Resilience Reconsidered: The need for modelling resilience in food distribution and trade relations in post nuclear war recovery

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Abstract

With a rise in global tensions among nuclear-armed states, preventative measures against nuclear war have once again attracted attention. However, recovery measures in a post nuclear war remain heavily neglected. A nuclear winter and its associated climatic effects would devastate global agriculture. Understanding vulnerabilities in post nuclear war trade networks could inform efforts to mitigate collapse risks and enable recovery across such scenarios. We posit that even in a limited nuclear war, key trading chokepoints and infrastructure could be targeted. This could severely disrupt global trade and supply chains for food, essential medicine, fossil fuels, and fertilisers, resulting in widespread famine and increasing humanity's vulnerability to unforeseen aftershocks. The precise mechanisms and vulnerabilities in post nuclear trade and supply chains are poorly understood. Large fluctuations in price compounded by infrastructure destruction will impact every part of the post-catastrophic aid delivery process. The trajectory of this disruption and recovery will be critical in determining the extent of the resulting famine and loss of life. We reviewed the relevant literature for the nuclear winter hypothesis, relevant famine studies, and existing Complex Adaptive System research on trade and supply chains. Given the higher expected deaths might result from 250 to 550 detonations, the medium exchange size scenarios should be the priority for future resilience research. We identify three layers of enquiry that would help future

modelling work to address and understand nuclear resilience. Better understanding of reduced sunlight scenarios would be applicable to several classes of catastrophe beyond nuclear exchanges.

Introduction

Our current food system is built increasingly upon high-speed, globalised, supply chain networks, which have shown to be vulnerable in the event of crisis (Bailey & Wellesley, 2017). Most recently, global inflation from the combination of COVID-19, the Ukraine-Russia war, and commodity and fuel price instability have renewed interest in supply chain resilience, from both commercial and humanitarian perspectives. Yet, the impacts of an industry- and infrastructure-disabling nuclear war or volcanic winter could be even more dire. Crippled infrastructure, particularly in healthcare, sanitation, industrial agriculture, and wider damage to supply chains, as well as the ensuing famine could increase humanity's vulnerability to social instabilities, epidemics (Leaf A., 1986, PSR., 2013) and other unforeseen aftershocks (Denkenberger et al., 2017, Walika et al., 2023).

Examples from History, Climate, and Society (herein HCS) studies (e.g. Redman et al., 2007, Zhang et al., 2019, Ljungqvist et al., 2024) have shown that civilisational crisis and collapse could be possible under cascading and compounding shocks, such as those described by Pescaroli & Alexander (2018), to fragile trade relations. The impact of abrupt sunlight reduction scenarios (herein ASRS) is particularly concerning. In these scenarios the amount of sunlight reaching the Earth is obstructed by soot, dust or other particles in the atmosphere, inducing a cooling effect which could significantly curtail our agricultural productivity. The feasibility and cost-effectiveness of resilient foods and the case for mitigation against ASRS such as nuclear winter or major volcanic eruptions have been previously addressed (Baum et al., 2015, Denkenberger & Pearce, 2016, Denkenberger et al., 2017, Rivers et al., 2022, Denkenberger et al., 2022). We posit that in an ASRS caused by a nuclear exchange, vulnerable isolated populations may be more susceptible to food insecurity and less resilient to subsequent environmental changes and potential mismanagement of limited resources. However, studies have suggested that under the right circumstances and adequate mitigation strategies, several island populations could become catalysts for recovery (Boyd & Wilson, 2023). In particular, we posit that trade links are key to mitigation and recovery from such risks, and thus would be relevant to several classes of collapse (Baum et al., 2019).

The upshot of all the above is that understanding, protecting, and promoting trade resilience between any 'nodes of persisting complexity' (King & Jones, 2021, Boyd & Wilson, 2023) may be vital to the post-catastrophic recovery of our civilisation.

In this paper, we review the destructive impact and cascading effects from the use of nuclear weapons, as well integrating analyses of nuclear war with knowledge from adjacent fields that inform understandings of societal resilience. This is followed with a review of peculiarities and conditions contributing to recent famines and the potential impact of nuclear war on trade and supply chains. We outline the need to adapt ecological resilience thinking and complex systems modelling for integrating both climate impacts and human systems to further understand these cascading risks. Finally, we outlined three corresponding avenues for further research that can inform actionable interventions.

Impact of nuclear war and other ASRS, the scientific basis

Humanity lives with geopolitical conditions that continue to threaten nuclear escalation. Recent developments have seen disarmament and non-proliferation treaties lapse, for example, the diplomatic failures surrounding the renewal of the new START treaties (US Department of State, 2023), modernisation of nuclear arsenals, and ongoing conflicts. Whether or not the specific conditions for an ASRS occur, the destruction of essential infrastructure, an escalating breakdown of Great Power restraint, and irradiation of vast areas are all serious concerns resulting from nuclear detonations. In what follows we review the destructive power of nuclear weapons and associated catastrophic risks.

The median destructive power of a modern day thermonuclear weapon is orders of magnitude larger than the *Little Boy* & *Fat Man* detonated upon Hiroshima and Nagasaki, which had a respective yield of 18 to 21 kT of TNT (Kristensen & Korda, 2023). The right conditions allowed even the relatively 'light' *Little Boy* to create a firestorm over Hiroshima. With 1,670 and 2,673 deployed strategic nuclear warheads from the United States and the Russian Federation respectively (ibid.), a limited exchange can expect detonations of between a few hundred to thousands of warheads. With the current widespread deployment of variable yield systems ranging between ten to few hundred kilotons, it is difficult to estimate the expected yield of a nuclear warhead. Despite decades of civil and political campaigning efforts for complete disarmament after the Cold War, the limited success in disarmament[1] and the continuation of deterrence strategy in a multipolar world (Geist E., 2023) means that current stockpiles remain a civilisational risk.

Early discussion of the mechanisms of an ASRS from a nuclear war e.g. (Crutzen & Birks 1982) postulated that countervalue[2] nuclear detonations over dense cities could release intense heat within the blast radius, igniting most carbon based materials, starting multiple fires, and causing mass amounts of soot to be released. As materials such as black carbon are excellent absorbers of heat, they loft high into the stratosphere, blocking the incoming insolation that regulates the Earth's greenhouse effect. Dispersion becomes difficult as the particles cause disruption to the temperature gradient and slow down the Brewer-Dobson circulation (Mills et al., 2014, Coupe et al., 2019).

Later elaboration by the Rutgers University group concluded that nuclear winter could be significantly more severe than previously modelled (Toon et al., 2008, Mills et al., 2014,

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[1] New START specifically caps the number of long-range missiles each country can deploy to 1,550 and allows for a maximum of 700 long-range missiles and bombers. Participation in the new START was unilaterally suspended by the Russian Federation on 21st February, 2023.
[2] The goal of countervalue targeting is to threaten an adversary with the destruction of its socioeconomic base in order to keep it from initiating a surprise nuclear attack (first strike). (Britannica, 2014)

Coupe et al., 2019), while others have suggested less severity (Reisner et al., 2018, Wagman et al., 2020). The nuclear winter hypothesis suggests that most fatalities and impact from nuclear war would be caused by the climatic effect on global agriculture rather than from direct detonation impact. This was not widely understood by the general public back in 1987 (Green et al., 1987), and a more recent survey has not indicated growth in understanding (Ingram P., 2023).

There have been a very limited number of studies and/or models looking into the coupling of ASRS climatic effects and the consequences on global agriculture (Glomseth R., 2024). The most widely referenced foundation modelling for multiple scenarios (*see Table 1.*) was published by Xia et al. (2022) from Rutgers University.

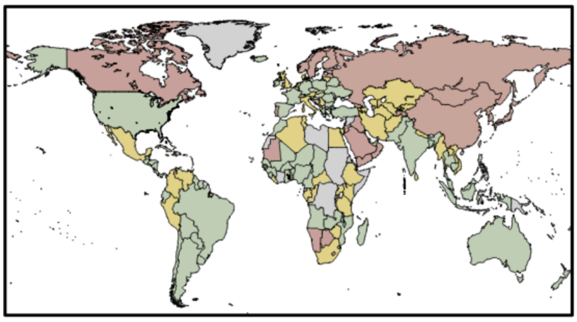
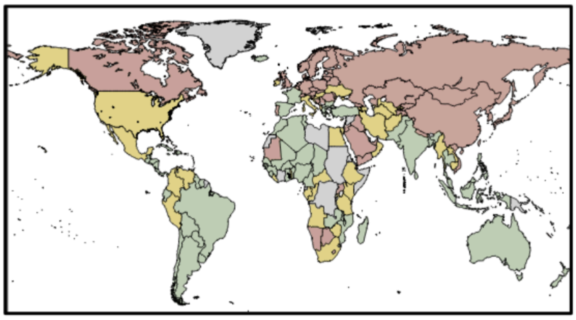
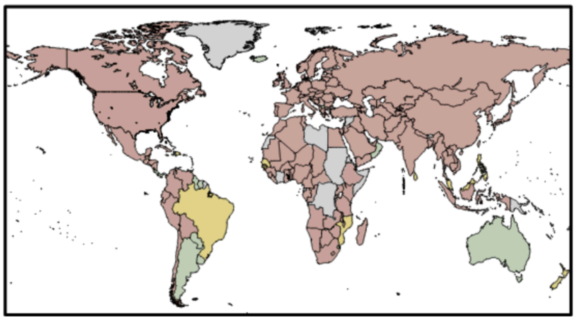
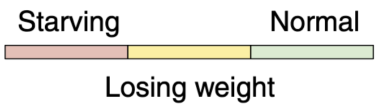
<table>
<tr><th>Stratospheric Soot</th><th>Partial livestock consumption (no trade)</th></tr>
<tr><td>27 Tg</td><td></td></tr>
<tr><td>37 Tg</td><td></td></tr>
<tr><td>150 Tg + 50 % food waste</td><td></td></tr>
<tr><td></td><td>
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Table 1. Human condition at Year 2 under the scenario comparing 27, 37, and 150 Tg of stratospheric soot injected, assuming no trade, partial livestock preserved, and half of household waste is added to food consumption. Partial livestock adaptation scenarios consider that humanity would respond to ASRS famine by retaining some animal husbandry; Figure adapted with material from Xia et al., "Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection," published 2022, Springer Nature.[3]

Fortunately for humanity, we have only twice seen the use of nuclear weapons in warfare in the past 79 years, as of 2024, in Hiroshima and Nagasaki. If the extended period of relative peace continues, humanity could optimistically expect the risk of nuclear exchanges to diminish gradually over time. A shift towards a more precarious position may occur if the global norm is violated. The next nuclear exchange, if it occurs, will inherit the prior

[3] Having more animal feed transferred to human feed will save more lives (Xia et al., 2022: Figure. 5.), and these key grains can be supplemented by animal products, by-products, and non-traditional resilient foods to help fulfil the global population's nutritional requirements (Pham et al., 2022).

probability from the last exchange (see *Supplementary S1: Figure 1A, B; Table 1, 2, 3, 4*), resulting in a higher death toll expectation. The actual probability may be lower since any amount of nuclear exchanges will be catastrophic, and it might discourage future use once deployed again. On the other hand, as adopted in the position of this study, an hypothetical exchange might damage the current taboo of nuclear exchange, which might result in normalising its use in future conflicts despite the humanitarian consequences.

In the event of any ASRS, the particulars of the scenario would determine the climatic consequences for global agriculture and famine. The severity of ASRS is a function of soot yield from detonations and the climatic impacts of lofted stratospheric soot. However, there are still substantial disagreements between the various groups on modelling the process, nuclear weapons' immediate impact, firestorms, and stratospheric soot. The recent modelling discussion is summarised below (*see Table. 2.*).

Group	**Base climate model**	**Fire-storm model**	**Scope**	**Deton-ations**	**Soot from fire-storm**	**Fuel den-sity**	**Secon-dary igni-tion**	***E*-folding (strato-sphere)**	**Bio-phys-ical crop model**
Rut-gers Univer-sity (Mills et al., 2014 & Coupe et al., 2019)	CESM (WACCM4)	N/A Ass-ume all detona-tions lead to fire-storms	Russia-United States	4,400 (100 kT each)	Linear	N/A	Yes	8.4 years (Mills et al., 2014), 3.5 years (Coupe et al., 2019)	CLM5crop (Xia et al., 2022, Jäger-meyr et al., 2020, Hoch-man et al., 2022)
Los Alamos Nation-al Labor-atory (Reis-ner et al., 2018)	CESM (WWACCM4)	xRage, HIGRAD-FIRETEC	India-Paki-stan	100 deton-ations (15 kT)	Non-linear (50 % fire-storm)	1 g cm^{-2}	No	4.2 years	N/A
Lawr-ence Liver-more Nation-al Labor-atory (Wag-man et al.,	EAMv1	WRF	India-Paki-stan	100 detona-tions (15 kT)	Non-linear, depen-ding on fuel-density pre-scribed	1, 5, 10, 16 g cm^{-2}	No	1.1 years(AT); 3 years (LM-Aug); 2.3 (UT-Jan)	N/A

2020)									

Table. 2. A brief overview of the parameters of recent geophysical nuclear winter modelling.

The Rutgers University group was the first to extend the modelling from Crutzen & Birks (1982) and consolidated the nuclear winter ASRS phenomenon (Turco et al., 1983). The group became increasingly pessimistic about nuclear winter from 1983, 2007, 2008, and in 2019 (Robock et al., 2007, Toon et al., 2008, Coupe et al., 2019). The most recent CESM(WACCM4)[4] based modelling from Coupe et al. (2019) simulated a large global nuclear exchange with 150 Tg of stratospheric black carbon. Black carbon is injected into the upper-troposphere uniformly over Russia and the United States, at a rate which decreases linearly over a 1-week period. The CARMA component of the WACCM4 model allows for more precise fractal modelling of how changes in aerosol size can affect absorption and extinction of radiation, resulting in a shorter *e*-folding[5] time compared to previous studies from the same group. They used no firestorm modelling, unlike the Los Alamos and Lawrence Livermore groups. The Rutgers group assumed that all countervalue detonation will result in firestorm. At 150 Tg, their results show a global surface temperature drop between -5 ^{o}C to -10 ^{o}C can persist up to 7 years post detonations.

In 1945, a group of scientists at the Los Alamos National Laboratory developed the first nuclear weapon. 73 years later, using a scenario of nuclear exchange between India and Pakistan (*see Figure. 2.*), the contemporary Los Alamos group modelled the results using the CESM(WACCM4) model in combination with a controlled-burn area simulation derived from HIGRAD-FIRETEC (Reisner et al., 2018). The fuel load density is benchmarked to measurements from suburban Atlanta; this area was chosen as they believed that while suburban Atlanta has lower building density, its infrastructure would burn at a higher intensity given average differences in building material. The expectation was that this would be comparable to an India-Pakistan exchange. The fuel-loading assumption incorporated estimations from various types of buildings, but has been contested (Robock et al., 2019, Reisner et al., 2019). Additionally, the study differentiated between thick and thin fuel density loading, as well as the average temperature Probability Density Function, with lower and higher ramping rates contributing towards slower and faster spreads respectively. The modelling suggests that soot lofted into the stratosphere requires favourable conditions such as light shear wind-force in the troposphere. The fractal shape of black carbon soot also increases the surface-to-mass ratio which hinders gravitational settling. Furthermore, the study noted that the quick conversion of hydrophobic-to-hydrophilic properties of black carbon at different altitudes of the troposphere also play a role in decreasing the amount of soot reaching the stratosphere as a result of precipitation fallout. The modelling resulted in a range of soot between 2.39 to 3.69 Tg, of which 0.8 Tg were lofted into higher altitude, but they also applied the climatic modelling to 5 Tg, of which 3.7 Tg were lofted (Mills et al., 2014) for comparability. Interpretation of Mills et al. (2014), which is the worst case scenario, the modelling suggests a decrease in global surface temperature of -2 ^{o}C four years post detonation, followed by quick amelioration after the fifth year. Conversely, when considering the ensembled outcome for various full chain models, there was a modest temperature drop

[4] CESM(WACCM4) is a fully-coupled climate model with an atmospheric model featuring physical, chemical, and aerosol components which can produce modes of variability in the whole atmosphere.
[5] *e*-folding lifetime measures the time interval in the exponential rate of decrease in particles; a longer *e*-folding lifetime indicates longer duration of soot residency in the stratosphere.

which did not exceed -0.5 °C at the 95th percentile, and a gradual amelioration occurring over the subsequent decades post detonation.

Finally, the Lawrence Livermore National Laboratory also used the scenario of the India-Pakistan exchange as a study baseline. The fuel load and simulations were calculated from the 10 most populous cities from each respective state (20 in total) (Wagman et al., 2020). For each city, 100 simultaneous mass fires were assumed in the affected cities. A specified 12.57 km^2 area was prescribed for each blast with a 30 minute linear ramp-up. The experiment used a multi-fuel loading scenario of 1, 5, 10, 16 g cm^{-2}, at various atmospheric height injections. Compared to the WACCM4 model, the EAMv1[6] has a higher black carbon anomaly and high latitude ozone depletion. Fuel loading scenarios lower than 1 g cm^{-2} with injection below the tropopause were removed by the model, as the black carbon was quickly dispersed. In simulations using local meteorology, black carbon was injected higher into the upper troposphere than studies from the Rutgers University and Los Alamos group. Comparison using the 5 Tg fuel loading scenario, the duration of black carbon reaching the stratosphere was significantly reduced and subsequent lifetimes were shorter than the both groups. The multi-fuel loading scenarios had a corresponding soot release of 0.31, 1.56, 3.13, and 5 Tg respectively. The EAMv1 model generally has a less rapid rainout, lower ozone depletion, and higher lofting into the stratosphere when compared to the WACCM4 models, corresponds to global decrease of -1 to -3 °C (Kelvin was used in Wagman et al. (2020)) by year three regardless of injection mode.

Note that there are no biophysical crop models which used the ASRS studies results from the Los Alamos and Lawrence Livermore National Laboratory as climatic input. This suggests a potential gap in understanding the agricultural impacts of nuclear war, and the need for more modelling across a broader range of assumptions and scenarios.

Moreover, limited research has attempted to model the full chain of impact from nuclear climatic impacts on agricultural productivity to the consequent scope of famine extent. We also found that consideration for international trade as a mechanism to reduce famine extent were often excluded from the models (e.g. Xia et al., 2022, Jägermeyr et al., 2020). While the study from Hochman et al. (2022) made an attempt to extend the biophysical crop impact model from Jägermeyr et al. (2020) into economics and commodity price effects, neither have modelled trade as part of the economic component. The inclusion of trade in post nuclear war scenario assessments is fundamental to accurately parameterising the post catastrophe impacts and the extent of famine, since there have been many examples of how deliberate trade restrictions have been historically connected to worsening of outcomes for smaller food insecurities in the last centuries. We posit that there would likely be an initial shock to trade networks, followed by partial resumption over time as infrastructures are repaired and trade relations resume. The trajectory of this trade disruption, food price, and recovery will be critical in determining the extent of any nuclear winter famine and loss of life. Prudent investigation into post-catastrophe trade disruption can inform preparedness and policies to mitigate nuclear winter risks.

[6] EAMv1 is an atmospheric model with a middle atmospheric focus, designed for studying multidecadal and longer timescale changes.

Studying other fields may help understanding of the impact of nuclear war

Previous interpretations of nuclear winter climate impacts have not been contextualised with relevant insights from adjacent fields. For example, such simplified modelling approaches overlook essential factors in trade. Additionally, many studies have not adequately connected nuclear winter scenarios with palaeoclimatology and broader historical societal studies. Historical instances of successful adaptation to sudden drops in global temperature have occurred, but there have also been cases of maladaptation which resulted in collapse, most notably, the collapse of Norse Greenland settlements in the 12^{th} to 15^{th} Century (Dugmore et al., 2007, Dugmore et al., 2012). It is therefore vital to understand the extent to which nuclear winter and/or associated trade disruptions may be analogous to past anomalies. This will provide relevant variables from diverse disciplines that may be key to understanding current adaptations for resilience.

There is a long history of attempts to couple near and long-term climatic oscillation and economics studies since Hungtinton E. (1913), in HCS studies. Through triangulation of textual, ecological, archaeological, and geochronological records, scientists and economists are able to reconstruct past societal adaptation and changes (Rasmussen et al., 2014, Degroot et al., 2022). Many recent HCS studies have been directed towards explaining the causality and correlation between climate anomalies and large-scale human crises in pre-industrial times (e.g. Redman et al., 2007, Zhang et al., 2019, Ljungqvist et al., 2024). Thus, it is perhaps useful to interpret potential ASRS-induced cooling alongside events of comparable magnitude within the Holocene, which share closer atmospheric states. The closest paleoclimatological cooling event analogous to a significant ASRS might be the cooling event that occurred 8.2 kya., which might have been triggered by the disruption of the thermohaline circulation, resulting in cooling of ~ -1 to -3 ^{o}C in the northern hemisphere (Alley et al., 1997, Alley & Ágústsdóttir, 2005, Kobashi et al., 2007, Matero et al., 2017). Modelling work on the temperature decrease from a large nuclear exchange could yield the minimum of a climatic effect similar to or cooler than the 8.2 kya. event (≤ -3 °C), albeit with a considerably more rapid onset. Xia et al. (2022) approximates that 16 Tg produced by a countervalue detonation of 250 nuclear weapons can already produce a comparable ASRS cooling effect. Furthermore, as modern agriculture developments have been adapting to expected global warming, the migration of warm weather crops towards higher latitudes (Sloat et al., 2020) would likely cause extra vulnerabilities to the Northern Hemisphere grain supply.

Probability modelling of nuclear exchange at various scenarios

In an effort to prioritise the potential devastating effects of different nuclear exchange scenarios and the potential impact on the post-moratorium of an exchange, we attempted to model the probabilities of nuclear exchange at various scenarios from 2024 to 2050. To estimate the expected deaths (*see Figure 1.*) of nuclear exchanges of various scenarios, we need to parameterise the following. First, the probability of a nuclear exchange happening; Second, when an exchange occurs, what is the respective probability of various scenarios (exchange sizes); Third, the expected fatalities from both direct impact and starvation. The four scenarios used in the probabilities and expected deaths calculations were taken from

Xia et al. (2022).

1. The Beta distribution is used to model the probability of a nuclear exchange, and this probability decreases annually assuming the currently observed peace period continues (Laplace's Law of Succession).
2. Probabilities of the detonation size scenarios were constructed using Beta Cumulative Distribution Functions; parameters for the least square estimation were derived from the online prediction market Metaculus (*see Supplementary S2*).
3. Four scenarios of detonation sizes of 100 (15 Kt), 250 (100 Kt), 550 (100 Kt), and 4400 (100 Kt) and their consequent combined fatalities from both direct impact and death from starvation at the end of year 2 were applied in expected deaths modelling taken from (Xia et al., 2022: Table. 1.) (*see Supplementary S2*).

Exchange scenarios of 100 and 250 nuclear weapons are considered to be limited exchanges, likely between regional states with a small nuclear arsenal (e.g. India-Pakistan or China), meanwhile exchanges for 550 above can only be expected from global powers such as the United States and Russia, who could feasibly deploy such a large quantity of warheads.

There are a few key uncertainties in the probability modelling, first the assumption of temporal decay in the nuclear exchange probability is an idealised assumption, which could be controversial. Secondly, the use of predictive market probabilities as an input for estimating the probabilities of various detonation size scenarios carries uncertainties and limitations to crowd-sourced forecasting. We therefore encourage the reader to take the expected calculation with a grain of salt, and refrain from using the suggested number for intercausal comparison.

We found that medium sized nuclear exchanges are significantly more probable, despite lower predicted fatalities than large exchanges. While in medium sized exchanges, the limited climatic cooling significantly constrains the predicted death contribution from an ASRS induced famine (*see Figure. 1., Xia et al., 2022: Table 1.*), the higher probabilities modelled adjusted for higher expected deaths compared to large exchanges. If we are certain (probability of detonation = 1) that some scale of nuclear exchange would happen next year (2025), death tolls in various exchange scenarios from Xia et al. (2022) are calculated to be ~ 622 millions for 250 detonations and ~ 21 millions for 4400 detonations. Furthermore, Infrastructure disruption and destruction, and a potentially hostile geopolitical climate could amplify the impact of famine, beyond what might be expected from climate impacts alone. Non-climatic factors are potentially just as significant for famine analysis and mitigation.

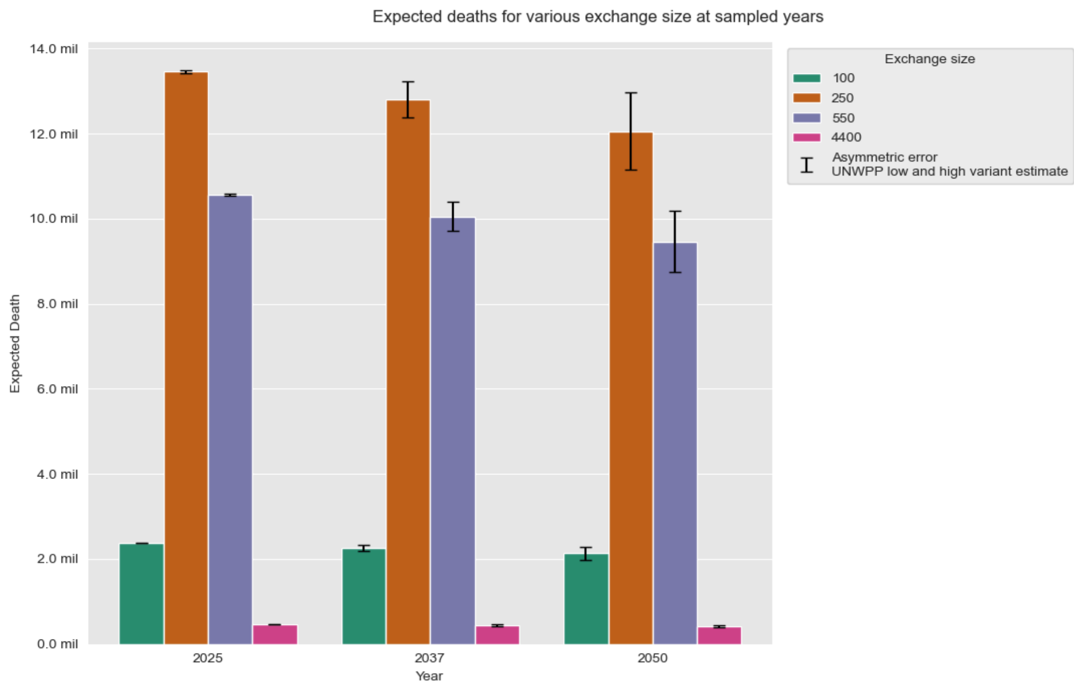

Figure 1: Expected deaths calculated for various detonation sizes if nuclear war happens in the year 2025, 2037, and 2050 non cumulatively, predicted expected deaths combine direct fatalities and fatalities from starvation at the end of year 2 (Xia et al., 2022: Table 1.). An exchange of 4400 (150 Tg) is highly unlikely (see Supplementary S2), and therefore the expected deaths are comparatively low. This expected deaths calculation suggests it is most important to focus on mitigation measures for 250 to 550 detonations in the near-term. The gradual decrease in expected deaths across all scenarios through the years can be attributed to reduction in annual probabilities of nuclear war . Population increases were taken into account using UN World Population Prospects estimate variants (UN DESA., 2024) (see Supplementary S2: Figure 2, 3; Table 5, 6.).[7]

Causes of large famines after the Third Agricultural Revolution

To further examine the cascading impacts of infrastructure-disabling catastrophe and adaptation in hostile geopolitical climates, understanding recent historical cases with empirical descriptions and data can be valuable in illustrating the general dynamics of famine. Focusing directly on recent famines allows us to inspect the role of key actors and conditions in order to better understand potential vulnerabilities (Devereux S., 2000, Pinto et al., 2014). In our considerations, we also disregard famines directly related to the World Wars. The majority of the remaining, if not all of them, are characterised by the uniquely closed economic systems of the Soviet Union and Maoist China, and therefore their relevance to scenarios involving disruptions in the global supply chain is somewhat limited.

Crucially, at least since the Green Revolution, which saw a great incorporation of agricultural mechanisation and use of high-yield GMO crops. It is not justifiable to attribute larger hunger events and famines solely to limited food production (Conway G., 2012: 54-62). There have

[7] No economics, trade, or cascading vulnerabilities were considered as they are very under-researched. It is highly likely cascading infrastructure failures would compound this further in every scenario. As expected, medium nuclear exchanges have higher expected deaths due to their higher probabilities.

been significant advances in agrotechnology which led to greater production, such as the widespread adoption of synthetic fertilisers, improved crop varieties, and irrigation. In several instances of shorter crises and mass famines of the late 20th and early 21st Centuries, food sovereignty, trade, socio-economic policies, and siloing of local food either for export or for political favour were the main causes, not the inability to produce (Conway G., 2012: 64-77, de Waal A., 2017). This section will provide a brief overview of the severe famines to date, examining their origins and lasting impacts.

Throughout 1974, a famine in Bangladesh led to the excess mortality of approximately 1 million people (Devereux S., 2000, ó Gráda C., 2009, Hasell & Roser, 2023). At first glance, the famine was caused by severe flooding of the Brahmaputra River from June to September, a critical period for the rice harvest. However, in 1974, rice and wheat output per capita actually peaked compared to surrounding years. Sen argues that the price of rice began increasing well before the floods, leading to disaster when paired with falling wages and, due to the floods, decreased employment opportunities for rural labourers that summer, leaving rural communities priced out of the market and vulnerable to starvation. At the time of the famine, Bangladesh was heavily dependent on food imports and maintained only small emergency food stocks. The United States, which provided the bulk of Bangladesh's food aid, threatened to cut off assistance unless the state ceased its exports to Cuba. Desperate, Bangladesh complied in order for food aid to be resumed, and its international trade profile suffered at a time of already-eroded foreign earnings (Sen A., 1981). Among other possible interventions, this episode highlights the necessity for governments to implement prudent price controls in the event of food insecurity, as well as the maintenance of good-faith international aid transfers.

The Second Congo War lasted from 1998 until at least 2002. Over 90% of the 5.4 million excess deaths can be directly attributable to conditions such as disease, diarrhoea, and malnutrition rather than from direct violence. Most of these deaths could have been prevented if not for the destruction of infrastructure during the First and Second Congo Wars, as well as the ongoing insurgency, which exacerbated health service disruption and food insecurity (Coghlan et al., 2007). Here we can see highlighted the need for robust, local and international humanitarian and medical relief infrastructure designed to work in crisis scenarios, not just the normal case.

As a final example, the ongoing famine in Tigray, Ethiopia has claimed over 300,000 lives and put 4 million people (70% of the population) into a situation of acute food insecurity (WFP., 2023). This is as yet the most severe famine to begin in the 21st Century, caused by a combination of local war in Ethiopia, regional drought, and global price inflation originating from COVID-19 and import disruption due to the Russian invasion of Ukraine. Due to massive population displacement, not only are families and communities often unable to access food distribution points, but neighbouring communities in the Afar and Amhara regions are now experiencing severe hunger (IPC Phase 3.5-4) (IPC., 2021). This situation enabled by a disruption in trade shows how it is crucial to ensure the continuation of international trade in an ASRS or other global catastrophe, in order to keep food flowing across borders, preventing or easing migration crises which can leave all communities worse off.

Each and every famine has had its own set of peculiarities and conditions, but the severity is often a complex interplay between existing conflict, geopolitics, state policies, climatic conditions, and market environment. As elaborated, modern scenarios have been worsened by localised socio-economic policies and infrastructure collapse, as well as by the global macro-environment.

We have been fortunate that humanity has not experienced worldwide disruption to our food and trade systems since World War II. However, the unique combination of an ASRS coupled with the social, political, and economic interconnectedness of the current food and fuel supply chain provide conditions for a catastrophe on a scale we have yet to encounter. The precise mechanisms and vulnerabilities in post nuclear war scenarios, and how trade and supply chains might adapt, remain poorly understood. Limited studies in both peacetime and ongoing conflicts have suggested that food and commodity prices are heavily dependent on the price of fossil fuels (Saâdaoui et al., 2022, Alexander et al., 2022). Thus, in the event of widespread infrastructure collapse, the world and every part of the aid delivery and recovery process would be at risk.

Impact on Trade and Supply Chains

Building on the historical basis for understanding famine, recent events have shown how coupled and fragile supply chains remain today. It is therefore instructive to look at the slew of factors that contributed to 2019–22 price volatility and resulting effects on both commercial and humanitarian supplies.

The COVID-19 induced supply chain disruption of 2019-22 coupled with geopolitical instabilities led to key commodity price fluctuations, whose multifaceted ramifications are ongoing (Nasereldin et al., 2020, Aday & Aday, 2022, Saâdaoui et al., 2022). Favourable trade relations and resilience infrastructures (Bailey & Wellesley., 2017) thus play a large role in price stability and hedging against such exposures. However, certain historical models may lack applicability given contemporary levels of interconnections. In an event of catastrophic impact, understanding the mechanisms of how to quickly rebuild can inform policy decisions now to adequately prepare for ASRS and distribute resilient foods and other essential commodities.

A range of factors, from fertiliser inputs to fuel for global freight, ensure the price of food is inextricably linked to the price of fuel in production, processing, distribution, and trading (Baffes J., 2007, de Nicola et al., 2016, Chowdhury et al., 2021, FAO., 2022, Romanello et al., 2022). The food importing and most disadvantaged communities would disproportionately bear the worst health consequences (Alexander et al., 2023, Alabdullah Ö., 2023). Humanitarians working on the front-line of long crises of food instabilities in Yemen and Syria suggest that infrastructure collapse poses a significant risk to the humanitarian supply chain convoy, as fuel has to be safeguarded and carried along with it. Infrastructure related accumulated penalty costs of transportation could reduce the quantity of food deliverable to the most vulnerable, making the 'last mile' most sensitive to price fluctuations (Balcik et al., 2008, Alabdullah Ö., 2023).

The cascading events of COVID-19, the Ukraine-Russia war, and the 4-day obstruction of the Suez Canal by the ship *Ever Given* 長賜輪 *(IMO 9811000)* between 23rd and 29th March, 2021 made for sensational news, although the effect on food prices were short-lived as the global supply chain had enough slack to stabilise the market (OPEC., 2021). Nonetheless, the cascading disruptions proved costly and contributed to localised supply chain shocks, calling for industry reconsideration to the dominant 'closed-system' resilience paradigm (Wieland et al., 2023). Furthermore, there are well-documented societal implications from food price volatility and related economic crises (Zhang et al., 2011., Ljungqvist et al., 2024). The First and Second Arab Springs are recent examples of how volatility in food prices became the catalyst for social instability in already fragile, structurally unsustainable, food insecure regions (Malik & Awadallah, 2013, Korotayev & Shishkina, 2020). It is still too early to determine the resulting socioeconomic effects in the MENA region.

There are good reasons to suspect that in the case of a large nuclear exchange, key infrastructures such as trading chokepoints and fossil fuel infrastructures will be destroyed as countervalue targets alongside population centres (Conover C. J., 1977). Much evidence exists in historical conflicts, and more recently in the partial destruction of the Nord Stream 1 and 2 gas pipelines (Nord Stream AG., 2022).

Resilience to civilisational collapse in the aftermath of global catastrophe requires securing and stabilising food supplies to sustain surviving populations that will be vulnerable to starvation and epidemics (Moersdorf et al., 2024). In large disasters, international aid organisations frequently depend on the assistance of military engineers from major powers to preserve order and coordinate aid operations (Barber E., 2013). However, in an event of substantial nuclear exchange that incapacitates military and infrastructure capabilities, the military's function as a substitute for civilian infrastructure might become infeasible, particularly as certain wargaming exercises assume total cessation of logistical operations after such an extreme event (Anonymous, 2023). Furthermore, the 'cold-chains' required for particular critical medicines such as vaccines are susceptible to energy supply loss (Romanello et al., 2022), with the risk of local sourcing required for alleviation of chaotic humanitarian logistical responses undermined. A perspective shift towards risk analysis of the co-movement of fuel and food prices would be useful, particularly in the atypical global market scenario arising from catastrophic infrastructure and supply-chain disruptions.

Complex Systems Modelling of Trade and Supply Chains for Catastrophe Resilience

The humanitarian logistics and supply chain is not only affected by price fluctuations of global fuel and commodity price, but also deals with extra challenges such as local infrastructure and institutional collapse (Balcik et al., 2008). Today's humanitarian aid and supply chain is a mature industry with many familiar organisations, where permanent humanitarian logistics clusters and rapid deployment of temporary depots are common practice among UN agencies and the international aid community (Alabdullah Ö., 2023). Yet, coordination among key players during past crises suffered from both disorganisation and internal politics. Several recent systematic literature reviews (e.g. Jahre M., 2017, Perdana et al., 2022, Altay et al., 2023) suggest that although there are major differences between operating the commercial and the humanitarian supply chain, there are important commercial practices and metrics for improvement that the humanitarian sector can learn from. For example, Schiffling et al. (2020) used case studies from the January 2010 Haiti earthquake and the July 2010 Pakistan flood to illustrate the various motivations of different aid agents. Motivational misalignment among various agents emerge from disorganisation and internal competition, leading to avoidable loss of lives.

Due to the increased and often irreducible interconnections of global supply chains, we suggest that certain methodological advances, such as Complex Adaptive Systems modelling will be particularly adequate in improving our understanding of such systems. Complex Adaptive System modelling is a modelling paradigm which seeks to simulate and study systems with a large number of components, their interaction and adaptation, the method ensures that essential feedback and possible critical transitions are encompassed (Holland J., 2006). Existing literature on resilience (outside the context of nuclear war) has made suggestions for a paradigm shift in adopting ecological resilience thinking, and has already made use of the Complex Adaptive System approach in both commercial and humanitarian spaces. Such methodologies might help harmonise and prioritise recovery even in humanitarian logistical challenges on a smaller scale than recovery from nuclear war (Wieland & Durach, 2021, Wieland et al., 2023) and suggest a path forward for future work.

Limited attempts to model the disruption of maritime chokepoints using complex system modelling have revealed key insights. Meza et al. (2022) used a geospatial Agent-Based Model to simulate the disruption to the global LNG supply chain by shutting down the key maritime chokepoints of the Panama Canal, the Suez Canal / Bab-el-Mandeb (BEM) Strait, and the Strait of Malacca. The study found that the LNG supply from North America is most sensitive to disruption from the Panama Canal, as the cost of shipping re-routed through the Strait of Malacca became prohibitively expensive, in turn increasing demand for LNG production from the Asia Pacific regions. The modelling suggests that this will cause a four-fold increase in LNG transited via the Cape of Good Hope and through Strait of Gibraltar, making the Strait of Gibraltar the most crucial chokepoint in such an event. The Strait of Hormuz is also identified as having a paramount importance as the closure of it would disrupt all of Middle-East exports.

Komiss & Huntzinger (2011) looked at a short-term disruption of 90 consecutive days to the oil supply chain at various maritime chokepoints. The study imposed various levels of disruptions, from 20, 50, to 100 % drops in oil transportation. Input-Output and Keynesian expenditure models were used to look at the effects on global productivity and employment. While disruption was not modelled close to the prolonged timescale of nuclear winter, in which the disruption would span several years to a decade, the study suggests that due to the lack of overland pipeline alternatives, the short-term impact of disruption in the straits of Hormuz and Malacca would be disproportionately large.

Jehn et al. (2024) presented a network trade analysis on how a small ASRS (37 Tg) and Global Catastrophic Infrastructure Loss (herein GCIL) might affect the exchanges of four major food crops which accounts for 60% of current global calorie intake. Through a Jaccard distance analysis, the study explored the changes in countries' trade communities in events of GCIL and ASRS. Countries were classified at various levels of hubs and non-hubs according to their regional roles, and assessments were made on each major crop on how their relationship would change. For example, the study found that in the ASRS scenario, Australia, Argentina, and France are the top three wheat exporting nodes. While ASRS scenario alone will have a higher negative impact to yield and trade, there are variations between warmer and cooler food crops. When combined with GCIL, impacts would be uniformly catastrophic to yield and food trade for all crop types. The ASRS scenario from the US-Russia exchange would have a bigger impact on trade communities and trade network stability than the regional India-Pakistan exchange. For the GCIL scenario alone, the most negatively impacted countries would be those majorly dependent on intensive agriculture.

In our focus on catastrophic ASRS scenarios, the survival of up to half of Earth’s current population hinges upon appropriate mitigation measures. Adaptive scenario modelling that could find optimalities in various interventions under different ASRS scenarios will be required. Exploratory modelling, such as that used within wider Decision Making under Deep Uncertainty (DMDU) (Marchau et al., 2019) which includes systems dynamic or agent-based simulations done at scale, could potentially offer us insight into the complex dynamics between post-catastrophic policies, food and fuel production, trade dynamics, and price trajectories at different levels of ASRS scenarios. This would enable further investigation into cost-effective resilience responses which could be robust across multiple cascading risk scenarios.

Science Policy Interface

In the interest of prioritisation, and to provide a pragmatic basis for future work to explore vulnerabilities, we now outline three broad research pathways that could help resolve the uncertainties highlighted in this paper, as well as suggested future research that will increase our adaptive capacities of nuclear resilience.

A fruitful avenue for further research would include systems mapping of essential trade networks and systems relevant to soft commodities, traditional foods, and new resilient foods (Pham et al., 2022), as well as governance and knowledge systems associated with wider resilience and recovery concerns (Simonsen S., 2015). Appropriate modelling which combines complex system approaches, econometrics, and robust decision making (Bankes S., 1992) can inform the eventual development of strategies for mitigating nuclear winter risks. Through more explicitly designed decision making processes, policy makers could better deal with the inherent complexities and irreducible uncertainties in Global Catastrophic Risks management, enabling better informed public discussion. Integrating the detection of ‘weak signals’, such as emerging trends around vulnerabilities, combined with the above recommended modelling and local knowledge derived through collective intelligence, for example by participatory methods, could provide greater tractability in resilience building strategy (Dal Prá et al., 2023). Such processes enable engagement of local knowledge and multiple stakeholders in a structured way, designed to facilitate robust consensus. This would engender more confidence in tackling problems that have bedevilled insufficiently coordinated humanitarian and government organisations.

In particular, an integrated analysis that involves policy makers and industry stakeholders in the food and commodity supply chains is vital to derive practical insights. Comparative analysis of bilateral opportunities, for example Revealed Comparative Advantage analysis for trade relationships in the world system, is another potential anticipatory intervention to assist with coordination. Most of all, building in resilience factors, such as redundancies in resilient foods, diversity in commodities and production, and other mitigation measures against fuel dependency (e.g. Boyd et al., 2023) which take into account the materials and systems that ensure the necessity of life alongside a 'Just-In-Case' approach to supply chain, rather than 'Just-In-Time' are crucial.

Efforts to understand and mitigate the impact of nuclear war at different severity levels might be criticised on the basis that it risks escalation. For example, one can imagine arguments against such analysis as justifying the non-existential risk of nuclear weapons usage, on the basis that if societies are better prepared this would imply such wars are winnable. This would constitute an infohazard as it might provide justification to certain leaders to use such weapons (Green W., 1988, Dill et al., 2022). Naturally this is not the intention, nor will it be the outcome if handled with sensitivity and caution around claims made. The intention is that further modelling can increase robustness against a range of ASRS outcomes, of which nuclear is a signal case. Such analysis will be informative especially for those non-nuclear armed, non-combatant populations who would otherwise have no influence over the course of a nuclear war. Furthermore, a lack of preparedness makes it more likely that any cascade from a catastrophe growing in severity could culminate in a civilisational collapse. If other extreme risks are given their due, so should the neglected aspects of nuclear risk, and indeed, recovery implicit from those. If you fail to prepare, you prepare to fail. Considering contemporary trends and the apparent irreducibility of nuclear stockpiles to below numbers required for protection from ASRS, the general utility of worst case scenario planning remains, as does the need for relevant aspects of this to be in public science, and not simply classified contingency planning.

The purpose of modelling here would be for three broad layers of eventual recommendations to be developed for investment, trade, and diplomatic opportunities. These include:

1. **Scenario exploration of severity levels**: How would global systems respond to various levels of chokepoint disruption and nuclear exchanges (e.g. 250 to 550 weapons)? Would global resilience be more sensitive to the climatic effects on food production or the destruction of fuel and transportation infrastructures? In particular, testing different assumptions and scenarios ranging from the currently common assumption of 'total cessation of trade' progressing up through various levels of reduced and continuing trade are recommended.

2. **Identifying key locations and agents for trade recovery**: How do countries and their economies, especially in 'nodes of persisting complexity' (King & Jones, 2021) or those that administer trade chokepoints, respond effectively and bolster resilience to these scenarios? This analysis may also include non-state actors such as port authorities, shipping companies, insurance and reinsurance firms etc. Through exploring the range of scenarios in which it is cost-effective to build resilience using trade redundancy, or instead increasing the production of resilient foods, or a mixture of both, preparedness can be enhanced.

3. **Recovery networks, strategies, and policies discovery**: Is it possible to then identify mutually beneficial scenarios, as catalysts for productive policy interventions? One promising route is by collating stakeholders across the above identified sectors, targeting resilience building with methodologies such as DMDU to identify optimalities in possible policies across these varied scenarios. Thus, robust strategies can be discovered for stable applicability across different severity levels, building on prior analyses for pragmatic interventions to reduce societal vulnerabilities.

As such, these three layers would develop direct enquiry around severity, then networked chokepoints and linchpins worth extra preparedness and care around, and finally actionable interventions generated by multi-stakeholder decision making.

Conclusion

In summary, this scoping review has highlighted studies of the predicted impact of nuclear exchanges, their probabilities and growing likelihood, as well as the limited existing work pairing nuclear winter research to related fields such as paleoclimatology and societal collapse. In doing so, we identify gaps with a pressing need for greater clarity. In particular, we compared historic, near-term, and ongoing famines and examined their complex emergence from multiple factors such as fuel availability and coordination problems. We suggested methodologies and resilience considerations that could mitigate such problems, and identified three layers of enquiry that would help future modelling work address and understand nuclear resilience. Firstly, how do global systems respond to major disruptions? Which factors are most integral for global resilience? Secondly, how can states and non-state actors respond effectively to global crises? How can they proactively bolster resilience? Thirdly, how can we identify mutually beneficial policy interventions? Which methodologies should we use? Any investigation into the enquiries identified is not only discretely crucial, as the gaps correspond to potential cascading failures from a nuclear exchange, but it would also have applicability to a range of other GCR scenarios if prepared for effectively. If research into overlaps and divergences between scenario severities and types were conducted systematically, as suggested in the three layers of enquiry, important insights could be gleaned about some of the most severe risks our civilisation faces.

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