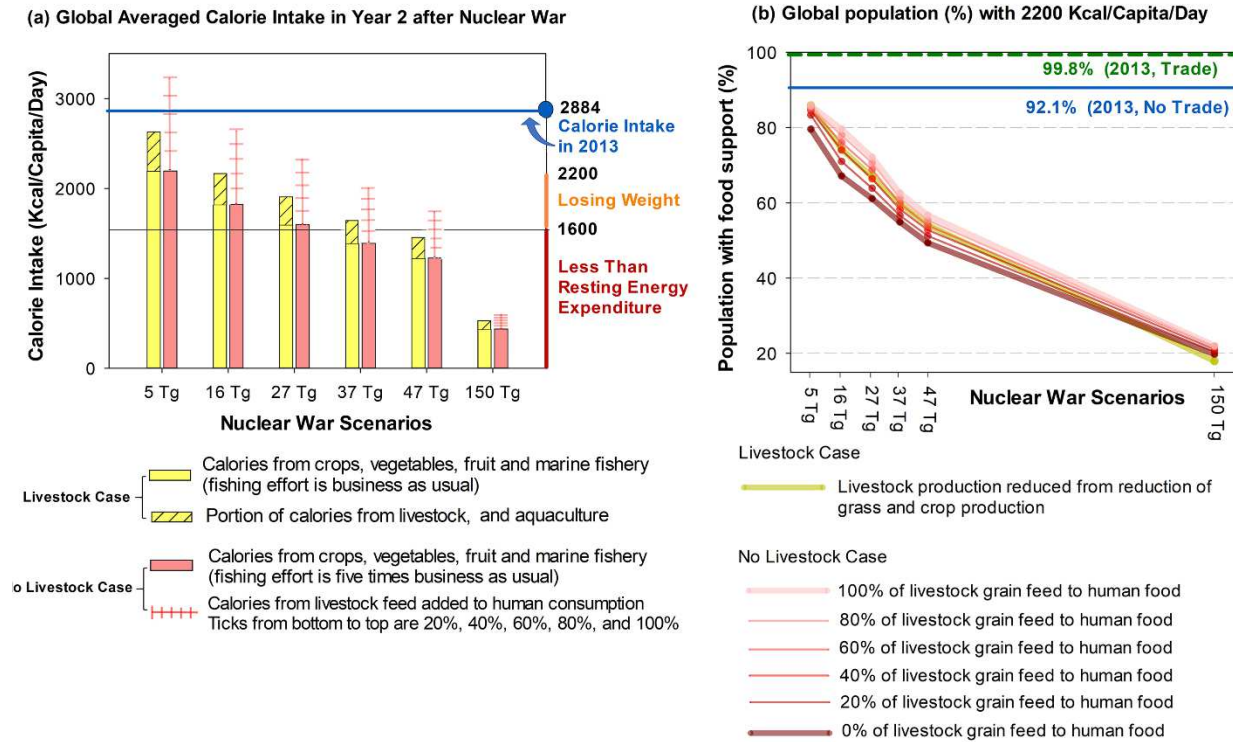


427 **Figure 4.** Food availability (Kcal/Capita/Day) in Year 2 after different nuclear war soot injections.
 428

429 The left two maps are the caloric intake status in 2013 with international trade on and off, the
 430 middle column is the *Livestock Case*, and the right column is the *No Livestock Case* with 50% of
 431 livestock feed used for human food. All assume no international trade and that the total calories

432 are evenly distributed within each nation. Food consumption of less than 2200 Kcal/Capita/Day
433 would not allow an average seized adult to maintain their weight, and less than 1600
434 Kcal/Capita/Day would be less than needed to maintain a basal metabolic rate (also called resting
435 energy expenditure)²⁴, and thus would lead to death after an individual exhausted their body energy
436 reserves in stored fat and expendable muscle. Australia is the only nation with enough calorie
437 intake under the 150 Tg scenario, but it may be greatly overestimated. After we turn off
438 international trade, wheat contributes almost 50% of the calorie intake in Australia, and production
439 of rice, maize, and soybean in Australia are less than 1% that of wheat²². Therefore, the wheat
440 response to simulated nuclear wars largely determines calorie intake in Australia. Since we use
441 spring wheat to represent wheat, and simulated spring wheat in Australia shows increasing or small
442 reductions under nuclear war scenarios in which more favorable temperatures occur for food
443 production, the calorie intake in Australia is more than other nations.

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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.

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