Marine wild-capture fisheries after nuclear war

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Nuclear war, beyond its devastating direct impacts, is expected to cause global climatic perturbations through injections of soot into the upper atmosphere. Reduced temperature and sunlight could drive unprecedented reductions in agricultural production, endangering global food security. However, the effects of nuclear war on marine wild-capture fisheries, which significantly contribute to the global animal protein and micronutrient supply, remain unexplored. We simulate the climatic effects of six war scenarios on fish biomass and catch globally, using a state-of-the-art Earth system model and global process-based fisheries model. We also simulate how either rapidly increased fish demand (driven by food shortages) or decreased ability to fish (due to infrastructure disruptions), would affect global catches, and test the benefits of strong prewar fisheries management. We find a decade-long negative climatic impact that intensifies with soot emissions, with global biomass and catch falling by up to 18 ± 3% and 29 ± 7% after a US–Russia war under business-as-usual fishing—similar in magnitude to the end-of-century declines under unmitigated global warming. When war occurs in an overfished state, increasing demand increases short-term (1 to 2 y) catch by at most ∼30% followed by precipitous declines of up to ∼70%, thus offsetting only a minor fraction of agricultural losses. However, effective prewar management that rebuilds fish biomass could ensure a short-term catch buffer large enough to replace ∼43 ± 35% of today's global animal protein production. This buffering function in the event of a global food emergency adds to the many previously known economic and ecological benefits of effective and precautionary fisheries management.

food from the ocean | fisheries management | abrupt climate change | nuclear winter | global food security

Nuclear weapons continue to pose a threat to humanity. Although global nuclear weapons stockpiles are lower today than at their peak in 1986, arsenals are growing in India, Pakistan, and North Korea, adding to those already maintained by the United States, Russia, China, France, the United Kingdom, and Israel (1–4). The United States and Russia are both undertaking extensive modernization programs for warheads and delivery systems (5, 6), and increased tension in South Asia and recent failures to renew arms control treaties have intensified concerns about the prospect of imminent nuclear war (7, 8). Beyond the devastating direct impacts, the soot inputs from fires ignited by nuclear air bursts are likely to cause global cooling and reductions in sunlight (9–13), similar to historical volcanic eruptions (Table 1) (3, 14–23). Nuclear-war–driven climate perturbations are expected to disrupt global primary productivity, with a potential threat to human lives through crop failure in breadbasket regions and subsequent food shortages worldwide (24–28).

Modeling approaches make it possible to evaluate the effects of nuclear war of varying magnitudes, with the model simulations used here (3, 15) agreeing well with earlier simulations in terms of climate response (12, 16, 17, 29). Process-based crop modeling frameworks have recently made it possible to further investigate potential implications of a nuclear conflict for global food security. Jägermeyr et al. (28) found that even a limited regional nuclear conflict between India and Pakistan, using less than 1% of the world's nuclear weapons (5-Tg soot), is likely to decrease global caloric crop production by 11% for 5 y. This decrease would be four times larger than the highest observed historical anomalies. The high-latitude production shock would propagate globally through food trade dependencies. These alarming findings make it important to investigate how other parts of the global food production system may be affected by a nuclear war, in particular global fisheries, on which many societies depend (30, 31).

The responses of global marine ecosystems and fisheries to both volcanic and nuclear-war–driven abrupt climate perturbations are largely unknown. Here, we explore the impacts of

Significance

Nuclear conflict poses the chilling prospect of triggering abrupt global cooling, and consequently, severely reduced crop production. However, the impacts on marine fisheries are unknown. If agricultural yields fall on land, could we turn to the sea instead? Here, we show that agricultural losses could not be offset by the world's fisheries, especially given widespread overfishing. Cold temperatures and reduced sunlight would decrease the growth of fish biomass, at worst as much as under unmitigated climate change. Although intensified postwar fishing could yield a small catch increase, dramatic declines would ensue due to overharvesting. However, effective prewar fisheries management would create a substantial buffer of fish in the ocean, greatly increasing the oceans' potential contribution during a global food emergency.

ENVIRONMENTAL SCIENCES

SUSTAINABILITY SCIENCE

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Table 1. Overview of nuclear-war–driven climatic perturbations

	Soot load	Warring nations	Δ Radiative forcing, W·m^{-2}	Δ SST, °C	Δ NPP, %	Anomaly duration, y	Description
War simulations used in this study	5 Tg	India and Pakistan	−10.9	−0.5	−3	∼10	Lower-end regional conflict; 100 15-kt weapons
	16 Tg	India and Pakistan	−31.1	−1.4	−7	∼10	Intermediate regional conflict; 250 15-kt weapons
	27 Tg	India and Pakistan	−46.9	−2.3	−10	∼10	Intermediate regional conflict; 250 50-kt weapons
	36 Tg	India and Pakistan	−57.8	−2.9	−12	∼10	Higher-end regional conflict; 250 100-kt weapons
	47 Tg	India and Pakistan	−68.7	−3.5	−16	∼10	Upper-limit regional conflict; 500 100-kt weapons
	150 Tg	Russia and United States	−115.3	−6.4	−37	∼10	Nuclear superpower conflict; ∼4,400 100-kt weapons
Previous war simulations	5 Tg	India and Pakistan	∼ −10	−0.8	NA	∼10	From ref. 16
	5 Tg	India and Pakistan	−8.2 to −10	−0.1 to −0.6	NA	∼10	From ref. 17, range depends on war duration
	150 Tg	Russia and United States	−84.7	NA	NA	∼10	From ref. 18
		Perturbation					
Other climatic perturbations		Pinatubo eruption (1991 CE)	−6.5 ± 2.7	∼ −0.1	NA	∼2	Refs. 19–21
		Tambora eruption (1815 CE)	−17.2 ± 4.9	∼ −1	NA	∼2	Refs. 19–21
		Samalas eruption (1257 CE)	−32.8 ± 9.6	∼ −1 to −2	NA	∼2	Refs. 19–21
		RCP 2.6 global warming (2100 CE)	+2.6	0 to +1	−2 to +1	—	Refs. 22 and 23
		RCP 8.5 global warming (2100 CE)	+8.5	+2 to +4	−11 to −4	—	Ref. 22

Radiative forcing, sea surface temperature (SST), and oceanic net primary productivity (NPP) anomalies are the maximum annual global means. Anomaly duration is the atmospheric residence time of aerosols. Details for India–Pakistan scenarios are in ref. 3, and for United States–Russia in ref. 15. Previous nuclear war simulations, historical volcanic anomalies, and projected global warming anomalies are given for comparison. NPP has not been reported for previous simulations of nuclear war or volcanic eruptions, indicated by not available (NA).

nuclear war scenarios on wild-capture fisheries. Fish and other seafood provide almost 20% of the animal protein consumed by the global human population, out of which wild-caught seafood—the focus of the present study—make up approximately one-half (∼80 to 120 Mt·y^{-1}) (32, 33). Furthermore, wild-caught seafood (herein simply "fish") is a particularly important source of essential micronutrients in developing countries, with almost 1 billion people at risk to become micronutrient deficient if global fish catches fall (31). Concerningly, global catches have been stagnant or slightly declining since the 1990s (Fig. 1) (32, 33), and in a majority of the world's fisheries, biomass is depleted below the level that generates the maximum sustainable yield (B_{MSY}) (34). This indicates that present-day catches exceed the limits of productivity in many regions, and effective management measures, which are crucial to remedy this situation (35), have been projected to increase global fish biomass by 200 to 800 Mt (34). A closer investigation into the response and potential of the global fishery under an abrupt global food emergency is therefore warranted.

While fishing pressure has a major impact on fish populations and their ability to reproduce, the production of fish biomass also depends on environmental characteristics, most importantly net primary production (NPP) and water temperature (36, 37). Since a nuclear war is expected to cause global cooling and decrease oceanic NPP (3, 15, 38), it is likely to have a significant impact on global fish catch. However, it is unknown how these global-scale shifts in NPP and temperature could combine to affect marine ecosystems and marine food productivity, and whether these effects would worsen or mitigate the predicted losses in agricultural food production.

Beyond direct climatic perturbations, a nuclear conflict is also likely to cause socioeconomic perturbations that change global fishing behavior. Altered climate conditions leading to decreased crop production on land (24, 25, 27, 28) could cause a general decrease in caloric supply and limit aquaculture and livestock production due to their dependence on feed (39, 40). This would

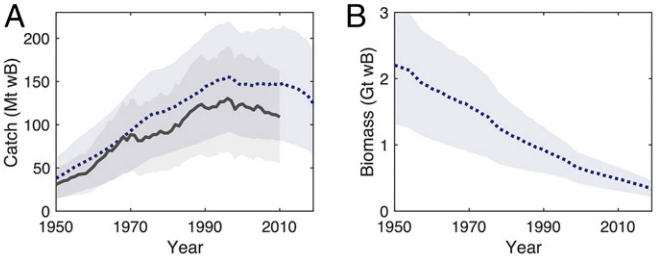

Fig. 1. Prewar trajectories of global fisheries. Simulated (*A*) annual wild fish catch (megatons wet biomass) and (*B*) total wild commercially targeted fish biomass (gigatons wet biomass) over 1950 to 2019 from the prewar fisheries baseline using the BOATS model with no fisheries regulation. Shaded areas show the SD for the five parameter ensemble runs, and the dotted lines show the ensemble mean. The fishery and ecosystem state in 2019 are used as initial conditions for the nuclear war scenarios. In *A*, the gray solid line shows empirical global catches from ref. 33, with uncertainty indicated by the shaded area.

likely raise the demand for wild-capture fish as a source of animal protein, leading to an increase in price and intensified fishing. For example, the Tambora volcanic eruption in 1815 and the associated crop failures triggered a hundredfold increase in the exported catch of marine pelagic fish in the Gulf of Maine (41). On the other hand, substantial damage to fisheries infrastructure (e.g., ships, harbors, fuel supply, processing facilities) along with supply chain disruptions could lead to reduced fishing effort, as would unsafe ocean travel due to geopolitical instability (42). Although difficult to predict, such socioeconomic changes may greatly influence fisheries outcomes after a nuclear war.

This study explores the effects of six nuclear war scenarios (Table 1) on the global biomass and catch of fish: five India–Pakistan scenarios of increasing intensity with black carbon (soot) loads of 5 to 47 Tg (details in ref. 3) and one substantially larger US–Russia war injecting 150 Tg of soot (details in ref. 15). All war scenarios are generated by a state-of-the-art Earth system model (Community Earth System Model–Whole Atmosphere Community Climate Model [CESM-WACCM]; *Materials and Methods*). Output from CESM-WACCM is used as input to the Bioeconomic Marine Trophic Size-Spectrum (BOATS) model, a process-based ocean ecosystem model with dynamic fishing that has been used in a number of future climate applications (23, 43–46). With an unregulated prewar fisheries baseline simulation as the starting point (Fig. 1 and *Materials and Methods*), we use BOATS to model the impact of nuclear war on global fisheries. Bracketing a range of possible changes in fishing behavior due to the war, we explicitly model five simplistic socioeconomic responses: business-as-usual (BAU) fishing and a large or very large increase (F+, F++) or decrease (F−, F−−) in fishing intensity (Table 2 and *Materials and Methods*). We also investigate how strong prewar fisheries management improves the ocean's capacity to alleviate food losses (*SI Appendix*, Fig. S8 and *Materials and Methods*). Beyond quantifying the effects of nuclear war, these simulations illustrate the potential effects of large volcanic eruptions or of socioeconomic shocks on global marine capture fisheries.

Results

Below, we present the impacts of both nuclear-war–driven climatic perturbations (soot inputs, Table 1) and socioeconomic fishing responses possibly triggered by the global crisis (Table 2). For clarity, we hereon define a scenario as a specific combination of soot input and socioeconomic response. First, we present an overview of the impacts in year 2 postconflict, pinpointing the initial, transitory effects of altered fishing behavior. We then describe the longer-term (15-y) fisheries trajectories for all scenarios, illustrating the duration and rate of recovery. Then, we investigate the spatial patterns of change and link these to national-level seafood dependence for the 5-Tg case. Finally, we show how strong fisheries regulation increases the potential for higher global catches postwar. Unless otherwise stated, presented relative changes are anomalies from the BAU-control scenario, which has no war and BAU fishing behavior (*Materials and Methods*). In the text, we generally present numbers for the end-member cases of 5- and 150-Tg soot inputs.

Initial Impacts on Catch and Biomass. Nuclear-war–driven climate perturbations (Table 1) generally lead to significant short-term losses in global fish catch and biomass in year 2 postwar (Fig. 2 and *SI Appendix*, Fig. S1). Larger soot input exacerbates losses, and the effect is linear with the associated reduction in photosynthetically active radiation (PAR) (*SI Appendix*, Tables S1–S4 and *Materials and Methods*), which presumably drives the net reduction in global NPP (*SI Appendix*, Fig. S6). On average for all socioeconomic fishing responses, catch and biomass decrease by ∼2% and ∼1%, respectively, for every 1 Tg of soot (∼4% and ∼3%, respectively, for every 10% decrease in PAR).

Under BAU fishing, global biomass decreases by 1.6% (±0.7%, SD of the five BOATS ensemble runs; *Materials and Methods*) in the scenario with a 5-Tg soot input, and up to 18 (±3.5)% in the 150-Tg scenario (Fig. 2*A* and *SI Appendix*, Fig. S1*A* and Tables S1 and S3). Since this biomass decrease also leads to a decrease in the global fishing effort (Eq. **1**), catches fall more than biomass: by 2.4 (±0.8)% under 5 Tg, and up to 29 (±7)% in the 150-Tg case (Fig. 2*B* and *SI Appendix*, Fig. S1*B* and Tables S2 and S4).

If the conflict is followed by intensified fishing due to increased demand (F+, F++; Table 2), catch initially increases at the expense of biomass. Under the 5-Tg soot input, where the climatic effect is relatively small, F+ and F++ generate catch increases of 13% (±17%) and 17% (±14%), respectively, in year 2 postwar (Fig. 2*B*). At the same time, F+ and F++ cause a 10% (±4%) and 23% (±9%) global biomass decline (Fig. 2*A*). Larger climate perturbations cause more rapid biomass collapse and can preclude a net increase in catch. In the 150-Tg case, representing the strongest perturbation, even the greatly intensified fishing effort in F++ fails to compensate for the large negative climate impact, as global catches still fall by 14% (±20%) (Fig. 2*B*).

Conversely, decreased fishing intensity due to decreased ability to fish (F−; F−−) decreases catch but creates a net increase in biomass despite the climate-driven losses for almost all soot inputs (Fig. 2). Under the 5-Tg soot input, F− and F−− result in substantial falls in global catch of 23% (±19%) and 52% (±24%), respectively. This increases global biomass by 7% (±4%) and 26% (±7%), respectively. Larger soot inputs both exacerbate the falls in catch and diminish the biomass recovery that is enabled by the lowered fishing pressure. Again, the climatic effect is linear with PAR (Fig. 2 and *SI Appendix*, Tables S1 and S2).

Decadal Fishery Response. Longer-term global fisheries trajectories under BAU fishing (Fig. 3 *A*–*C*) show the general decrease

Table 2. Overview of modeled socioeconomic responses

Socioeconomic response	Code	Drivers	Implementation
Business-as-usual	BAU	Socioeconomic parameters unaffected by war	Unchanged fish price (*p*) and fishing cost (*c*)
Intensified fishing	F+	Crop failure, food system collapse, increased fish demand	Twofold increase in *p*
Greatly intensified fishing	F++	Severe crop failure, food system collapse, greatly increased demand	Fivefold increase in *p*
Decreased fishing ability	F−	Fuel scarcity, infrastructure destruction, security concerns	Twofold increase in *c*
Greatly decreased fishing ability	F−−	Severe fuel scarcity, infrastructure destruction, security concerns	Fivefold increase in *c*

Price and cost changes are implemented instantaneously (step change) in the year of the war. Each socioeconomic response combined with a war-driven climatic perturbation (Table 1) makes up a model scenario. Details are in Socioeconomic Responses.

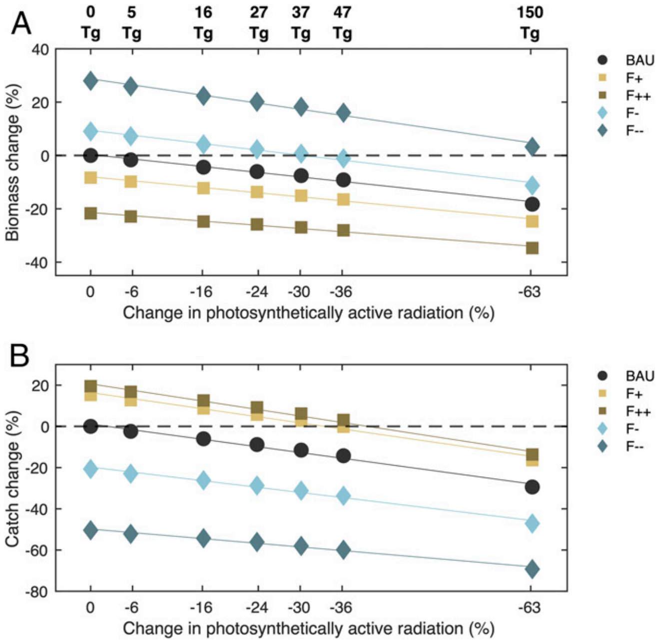

Fig. 2. Short-term impacts of nuclear war on global fisheries. Panels show the average percent difference in (*A*) biomass and (*B*) catch between the business-as-usual (BAU) control simulation (no war) and different nuclear war simulations (5 to 150 Tg), in year 2 postconflict. Each value is plotted against the war scenario (soot input indicated on upper *x* axis) and its associated percent reduction in global photosynthetically active radiation (PAR). The slope for each marker type shows the impact of the climatic perturbation (for a given socioeconomic response F+/−; see Table 1), while the vertical spread between marker types shows the effect of the socioeconomic responses. Statistics for linear regressions are given in *SI Appendix*, Tables S1 and S2.

and subsequent recovery in global fish biomass and catch in the decade postwar. In the 5-Tg case, global catch decreases by at most 3.6% (±1.4%), occurring in year 5 postwar (Fig. 3*A*). In contrast, with a 150-Tg soot input, the largest catch decrease is 31% (±9%) in year 3 postwar. Trajectories for the intermediate soot loads consistently lie in between. Eventually, both biomass and catch recover relative to the control climate, with recovery taking ∼14 y and somewhat exceeding the BAU-control (Fig. 3 *A* and *B*). Due to the climate-driven biomass decline, which renders fishing less profitable, modeled fishing effort begins to decrease immediately after the war and lags harvest and biomass (Fig. 3*C* and Eq. **1**).

Increase in fish demand (F+, F++) in turn increases fishing effort. After an initial increase in catch, biomass is depleted, driving a fishery crash in all scenarios that lasts until the end of the simulation (Fig. 3 *D*–*F* and *SI Appendix*, Fig. S2 *A*–*C*). Catches drop below the BAU control 2 to 3 y postwar, and stabilize about 45% and 75% lower by the end of the 15-y simulation. For all soot inputs, biomass under F+ decreases, at most by 50 to 60%, and under F++ by about 84%. This biomass depletion means that the largest intensification of fishing (F++) leads to the lowest total catch when integrated over the whole 15-y postwar period: Under the 5-Tg and F++ scenario, cumulative catch falls by 38%.

If the war induces a substantial decrease in fishing (F−, F−−), global catches initially decrease and fish biomass rapidly begins to recover (Fig. 3 *G*–*I* and *SI Appendix*, Fig. S2 *D*–*F*). The decline in catch, down to 49% (±8%) in the F− and 150-Tg scenario, is maintained for the first 4 y, but eventually the recovering fish biomass increases catches long-term. By year 5 postwar, catch has begun to exceed the BAU control catch for all soot inputs. At the end of the simulations, global biomass is almost double and fourfold under F− and F−−, respectively (Fig. 3*H* and *SI Appendix*, Fig. S2*E*), and catches increase by ∼60 and 140% (Fig. 3*G* and *SI Appendix*, Fig. S2*D*). Thus, the total cumulative catches over the 15-y postwar period is almost 30% higher under the 5-Tg and F−− scenario (in contrast to the cumulative 38% decrease under 5 Tg and F++). The greatly decimated effort (Fig. 3*I* and *SI Appendix*, Fig. S2*F*) and higher biomass lead to increased catch efficiency, similar to observations in the North Atlantic after the end of World War II (42), which makes the fisheries more economically efficient.

Regional Patterns of Change. While the climatic perturbations decrease the total global fish catch postwar, there is substantial spatial variability, with increasing catch in some regions (Fig. 4). Averaged over the first 5 y postwar under BAU fishing, catch increases patchily in the tropics and subtropics, particularly in the Atlantic Subtropical Gyres under higher soot input scenarios. The largest decreases in catch occur along the equator and midlatitudes. These spatial patterns generally follow spatial changes in NPP following the war predicted by CESM (*SI Appendix*, Fig. S3), with some influence from changes in water temperature (*SI Appendix*, Fig. S4). Spatial patterns of catch change under increasing or decreasing fishing pressure are similar to the patterns under BAU (*SI Appendix*, Figs. S5 and S6).

The spatial patterns translate into differential impacts on the catches of individual fishing nations (Fig. 5, *SI Appendix*, Table S5, and *Materials and Methods*). Here, we focus on the 5-Tg BAU scenario for comparison with the investigation of crop yields by (28). Under this lower-impact scenario, several major fishing nations, such as Russia, Canada, Japan, and the United States, see substantial catch losses in their territorial waters under the modeled climatic perturbations. Some lower-latitude fishing nations like Mexico, Peru, Greece, and Somalia experience increased catch potential. However, equatorial island nations, who are most dependent on marine food supply, suffer some of the largest declines. A comparison with the country-level dependence on marine ecosystems for nutrition (47) suggests that these island states are particularly vulnerable to the predicted fall in catches (Fig. 5*B*), among which Indonesia is the most populous country by far.

Benefits of Fisheries Regulation. Strong prewar management of fisheries greatly increases the capacity of marine fisheries to mitigate agricultural losses (Fig. 6). If global fisheries are strongly regulated to maintain a healthy biomass before the onset of the conflict (*SI Appendix*, Fig. S8 and *Materials and Methods*), the short-term catch increase under intensified fishing postwar is greatly enhanced (*SI Appendix*, Fig. S9). Under a 150-Tg and F+ scenario (Fig. 6), shown here to illustrate the extent to which intensified fishing could alleviate an extreme food crisis, global catch increases by 430% (±350%) relative to the unregulated BAU control. This increase is achieved despite the substantial climatic impact associated with the 150-Tg soot input (Fig. 2*A*). Catch rapidly decreases in the second year but remains somewhat higher than in the unregulated case until ∼10 y postwar.

Discussion

In summary, nuclear-war–driven climatic perturbations have an overall negative effect on fisheries that increases with soot input, despite positive impacts in some subtropical regions. However, socioeconomic responses to the nuclear war could greatly influence the trajectories of global fish catch and biomass. In the absence of strong prewar management, if the nuclear war leads to intensified fishing (for example due to terrestrial food shortages) a small increase in the global catch is possible for the first

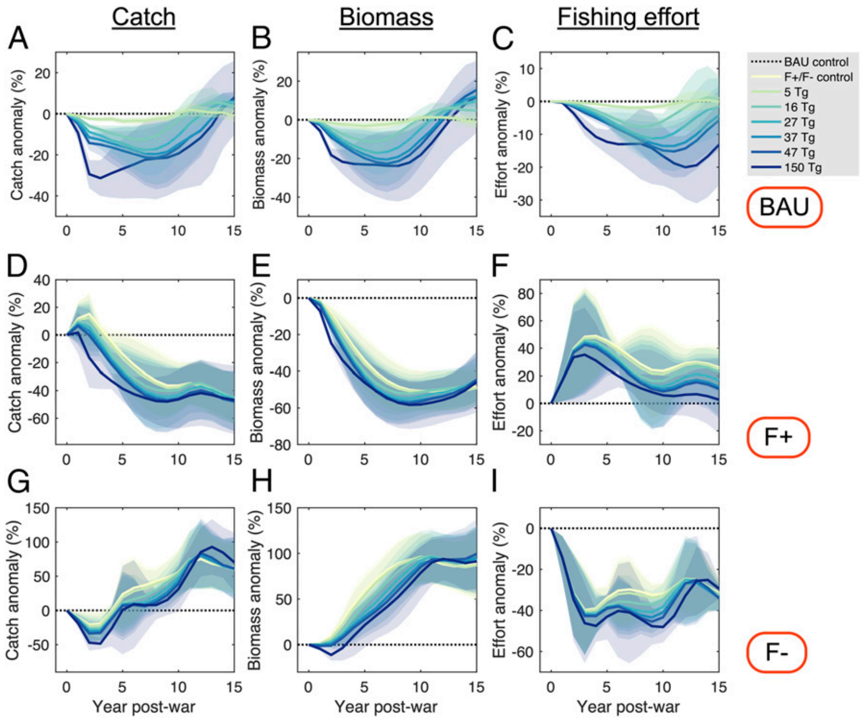

Fig. 3. Global fishery developments postwar. Panels show the percent anomaly from the BAU control scenario (dashed line) for all soot inputs (solid lines). Upper row (*A*–*C*) shows trajectories of catch, biomass, and fishing effort under BAU fishing, middle row (*D*–*F*) shows trajectories under the intensified fishing scenario F+, and lower row (*G*–*I*) shows trajectories under the decreased fishing scenarios F−. The shaded areas show SD for the five parameter ensemble runs, while the solid lines are the ensemble mean. The light yellow lines in *D*–*I* show the F+ and F− responses in the absence of a climatic perturbation, i.e., the F+ or F− control.

few years postwar. This however rapidly depletes the fish stocks and is followed by a precipitous decline in catches. Strong fisheries regulation prewar could instead allow catches to become many times higher than normal in the first year postwar, even despite large soot inputs. A decrease in fishing because of damaged infrastructure would lead to relatively large short-term catch decreases in a potentially critical time for global food security.

Role of NPP, Temperature, Fishing, and Adaptation. The effect of the nuclear-war–driven climatic perturbations on global fish catch can largely be explained by the effects of NPP, temperature, and fishing pressure. Cooling slows the growth rates of fish, while lower NPP input decreases the amount of energy available for the ecosystem, causing the postwar decrease in simulated biomass and catches (43, 48). However, cooling also has a positive impact on the steady-state fish biomass, by increasing the efficiency with which energy supplied by NPP can accumulate as biomass in large organisms (43, 48). This accumulation is most apparent for the simulations in an unfished ocean (*SI Appendix*, Fig. S7), but is less pronounced in fished systems, where growth rates limit fish biomass more than NPP. We underline that the representation of ecological processes in BOATS greatly simplifies trophic exchanges and does not include fish movement, and that it has a relatively high sensitivity to temperature when compared with other models (23). Still, integrated globally, the modeled catch decrease under BAU fishing is similar to the decrease in global oceanic NPP caused by the different soot inputs (*SI Appendix*, Fig. S7*B*) and is consistent with macroecological theory.

We note that both the nuclear-war–driven climatic perturbations and anthropogenic global warming have negative impacts on marine fisheries, even though the former causes cooling and the latter, warming. Model projections of the long-term (year 2100) decrease in global fish biomass or catch potential under unmitigated climate change (RCP 8.5), range from ∼12 to 25%, while strong mitigation (RCP 2.6) likely limits the decrease to <5% (23, 45, 49, 50). In comparison, the 150-Tg case yields maximum declines in catch and biomass of 31% and 24%, respectively, under BAU fishing (<4% in the 5-Tg case). Thus, the negative impacts of unmitigated climate change on fisheries almost reach those of a large-scale nuclear war between the United States and Russia. However, the abruptness and duration of the negative impacts differ greatly, as do the underlying causal mechanisms. A nuclear conflict generates a net global decrease in oceanic NPP (*SI Appendix*, Fig. S7), likely attributed to a reduction in sunlight reaching the ocean surface (51), in turn leading to a decrease in global catch and biomass. In contrast, the reductions under global warming result from a combination of NPP decreases driven by increased stratification (52), the decrease in the size of phytoplankton (53), and the metabolic effects of warming on fish physiology (48).

Our results also suggest that the marine fish catch is relatively more robust to the effects of a nuclear conflict than land-based food production. While total global fish catches here decrease by ∼4% under the 5-Tg scenario, Jägermeyr et al. (28) found an 11% decline in global crop production for 5 y under the same soot input. This difference arises because the ocean does not cool as much as land (cf. figure S6 in ref. 3), and because of the assumed adaptability of fish, and in turn fisheries, to a cooling environment. In contrast to crops, most fish stocks rapidly move and migrate in response to climate variations (54). Here, fishing fleets in turn increase their fishing effort in regions with climate-driven biomass increases, and vice versa, which alleviates global catch losses. This assumption is supported by the global ubiquity of fishing and the fleet's ability to track seasonal fish movements (55, 56). For agricultural systems, where the war-driven climate effects are most severe in regions that produce several major

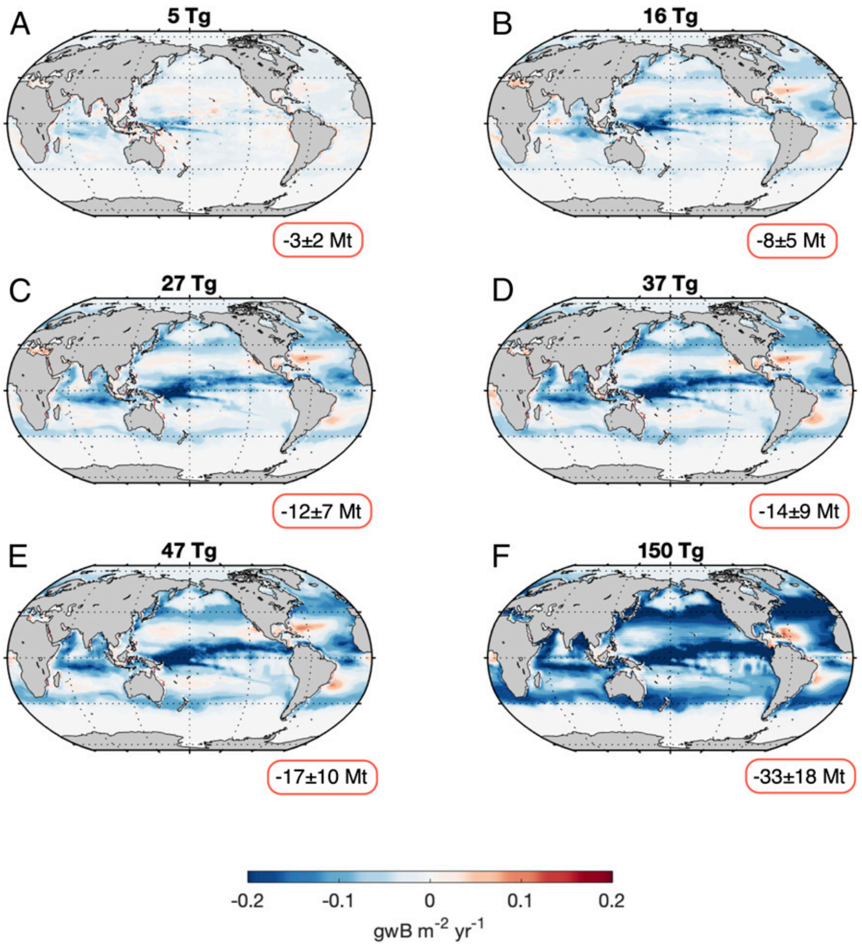

Fig. 4. Spatial distribution of changes in fish catch. Panels show six different soot inputs under BAU fishing, averaged over the first 5 y postwar. *A–F* show the mean difference in annual fish catch per square meter between the control (0 Tg) and the 5- to 150-Tg soot inputs of the five ensemble runs. In the *Lower Right* corner, the global catch difference in the 5-y period is indicated (ensemble mean and SD).

crops, the limited ability to rapidly adjust production to the changing climatic conditions (57) exacerbates crop losses.

Food System Linkages. Both the drivers of fishing and the importance of global fish catches are interlinked with the impacts of nuclear war on other parts of the global food production system. Cereal production is about 25 times larger than fish catches globally (58), with the caloric content per gram of cereals being almost six times that of fish (59). This makes offsetting the losses of calories from agriculture very difficult. Still, it is reasonable to expect that cereal production losses postwar, estimated at 11% already under the 5-Tg case (28), would impair the production of other animal protein and increase the overall need for other foods. Here, the increase of global catch under greatly intensified fishing is limited to at most 30% in the 5-Tg case (and less under larger climate perturbations), ∼30 $\mathrm{Mt{\cdot}y^{-1}}$ if using the present-day catch of ∼100 $\mathrm{Mt{\cdot}y^{-1}}$ as a baseline (32, 33). Such an increase would constitute a significant but small contribution to global food security. However, strongly regulated global fisheries could theoretically generate "emergency catches" several hundred percent higher than unregulated fisheries. Since a catch of ∼100 $\mathrm{Mt{\cdot}y^{-1}}$ makes up roughly 10% of the total animal protein supply (32), our results suggest that the 430% (±350%) increase in global catches enabled by strong prewar management (Fig. 6) could offset a loss of ∼43% (±35%) of the present-day annual supply of all other animal protein (cultured fish, meat, dairy, and eggs). Although short-lasting, such a buffer could be extremely valuable to mitigate a global food emergency and allow time for adaptation.

We also underline that the direct impacts of cereal production losses on fish demand are uncertain considering the differences in nutritional values and total production. The demand for fish may be more strongly connected to the production of other animal protein products (60), in particular aquaculture products, for which the effects of nuclear war are poorly explored (61). Furthermore, the capacity to adapt conventional agricultural production systems (28) and to scale up production of alternative foods (fungi, bacteria, etc.) in the event of a crisis (62) could impact the demand for fish as well as the consequences of falling global catches.

Contamination of food due to nuclear fallout is a further concern for food security. Close to sites of nuclear power plant accidents, fish can become highly contaminated by radioactive pollution (63, 64). However, radionuclides are strongly diluted in the ocean given the large volume of water, and the range and intensity of contamination of marine systems have been limited in past accidents (64–68). Although it is yet unexplored how the nuclear war scenarios used here would affect oceanic radionuclide concentrations, seafood appears less likely to be sensitive to nuclear fallout than terrestrial foods. This suggests that fish caught outside of the immediate war areas could provide a relatively safe food source, which might further increase demand.

It is important to underline that the fish biomass in BOATS represents only the fish and shellfish that have historically been

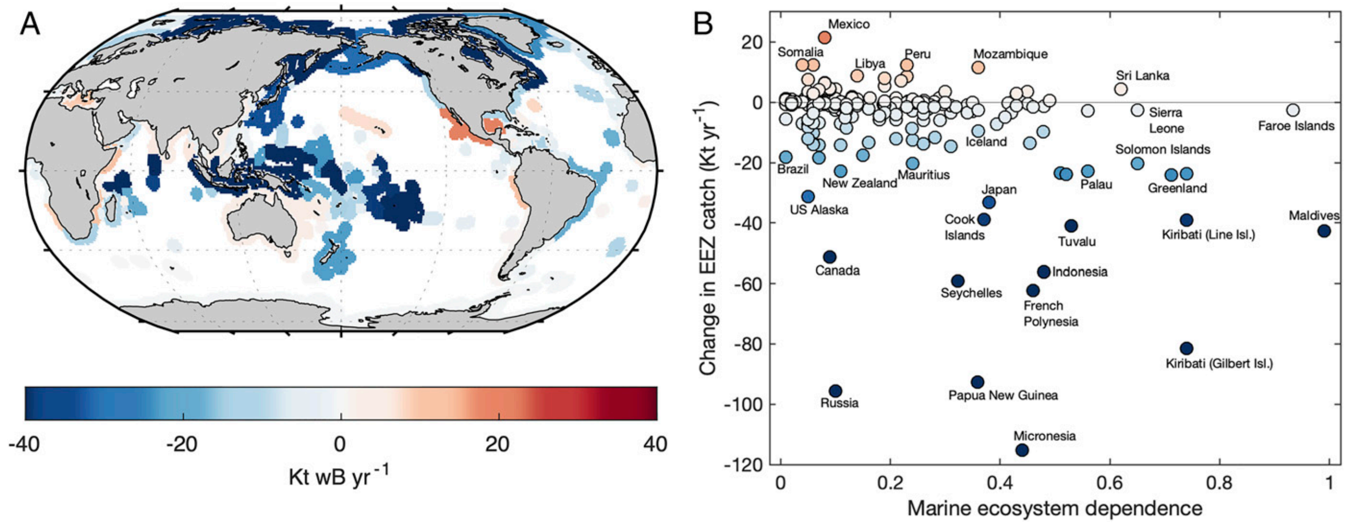

Fig. 5. Country-level fish catch changes under the 5-Tg and BAU fishing scenario. In *A*, the color of each exclusive economic zone (EEZ) shows the total change in modeled catch (1,000 ton wet biomass·y^{-1}) relative to the BAU control scenario, averaged over the first 5 y postwar. In *B*, change in EEZ catch vs. national-level dependence on marine ecosystems for nutrition is shown.

targeted by fisheries (i.e., those reported in the Sea Around Us Database) (33). In the event of global food shortage, it is possible that new marine organisms would become targeted by fisheries, expanding the scope for increasing marine catches. The total biomass of all fish species is highly uncertain (69), meaning that this potential is poorly known, but the biomass of unexploited mesopelagic fishes is believed to be larger than the total global biomass of currently exploited wild finfish (70). If a global food crisis would induce the rapid development of more effective harvesting technologies for these dispersed fish and other currently unexploited species, fisheries could further mitigate terrestrial crop failures, but with potentially large and poorly understood consequences for marine ecosystems (71, 72).

The conflict-driven changes in the global fish supply would likely have highly variable regional impacts, given the importance of factors like local food production capacity, purchasing power, and trade network functionality (73). We here find that the modeled climatic perturbations would cause the largest fall in fish catches in developed high-latitude countries, which are also the hardest hit by crop failures (28), and in developing equatorial island nations, which are highly fish dependent (47). This suggests potential synergistic effects on regional food security, in particular if the drop in global food production reduces the willingness or ability to trade. At the same time, regional variations in management effectiveness and the resulting biomass levels (35) (*Uncertainties and Limitations*) should also strongly impact the regional consequences. Overall, further investigation of the interdependencies between fishing, aquaculture (mediated through wild-caught fish being used as feed), and the rest of the food production system in the event of a global food crisis is needed.

Uncertainties and Limitations. This work quantifies the response of global marine ecosystems and fisheries to abrupt, extreme climatic cooling. As a result, the associated uncertainties are bound to be large. An advantage of BOATS is that its key ecological processes (growth, metabolism, mortality, and reproduction) are affected in a mechanistic way by changes in temperature and NPP (43, 48), increasing the model's generalizability. The modeled fish productivity response to anthropogenic climate change in BOATS agrees well with fish population-based (rather than ecosystem-based) estimates (23, 74). This, together with the use of an optimized ensemble of parameterizations that allow us to explore a large part of the uncertain parameter space (44, 45), increases the confidence in the model results.

Still, the extreme rate and magnitude of climatic change modeled here may have consequences that are not accurately captured by BOATS. The model implicitly assumes that species will quickly migrate and adapt to the changing environmental conditions, and is unable to capture the importance of keystone species, or the seasonal timing of reproduction and feeding interactions. These factors may severely and perhaps irreversibly affect marine ecosystem productivity under rapid climatic change (75–77). The importance of such unresolved mechanisms is expected to be larger in ecosystems where the rate of adaptation is lower than the rate of climatic change (78)—which is especially rapid in this study. For example, nearshore and coral reef systems have previously been suggested to be the most sensitive to rapid cooling (75). The maintained biomass growth in BOATS may therefore be optimistic in such regions, as it disregards the risks for climate-driven nonlinear ecosystem and productivity shifts due to noninstantaneous adaptation. Nonetheless, the increase in the productivity of some species and decrease in others in the Gulf of Maine after the 1815 Tambora eruption (41), which had a greater radiation anomaly than the 5-Tg case modeled here (Table 1), lends some credibility to the assumption of regional species substitutability in BOATS even under the rapid climatic changes that could be caused by a nuclear war. We also emphasize that neither BOATS nor CESM resolves the potential impacts of nuclear-war–driven changes in ocean acidification (as described in ref. 38) on marine organisms. Work is currently underway to simulate the response of coccolithophores to acidification in CESM (79); future studies will explore this idea further.

An important simplification in the present study is that the prewar fisheries baseline (Fig. 1) assumes that there is no effective fisheries management. Fishing effort instead evolves as predicted in an open access fishery, where effort only decreases when profit becomes negative (Eq. **1**) (80, 81). We use this assumption because it better reproduces the development of global catches (Fig. 1), but note that it leads to a progressive decrease of fish biomass (45, 82) that is pessimistic. Indeed, while there is evidence of widespread biomass depletion worldwide (34, 83, 84), current management methods have curtailed overfishing

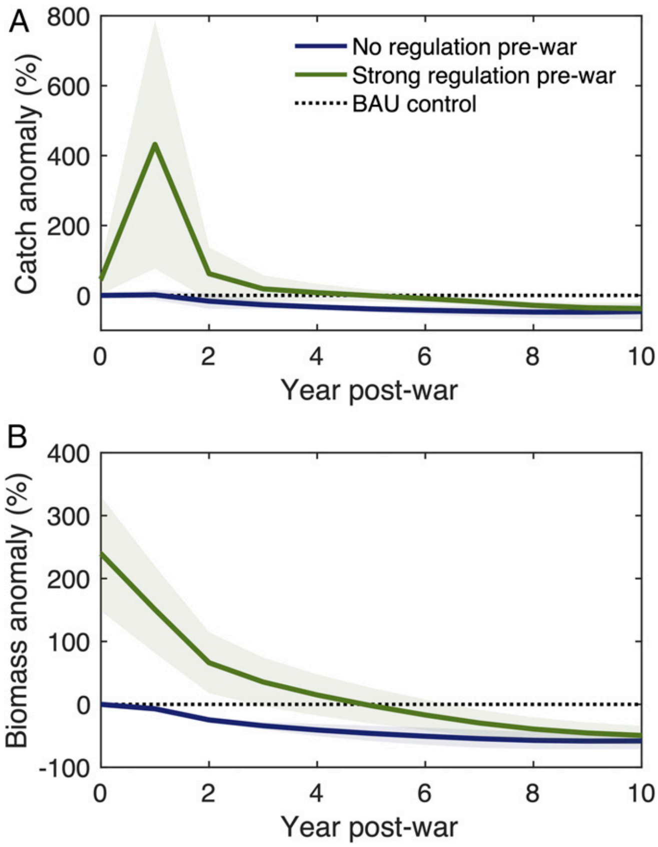

Fig. 6. Contribution of well-regulated fisheries to postwar food security. (*A*) Catch anomaly (percentage) relative to the BAU control (dashed line), and (*B*) the associated anomaly for commercially targeted fish biomass. Both panels show trajectories under the 150-Tg and intensified fishing (F+) scenario and contrast the impact of strong (green) vs. no (blue) prewar fisheries regulation. Despite the substantial negative impact of the 150-Tg soot input (Fig. 2*A*), strong prewar regulations allow a many-fold catch increase immediately after the war by providing a large buffer of fish biomass.

and increased biomass to a significant degree in more than half of the fisheries where stock assessments are made (which themselves make up 40 to 50% of the total global fish catch) (35). Thus, the fisheries in several well-managed regions would respond more like in the simulation with a strongly regulated global fishery prewar (Fig. 6 and *SI Appendix*, Fig. S9).

Furthermore, we emphasize that the impacts that nuclear conflicts themselves might have on the effectiveness of management are highly unpredictable, but potentially important. Lack of resources for fisheries regulation, stronger incentives for illegal fishing, and collapse of international management organizations could impair management. On the other hand, war fosters increased (parochial) cooperative behavior, which is a key element in effective fisheries management (85). This, or strict war-induced (possibly military) protection of countries' exclusive economic zones (EEZs) and their marine food resources could actually improve management effectiveness.

Since the realized effect of nuclear war on global fishing behavior is highly uncertain, the socioeconomic scenarios were chosen to bracket a large possible range of alternative behaviors. This approach provides a generalizable understanding of the system's response to perturbations, but not a prediction of the most likely outcome. Consequently, the socioeconomic scenarios generally have a larger impact on global catches than the climatic perturbation (Fig. 2*B*). We speculate that a war might increase both fish prices and fishing costs (with opposing effects on fishing effort), that a larger war would cause larger increases, and that the prices and costs could eventually return to the prewar level. Further socioeconomic scenario development could explicitly address such counteracting effects and potential responses in the spheres of governance, markets, and fisheries technologies (86).

Resilience of Fisheries in the Face of Large-Scale Shocks. The findings presented here are instructive for understanding possible global fisheries responses also under other shocks, both climatic and market-related. Large-scale volcanic eruptions would cause similar climatic perturbations (Table 1) with the associated effects on ecosystems and food production systems, while global fuel crises or food price spikes may also arise due to other factors (87). Volcanic eruptions large enough to have substantial global impacts have a global return period of about 500 to 1,000 y but are unpredictable and have been associated with widespread famine and plagues (29, 88–91). Furthermore, the unfolding COVID-19 pandemic is expected to cause a global food emergency (92), which is already having diverse and rapidly evolving impacts on fisheries (93). Beyond crises, fish prices have been rising over the past 20 y (58, 94), and intensified demand, for example mediated by a slowdown of aquaculture growth (32), could induce intensified fishing if unregulated.

Most importantly, our results show that poorly managed fisheries have a much lower capacity to contribute to global food emergencies than do well-managed fisheries (Fig. 6). For a short pulse in fishing intensity, the magnitude of this emergency catch potential is essentially proportional to the management-induced increase of fish biomass left in the ocean. Thus, management interventions that increase the biomass of fish globally help to buffer against food shocks. This result shows that effective fisheries management serves not only to achieve sustainability (34, 50), but also provides a proactive contribution to the resilience of the global food supply. Beyond showing how global marine fisheries are impacted by climatic and socioeconomic perturbations after a nuclear war, our generalizable findings thus also add to the imperative of effective fisheries management (95).

Materials and Methods

To explore the potential impacts of nuclear conflicts on fisheries, we investigate six climatic perturbations of regional and larger-scale nuclear wars (Table 1) (3, 15), an ensemble mean of three control climate runs without soot injection, and five socioeconomic fishing responses (Table 2). The climate control run is first used to create the prewar fisheries baseline up until 2019. Using the state of the fishery in 2019 as the initial condition, we model how a nuclear war in the following year (year 1 postconflict), with and without accompanying changes in fishing behavior, impacts global fish biomass and catches.

Climatic Perturbations after Nuclear War. The climate impacts of nuclear war are modeled using the CESM, version 1.3, a state-of-the-art coupled climate model consisting of atmosphere, ocean, land, and sea ice components. CESM implements the Parallel Ocean Program physical ocean model (96), here at nominal 1° horizontal resolution and with 60 vertical levels, and the Biogeochemical Elemental Cycling (BEC) ocean ecosystem–biogeochemistry module, which represents the lower trophic levels of the marine ecosystem, and a dynamic iron cycle (51, 97–101). Similar to other Coupled Model Intercomparison Project (CMIP) class models (102, 103), BEC simulates three phytoplankton functional types: diatoms, small phytoplankton, and diazotrophs as well as one zooplankton functional type. The productivity (carbon fixation) of the three phytoplankton groups are combined to generate NPP (104), which is used, along with model-derived sea surface temperature, to drive the offline fisheries model. The CESM-BEC ecosystem and biogeochemistry model is well validated in a variety of scenarios and performs favorably when compared with other CMIP class models (e.g., refs. 101, 105, and 106, and references therein).

The climatic response to nuclear war is simulated by injecting black carbon (soot) into the atmosphere above the South Asian subcontinent (India and Pakistan exchange) (3), or over the United States and Russia (15). Atmospheric circulation and chemistry is simulated in CESM using the WACCM (107) with nominal 2° resolution and 66 vertical levels, a model top at ∼145 km, and uses the Rapid Radiative Transfer Model for GCMs (108) for the radiative transfer. The Community Aerosol and Radiation Model for Atmospheres (109, 110) is coupled with WACCM to simulate the injection, lofting, advection, and removal of soot aerosols in the troposphere and stratosphere, and their subsequent impact on climate (111). The India–Pakistan scenarios (5 to 47 Tg; Table 1) and United States–Russia scenario (150 Tg) build on previous work by Mills et al. and Miller et al. (12, 14) and Robock et al. (29), respectively.

Global Fisheries Model. The BOATS model is used to estimate climatic and socioeconomic impacts on global marine fish biomass and catch through time. We use the model thoroughly described in previous publications (43–45), with improved accuracy of fish biomass in high-nutrient, low-chlorophyll regions (112) and a newly developed regulation component from (46). BOATS calculates fish biomass of three independent fish groups categorized as small, medium, and large fish (defined by maximum sizes of 0.3, 8.5, and 100 kg, respectively) in noninteracting oceanic grid cells with a 1° horizontal resolution. Fish in each group grow to their maximum size from a common smallest size (0.01 kg) along the so-called size spectrum (113), and the resulting biomass depends on the amount of energy available from oceanic NPP, temperature-dependent metabolic growth and mortality rates, the fraction of energy allocated to reproduction, and reproductive success (43). Gridded maps of vertically integrated NPP along with sea surface temperature from CESM are used as input to the model. We underline that BOATS resolves only the subset of marine fish biomass that has been targeted by fisheries, for which model estimates can be compared with and constrained by global catch data (33).

In BOATS, fishing effort evolves dynamically in each grid cell and fish size group, responding to changes in the biomass and the model's economic forcings (44, 46). As is common in models simulating fishing activity (114), it is assumed that profit is a main driver of fishing behavior, but also that fishing behavior can be more or less strongly influenced by regulation (management). BOATS represents the effort put into fishing each of the three fish size groups ($k = 1, 2, 3$) as nominal fishing effort, E_k (in watts per square meter; reflecting the boat power), which evolves over time as a function of the average profit, the regulation target for fishing effort, $E_{targ,k}$ (in watts per square meter), and the regulation effectiveness S (dimensionless; $S \geq 0$) in a grid cell:

$$\begin{aligned}\frac{dE_k}{dt} &= K_e\frac{revenue_k - cost_k}{E_k}e^{-S} + K_s(E_{targ,k} - E_k)(1 - e^{-S})\\ &= K_e\frac{pqE_kB_k - cE_k}{E_k}\,e^{-S} + K_s(E_{targ,k} - E_k)(1 - e^{-S}),\end{aligned} \qquad [1]$$

where p is the ex-vessel price of fish (the price at which the catch is sold when it first enters the supply chain; \$·grams wet biomass^{-1}), c is the cost per unit of fishing effort (\$·watts^{-1}·second^{-1}), q is the catchability (meters^2·watts^{-1}·second^{-1}), B_k is the fish biomass (grams wet biomass·meter^{-2}), K_e (watts^2·meter^{-2}·\$$^{-1}$) is the fleet dynamics parameter (which scales the rate of effort change with respect to profit), and K_s (meters^2·second^{-1}) is the regulation response parameter (which scales the rate of effort change with respect to regulation). The catch is the product qE_kB_k, where the catchability q reflects the effectiveness with which a given unit of fishing effort catches fish, and incorporates both gear technologies, fish finding or aggregating technologies, and skill and knowledge of the crew.

As Eq. **1** states, the key factors determining the level of fishing effort in BOATS are B_k, p, c, and q (44) and the regulation parameters $E_{targ,k}$ and S. If S approaches zero (no regulation), the nominal fishing effort will decrease if c increases (increasing total cost), and increase if p or B_k increase (increasing revenue), all else being equal. In line with the theory of open access fisheries (80, 81), at unregulated equilibrium fishing effort stabilizes at a level that generates zero profit.

Prewar Fisheries Baseline. We use BOATS with simple historical representations of fish price, fishing cost, and catchability, to create a prewar fisheries baseline simulation determining the prewar state of fisheries and ecosystems. Based on the findings in ref. 45, the prewar fisheries trajectory is hindcasted by forcing the model with constant c (1.8×10^{-4} \$ kW^{-1}), constant p (1.1 \$ kg^{-1}), increasing q (5% y^{-1}), and no regulation ($S = 0$), with the climate control from CESM as input. Although these socioeconomic approximations are simplistic, they are within the ranges of empirical estimates (82, 115–117), and reproduce the historical evolution of global fisheries, with an increase, plateau, and slight decline of global catches and a continuous decrease in global fish biomass (Fig. 1). The global distribution of fish biomass and fishing effort in model year 2019 are saved to use as initial conditions for the nuclear war simulations.

To investigate the benefits of strong preemptive fisheries management, we create an alternative prewar simulation. We use the dynamic fisheries regulation component described in ref. 46, and assume strong regulation effectiveness ($S = 10$) and regulation toward the local MSY target ($E_{\mathrm{MSY},k}$). $E_{\mathrm{MSY},k}$ is estimated for the long-term monthly mean of the climate control from CESM in each grid cell. This approach results in global catch and biomass trajectories similar to the unregulated baseline, but with higher catch and biomass in the last decades thanks to strong management (*SI Appendix*, Fig. S8).

Socioeconomic Responses. Due to the large uncertainty of the effects of a nuclear war on global fishing behavior, we here use simple, exploratory socioeconomic responses. We modify two of the key economic model forcings, ex-vessel price of fish (p) and cost of fishing effort (c), to induce intensified or decreasing fishing as a response to a nuclear war. Intensified fishing is modeled by an instantaneous step increase in p, either a doubling (F+) or a factor-of-5 increase (F++) in the year of the war. Decreased fishing is modeled here by an instantaneous twofold (F−) or fivefold (F−−) step increase in c. Finally, as a comparison, we model a BAU scenario where c and p remain unchanged throughout the war scenarios. When investigating the effect of preemptive management, we use the BAU, F+, and F++ scenarios combined with an immediate reduction of the regulation effectiveness to zero ($S = 0$). Reduced regulation effectiveness is not necessarily the most likely socioeconomic response (*Uncertainties and Limitations*), but was applied for consistency with the other postwar scenarios. In all simulations, fishing effort evolves dynamically with a monthly time step, in response to the changes in p, c, q, and B_k (Eq. 1).

The cost and price increases used here (two and five times) were guided by the sparse available observations. First, the increases are substantially higher than historical variations (56, 94, 115, 118), since there is a large potential for extensive socioeconomic changes postwar. In particular, the risk of unprecedented food shortage even under the 5-Tg emission scenario (28), the relatively high volatility of fuel prices (119), and the hundredfold intensification of fishing recorded in one region after the Tambora eruption (41), warrant an investigation of large variations. Still, intensified fishing requires real fishing capital; boats, gears, and crews. Although the substantial overcapacity present in many regions today could be mobilized postwar, the need for capital still constrains fisheries expansion. Therefore, we do not investigate higher price increases.

Model Runs. Impacts of nuclear conflict and accompanying behavioral changes in the fishery were modeled for a 15-y period postwar using a total of seven soot inputs (including the controls) and five socioeconomic responses. We use the combination of BAU fishing and unchanged climate conditions—the "BAU control"—for comparison with all other scenarios, generating the percent changes given in the results. In addition, we simulate the impact of the climate scenarios on fish biomass in an unfished global ocean (see *SI Appendix, Impacts of nuclear war on the unfished ocean* and Fig. S7), and the impact of the BAU, F+, and F++ scenarios on a strongly regulated global fishery (Fig. 6 and *SI Appendix*, Fig. S9). To estimate the uncertainty in BOATS model predictions, each of the model runs (including the prewar baselines) was repeated five times using different sets of parameter combinations derived from the model calibration process (44) (values given in table S1 of ref. 45). The five different parameter sets (the parameter ensemble) span a large range of the possible parameter space (SI in ref. 45), and results are presented with the ensemble mean and SD.

EEZ Catch Changes and Marine Ecosystem Dependence. The total catch change is calculated for each EEZ by summing over the area, taking the average of the ensemble runs and over the first 5 y postwar. We use the country-level nutritional dependence from ref. 47 to indicate vulnerability, or the integrated dependence on marine ecosystems for countries lacking values for nutritional dependence. Dependent territories lacking data in ref. 47 were assigned the same value as their controlling central state. Disputed areas and joint regime areas were excluded from the analysis in Fig. 5*B*.

Data Availability. Model output data and code for the fisheries model have been deposited in Zenodo repositories (http://doi.org/10.5281/zenodo.4110876 and http://doi.org/10.5281/zenodo.4117477).

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