Island refuges for surviving nuclear winter and other abrupt sun-reducing catastrophes

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ABSTRACT

Some island nations in the Southern Hemisphere might survive a severe sun-reducing catastrophe such as nuclear winter and be well-placed to help reboot collapsed human civilization. Such islands must be resilient to the cascading effects abrupt sunlight reduction scenarios (ASRS) would impose beyond the impacts on agricultural systems. We aimed to identify island nations whose societies are most likely to survive nuclear winter or other ASRS. We also aimed to conduct a case study of one island nation to consider how it might enhance its resilience and therefore its chance of aiding a global reboot of complex technological society. We performed a threshold analysis on food self-sufficiency under severe nuclear winter conditions to identify islands. We then profiled each island across global macro-indices representing resilience factors reported in the literature. We undertook a case study of the island nation of New Zealand. The island nations of Australia, New Zealand, Iceland, the Solomon Islands and Vanuatu appear most resilient to ASRS. However, our case-study island nation of New Zealand is threatened in scenarios of no/low trade, has precarious aspects of its energy supply, and shortcomings in manufacturing of essential components. Therefore, inadequate preparations and critical failures in these systems could see rapid societal breakdown. Despite some islands' favourable baseline conditions and apparent food security even in a severe ASRS, cascading impacts through other socio-ecological systems threaten complex functioning. We identified specific resilience measures, many with co-benefits, that may protect island nodes of sustained complexity in ASRS.

KEY WORDS

Abrupt sunlight reducing scenarios, ASRS, Asteroid/comet impact, Australia, existential risks, global catastrophic risks, Iceland, islands, multiple breadbasket failure, MBBF, New Zealand, nuclear war, nuclear winter, refuges, resilience, supervolcano, volcanic winter

SUMMARY

A food surplus means some island nations might survive nuclear winter. However, high trade dependence means islands such as New Zealand risk technological and social collapse unless there is investment in resilience. Twitter: @Matt_adapt

1. INTRODUCTION

Global catastrophic risks (GCRs) could inflict serious damage to human wellbeing on a global scale (Bostrom & Cirkovic, 2008), exceeding humanity's collective ability to respond, potentially killing billions of people. Existential catastrophes are those GCRs that would either cause human extinction or prevent a full recovery (Ord, 2020). A global catastrophe could occur if sunlight reaching the earth were abruptly reduced (Rivers et al., 2022). Abrupt sun-reducing scenarios (ASRS) plausibly include nuclear winter (Coupe, Bardeen, Robock, & Toon, 2019), massive volcanic eruption (Rampino, 2008), and asteroid/comet impact (Chiarenza et al., 2020), in which material such as soot, sulphur dioxide or dust is injected into the stratosphere, spreading globally. Resulting global climate impacts, including a drop in mean temperature, could severely limit food production (Rivers et al., 2022).

The risk from asteroids/comets is likely very low because most larger bodies have been tracked (Reinhardt, Chen, Liu, Manchev, & Paté-Cornell, 2016). However, the risk from nuclear war is plausibly rising due to geopolitical instability and new technology. The potential impact from large volcanic eruptions may also be rising due to anthropogenic climate change (Aubry et al., 2021) and declining country-level food security (Schramski, Woodson, Steck, Munn, & Brown, 2019). ASRS have impacts beyond temperature change, including effects on precipitation (Coupe et al., 2019), ozone (Bardeen et al., 2021; Osipov et al., 2021), phytoplankton (Coupe et al., 2021), marine food (Scherrer et al., 2020), and human systems such as energy, trade, social cohesion, communications (Baum & Barrett, 2018; Green, 1989), and human health and psychology (Boulton & Dunn, 2020). These impacts could be magnified if strategic global pinch points are affected (Mani, Tzachor, & Cole, 2021). Many of these consequences are yet to be fully understood.

GCRs can be classified according to critical systems they affect (Avin et al., 2018), and damage to one critical system can cascade to cause failures in others (Homer-Dixon et al., 2015). Human systems are complex adaptive systems embedded in complex ecological adaptive systems (Walker & Salt, 2006), and there is potential for unpredictable cascading effects and widespread harm from GCRs. Such uncertainties underscore the need for multiple 'lines of defence' that address the origin of a risk, its scale-up mechanism, and how it might manage to affect everyone on Earth (Cotton-Barratt, Daniel, & Sandberg, 2020). Where it is possible and cost-effective to do so, we should aim to prevent, respond to, and ensure resilience against ASRS. We should also plan how to recover should things go poorly.

Refuges have previously been suggested as one measure to provide resilience against GCRs, ensuring that the threat does not spread to affect everyone (Beckstead, 2015; Jebari, 2015; Maher & Baum, 2013). Such refuges might include isolated bunkers (Baum, Denkenberger, & Haqq-Misra, 2015), submarines (Turchin & Green, 2017), or small islands (Turchin & Green, 2019). Larger islands might sustain 'nodes of persisting complexity' thereby ensuring successful continuation of technological civilization (King & Jones, 2021), or provide optimal refuges against extreme pandemics (Boyd & Wilson, 2019, 2021b).

ASRS are likely to have heterogeneous impacts around the world. Islands in the Southern Hemisphere might do better than Northern Hemisphere landmasses (Ord, 2020; A Robock, 2010), because of the thermal moderating influence of the ocean. Integrated atmosphere, ocean and crop modelling supports this claim (Xia et al., 2021). Extinction risk and existential catastrophe by collapse of civilization are not thought likely to result from nuclear war (Ord, 2020). However, this conclusion seems optimistic given the remoteness of some islands, their often high dependence on trade, potential lack of food and energy self-sufficiency, and nuances of local ecological, technological, and cultural systems, which have not been analysed.

In this paper, we aimed to identify the island nations whose societies are most likely to survive a nuclear winter or other ASRS. We then aimed to apply a threshold analysis of self-sufficient food production under nuclear winter conditions to determine which islands might continue complex societal functioning when isolated. We then profiled these islands with respect to their resilience to degradation of key systems during ASRS and periods of isolation. Finally, we aimed to provide a detailed case study of one island nation and then identify how such islands might enhance their resilience to aid a global reboot of complex technological society following ASRS.

1.1 Nuclear war and other ASRS

Risk is a reflection of consequences and the uncertainties involved (Aven, 2020). There is uncertainty about the probability of nuclear war, and there is uncertainty about its consequences.

1.1.1 Probability of ASRS

In peaceful times there is a real chance of inadvertent nuclear war through human error or miscalculation, accident, component fault or compromise (Baum, de Neufville, & Barrett, 2018). In times of crisis 'triggering events' (Hellman, 2008), such as the Cuban Missile Crisis (or Russian invasion of Ukraine in 2022), or irrational leaders, further raise the risk. The probability of inadvertent nuclear war between the United States (US) and Russia has been estimated at close to 1% per annum (Barrett, Baum, & Hostetler, 2013) a figure supported by estimates considering all kinds of nuclear war (Rodriguez, 2019b). Catastrophic volcanic eruptions with similar major climate impacts (VEI 8 or above) likely occur approximately every 17,000 years (95%CI: 5,200–48,000), and those of VEI 7 and above (eg, Mt Tambora in 1815, which contributed to famines in Europe, India and China (Brönnimann & Krämer, 2016)) have a modelled recurrence rate of 1,200 years (680–2,100) (Rougier, Sparks, Cashman, & Brown, 2018). The probability that an asteroid/comet impact leads to the deaths of more than one million people is estimated at approximately $1x10^{-8}$ per annum (Reinhardt et al., 2016).

1.1.2 Consequences of ASRS

The effects of nuclear war depend on the number of bombs detonated, their targets, the amount of soot lofted into the stratosphere, the impacts of this on climate and oceans, as well as how humans respond. Cascading effects could impact every human system (Baum & Barrett, 2018).

There is great contingency and uncertainty, but devastating 'nuclear winter' lasting 5–10 years is supported in modelling studies of large US-Russia nuclear wars (Coupe et al., 2019; A Robock, Oman, & Stenchikov, 2007), and smaller regional nuclear wars (Mills, Toon, Lee-Taylor, & Robock, 2014; A. Robock et al., 2007).

A scenario where 5 teragrams (Tg) (equivalent to 5 megatonnes) of soot enters the stratosphere is possible with a regional nuclear conflict. This could lead to mean global cooling of 1.8°C and the greatest global food shortage in recent history (Jagermeyr et al., 2020; Xia et al., 2021), including severe impacts on food trade (Jagermeyr et al., 2020). In a full-scale NATO-Russia conflict, 150 Tg soot (representing the detonation of the majority of the weapons in the world’s arsenals) could reduce global agricultural production across the next several years by 80% and nearly 100% in many Northern Hemisphere countries (Xia et al., 2021). However, controversy exists around the severity of climate impacts (Hess, 2021; Alan Robock, Toon, & Bardeen, 2019), many nuclear weapons are not actively deployed, and a more likely scenario resulting from a full-scale war between the US and Russia has been estimated to be likely to produce 30 Tg soot (90%CI: 14–66) (Rodriguez, 2019a). This could still kill 30–75 million people immediately, and have severe effects on agriculture and fisheries (Rodriguez, 2019a; Xia et al., 2021). Access to export markets and supply chains could be cut (Green, 1989) with disastrous feedback effects. We list the potential effects of nuclear war in Table I.

[Table I about here: note tables are at end of document]

The impacts of a volcanic winter resulting from a Toba-sized (VEI 8) eruption might be similar, though driven largely by sulphur dioxide in the stratosphere, and may not be as long-lived (perhaps up to 5 years of significant global temperature anomaly) (Black, Lamarque, Marsh, Schmidt, & Bardeen, 2021), with some risk of millennial scale climate impact (Baldini, Brown, & McElwaine, 2015).

1.1.3 Distribution of consequences

The impacts of nuclear winter (or other ASRS) would not be evenly distributed. Physical destruction and radioactive contamination are most likely to occur in the Northern

Hemisphere. Temperature decline would be most severe in Northern Hemisphere continental land masses, and least severe over the Southern Hemisphere oceans (Coupe et al., 2019; Jagermeyr et al., 2020; A Robock et al., 2007). Crop yields may drop precipitously in China, Russia, Europe and North America but remain comparatively unaltered in the tropics where growing seasons might persist (Jagermeyr et al., 2020; Xia et al., 2021). However, only 66 of 164 countries in one study were food self-sufficient (this number declined in recent decades) (Schramski et al., 2019).

It is our hypothesis that island nations, particularly in the Southern Hemisphere, would typically suffer less from ASRS. Complex technological society on such islands might persist, and targeted preparation could increase the probability of a global recovery. We now test this hypothesis with our food threshold analysis, island profiles, and case study.

2. METHODS

2.1 Food self-sufficiency threshold analysis

To calculate the food supply for island nations under nuclear winter conditions we first identified with a literature search the most comprehensive model of food production in nuclear winter scenarios, that of Xia et al (Xia et al., 2021). This modelling covered most countries in the world, modelled crops and marine fish, and modelled six nuclear winter scenarios ranging from 5 Tg to 150 Tg. We identified all the island nations in Xia et al's analysis, and then obtained independent assessments of baseline dietary energy production (DEP) from two sources (1) peer-reviewed analysis of global food production, namely 2013 DEP (Schramski et al., 2019), and (2) our own bottom-up calculation of DEP for New

Zealand exports using the Statistics New Zealand Harmonised System for export data (Wilson, Prickett, & Boyd, 2022). We then applied the modelled calorie reduction (%) results obtained by Xia et al for the major crops and marine fish averaged over the first five years for 5, 27 and 150 Tg nuclear war scenarios, to these independent estimates of DEP. This contrasts with Xia et al's approach of applying the modelled reductions to baseline energy intake, as opposed to DEP. Consistency checks were performed by doing the same calculation using the results for combined wheat and maize production for island nations in another 5 Tg nuclear winter crop model (Jagermeyr et al., 2020). We also identified modelled changes in marine fishing for islands in nuclear winter scenarios (Scherrer et al., 2020).

To identify the island societies most likely to survive a severe ASRS we first eliminated islands with negative baseline DEP balance. We then eliminated islands whose DEP fell below a 2,200 kcal/capita/day threshold across the scenarios examined (ie, under 5 Tg, 27 Tg and 150 Tg conditions). This threshold was the same threshold used by Xia et al and represents the approximate minimum DEP for an average human to avoid losing weight (although this varies with population age-structure, average BMI and average physical activity levels) (National Research Council, 1989). For remaining islands, with surplus DEP in nuclear winter conditions above this threshold, we calculated the carrying capacity, ie, how many additional people their DEP could feed at 2,200 kcal/capita/day.

2.2 Island nation profiles across resilience factors

To identify the factors that potentially increase an island nation's resilience to the impacts of nuclear war, we performed a literature search and identified the following: a recent comprehensive model of the effects of nuclear war (Baum & Barrett, 2018), a large mixed methods study for the possible impacts of nuclear war on an island nation (New Zealand), based on 20 background papers (Green, Cairns, & Wright, 1987), three studies on island refuges in pandemic situations detailing self-sufficiency and resilience factors (Boyd & Wilson, 2019, 2021b; Turchin & Green, 2019), these studies interpreted, for the island context, the relevant findings from the literature on refuges, we also identified a study of nodes of persisting complexity in the context of GCRs, focusing on islands and detailing resilience features (King & Jones, 2021). A summary of likely impacts and resilience factors from this literature, is presented in Table II, with an aggregate of 13 key factors collated in the bottom right cell. We used these 13 factors to identify metrics which we then used to profile islands on their potential resilience to ASRS. Table III details the 13 factors relevant to ASRS resilience, the macro-indicator used to measure it, and the rationale for choosing these metrics.

[Table II about here]

[Table III about here]

2.3 Case study: New Zealand

The case study of New Zealand covered the themes of the 1987 New Zealand Nuclear Impacts Study (Cronin & Green, 1989; Green, 1989; Green et al., 1987), updated with information about New Zealand in 2022, with reference to the resilience factors just identified.

3. RESULTS

We identified 38 island nations for which Xia et al provided modelled estimates of dietary energy reduction (%) across six nuclear winter scenarios. Xia et al presented data on dietary energy intake for 15 (39%) of these islands under baseline, ‘no food trade’, and modelled nuclear winter conditions. Fifteen islands appear in Jagermeyr et al’s analysis of wheat and maize production in a 5 Tg scenario (all of which appear in Xia et al’s analysis).

3.1 Dietary energy production threshold analysis

Our secondary analysis of Xia et al’s results found the baseline energy intake of 15 island nations vs 127 non-island nations was 2,969 vs 2,885 kcal/capita/day (p = 0.52) with trade, and 2,263 vs 1,980 (p = 0.43) under 'no food trade' assumptions, ie, no statistically significant differences at baseline.

These same island nations (in aggregate) under modelled conditions continue to have an average energy intake of >2,200 kcal/capita/day in all nuclear war scenarios except 150 Tg, when the average of the 15 islands falls to 1,294 kcal/capita/day (vs 420 for non-islands) (p = 0.0012). When considered separately, only five of the 15 islands fall below a probably survivable threshold of 1,600 kcal/capita/day in the 27 Tg scenario (comparable to a likely US-Russia nuclear war, see above). Non-islands in the analysis fall below 2,200 kcal/capita/day on average even in the 5 Tg case. In Xia et al’s ‘no livestock’ 150 Tg scenario, where livestock are culled and eaten, island vs non-island intake was 1,397 vs 593 kcal/capita/day (p = 0.0015).

Furthermore, secondary analysis of Xia et al's results shows that of the 27 nations experiencing 10% reduction in energy intake, or less, in the 150 Tg (severe) scenario, 17 (63%) were island nations even though only 38/168 (23%) of the dataset were islands (note, this does not necessarily mean intake would be sufficient for any given island).

When we applied Xia et al's modelled calorie reduction (%) to the baseline DEP estimates of Schramski et al, we identified five islands (of 38) with >2,200 kcal/capita/day DEP in the 150 Tg scenario (Australia, New Zealand, Iceland, the Solomon Islands, and Vanuatu), and eight islands in the 5 Tg scenario (the preceding five plus Mauritius, Indonesia, and the Philippines). The same analysis of Jagermeyr et al's 5 Tg scenario revealed four island nations with DEP >2,200 kcal/capita/day (Australia, Indonesia, New Zealand, and the Philippines), however Iceland, Mauritius, Solomon Islands and Vanuatu were not part of Jagermeyr et al's analysis.

Theoretical carrying capacity (in addition to the current permanent population) based solely on DEP under the 150 Tg scenario, for the eight islands identified above, ranged from +85 million additional people for Australia to -61 million for the Philippines. For the 5 Tg scenario it ranged from +297 million for Indonesia to +42,000 for Mauritius. Results for these eight island nations are displayed in Table IV.

[Table IV about here]

3.2 Island resilience profiles

Table V profiles the eight islands meeting the 2,200 kcal/capita/day food threshold against the 13 resilience factors identified in the literature search.

[Table V about here]

3.2.1 Australia

Australia has the largest excess food production under simulated nuclear winter scenarios. It also scores the best, in aggregate, across the other metrics of resilience to ASRS. Australia's food supply buffer is gigantic, with potential to feed many tens of millions of extra people. Good quality infrastructure, vast energy surplus, the second highest health security in the world, and triple the defence spending of any other island in our analysis, all suggest Australia has the potential to thrive during an ASRS. That said, Australia may be a target in a nuclear war based on its AUKUS alliance, and US-aligned intelligence stations (eg, Pine Gap). For example, the latter could be targeted with nuclear explosions eg, to destroy facilities or designed to produce electromagnetic pulses (EMP). Like all the islands, Australia may be beset by creeping degradation if cut off from international trade. However, proximity to Indonesia provides a potential major regional trading partner for food, fuel, and manufactured components. Australia may be a target for refugees or invaders and would need to plan for this. Central and local governments are also increasingly focused on immediate crises (eg, droughts, floods, and wildfires) which may compete with other contingency planning.

3.2.2 Iceland

Modelling of nuclear winter indicates that Iceland may suffer less climate impact than continental Europe (-70% crop production vs eg, -99.9% for Germany in a 150 Tg scenario). The Icelandic population is well educated, there are abundant fish resources, and most electricity generation is hydroelectric. Energy self-sufficiency has risen from 50% in 1971 to nearly 90% in 2018 (International Energy Agency, 2019). On the other hand, Iceland is a member of NATO and could be a nuclear target. Volcanoes pose a long-term threat and Iceland suffered a devastating eruption in 1783. Iceland imports all its oil, used predominantly for road transportation and fishing (International Energy Agency, 2019). Nevertheless, it is starting to produce hydrogen as a transport fuel. Road transport could be minimised by relocating additional citizens to the single large city of Reykjavik (where 63% already live); however, fishing appears essential to Iceland's survival in an ASRS. Oil reserves, or additional biofuel from agricultural residues and/or hydrogen production would be an important resilience measure. With a small economy, Iceland would likely suffer from a lack of imported commodities and infrastructure degradation. However, it may have access to North America, UK and Europe, if some of these countries are not completely devastated by war, famine, or social collapse. Iceland has no military but a small coast guard and without bolstering defence capability may be vulnerable.

3.2.3 Solomon Islands and Vanuatu

The Solomon Islands and Vanuatu are examples of islands that are probably natural refuges in ASRS. With tropical geography and abundant food production, some people will almost certainly survive. Although they lack energy self-sufficiency (less than 50% in both cases), traditional and low-technology production methods are common. Although at risk of difficulties with communication, volcanic or asteroid/comet induced tsunamis, and the arrival of infectious disease, these islands are remote, numerous and innately resilient. However, neither island nation possesses a high-technology manufacturing or knowledge economy, and survivors would be unlikely to catalyse a global reboot of collapsed digital or industrial civilization. Nevertheless, they could potentially participate in trade with other nearby nations eg, Australia and New Zealand.

3.2.4 Indonesia, the Philippines, and Mauritius

Although modelling suggests that Indonesia, the Philippines, and Mauritius may not be able to produce enough food for their populations in a 150 Tg (severe) scenario, they are likely to be some of the few island nations able to do so in a 5 Tg scenario, due to the lesser climate impacts in these tropical locales. That said, diverse archipelagos likely harbour some islands that are individually self-sufficient, potentially highlighting the importance of robust local governance. There is potential for persisting regional trade between Indonesia, the Philippines and Australia. Indeed, Indonesian energy production excess (largely coal and natural gas) would cover the Philippines' shortfall, although combined oil production is still not sufficient to meet oil needs (International Energy Agency, 2019). Mauritius is severely dependent on energy imports, with lack of manufacturing capability, and potentially prone to ungraceful degradation of its digital and industrial infrastructure. Indonesia and the Philippines are both manufacturers but suffer low social cohesion and are prone to political instability and elite corruption. The Philippines additionally has low infrastructure quality. Indonesia harbours many of the world's large volcanoes from which an ASRS could originate (eg, Toba and Tambora eruptions). In a mild ASRS Indonesia has the potential, with planning, to feed many millions of refugees or populations of neighbouring countries.

3.3 Case Study: New Zealand

New Zealand is sometimes thought likely to survive a nuclear winter due to its abundant food supply and geographical location. Table V displays additional resilience factors that might support this thinking. However, 1980s studies, including a study involving 300 industry experts, government officials, a survey, and role plays with citizens, found that New Zealand was severely at risk from nuclear war due to its dependence on trade, energy imports and the intricate interdependence of societal systems (Green, 1989; Green et al., 1987; Preddey, Wilkins, Wilson, Kjellstrom, & Williamson, 1982). These concerns remain relevant today.

In a nuclear winter, even a one-degree Celsius mean temperature drop might add 15–50 additional frost days in New Zealand (Green et al., 1987). Food production could decrease 2.3% (four crops and fish) (Xia et al., 2021), to 14.2% (wheat and maize) (Jagermeyr et al., 2020) in a 5 Tg scenario, and up to 58.2% in a 150 Tg scenario (Xia et al., 2021). The 1980s models indicated that pasture growth might reduce by 34–66% in spring months according to location, or by 19–36% for the year (Green, 1989). However, this would not reduce New Zealand's food production below 2,200 kcal/capita/day, given baseline DEP of 9,570 kcal/capita/day (Schramski et al., 2019), including currently exported food totalling at least 8,150 kcal/capita/day (accounting for wastage) (Wilson et al., 2022). Diverted export dairy alone (eg, milk powder, cheese and butter) could provide 142% of dietary energy requirements in a 150 Tg scenario (Wilson et al., 2022).

Despite New Zealand's food production surplus, severe physical damage to Northern Hemisphere infrastructure (including ports, airports, energy, digital and communications infrastructure), the effects of EMP (eg, an attack on Australia), and possibly catastrophic near-100% crop failures in Europe and North America, might lead to hoarding, internal conflict, and an inability to trade. As the most isolated temperate land mass in the world, supply chain issues have plagued New Zealand before (Dennis, McGuinness, & Boven, 2015) and the country's extreme dependence on international shipping lanes concerns its Ministry of Transport (Ministry of Transport, 2022).

Road transportation is the single largest energy consumer in New Zealand (35.7% of all energy use), greater than all industry use (30.4%). New Zealand has an electric vehicle fleet currently just 1.2% of light vehicles (EECA, 2021), lacks an extensive rail network, and faces the problem of transporting goods from remote farms and between the two main islands. However, New Zealand's oil self-sufficiency has fallen to 20% (International Energy Agency, 2019), and since the 2022 closure of the only oil refinery (Piper, 2022), New Zealand is completely dependent on imported refined fuel, with just 20 days of onshore reserves (Woods, 2022). A synthetic petrol plant was closed in 1997. Milk (New Zealand's dominant agricultural product by calories) needs to be transported every day and without electric trucks or rail this requires refined fuel. The International Energy Agency has tracked New Zealand's decreasing total energy self-sufficiency from 92% in 2010 to 76% in 2018 (pre-Covid, Table V). New Zealand generates substantial hydroelectricity, but the distribution network is configured to supply 13% of the electricity to an aluminium smelter at the extreme south of the country. Furthermore, New Zealand imports many essential commodities (for example chemicals, lubricating oils, tyre rubber, valves), lacks a sophisticated manufacturing sector to produce replacement components, and has previously had to import international experts and components to repair, for example, wastewater infrastructure, the gears of an inter-island ferry, and a major fuel pipeline. All of these problems are compounded for sectors where critical operational data are stored overseas in the cloud (where New Zealand is almost entirely dependent on two suppliers). Industries such as banking could fail if data are not accessible locally, making earning and payment impossible.

Combined, these shortcomings mean New Zealand could experience catastrophic limitations in transportation (including interisland shipping), lack of fuel, or irreparable damage to infrastructure for growing, harvesting, processing, packaging, transport, and refrigeration of food. At risk also are communications or electricity infrastructure (including the single interisland high-voltage DC cable, failure of which would lead to a serious mismatch in energy production and consumption). Such failures would have devastating cascading impacts across almost all sectors impeding coordination and distribution, heightened by the need to pivot export food to the domestic market, possibly in the context of rationing, hyperinflation, or price collapse. Energy disruptions could hinder manufacturing and lead to communication systems breakdown. Lack of clearly communicated information about risks, contingencies, plans, or rationing could contribute to social destabilisation and maladaptive behaviour. Fear of scarcity, combined with psychological trauma, or concern for loved ones, could see an exodus from urban areas, absenteeism, and further degrading societal functioning.

This situation may require strict maintenance of law and order, particularly if rationing of fuel, healthcare, or even food is required. Risk of unrest is probably increased if such plans are not publicised ahead of time. Although New Zealand has committed defence spending of US$3.0 billion per annum ($592 per capita), substantially higher than many of the islands meeting the food production threshold above, it may struggle to enforce local rationing if social cohesion falters. With respect to invasion risk, New Zealand has only 9,000 active-duty military personnel. New Zealand has two naval frigates with offensive, air defence, attack helicopter and antisubmarine capability. But there is no air force strike capability.

Although superficially, when inspecting macro-indicators (Table V), New Zealand appears well-placed, systems may not be resilient to major shocks. Locally irreparable failures could lead to ungraceful degradation of essential systems, and beyond certain thresholds there could be catastrophic cascading effects in a cycle of decline to around pre-industrial levels. Even if communication is still possible, there could be a climate of mis- and dis-information, the likes of which fuelled an occupation of the grounds of the New Zealand Parliament during the Covid-19 pandemic in 2022. Without significant planning, sustaining a complex digital, industrial and modern agricultural society is not guaranteed.

It is unclear what planning exists for such cascading failures, since New Zealand's National Risk Register is classified, impeding communication of risk to the public and industry. Additionally, a summary of public consultation on the topic for New Zealand's newly mandated 'National Security Long-term Insights Briefing' did not mention the words 'nuclear' or 'volcano' (New Zealand Government, 2022), although 'food security' was mentioned in the context of climate change.

Food supply generally has been the focus of many studies into the resilience of the world to ASRS. However, the case of New Zealand shows local characteristics could lead to resilience failures and cascading harm through complex socio-ecological systems. The possibility that central government becomes ineffective is real, indeed greater local decision-making (eg, by local government) might be desirable in many scenarios. Several factors could be addressed to improve New Zealand's situation. We have compiled a number of these in Table VI, many of which would apply to any period of isolation experienced by New Zealand and many of which likely apply to other island nations. Contrary to the statement that '[i]t is hard to see why [New Zealand] wouldn't make it through with most of their technology (and institutions) intact (Ord, 2020), there are a number of paths to societal collapse in ASRS. 'Fundamental disruptions to New Zealand society would occur in the absence of direct targets or climatic change' (Green, 1989). This has implications for other islands, the ease and likelihood of coordinated upscaling of resilient food production (see below), and for global recovery.

[Table VI about here]

4. DISCUSSION

4.1 Survival, resilience, and recovery

Much research on nuclear winter has focused on climate impacts or food production and it has been thought that Southern Hemisphere island nations such as Australia or New Zealand might be relatively spared. However, studies in the 1980s identified that New Zealand could be vulnerable to a Northern Hemisphere nuclear war because of reliance on trade, increasing systems vulnerability, interdependency of sectors, and a lack of planning (Green, 1989).

Findings of the present study suggest that some island nations should be able to produce enough food for their populations even during a very severe ASRS (eg, 150 Tg soot in the stratosphere, or an equivalently large volcanic eruption). These island nations are Australia, New Zealand, Iceland, the Solomon Islands and Vanuatu. This continuing ability to feed the entire population can be contrasted with modelled reduction of food production in China, France, Russia, the UK, and the US of more than 97% (Xia et al., 2021).

However, our analysis of resilience factors, and the case study of New Zealand, indicate that risks beyond food shortages might threaten the collapse of society, and perhaps even industry or industrial agriculture. These threats are largely the cascading consequences of interruptions to trade. These risks may be most severe in those locations most suited to surviving severe ASRS, namely remote island nations with complex technological societies. Sustained nodes of digital, industrial, and agricultural complexity are not guaranteed.

It has previously been thought that nuclear winter could risk human extinction. However, this seems unlikely via direct impacts, given the islands just identified. That said, there is a difference between surviving and thriving, and there is a further difference between thriving locally and restoring or 'rebooting' a path to global technological civilisation. The literature on the impacts of nuclear war, bunkers against catastrophic risks, island refuges, and persisting nodes of complexity, identifies a set of important additional resilience factors. Islands with food may yet be susceptible due to a lack of wider resilience.

Society can be seen as an infrastructure-of-infrastructures (Jovanovic, Chakravarty, & Jelic, 2021), a complex ecological system embedded within a complex ecological system (Walker & Salt 2006). The ecological concept of resilience is one of absorbing shock without transitioning to a new state. Yet ecological-social resilience theory tells us that the effects of perturbations are unpredictable and key 'slow variables' matter. Our case study of New Zealand indicates that slow variables such as diminishing supply of refined fuel, the failure of irreplaceable components, or unravelling social cohesion, may be important drivers of state transitions. In the case of ASRS the new equilibrium may be a non-digital, non-industrial, or non-agricultural state, making recovery much more difficult.

Realistically, central government intervention is needed to prepare for severe ASRS. There must be coordination of information and communication, financial backstops, prioritisation, and plans for rationing of things like fuel, energy, health care, food, and components. Solutions are possible, but this needs to be communicated, preferably ahead of time (Table VI). Identifying weaknesses in socio-ecological systems, and investing in the resilience of islands most likely to survive might be a cost-effective route to preventing existential catastrophe.

4.1.1 Adaptations

Preparing adaptive measures ahead of time is likely more robust than relying on a ‘grace period’ of weeks or months before the impacts of ASRS begin. We have outlined a suite of adaptations that might be considered based on our case study of New Zealand, aligned with the resilience factors derived from the literature (Table VI and Supplementary Table SI). Each island nation should ideally perform its own in-depth case study.

Food adaptions will be more important for locations with limited DEP in ASRS scenarios. These might include resilient seed stockpiles of winter-hardy crops such as potatoes or sugar beets, more use of community gardens and urban farming of micro-greens (Di Gioia, Petropoulos, Ferreira, & Rosskopf, 2021), and ‘future foods’ such as micro- and macro-algae, bivalve molluscs, or insects (Tzachor, Richards, & Holt, 2021). Even if some of these ‘future foods' such as insect larvae were only used for manufacturing pet food or poultry-feed, then this could still allow for diversion of other food for humans (eg, maize for poultry going to feed humans). Marine fish stocks can also be increased pre-crisis (Scherrer et al., 2020).

Energy resilience in our case study hinged mostly on reducing imported oil dependence. Where possible, island nations might secure domestic oil production and refining capability, and increase production of biofuels, hydrogen fuels, and electric vehicle use. Energy forms are important, ie, coal/wood is typically of little value for food transportation (unless converting vehicles to wood gasifiers) and islands' energy production and consumption profiles don't often align. Distributed home or small scale hydro, wave and wind installations may be more resilient overall (relative to large turbines on wind farms vulnerable to component failure). Geothermal energy could substitute distributed solar in ASRS. Case-by-case study is warranted to ensure supply, heating, transport, and sanitation.

Islands might look to strengthen political stability and social cohesion. Broad political participation, and improving ties between communities, agencies, and organisations may have improved social resilience during previous ASRS such as the Late Antique Little Ice Age (Peregrine, 2021). The insidious creep of mis-/dis-information must be mitigated. There may be lessons from the Covid-19 pandemic, the Russian invasion of Ukraine, and other global catastrophes. Information hygiene is an important area for ongoing research and resiliency building.

Many islands may not be able to secure food and energy self-sufficiency or guarantee ongoing supply without imported components and expertise. Every effort should be made to protect ongoing trade and manufacturing. If stable complexity, cooperation, sufficient food supply and a functioning society are lost, then a refuge or bunker within the island nation might provide a last line of defence against ongoing conflict, famine, infectious disease, and other cascading catastrophes.

4.2.2 Resilient foods

Resilient food describes a combination of strategies including crop substitution and relocation, low sunlight, nutrient and water use foods, ocean foods – eg, seaweed, cellulosic sugar and single cell protein 'industrial food', and synthetic foods. A combination of these approaches might in theory feed everyone in an ASRS (Pearce, Cole, Denkeberger, Griswold, & Abdelkhaliq, 2016; Rivers et al., 2022). However, there is likely to be a low-trust, low-capability global context after nuclear war, and the immense logistical exercise underpinning resilient foods largely depends on global cooperation and coordination, ongoing optimal food trade, energy trade, and trade in expertise and componentry, as well as societal stability, intact infrastructure, functioning transport, social cohesion, and low levels of hoarding or looting.

Given the potentially severe impact of ASRS, destruction of infrastructure, and our case study of New Zealand, we are uncertain that the modelling assumptions that demonstrate 'feeding everyone' might reliably hold. Nevertheless, we encourage more work on resilient foods, particularly for islands that individually are nearly food self-sufficient in 5 Tg scenarios, such as Cuba, Kiribati, and Madagascar (between 1,600 and 2,200 kcal/capita/day).

Additionally, one resilient food solution may not fit all. For example, in New Zealand, there appears to be sufficient food production and a shortage of fuel is more pressing than a shortage of food. Biofuel production might be ramped up, and dairy production appears excessive if exports cease, so substitution of dairy for diverse food crops or biofuels might be optimal. Our research underpins the importance of regional case studies.

4.2.3 Military

During an ASRS, islands may be at risk of internal social disorder (due to food or energy shortages or inequality of access to resources to meet basic needs), the arrival of overwhelming refugees (potentially bringing infectious disease in a context of bioweapon use, or an emerging pandemic), or even invasion.

A well-communicated plan to prioritise essential functions, ensure sufficient food supply, and then to distribute resources equitably, made prior to an ASRS, might be the best defence against disorder. Sophisticated use of quarantine (eg, offshore islands) and calculations of food carrying capacity might help in managing refugees. Naval and autonomous drone units providing surveillance might be more important than army personnel. Alliances among well-placed island nations ahead of a catastrophe might secure trade resilience and discourage attack (eg, Indonesia, Australia, the Philippines, and New Zealand).

But the risks may not be as great as thought. Elites that control limited resources may stay put in other countries, and ordinary citizens would likely be unable to travel in great numbers if commercial transportation is degraded. Somewhat paradoxically, a very bad ASRS might make invasion less likely (or impossible) amid widespread devastation, food and fuel shortages, or disabled industry. New Zealand, Iceland or Mauritius may be less accessible than Australia or Indonesia.

4.2 Next steps: Rebooting complexity, cost-effectiveness, and ethics

We have not yet examined the factors that might mean some islands are better placed than others to supply the technology and expertise to help restore a functioning global technological society. This is a topic for detailed further study but all the islands we identify could yet improve their potential by harbouring information, knowledge and expertise, developing sophisticated agricultural science, and complex industries including: advanced engineering, electronics, bioscience, energy diversity, as well as just institutions.

Similarly, our study has not examined the cost-effectiveness of food security measures, resilience strategies, and investment in advanced sectors to aid civilizational recovery. These analyses should now be done. Cost-effectiveness will depend on sectoral interconnectedness and should account for co-benefits against other risks, and for business-as-usual (see Table VI). Relatively low-cost interventions might include research, communication, encouraging individual-level resilience, and identifying local resources for emergency exploitation, although high-reliability interventions might be preferred.

This analysis also leads to the moral question of whether wider humanity ought to aid a range of these disparate island nodes on behalf of future generations, perhaps especially those with effective and just governance institutions, or a culture of scientific or other epistemic robustness. Perhaps such islands might be relieved of their obligations to contribute overseas development assistance in favour of maximal home resilience and reboot capability. Such additional questions warrant thorough examination.

4.3 Limitations

We acknowledge limitations of this work, including great uncertainty around the impact of both regional and global nuclear war, and the impact of other ASRS. Furthermore, modelled estimates of reduction in food production are based on selected crops and marine fish. Some of these are imported into New Zealand and some are not grown locally, so extrapolation to the impact on total DEP is provisional. However, our findings for New Zealand are consistent with previous local studies. Nevertheless, local crop/pasture studies should be undertaken, including analysis of pasture growth (eg, grass) where dairy and meat predominate. Xia et al identify that their model may overestimate Australia's wheat production, also these authors' models assume that not all animal feed could be eaten by humans, or substituted for human consumable crops. Additionally, our threshold DEP analysis ruled out islands unable to feed their entire populations, however, prioritising food supply using lifeboat ethics might ensure proportions of populations survive, at the risk of conflict. With respect to energy, total availability aggregated as millions of tonnes of oil equivalent does not account for energy form, likely resulting in overestimated energy self-sufficiency.

We did not study sub-national islands such as Tasmania, Hainan or Hawaii, or pseudo-islands such as South Korea, nor have we analysed some islands for which food modelling in nuclear winter does not yet exist, eg, Taiwan and Singapore. Some non-island locations may exhibit resilience. For example, although they might suffer severe agricultural disruption, Denmark and Sweden top the 2022 'Global Catastrophic Risk Index' as most the resilient nations

(Dahl, Lopez-Claros, & Miller, 2022), (Australia was 6th and New Zealand was 13th). Other countries like Brazil, Uruguay or Argentina may escape the worst climate impacts and continue food production (Coupe, Bardeen, Robock, & Toon, 2020; Xia et al., 2021), however, political or social factors, and the existence of land borders may make controlled and equitable distribution difficult, or mean an influx of immigrants or invasion. Nevertheless, all such locations should be studied in detail.

Finally, although we based our island resilience profiles on published research about the impacts of nuclear war, and the characteristics of potentially good refuges, much of this work is necessarily speculative. There is uncertainty around the best metrics and future work might include multi-sector expert panels to weight metrics and gather information from additional case studies.

5. CONCLUSION AND POLICY IMPLICATIONS

There will likely be pockets of survivors around the planet in even the most severe ASRS. However, trade in food, energy, components, and expertise is needed to maximise survival chances in the face of severe climate effects and the cascading impacts across many human and ecological systems. Collapse of technological society is possible even in locations considered most likely to survive. This may seriously impede cooperation, coordination, and resilient food production.

Our case study of New Zealand shows the value of detailed local study. Some assumptions about configurations for optimal food production might not apply everywhere. Although mere survival of many people is probable (especially in the Solomon Islands or Vanuatu), without trade there is a risk of widespread technological collapse. At present there is no widely understood planning for nuclear winter or isolation from trade. This may heighten the risk of unrest in the event of an ASRS. Risk communication is critical, along with some concept that solutions are possible.

Detailed case studies should be undertaken for each of the island nations discussed above. Some islands will have more resources to invest in this and could support others to do so. Scenario exercises, simulations, walk-throughs, and red-teaming of coordination and distribution issues, across agencies and sectors, could reduce the likelihood of transition from digital complexity to pre-industrial collapse.

The most likely persisting nodes of complexity (eg, Australia, New Zealand, Iceland) should consider developing resilience measures to maximise their potential as post-catastrophe catalysts for recovery. New Zealand should update its 1980s Nuclear Impacts Study. A focus on regional trade and alliances will likely be important. However, maximising resilience should not be the only goal, cost-effectiveness analyses and prioritisation across the spectrum of intervention for prevention, resilience and recovery should occur, accounting for co-benefits beyond GCR minimisation. This analysis package should be public and overseen by an apolitical central entity such as a commissioner for extreme risks (Boyd & Wilson, 2021a), helping to ensure that efficiency considerations don't dominate over resilience.

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Table I: Possible impacts of nuclear war and other abrupt sunlight reducing scenarios

Theme	Possible impact
Health	Burn injury, flash blindness, retinal burn, haemorrhaging, embolisms, other injuries, acute radiation syndrome, direct morbidity and mortality
	Chronic health harms, illness, food poisoning, cancer, sunburn, other human health harms, patient death
	Healthcare supply chain, healthcare disruption
	Malnourishment, infectious disease
Infrastructure/ energy	Fire, infrastructure damage
	Energy supply shift (fossil fuel, geothermal, nuclear power, wind, solar)
	Damage to electronics, fibre optics, satellite disruption
	Disruption to energy supply, telecommunications, transport, mobility, emergency services, supply chains, heating/cooling
	Loss of industries
Food/water	Water supply disruption (including freezing pipes), lack of potable water, dehydration
	Consumption of stockpiles, agriculture disruption, impact on ocean foods, food price rise, crop substitutions
	Food insecurity, hoarding of food (local/national), export bans, failure to trade, food riots, global food conflict, starvation
Society	Migration, evacuation, territory abandonment, refugee arrival, loss of law & order, smaller less centralised communities
	Unemployment, reduced outdoor activity, labour shortage, disrupted financial markets, disrupted trade, long-term collapse, violent conflict, human extinction (by indirect means)
	Diplomatic reactions, military reactions, shifted norms about nuclear weapons, nuclear electricity & other risks, survivor mental health

Theme	Possible impact
Climate/ Environment	Smoke/soot, reduced sunlight, reduced temperature & precipitation, increased UV radiation, ionizing radiation, decrease in phytoplankton productivity, ocean surface temperature change, ecological harm, biodiversity loss, shifted wind, change in greenhouse gas emissions
Potentially positive incidental effects (these may fail to occur)	Reduced global greenhouse gas emissions (long-term benefit), solar radiation management stops (raises temperature – a short-term benefit), reduced development of unsafe AI, nanotechnology, biotechnology, fewer infectious diseases (isolated populations, although malnourishment could increase), resilient food production with lower environmental harms, land allocation changes
Additional ASRS Impacts	
Large volcanic eruption	Lahars, mudslides, ash, or acid rain contaminates water supply, tsunamis, massive CO_2 emissions, millennial scale climate change, extinction risk due to resulting ecosystem damage, natural or engineered pandemics, conflict & nuclear war
Large asteroid or comet impact	Global blast shockwave, incineration risk (superheated air, hot rocks), seismic effects, tsunamis, dust, climate effects, extinction risk due to resulting ecosystem damage, natural or engineered pandemics, conflict & nuclear war

Note: content of table collated from Baum & Barrett 2018, Green et al 1987, Scherrer et al 2020, Xia et al 2021, Coupe et al 2019, Mani et al 2021

Table II: Derivation of factors potentially determining survival-level resilience for island refuges in the context of abrupt sun-reducing catastrophic scenarios (eg, nuclear winter, volcanic winter)

Study	**Key factors identified**	**High level interpretation**
Effects of nuclear war model (Baum & Barrett, 2018)	Effects of nuclear war: -Physical blast/thermal effects -Ionizing radiation -Electromagnetic pulse (EMP) -Blocked sunlight -Ozone layer loss -Agriculture disruption & food insecurity -Water supply disruption -Damage to infrastructure -Transport disruption -Energy supply disruption -Health care disruption & infectious disease -Telecommunications disruption -Human perceptions -General malfunction of society -Loss of law & order -Long-term collapse	Non-combatant island countries should avoid most of the blast, ionizing radiation, and EMP effects described by Baum & Barrett. Climate impacts and cascading impacts will reduce food supply. Energy supply, water, transport, telecommunications, and other infrastructure needs to be resilient. Infectious disease could take hold. People's perceptions, and societal function/cohesion/order could be particularly important for resilience.
New Zealand Nuclear Impacts Study (island specific) (Green, 1989; Green et al., 1987) - and to some extent earlier work: (Preddey et al., 1982)	New Zealand is vulnerable in nuclear war because of: -Trade dependence -Increasing vulnerability (eg, supply of components) -Interdependence between sectors -Lack of planning -Climate disruptions (food supply) -Potential refugees -EMP impacts -Panic, lack of cooperation/cohesion -Communication vulnerabilities	A country's ability to obtain (or manufacture) essential parts/supplies is critical, as is having resilient energy, food and communication systems, social cohesion is important, EMP impacts might be important (plausibly if Australia was a target) though not guaranteed to occur.

Study	Key factors identified	High level interpretation
	-Health impacts -Energy systems (maintenance, no trade) -Transport systems (maintenance, no trade) -Financial impacts -Environmental impact	
Island refuges and pandemic risk (Boyd & Wilson, 2019, 2021b)	Island refuges scored on the following: -Permanent population size -Education -Social capital -Political risk -Distance from nearest neighbouring nation -International tourist arrivals -Number of armed forces personnel -Food self-sufficiency -Energy self-sufficiency -GDP per capita -Health security -Covid-19 deaths -Natural hazard risk -Climate vulnerability	Distance, number of arrivals, Covid-19 deaths, natural hazard risk, climate change vulnerability, are probably not the most critical factors for a 5 to 10-year ASRS. Population size and education might be useful for reboot of global civilization. Social capital, political risk, armed forces, food and energy self-sufficiency, and health security are likely important in ASRS. GDP per capita is a proxy measure.
Island refuges (Turchin & Green, 2019)	Desirable features of refuges: -Remote -Sparsely populated -Fertile -Energy -High ground -Geologically stable -Accessible by ship -Legally suitable -Defensible -Resilient to climate change	Remoteness, sparse population, high ground, geologically stable, legal suitability, and climate change resilience are probably not the most critical factors for a 5 to 10-year ASRS. Food, energy, and defence are likely to be important

Study	Key factors identified	High level interpretation
Persisting nodes of complexity (King & Jones, 2021)	Criteria scored: -Climate change risk -Carrying capacity (sufficient agricultural production) -Isolation analysis -Self-sufficiency analysis (renewable energy, manufacturing, and infrastructure)	Isolation not ideal for ASRS if trade dependent, climate change vulnerability not as important in nuclear winter. Carrying capacity (food), energy self-sufficiency, manufacturing, and infrastructure are important in ASRS.
Summary of key variables/resilience factors for ASRS across these studies		**13 important domains for resilience of islands during ASRS:** -Energy self-sufficiency -Energy form used in agriculture and food distribution available -Food energy per capita surplus (in severe ASRS conditions) -Communication, transport, & water infrastructure resilience -Access to regional trading partners -Manufacturing capability -Social cohesion -Social capital -Political stability/risk -Defence -Population size -Education -Health security

Table III: Metrics used to profile the resilience of potential island refuges in catastrophic abrupt sun-reducing scenarios

Dimension of resilience	**Metric used (source)**	**Comments and Rationale**
Food self-sufficiency	Food self-sufficiency calculated under nuclear winter conditions (DEP from Schramski et al 2019; impact of nuclear winter from Xia et al 2021)	150 Tg and 27 Tg scenarios considered Islands will need enough food production capacity to supply dietary energy per capita (2,200 kcal/capita/day) after accounting for altered climate, wastage, spoilage, ability to distribute, etc
Energy self-sufficiency	'Total self-sufficiency' in energy, International Energy Agency (2019) data for 2017 (International Energy Agency, 2019).	Energy self-sufficiency as reported by the International Energy Agency is the total energy production in millions of tonnes of oil equivalent (before exports, and aviation and marine bunker fuel are subtracted, and before imports are added) divided by the total primary energy supply (TPES, which is all energy consumed by the energy (primary) sector when producing consumable energy. Pre-Covid-19 pandemic values used.
Communication	World Bank indicator for '% of population using the internet' (most recent year for which there is data) (World Bank, 2020a)	Any one measure of communication will only be a proxy but combined with 'quality of infrastructure' (see next row) then this should be indicative of communication resilience. Reliable/robust communications that can connect everyone might mean that plans can be shared and people's behaviour is coordinated. Ideally there would be robust digital technology, independent of the global internet, with data stored locally, and offline communications possible

Dimension of resilience	**Metric used (source)**	**Comments and Rationale**
Infrastructure resilience	World Bank Development Indicators 'overall quality of infrastructure' (most recent year, derived from World Economic Forum Global Competitiveness Index) (World Economic Forum, 2019)	Food and goods will need to be distributed (roads, vehicles, electric vehicles, rail, ships, aircraft)
Access to trading partners	Assessed qualitatively based on distance from major trading partners and access to local export markets	Trade may be important for food supplies, fuels, and parts/supplies to keep critical infrastructure running
Manufacturing capability	World Bank 'share in world manufacturing export index', from UNIDO industrial performance data (World Bank, 2019)	Relative index anchored to China = 1.0 Over time replacement parts and substitutions will be needed to keep infrastructure operating, ideal is an adaptable and diverse sector
Social cohesion	Fragile States Index, average of three 'cohesion' indicators, ie, 'security apparatus', 'fractionalized elites', 'group grievance' (Fund for Peace, 2018)	Need to avoid issues of mis- and dis-information, culture wars, degraded trust, inequity
Social capital	Global Sustainable Competitiveness Index 'Social Capital' domain, includes population health, equality, crime, freedom, and satisfaction (Solability, 2021)	A society that is healthier, more trusting, free, equal, and happy, is likely to prove more stable at the onset of, and throughout a prolonged crisis

Dimension of resilience	Metric used (source)	Comments and Rationale
Political stability	World Bank Governance Indicators ‘political stability and absence of risk index’, measures perceptions of the likelihood of political instability and/or politically-motivated violence (World Bank, 2020b)	Coordination and trust in governance at the national or local level might prove particularly important for coordination of difficult logistics in the catastrophe
Defence capability	Spending in US$ at 2020 prices and exchange rates, SIPRI military expenditure database (SIPRI, 2021)	Security is needed both from external threats, and internal disorder. Food/fuel may need to be rationed/controlled/protected. Carrying capacity must not be exceeded. Maintain law and order.
Education	World Bank education data ‘at least completed upper secondary, population 25+, total (%)’ (World Bank, 2021)	Proxy for inventiveness, innovation, agricultural science, and adaptability
Health security	Global Health Security Index (GHSI) 2021 (Bell & Nuzzo, 2021)	Protection from infectious diseases/pandemics (which risk undermining fragile complexity) Key factors will be public health, sanitation, nutrition, vaccines against pandemic diseases, medical stockpiles, quarantine facilities for refugees.
Population	World Bank ‘Population Total’ data for 2020 (World Bank, 2020c)	Not necessarily a determining factor, but more people is probably more resilient – up to a point. Eg, a very large population might be a greater risk of civil war if it becomes very unequal and factionalised.

Table IV: Potential food availability in nuclear winter scenarios for the island nations most likely to remain food self-sufficient (see *Methods* for the selection process)

Key parameter	Australia	Iceland	Indonesia	Mauritius	New Zealand	Philippines	Solomon Islands	Vanuatu
Population, Total (World Bank 2020)	25,700,000	366,000	274,000,000	1,270,000	5,080,000	110,000,000	687,000	307,000
Kcal/capita/day baseline production in 2013 (Schramski et al 2019)	12,938 (highest)	11,660	4,670	2,352 (lowest)	9,569	2,454	3,385	3,280
Temperature change 150 Tg scenario, indicative, will vary by exact location & season (Coupe et al 2019)	-5.0 (worst=)	-5.0 (worst=)	-2.5	-2.5	-2.5	-2.5	-1.0	-1.0
Precipitation change 150 Tg scenario, indicative, will vary by exact location & season (Coupe et al 2019)	0	-25%	-50% (worst=)	0	-25%	-50% (worst=)	-50% (worst=)	-25%
UV index (peak first decade) 150 Tg scenario, indicative, will vary by exact location & season (Bardeen et al 2021)	35	15	40 (worst=)	35	30	30	40 (worst=)	35
Kcal/capita/day for 5 Tg scenario applying Jagermeyr et al (2019) wheat/maize reduction to all DEP	10,712 (highest)	NA	4,101	NA	8,210	2,366 (lowest)	NA	NA
Kcal/capita/day for 5 Tg scenario, applying Xia et al (2021) 4 crops plus fish reduction to all DEP	12,989 (highest)	10,145	4,586	2,272 (lowest)	9,349	2,496	3,324	3,313
Kcal/capita/day for 27 Tg scenario (Xia et al 2021), applying 4 crops plus fish to all DEP	11,463 (highest)	6,868	4,227	2,322	7,837	2,241 (lowest)	2,935	3,153

Key parameter	Australia	Iceland	Indonesia	Mauritius	New Zealand	Philippines	Solomon Islands	Vanuatu
Kcal/capita/day for 150 Tg scenario (Xia et al 2021), applying 4 crops plus fish to all DEP	9,483 (highest)	3,486	**1,854***	**1,948***	4,000	**979*** (lowest)	2,939	3,146
Fish catch change tonnes 5 Tg scenario (Scherrer et al 2020)	4,200 (best)	-9,500	-56,200 (worst)	-20,300	-22,900	-1,100	-20,200	3,500
Fish catch change per capita (kg/annum) 5 Tg scenario (Scherrer et al 2020)	0.16	-25.9	-0.21	-16.0	-4.50	-0.01	-29.4 (worst)	11.4 (best)
Additional carrying capacity in numbers of people in 5 Tg scenario (calculated)	+126,000,000	+1,320,000	+297,000,000 (highest)	+41,500 (lowest)	+16,500,000	+14,700,000	+351,000	+155,000
Additional carrying capacity in numbers of people in 150 Tg scenario (calculated)	+85,000,000 (highest)	+214,000	-44,000,000	-145,000	+4,160,000	-60,800,000 (lowest)	+231,000	+132,000

Notes: *Bolded values indicate dietary energy intake below the 2,200 kcal/capita/day threshold used in this analysis.

Table V: Factors potentially favouring resilience of island nations to nuclear winter impacts (potentially also other sun-blocking catastrophes; most favourable scores in bold; see Table II for derivation of items)

Indicator (see notes for further details)	Australia	New Zealand	Indonesia	Iceland	The Philippines	Mauritius	Vanuatu	Solomon Islands
Food self-sufficiency after 150 Tg (27 Tg) scenarios in kcal/capita/day	**9,483 (11,463)**	4,000 (7,837)	1,854 (4,227)	3,486 (6,868)	979 (2,241)	1,948 (2,322)	3,146 (3,153)	2,939 (2,935)
Total energy self-sufficiency [a]	**320%**	76%	184%	88%	49%	16%	NA	NA
Communication (% of population using the internet)	87	91	54	**99**	47	65	26	12
Infrastructure quality score from 0–7 (world ranking)	4.70 (39th)	4.76 (34th)	4.13 (68th)	**5.60 (17th)**	2.96 (113th)	4.49 (50th)	NA	NA
Access to trade (qualitative analysis only)	See text	See text	See text	See text	See text	See text	See text	See text
Manufacturing capability (share of world manufactured export index, China = 1.0)	0.042	0.0079	**0.052**	0.00057	0.025	0.0007	NA	NA
Social cohesion (low score means better cohesion)	2.5	1.8	6.7	**1.0**	8.2	2.9	NA	6.4
Social capital score (world ranking)	54.1 (31st)	56.0 (20th)	46.1 (74th)	**64.1 (1st)**	41.8 (103rd)	47.3 (69th)	36.4 (144th)	41.9 (100th)
Political stability and absence of violence – score	0.85	**1.49**	-0.50	1.39	-0.79	0.89	0.90	0.64

Indicator (see notes for further details)	Australia	New Zealand	Indonesia	Iceland	The Philippines	Mauritius	Vanuatu	Solomon Islands
Defence capability US$ military spend (per capita)	**$27,536m ($1,072)**	$3,011m ($592)	$9,396m ($34)	$0m ($0) [b]	$3,733m ($34)	$18m ($14)	NA (NA)	NA (NA)
Education (% completed upper secondary education)	**80.0**	75.1	38.1	74.1	30.5	43.6	NA	NA
Health security (GHSI 2021 score)	**71.1**	62.5	50.4	48.5	45.7	39.7	25.9	23.3
Average ranking within these 8 island nations across all above items[#]	**2.1 (1st)**	2.5 (2nd)	4.4 (4th)	2.8 (3rd)	5.8 (6th=)	4.7 (5th)	5.8 (6th=)	6.3 (8th)

Items in this table are intended to profile the possible resilience factors for island nations in ASRS scenarios, as derived from: Baum & Barrett 2018, Green 1987, 1989, Boyd 2019, 2021, King & Jones 2021, Turchin & Green 2019, see Table II (above).

[#] Note: not all data available for all islands, average rank taken only across available data for each island (rank for food was counted for 150 Tg scenario, rank for defence was taken per capita, access to trade was evaluated qualitatively and not included in island nation average rank

[a] Some values for energy 'total self-sufficiency' were calculated by the authors for some islands from the other IEA data available.

[b] Additional context for the 'zero' military expenditure of Iceland: although the country has no army, it does have an armed coast guard which includes an air defence system (the latter involving four facilities and staff). As such, the annual expenditure on these capacities is likely to be at least US$20m per year.

Table VI: Resilience factors, corresponding adaptations, and co-benefits of investments to aid persisting complexity during nuclear winter, based on the New Zealand context (see a much-extended version of this table in the Supplementary Material).

Resilience factor	Further adaptations for resilience	Business as usual co-benefits
Planning	Include ASRS and trade isolation in a public National Risk Assessment and National Risk Register (and make these transparent to the public) Connect work-streams on food security and logistics risk with ASRS under the umbrella of global catastrophic risk Ensure central responsibility and accountability for extreme risk planning (eg, a Commissioner for Extreme Risk might need powers to overcome resistance from oil/gas/agriculture industries) Repeat the 1987 Nuclear Impacts Study, conduct cost-effectiveness analyses accounting for co-benefits on climate targets, inequality, health, economy Conduct simulations/walk-throughs and red-teaming exercises and communicate plans so it is known solutions are possible	Establishing responsibility for GCR planning would benefit a range of other risks Appropriate national planning for ASRS might contribute to global cooperative risk management Overcomes systemic risk associated with just-in-time supply chains
Food self-sufficiency	Make a detailed local study of food production and distribution under nuclear winter and zero trade/scarce fuel conditions, include expected yield under pre-industrial conditions Stockpile seed (especially cold-resistant crops) and manage marine stocks to ensure surplus in times of need	Diversification of agricultural production would provide resilience against a range of food security threats Empowering communities to produce and distribute food is low cost, and a culturally inclusive approach to food security

Resilience factor	Further adaptations for resilience	Business as usual co-benefits
	Ensure agricultural machinery can run on biodiesel, clean hydrogen, or electricity Encourage community and home gardens and urban food production, and research resilient foods Improve freshwater management and reduce the reliance on irrigation for food production.	
Energy security	Incentivise distributed renewable energy supply and storage Reduce oil dependence, while re-establishing refining capability until zero-imported-oil reached (or scale biofuel/hydrogen production) Conduct a cross-sector, inter-agency simulation/role-play of zero refined fuel imports and zero imported components Formulate broad principles of allocation and rationing plans for fuel	Enhanced pathways to reducing global greenhouse emissions, reduced impact of climate change More efficient homes, cheaper more reliable electricity supply
Communication	Research and prepare communication materials in a range of formats describing plans Ensure a two-way communication process between National Risk Register and experts, businesses and the public	A national risk conversation could elicit solutions for a range of risk scenarios not just ASRS Transparent governance and free flowing official information could reduce the impact of mis-/dis-information more generally

Resilience factor	Further adaptations for resilience	Business as usual co-benefits
	Invest in a first layer of redundancy across key communications infrastructure, ensure local internet independence, and ability to 'nowcast' information	
Infrastructure quality	Overcome underinvestment in infrastructure in New Zealand and audit critical locally-irreplaceable failure points (especially for energy, water, agriculture, transport, communications, and data storage) Conduct an audit of critical infrastructure susceptible to a severe EMP impact, stockpile critical replacement components Develop a New Zealand 'digital twin' to study the cascading impacts of breakdowns or failures of infrastructure (ie, a virtual representation of society/economy enabling simulation to test interventions) Strengthen the rail network, invest in electric/hydrogen powered transport and first layer redundancies for key infrastructure	Infrastructure investment may lead to economic opportunities Digital twin development could help study and optimise a range of societal systems Resilience to EMP may benefit solar flare scenarios Audits of critical infrastructure could pre-empt 'ordinary' failures and reduce systemic risk, such as that posed by having only four undersea fibre optic connections to the internet, and dependency on just two international cloud data hosts.
Access to trade	Reduce reliance on Northern Hemisphere export markets by diversifying regionally Ensure shipping infrastructure available for local/regional trade Australia and New Zealand could cooperate to maximize diversity	Reduction in costs of trade, shortened, more reliable supply lines

Resilience factor	Further adaptations for resilience	Business as usual co-benefits
Manufacturing capability	Recycle more locally and commission a study on New Zealand's manufacturing capabilities under the strain of ASRS	Local manufacturing could reduce carbon footprint of industry and provide local jobs
Social cohesion	Support inbuilt cultural resilience especially in Māori and Pasifika communities Actively work to overcome mis/dis-information (eg, regulation of tech platforms, changing algorithmic incentive structures) Conduct research on the drivers of social breakdown	Lowering the temperature on social media and/or reducing the 'perception gap' between opposing groups might help alleviate tensions in normal times (eg, around Covid-19 policies, election campaigns, etc)
Social capital	Invest in general measures that enhance population health, freedom, and satisfaction, and reduce crime and inequality	Factors such as health, satisfaction and lower crime meet day-to-day goals of government
Political stability	Strengthen politically neutral capacities in the public sector for analysing and managing extreme risks Strengthen capabilities of local government and indigenous governance (iwi-based organisations [large Māori social units/tribes]) Develop some rules for resource access and prioritisation (with a high degree of public involvement)	New Zealand is politically comparatively stable at present, but enhanced risk assessment and local governance would improve management across a range of risks
Defence capability	Security may require investment in drones and surveillance, fighter jets, or alliances with other potential island refuges such as Australia, Indonesia, or the Philippines	Increased regional security and efficiency gains (if some inter-operability and standardised equipment)

Resilience factor	Further adaptations for resilience	Business as usual co-benefits
Education	Bolster school education by meeting current curriculum aims through learning examples relevant to ASRS Improve public knowledge by making the National Risk Register open access and providing a facility for two-way communication with the public and experts on risks	A more scientifically literate population likely benefits the economy and aids wise policy decisions Improved general knowledge of risk and resilience benefits 'ordinary' risks and policy areas
Health security	Build on Covid-19 success and grow New Zealand's score against GHSI benchmarks, include focus on resisting novel infectious threats (bioweapons, engineered pathogens) Invest in a national Public Health Agency as part of ongoing health reforms	Increased resilience to future pandemic threats Improved public health and longer-lived population improves well-being and social capital