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ORIGINAL ARTICLE

# Mitigating imported fuel dependency in agricultural production: Case study of an island nation's vulnerability to global catastrophic risks

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**Abstract**

A major global catastrophe would likely disrupt trade in liquid fuels. Countries dependent on imported oil products might struggle to sustain industrial agriculture. Island nations importing 100% of refined fuels are particularly vulnerable. Our case study aimed to estimate the agricultural land area and biofuel volumes needed to feed the population of New Zealand in the absence of trade. Results showed that stored diesel would quickly be exhausted with ordinary use (weeks) and even with strict rationing (months). To preserve fuel, we found that farming wheat (requiring as little as 5.4 million liters [L] of diesel per annum) was more fuel-efficient than potatoes (12.3) or dairy (38.7) to feed the national population under a climate-as-usual scenario. In a nuclear winter scenario, with reduced agricultural yields, proportionately greater diesel is needed. The wheat would require 24% of current grain-cropped land, and the canola crop used as feedstock for the required biofuel would occupy a further 1%–7%. Investment in canola biodiesel or renewable diesel refineries could ensure supply for the bare minimum agricultural liquid fuel needs. Were subsequent analysis to favor this option as part of a fuels resilience response and as a tradeoff for routine food use, expansion in refining and canola cropping before a catastrophe could be encouraged through market mechanisms, direct government investment, or a combination of these. Logistics of biofuel refining scale-up, post-catastrophe, should also be analyzed. Further, biodiesel produced in normal times would help the nation meet its emissions reduction targets. Other countries should conduct similar analyses.

**KEYWORDS**

agriculture, biodiesel, biofuel, diesel, food security, global catastrophic risk, nuclear war, nuclear winter, resilience, sunlight reduction, trade disruption, volcanic winter

## 1 | INTRODUCTION

Global catastrophic risks have the potential to cause civilization collapse, and some may threaten human extinction (Bostrom & Cirkovic, 2008). These risks include nuclear war, extreme pandemics, technological catastrophes, massive volcanic eruptions, asteroid/comet impacts, or solar flares, among others. Collectively, these risks are not improbable, as suggested by a 2023 forecasting study, with superforecasters, non-domain experts, and the public all ranking nuclear catastrophe as the most likely catastrophic risk (4%–10% chance of killing >10% of the global population by 2100) (Karger et al., 2023).

A global catastrophe could cause immense disruption to global trade (Boyd & Wilson, 2022; Green, 1989; Mani et al., 2021). Major trade disruption could lead to shortages of critical commodities, such as liquid fuels, upon which much food production and distribution depend. Countries without the ability to produce petroleum fuels or without sufficient and accessible emergency stores risk rapidly depleting their stocks unless alternative energy is available, with food production and supply a key priority.

Island nations may be particularly susceptible to trade disruption, and many are high per capita consumers of, and net importers of, oil and petroleum products (e.g., Iceland, Australia, Taiwan, Ireland, New Zealand, and Japan; see Table 1).

  

**TABLE 1** Examples of OECD Islands and their dependence on imported oil products as reported by the IEA (International Energy Agency, 2021).

| Island nation (OECD) | Oil products[a] imported (2019) (PJ) | Oil products exported (2019) (PJ) | Net oil product import dependence (imports minus exports, 2019) (PJ) |
|---|---|---|---|
| New Zealand | 119 | 5 | 114 |
| Iceland | 38 | 0 | 38 |
| Australia | 1272 | 111 | 1161 |
| Ireland | 257 | 62 | 195 |
| Japan | 1719 | 798 | 921 |

Abbreviation: PJ, petajoules.

[a]Oil products comprise refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes, petroleum coke, and other oil products.

New Zealand consumed 16 MWh/capita in oil products, Japan 15 MWh, and Iceland 26 MWh in 2022 (Our World in Data, 2022). Being such a critical and highly in demand product, there is an argument for regulation or other measures aimed at catastrophe resilience. The Icelandic Ministry of Transport has investigated the logistics of locally producing biofuels from canola to supply that nation's essential shipping industry, finding that it could be feasible and cost-effective (Bernodusson, 2018).

The importance of considering island nations goes beyond the usual low-probability/high-impact reasoning for general interest in global catastrophic risk. In some catastrophe scenarios, islands like New Zealand may be especially likely to survive (Boyd & Wilson, 2019; King & Jones, 2021); these scenarios may include nuclear winter and pandemics (i.e., relatively important global catastrophe scenarios). Therefore, the during-catastrophe functionality of these islands may be important not just for their own sakes, but for the sake of the overall survival of human civilization, or even the human species. Food production is of course important to the functionality of any human population, and fuel supply is likewise important for food production. That makes the investigation of food and fuel supply within islands during a global catastrophe of potentially crucial significance to the survival of human civilization and the species.

Taking the example of New Zealand, we see that this country has a huge food production excess, exporting more than 3.9 times its per capita dietary energy requirements at more than 34,100 kJ/person/day (Wilson, Prickett et al., 2023). Sustaining the ability to export food is essential to the two thirds of countries that are net food importers (Schramski et al., 2019). Furthermore, when extrapolating from estimates of the export/domestic market split (Soliman & Greenhalgh, 2020), this country produces an additional estimated 13,600 kJ/person/day of dietary energy for the domestic market.

However, data from 2019 (pre-COVID-19 disruptions) showed this level of food production consumed approximately 295 million L of diesel and 33 million L of petrol annually for off-road (e.g., on-farm) uses, including agricultural vehicles and machinery (Energy Efficiency & Conservation Authority, 2021). This is in addition to on-road liquid fuel consumption to transport the produce. In total, the entire New Zealand economy consumed 3.701 billion L of diesel in 2019 (pre-COVID-19) for all purposes (Energy Efficiency & Conservation Authority, 2021).

Most liquid fuels consumed in New Zealand are imported from refineries in Singapore, South Korea, and Japan (MBIE, 2023b), which in turn are dependent on crude oil deliveries from distant sources, such as Saudi Arabia. New Zealand industry and agriculture are completely dependent on imports of these liquid fuels.

Recognizing the risk of diesel supply disruption, the New Zealand National Emergency Management Agency produced a National Fuel Plan (National Emergency Management Agency, 2020). This plan specifies "critical fuel customers" (including, e.g., emergency services, health care, and food distribution), but not the fuel volumes needed to support each essential service, and agricultural machinery does not appear to be included. This is possibly because the plan does not explicitly contemplate long-term (months/years) disruption.

Compounding concerns around liquid fuel supply are concerns about reduced agricultural yield during an abrupt sunlight reduction scenario (ASRS) resulting from catastrophes such as climate altering volcanic eruption (e.g., of magnitude equaling or exceeding that of the 1815 Tambora eruption; Wilson, Valler, et al., 2023), or due to quantities of soot that could be injected into the stratosphere by firestorms in a nuclear war, resulting in a nuclear winter. Such processes could cool the planet and increase the number of frost days (Coupe et al., 2019; Jagermeyr et al., 2020; Xia et al., 2022). These climate impacts might require reprioritization of agricultural production resources (Wilson, Payne et al., 2023), to favor resilient foods (Rivers et al., 2022), in order to maintain the quantity of food needed for domestic consumption.

Disruptions to fuel trade and/or the climate effects of volcanic or nuclear winter could lead food-exporting countries to scale back production of excess export foods to preserve their fuels for domestic food production. This could have major impacts on global food supply, further compounding trade catastrophe. Countries could attempt to optimize domestic food production by focusing on food products that minimize liquid fuel consumption per food energy output.

New Zealand, for example, may find that continuing production of dairy products that would ordinarily be exported may not be optimal in a global catastrophe where the shipping of milk solids is not possible and dairy production consumes a lot of liquid fuel. Increasing production of very high per-hectare (ha) food energy crops, such as potatoes, might make much more efficient use of limited liquid fuel. Additionally, catastrophe conditions (such as abrupt sunlight reduction due to volcanic or nuclear winter) could mean that producers need to substitute current practices with crops more optimized for these conditions. Wheat production in the New Zealand setting has been suggested as a particularly efficient strategy in the context of a nuclear winter due to wheat's relative efficiency (dietary energy per unit of cropping land) and hardiness to frosts (Wilson, Payne et al., 2023).

Local production of biofuels, such as biodiesel or renewable diesel, would allow some level of agricultural production to be maintained once stored diesel is exhausted. High biofuel use is possible with Finland aiming for 34% blending of biofuel in diesel by 2030 (International Energy Agency, 2022). On the other hand, some remote vulnerable countries produce very little domestic biofuel. New Zealand's biofuel production has accounted for just 0.1% of liquid fuel needs (Scion, 2018), and more recently, a Sustainable Biofuels Obligation Bill was abandoned by the New Zealand Government (MBIE, 2023a).

Given the issues just described and examining the case study of New Zealand, a particularly remote nation completely dependent on liquid fuel imports, we aimed to estimate the minimum volume of liquid fuel needed to sustain on-farm agricultural processes and transport produce to processing facilities in (i) a no trade scenario and (ii) a no trade scenario with severe nuclear/volcanic winter to feed the national population. We further aimed to determine how much biodiesel feedstock, how much land for growing it, and how much biofuel refining capacity is needed to sustain these essential agricultural processes. We estimated these requirements in terms of tonnes of seed and liters of fuel processed.

## 2 | METHODS

We determined (i) the annual food energy requirements for the New Zealand population, (ii) the volume of three staple agricultural products (wheat, potatoes, and dairy milk) required to supply those food calories, and (iii) how much diesel fuel is required to produce these foods. We then compared this volume of diesel to current New Zealand diesel consumption and storage. Finally, we determined how much biofuel feedstock would need to be produced locally to supply this volume of liquid fuel, both in baseline climate conditions and in a severe nuclear winter. The inputs to our model are listed in Table 2. Quality data exists for New Zealand quantifying food calories, agricultural production, and fuel consumption, but the climate, agricultural, and societal impacts of nuclear war are far more uncertain, as discussed below. We further discuss study limitations in Section 4.6 at the end of the article.

### 2.1 | Food energy requirements

We previously calculated the food energy and protein consumed by the New Zealand population to be 8686 kJ per person per day (16.2 trillion kJ/year) (Wilson, Prickett et al., 2023) and 81 g per person per day (151.2 billion g/year) (Wilson, Payne et al., 2023), respectively. This calculation was based on what is currently consumed as per a national nutrition survey (University of Otago & Ministry of Health, 2011) and the characteristics of the 2021 New Zealand population (Stats NZ, 2022b).

### 2.2 | Agricultural products

We focused on three agricultural products in turn, assuming for demonstration that each product alone was being used to feed the whole population. The products were selected for their relevance, dairy milk solids (i.e., cow milk processed into milk powder by drying), potatoes, and wheat, all of which are currently produced in New Zealand in significant quantities. Dairy milk solids were chosen because they easily account for the largest proportion of food calories produced in New Zealand (Wilson, Prickett et al., 2023). Potatoes are a high-yield crop in terms of production per ha (Reid & Morton, 2019). Winter wheat was found in a modeling study to be the most efficient crop for feeding New Zealand's population in a nuclear winter scenario (Wilson, Payne et al., 2023). This study assumed an increased frost period and optimized food for land use.

We sourced industry reports of New Zealand agricultural practice and production to determine the number of hectares farmed and average yields under business-as-usual to contextualize our results. We determined the minimum hectares to be farmed for each crop to provide the New Zealand population's food protein and energy needs. In the case of dairy and wheat, this meant obtaining minimum food energy, and in the case of potatoes, the minimum land area was determined by protein content. We calculated the mass of each minimum harvest so we could estimate minimum transport liquid fuel requirements.

### 2.3 | Liquid fuel requirements

We estimated the diesel consumption per ha for dairy farming by dividing total dairy sector diesel consumption reported by the New Zealand Energy Efficiency and Conservation Authority (EECA) (95 million L/annum in 2019) (Energy Efficiency & Conservation Authority, 2021), by the num-

**TABLE 2** Model inputs.

| Variable | Value | Source and comments |
|---|---|---|
| **Nutrition** | | |
| New Zealand (NZ) population (2021) | 5114,800 | Previously calculated (Wilson, Prickett et al., 2023) |
| Per capita food energy intake | 8686 kJ/day | Previously calculated (Wilson, Prickett, et al., 2023) |
| Per capita protein intake | 81 g/day | Previously calculated (Wilson, Payne, et al., 2023) |
| Population food energy intake | 16.2 trillion kJ/annum | Calculated in model from rows above |
| Population protein intake | 151.2 billion g/annum | Calculated in model from rows above |
| Potato food energy | 2360 kJ/kg | NZ Institute of Plant and Food Research (2022); |
| | | We note variation across three nutritional databases (NZ, Australia, and USA), the NZ "raw, with skin" ranges across 2130–2420 kJ/kg, and we have used the value for one common type of potato |
| Potato protein | 20 g/kg | NZ Institute of Plant and Food Research (2022) |
| Wheat food energy | 14,000 kJ/kg | NZ Institute of Plant and Food Research (2022) |
| Wheat protein | 134 g/kg | NZ Institute of Plant and Food Research (2022) |
| Milk solids food energy | 20,500 kJ/kg | NZ Institute of Plant and Food Research (2022) |
| Milk solids protein | 302 g/kg | NZ Institute of Plant and Food Research (2022) |
| Milk liquid to milk solid | 11.1 L/kg | Livestock Improvement Corporation (2020) |
| Milk mass | 1.03 kg/L | Online conversion tool (CoolConversion, 2023) |
| **Food production** | | |
| Current NZ horticultural land | 132,717 ha | Stats NZ (2021) |
| Current NZ grain land | 487,783 ha | Stats NZ (2021) |
| Current NZ cropped land | 620,500 ha | Sum of two rows above |
| Potato current crop area (NZ) | 9450 ha | Horticulture New Zealand (2022) |
| Potato yield | 90,000 kg/ha | Mid-point of NZ study data (Reid & Morton, 2019) |
| Potato diesel requirement | 118 L/ha | Chen et al. (2015) |
| Wheat current crop area (NZ) | 43,500 ha | Stats NZ (2022a) |
| Wheat yield | 9900 kg/ha | New Zealand Grain and Seed Trade Association Inc (2020); NZ data for 2020 (including wheat currently used for animal feed) |
| Wheat diesel requirement | 43 L/ha | Australian national average (Chen et al., 2015) |
| Dairy current production area (NZ) | 1,730,000 ha | Livestock Improvement Corporation (2020) |
| Dairy yield (milk solids) | 1232 kg/ha | NZ national average dry milk solids in 2020/21 (DairyNZ, 2023), which corresponds to 13,675 L/ha milk |
| Dairy diesel requirement | 55 L/ha | Calculated from national dairy sector off-road diesel consumption (Energy Efficiency & Conservation Authority, 2021), and dairy production area (above) |
| Canola seed yield | 3100 kg/ha | Food and Agriculture Organization of the United Nations; Conservative estimate, an NZ farm has reported an "unofficial new world record" yield of 6.3 t/ha (Tipa, 2015) |
| Canola current crop area (NZ) | 710 ha | Calculated from 2200 t NZ production in 2020 (Tridge, 2020), and yield per ha (above) |
| Canola diesel requirement | 62 L/ha | Baquero et al. (2011) |
| Canola seed to biodiesel yield | 0.4 kg oil/kg seed | Information from an NZ refinery: Pure Oil NZ. At this refinery "the crush plant has capacity to process 90 t of seed a day, producing 36 t of oil and 54 t of meal" (Chalmers, 2015). |
| | | Assumes 1:1 ratio of canola oil to biodiesel volume |

(Continues)

**TABLE 2** (Continued)

| Variable | Value | Source and comments |
|---|---|---|
| | | An adjustment made for an L of canola oil weighing 0.909 kg (USDA data) (US Department of Agriculture) |
| Canola biodiesel energy content | 0.9 (compared to fossil diesel) | The energy density of canola-derived diesel (relative to fossil diesel) can vary depending on the production process, e.g., one source cites −8.53% for biodiesel and −4.65% for renewable diesel (JD Supra, 2021) |
| | | Our adjustment of −10% should therefore be seen as conservative |
| Reduction in NZ agricultural yield due to severe nuclear winter | 61% | Xia et al. (2022); this is for the most severe nuclear war scenario with 150 Tg of stratospheric soot, with modeling across four crops and marine fish for NZ, applied to the nuclear winter scenario calculations for food yield and biofuel feedstock yield |
| **NZ diesel statistics** | | |
| National diesel consumption | 3.701 billion L/annum | Energy Efficiency and Conservation Authority (2021) |
| Diesel storage reserve | 212.9 million L | Calculated in model: 21-day proportion of annual consumption (21-day government diesel storage mandate) (MBIE, 2022) |
| Diesel storage reserve including government storage | 283.9 million L | 28 days of annual consumption (includes the above plus 7 days government procured storage) |
| NZ off-road diesel consumption (agriculture) | 295 million L/annum | Energy Efficiency and Conservation Authority (2021) |
| NZ off-road diesel consumption (dairy) | 95 million L/annum | Energy Efficiency and Conservation Authority (2021) |
| **Transport** | | |
| Wheat payload mass | 34,500 kg | Trucks vary in payload size, analysis based on Scania Hino 700 truck with NZ permit for 53 t gross vehicle mass and a 34.5 t payload (Verran, 2023) |
| Potatoes payload mass | 34,500 kg | As above |
| Tanker volume (for liquids transport) | 28,000 L | Fonterra NZ standard tanker (Chandar, 2022) |
| | | The same volume tanker was assumed for transporting biodiesel |
| Distance to transport produce | 20, 50, and 100 km | We tested three different distances, assuming where possible (North and South Islands) land use close to processing facilities is prioritized |
| Fuel economy by gross vehicle mass (GVM) | 0.549 L/km | GVM > 30,000 kg (heaviest category), NZ real-world study (Wang et al., 2019) |

ber of hectares of dairy production in New Zealand (1.73 million ha in 2019) (Livestock Improvement Corporation, 2020). The result (55 L/ha) was comparable to a previous estimate for Australia by the Australian Government (52 L/ha in Australia) (Chen et al., 2015).

For wheat and potatoes, the EECA report did not provide sufficiently fine-grained data to estimate per ha diesel consumption, so we sourced data from an Australian report benchmarking energy use on farms (Chen et al., 2015). This report provided Australian national averages for per ha diesel consumption in the production of wheat (43 L/ha) and potatoes (118 L/ha). These estimates of liquid fuel requirements include agricultural processes from land preparation through to and including harvesting.

In addition to fuel required for growing/production, products must be transported from farms to any additional processing sites and then distributed to citizens. On-road liquid fuel requirements were calculated by determining the minimum number of trips needed to move the mass of agricultural product an average of 20, 50, or 100 km (round trip) to processing sites.

We accounted for the capacity of transport vehicles (e.g., many milk tankers in New Zealand standardly carry 28,000 L, and although the payload of grain and potato trucks will vary, we based calculations on a Scania Hino 700 truck with New Zealand permit for 53 t gross vehicle mass and a 34.5 t payload; Verran, 2023). We also accounted for the fuel efficiency of heavy trucks in New Zealand, which has been estimated to average 0.549 L/km in real-world conditions (for the highest weight category of trucks) (Wang et al., 2019). Trucks will typically be empty at the start of the outward journey and fully laden by return.

## 2.4 | Nuclear winter scenario

Additionally, if the cause of liquid fuel trade disruption involves a nuclear war and subsequent nuclear winter, or other ASRS, crop yields may be reduced with a correspondingly higher minimum number of hectares needed to produce required food energy.

Information about nuclear winter comes from theoretical modeling, albeit supported by empirical observations of firestorms, soot lofting in forest fires, and volcanic impacts. More severe case assumptions about nuclear winter assume 150 teragrams (Tg, the same as megatonnes) of soot reach the stratosphere. However, controversy exists around the severity of climate impacts that a nuclear war might cause (Hess, 2021; Robock et al., 2019), with several authors arguing it would be considerably less than 150 Tg. Firestorms may be limited, and the number of detonations may be fewer than modeled as many nuclear weapons are not actively deployed. Models of nuclear war between India and Pakistan often consider just 5 Tg of stratospheric soot (Jagermeyr et al., 2020), or less than this (Hess, 2021), and a plausible scenario resulting from a full-scale war between the United States and Russia has been estimated to be likely to produce 30 Tg stratospheric soot (90%CI: 14–66) (Rodriguez, 2019). There is no scientific consensus on the maximum severity of any nuclear winter, so for this initial study of food and energy implications, we considered two scenarios: first, a global catastrophe that disrupts trade but leaves climate unchanged, and second, a nuclear winter scenario where 150 Tg of soot enters the stratosphere. We chose the latter because it is on the high end of published estimates, representing a relatively severe nuclear winter scenario.

To understand the potential extra liquid fuel needed for off-road agricultural processes in such circumstances, we applied the crop yield reduction estimated for New Zealand by the most comprehensive study of the impact of nuclear winter on agriculture to date (Xia et al., 2022). In this modeling study, 5 Tg of stratospheric soot was estimated to reduce New Zealand's crop yield by 7.9%, with 61% reduction in a 150 Tg scenario, due to reduced solar radiation and reduced precipitation. Xia's analysis emphasizes that the impact of nuclear winter is very uncertain potentially causing single digit through to near total reduction in crop yield (varying by region and scale of conflict). Although we analyze just one scenario, policymakers must deal with uncertainty as we discuss in Section 4.6.

Simple extrapolation of the 61% reduction reported by Xia et al. would mean 2.6 times more land needs to be farmed for the same food calorie or protein yield, or volume of biofuel feedstock. For parsimony, we assume that 2.6 times the land requires 2.6 times the fuel consumption. Less fuel might be used if fuel sparing "no till" agricultural methods are employed, or more land might be needed if yield is even lower due to shortages of fertilizers, agrichemicals, or other industrial inputs and poorer land quality. We discuss these uncertainties in Section 4.

## 2.5 | Liquid fuel sources

We compared our findings for the minimum volume of liquid fuel needed to produce enough food calories and protein through farming wheat, potatoes, or dairy to feed the New Zealand population, with the sources and supplies of diesel in New Zealand. The report by EECA estimates that 3.701 billion L diesels were consumed in New Zealand in 2019 (a year unaffected by disruptions due to the COVID-19 pandemic). The New Zealand Ministry of Business Innovation and Employment reported that 134.55 PJ (petajoules), approximately 3.5 billion L, of diesel was imported to New Zealand in 2022 (MBIE, 2023b), and the discrepancy between this import figure (lower) and the 3.701 billion L consumption estimate provided by EECA (higher) is likely due to some domestic refining at the Marsden Point Refinery, which closed in April 2022.

In 2022, the New Zealand Government announced plans to mandate that petroleum suppliers maintain a 21-day onshore reserve store of diesel, whereas the government plans to procure an additional 7-day' onshore supply (MBIE, 2022). We estimated the volumes of diesel intended to be held in these 21- and 28-day reserves as fractions of annual national consumption to allow comparison with our results on liquid fuel minimum requirement for food production. This proposed 28-day storage totals approximately 284 million L (see Table 2).

Another potential source of liquid fuel is domestically produced biofuel. A key biofuel feedstock, canola (rapeseed), is grown in commercial quantities for food oil production, and it is also a relatively frost resistant crop (Wilson, Payne et al., 2023). Therefore, we focused on canola as a relatively feasible example of where New Zealand might source biodiesel feedstock in a no trade scenario. We estimated how much land would need to be dedicated to feedstock production (assuming appropriate biodiesel refining capability existed) to supply the volume of liquid fuel needed to support minimum food production (for wheat, potatoes, or dairy as above).

We obtained data on canola seed yield per ha (Food and Agriculture Organization of the United Nations) and the yield of canola oil from seed at a New Zealand canola food oil processing facility (Chalmers, 2015). Diesel consumption for canola production was obtained from the Australian farm

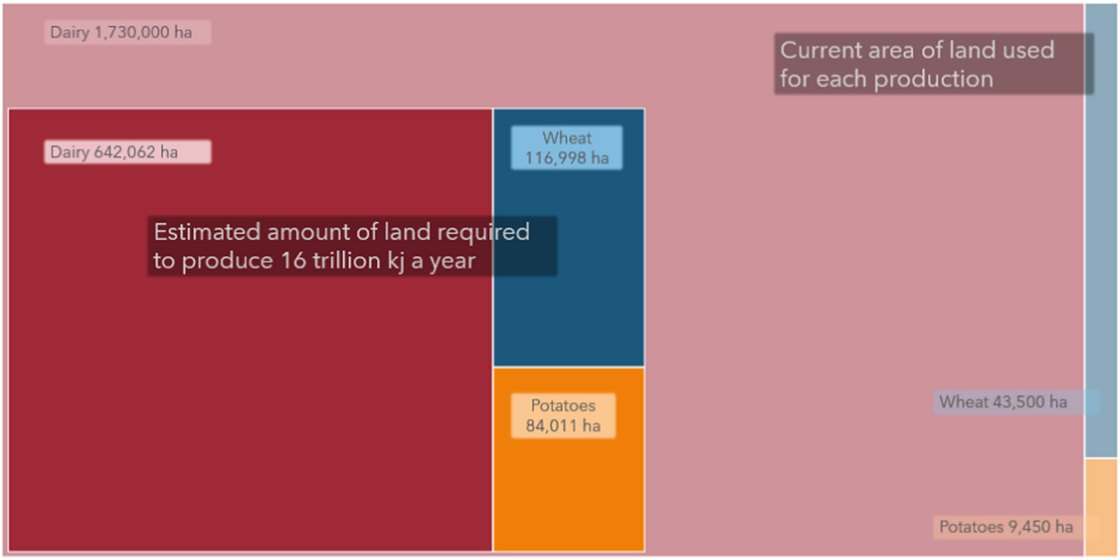


**FIGURE 1** Land area requirement (ha) comparing current production mix (outer border—includes area behind colored boxes), with minimum land area needed to support the New Zealand population in the baseline (i.e., no nuclear winter) scenario (colored boxes—note, only one colored region is needed to equate with national dietary protein and energy intake).

energy benchmarking report as above (Chen et al., 2015). An adjustment of 10% was also made for the potentially lower energy density of canola-based biodiesel versus fossil diesel (see Table 2). We also estimated the area of canola production (ha) needed in turn to produce the biofuel needed to support the canola farming itself.

We calculated the volume of liquid fuel needed to prepare and harvest canola, transport it to a refinery, and then transport the canola biodiesel to farms. This was the sum of:

- Production of canola: (ha canola × L/ha to produce)
- Transport of canola seed to refinery: ((canola seed kg/ha × ha)/(max transport load)) × (km × L/km)
- Transport of biodiesel to wheat/potato/dairy farms: (total biodiesel yield/max tanker load) × (km × L/km).

All relevant model inputs are listed in Table 2.

## 3 | RESULTS

Table 3 presents results for the three food products, including the minimum land area that would be required for each product to feed the entire New Zealand population, the off-road (on farm) diesel fuel consumption to produce the food, the minimum diesel required to transport the food from farm to processing facilities and therefore total diesel requirement to ensure that the population can be fed under baseline climate-as-usual conditions, and also in severe (150 Tg) nuclear winter conditions.

Under normal climate conditions, approximately 117,000 ha of wheat, 84,000 ha of potatoes, or 642,000 ha of dairy are needed (Figure 1). This rises to 300,000 ha, 215,400 ha, and 1.65 million ha, respectively, under a severe nuclear winter scenario (150 Tg) (Figure 2). Minimum diesel requirement ranges from 5.4 million L/annum (wheat, 20 km transportation, baseline climate) to 107.6 million L/annum (dairy, 100 km transportation, 150 Tg scenario) to supply these food sources in these scenarios.

Table 4 displays the crop area of canola required as a feedstock if the liquid fuel requirements in Table 3 were to be obtained from domestic canola-based biodiesel alone. The cropping area of canola required for biodiesel ranges from 4398 to 224,765 ha depending on the climate scenario and food product analyzed.

Production of the canola feedstock in Table 4 would in turn require additional liquid fuel. We calculated this by accounting for liquid fuel needs per ha during canola production, transport of canola seed to a refinery, and transport of refined canola biofuel back to canola farms. In the case of the "baseline, 20 km, wheat" scenario, this requires 5.17% more canola crop (228 ha) in addition to that in Table 4 (see Table 5). Across all scenarios, an additional 5.17%–14.54% of canola feedstock land area (228–32,675 ha) is needed for the production of the canola itself. This additional canola is recursively needed (i.e., another 5.17% of the 5.17% to produce that canola, etc.) but additional iterations are ignored for the purposes of our modeling after the first approximation.

### 3.1 | Comparison to current cropping

These results can be expressed as proportions of currently cropped land in New Zealand. In the baseline climate (no nuclear winter) scenario, the farmed area of wheat required

**TABLE 3** Estimates of land area and stored fossil diesel requirements per year to produce enough wheat, potatoes, or dairy product and to truck edible product to urban markets (at the volume required to feed all New Zealand citizens for a post-catastrophe year during which no fuel imports occurred).

| Variable | Wheat | Potatoes | Dairy (milk) |
|---|---|---|---|
| Current NZ production (land used) | 43,500 ha | 9450 ha | 1730,000 ha |
| Production to provide food energy and protein for entire NZ population (baseline climate scenario) | 116,998 ha | 84,011 ha | 642,062 ha |
| Production to provide food energy and protein for entire NZ population (150 Tg nuclear winter climate scenario) | 299,995 ha | 215,412 ha | 1646,312 ha |
| Off-road diesel requirement (baseline climate scenario) | 5030,910 L | 9913,250 L | 35,257,724 L |
| Off-road diesel requirement (150 Tg scenario) | 12,899,770 L | 25,418,589 L | 90,404,422 L |
| Production volume (to feed NZ population, as above) | 1158,279 t | 7560,953 t[a] | 8780,322,418 L |
| Trips needed to transport produce (truck or tanker) | 33,573 trips | 219,158 trips | 313,583 trips |
| Transport diesel required (assuming 20 km round trips) | 368,635 L | 2406,356 L | 3443,141 L |
| Transport diesel required (assuming 50 km round trips) | 921,587 L | 6015,889 L | 8607,852 L |
| Transport diesel required (assuming 100 km round trips) | 1843,175 L | 12,031,778 L | 17,215,704 L |
| **TOTALS** | | | |
| Total: Baseline climate scenario, minimum diesel required (off-road + transport) 20 km | 5399,545 L | 12,319,605 L | 38,700,865 L |
| Total: Baseline climate scenario, minimum diesel required (off-road + transport) 50 km | 5952,498 L | 15,929,138 L | 43,865,576 L |
| Total: Baseline climate scenario, minimum diesel required (off-road + transport) 100 km | 6874,085 L | 21,945,027 L | 52,473,428 L |
| Total: Severe nuclear winter (150 Tg) scenario, minimum diesel required (off-road + transport 20 km) | 13,268,405 L | 27,824,944 L | 93,847,562 L |
| Total: Severe nuclear winter (150 Tg) scenario, minimum diesel required (off-road + transport 50 km) | 13,821,357 L | 31,434,478 L | 99,012,273 L |
| Total: Severe nuclear winter (150 Tg) scenario, minimum diesel required (off-road + transport 100 km) | 14,742,945 L | 37,450,366 L | 107,620,125 L |

[a]This mass of potato provides the food energy requirement for 5.6 million people, but the protein requirement for 5.1 million. To reduce this inefficiency, smaller amounts of potato could be produced if some additional protein was obtained from high protein plant foods (e.g., nuts and legumes) and/or high protein animal foods (dairy, eggs, and meat).

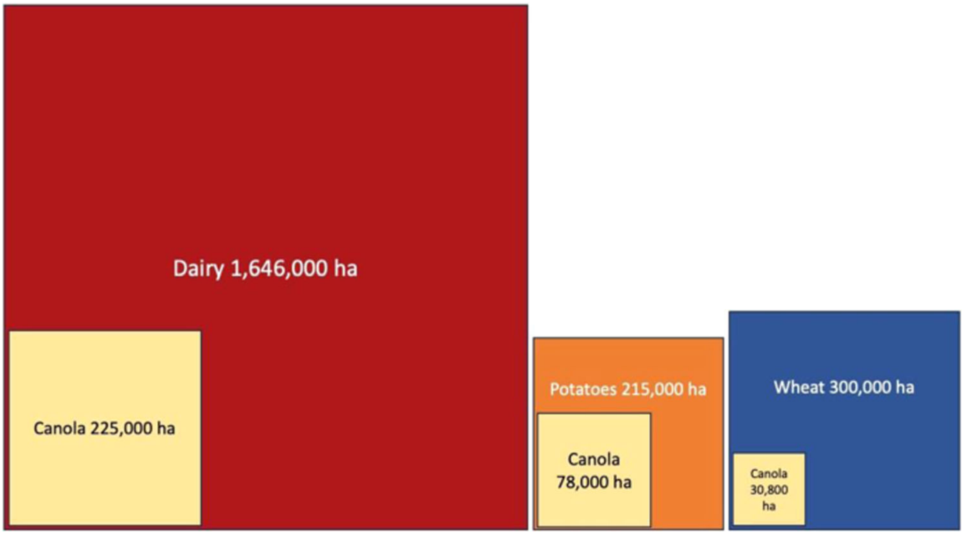


**FIGURE 2** Land area required for selected crops to feed the New Zealand population in severe nuclear winter scenario, and corresponding land area needed for biofuel feedstock (see Table 4) to sustain production (150 Tg nuclear war scenario, with 100 km produce transport assumption).

**TABLE 4** Minimum cropping land of canola feedstock needed to supply agricultural off-road and transport biodiesel to feed the New Zealand population by food product.

| Scenario | To supply wheat (ha) | To supply potatoes (ha) | To supply dairy (milk) (ha) |
|---|---|---|---|
| Baseline climate, 20 km transport | 4398 | 10,035 | 31,522 |
| Baseline climate, 50 km transport | 4848 | 12,975 | 35,729 |
| Baseline climate, 100 km transport | 5599 | 17,875 | 42,740 |
| 150 Tg scenario, 20 km transport | 27,711[a] | 58,112 | 196,001 |
| 150 Tg scenario, 50 km transport | 28,866 | 65,651 | 206,787 |
| 150 Tg scenario, 100 km transport | 30,791 | 78,215 | 224,765 |

[a]In the nuclear winter scenarios, two variables impact canola, first the reduced yield of food crop, necessitating more land area (for dairy, wheat, or potatoes) and hence more biofuel feedstock, and second the reduced yield of canola itself, necessitating even greater canola area.

**TABLE 5** Minimum additional biodiesel volume per year (biodiesel feedstock land area, ha of canola crop) required for the production/transport of canola feedstock in Table 4.

| Scenario | To supply wheat | To supply potatoes | To supply dairy (milk) |
|---|---|---|---|
| Baseline climate, 20 km transport | 279,369 L (228 ha canola) | 637,408 (519 ha) | 2002,357 L (1631 ha) |
| Baseline climate, 50 km transport | 319,044 L (260 ha) | 853,775 L (695 ha) | 2351,121 L (1915 ha) |
| Baseline climate, 100 km transport | 389,737 L (317 ha) | 1244,209 L (1013 ha) | 2975,066 L (2423 ha) |
| 150 Tg scenario, 20 km transport | 1760,252 L (3676 ha)[a] | 3691,394 L (7709 ha) | 12,450,280 L (26,002 ha) |
| 150 Tg scenario, 50 km transport | 1899,491 L (3967 ha) | 4320,089 L (9023 ha) | 13,607,411 L (28,419 ha) |
| 150 Tg scenario, 100 km transport | 2143,269 L (4476 ha) | 5444,382 L (11,371 ha) | 15,645,376 L (32,675 ha) |

[a]In the nuclear winter scenario, two variables impact canola, first the reduced yield of food crop, necessitating more land area (for dairy, wheat, or potatoes) and hence more biofuel feedstock, and second the reduced yield of canola itself, necessitating even greater canola area.

**TABLE 6** Canola feedstock required to supply biodiesel to produce food for the New Zealand population expressed as (a) multiple of estimated 2020 canola cropping area, (b) proportion of total current grain-cropped land in New Zealand.

| Scenario | To supply wheat | To supply potatoes | To supply dairy (milk solids) |
|---|---|---|---|
| **(a) Increase factor for required canola cropping compared to business-as-usual** | | | |
| 20 km baseline | 6.5 | 14.9 | 46.7 |
| 50 km baseline | 7.2 | 19.3 | 53.0 |
| 100 km baseline | 8.3 | 26.6 | 63.6 |
| 20 km 150 Tg | 44.2 | 92.7 | 312.8 |
| 50 km 150 Tg | 46.3 | 105.2 | 331.4 |
| 100 km 150 Tg | 49.7 | 126.2 | 362.8 |
| **(b) Proportion of current grain-cropped land area** | | | |
| 20 km baseline | 0.9% | 2.2% | 6.8% |
| 50 km baseline | 1.0% | 2.8% | 7.7% |
| 100 km baseline | 1.2% | 3.9% | 9.3% |
| 20 km 150 Tg | 6.4% | 13.5% | 45.5% |
| 50 km 150 Tg | 6.7% | 15.3% | 48.2% |
| 100 km 150 Tg | 7.2% | 18.4% | 52.8% |

is 269% of the current area of wheat farmed land or 24% of all currently grain-farmed land. Farmed area of potatoes required is 889% of currently potato farmed land or 63% of all current non-grain horticultural land. Dairy requires only 37% of current dairy farmed land.

In the severe nuclear winter scenario, wheat requires 690% of current wheat area or 62% of all grain-farmed land. Potatoes require 2279% of current potato farmed land area or 162% of current horticultural land area. Dairy requires 95% of current dairy farmed land.

Table 6 shows how much the current cropped area of canola would need to be expanded to produce the required feedstock if canola biodiesels were the only diesel supply, as well as what proportion of New Zealand's current grain-cropped land area this would require. We see that 6.5 times the current canola cropped area (or just 0.9% of all grain-farmed land) is needed to supply biodiesel in the "baseline climate, 20 km transport, wheat" scenario. In contrast, 362.8 times the current area (52.8% of all grain-farmed land) is needed in the "severe nuclear winter, 100 km transport, dairy" scenario.

Results also imply how many people could be fed if land use was optimized for continued production of our three study crops, that is, in the 150 Tg scenario if 100% of all existing dairy land use was able to be sustained (this would feed 1.05 NZ populations), and 100% of all current horticultural land was used for potatoes (0.61 NZ populations), and 100% of all grain cropped land was used for wheat (1.63 NZ populations), then 16.8 million could theoretically be fed (or 43.2 million people in the no winter scenario). But this is provided there is liquid fuel (or feedstock and a means to refine it) and other agrichemical inputs (or substitutes).

# 4 | DISCUSSION

## 4.1 | Context and key message

We have analyzed the liquid fuel needs of national food production for the case study of a developed, temperate climate, and island nation (New Zealand). To maintain food production should liquid fuel imports become unavailable for an extended period, it is necessary to identify a plan for self-sufficiency through the crisis.

There are a range of alternatives for meeting the fuel needs for food production in addition to biodiesel. These include electricity, hydrogen, other biofuels, or other novel fuels with engine conversion. Each could contribute in varying proportions at different stages of self-sufficiency development.

Understanding the optimal mix of petroleum stocks and each alternative fuel at different timepoints is a complex planning and evaluation exercise that requires knowledge of the existing vehicle fleet and is beyond the scope of this study. However, the foregoing demonstrates that biodiesel via canola oil is a viable alternative on a sustainable basis, and a biodiesel production capability could be a useful part of any plan.

New Zealand's fuel stockholdings are small relative to comparable countries (MBIE, 2022), and there is value in improving self-sufficiency quite quickly. Scaling up hydrogen trucks and the associated infrastructure for hydrogen distribution will take time. Electric trucks could be imported more rapidly for on-road transport of food produce, but the electrification of critical on farm machinery would take much longer and be more costly per L of diesel displaced.

This is due to conversion challenges and limited availability of electric agriculture vehicles.

This highlights the value of biodiesel as a component of any self-sufficiency mix for its ability to deliver a drop-in alternative for on-farm machinery and quickly provide near-term self-sufficiency for on-road food transport. Although increasing New Zealand's stockholding of diesel reserves is the other important way in which on-farm machinery could be sustained through a crisis, such storage tanks are expected to quickly become stranded assets given projected petroleum sales as the economy decarbonizes. Investment in a biorefinery with a considerably longer useful life and an ability to sustain food production for a longer period of crisis may outperform storage tank investment, depending on the assumptions used.

It is important to understand how much liquid fuel is needed to sustain the most efficient and minimal level of essential services (agriculture in the present study, but other critical industries should be analyzed) and to develop a fuel rationing and prioritization plan, in preparation, should a global catastrophe occur.

Our results imply that post-catastrophe, focusing on the most efficient crops (e.g., wheat), New Zealand needs the ability to cultivate a minimum of approximately 4600 ha of canola (assuming a normal climate, and that crop transport can be limited to an average of 20 km) or 35,000 ha of canola (if there is severe nuclear winter, and crop transport is limited to an average of 100 km). This would produce 14,000–43,000 t of canola seed (or equivalent biofuel feedstock), and a refining facility or facilities that can process this volume of canola seed into approximately 5–17 million L of biodiesel. This could sustain agricultural processes at the fuel intensity required by wheat to supply 100% of the food calories needed by the New Zealand population. Capacity needed to process this feedstock to biofuel is approximately the same as a current New Zealand canola food oil refinery (Pure Oil NZ in Rolleston, which processes about 36,000 kg oil per day, which is ~14 million L per annum).

We emphasize that these are minimum requirements, and many factors such as the production of less fuel-efficient crops (e.g., for dietary diversity), greater transport distance requirements, inefficiencies in production or transport, more severe climate impacts, and so on, would increase the amount of fuel and therefore canola seed required.

## 4.2 | Summary of main findings

In the event of a global catastrophe halting liquid fuel trade, New Zealand's onshore diesel reserves of 213 million L would deplete in 28 days at current consumption rates. If rationed strictly for essential food production and transportation to processing facilities, these reserves could last for 2 or more years, depending on the agricultural context and environmental conditions in our study (though diesel fuel is commonly considered able to be stored for 6–24 months when kept in proper conditions). However, only 8% of the country's annual diesel is used for off-road agriculture, and many other pressing needs would compete for this supply, greatly reducing the time it would last.

Given our scenarios, New Zealand's stored diesel would be consumed in months, even with a 90% usage restriction. Therefore, in a prolonged crisis, locally produced fuels, like biofuels, would, at present levels of electrification and industrialization of agriculture, be vital for sustaining food production for the nation.

We have shown that it is relatively straightforward to estimate the minimum biofuel production needed to supply, in sustainable fashion, the minimum agricultural fuel needed to feed a national population. The required volume of locally produced biofuel can be minimized by strict fuel rationing, and by prioritizing survival-essential processes such as agricultural production and food transport.

High food-energy crops like wheat and potatoes are more fuel-efficient than dairy products. In a trade cessation scenario, constructing biofuel refineries or ramping up the production of suitable feedstock, like canola, might become challenging. Hence, advanced preparations, including investing in biofuel refineries and boosting feedstock production, should be considered. Preparatory investments, increasing land area of relevant crops in anticipation, and planning for scale-up post-catastrophe could all be important and would help maximize the use of any transitional period.

Considering New Zealand's context, the nation could implement a catastrophe fuel insurance policy by expanding canola cultivation, a feedstock already produced commercially for food oil. Alternative biofuel sources are available (e.g., linseed, tallow, forestry waste, willow, or other feedstocks), and a comparative analysis would be valuable, but canola stands out due to its established production in New Zealand and direct conversion potential to biodiesel or renewable diesel.

To minimize the volume of biofuel production required, a judicious post-catastrophe pivot to low fuel-intensity food products would be sensible. Our results show that there is substantial variation in liquid fuel requirements across agricultural products. For example, a hypothetical supply of food for New Zealand's population using just wheat would require expanding wheat production from the current 8.9% of grain-farmed land area, up to 24%–62% of grain-farmed land (land used for growing fodder crops could potentially be substituted), whereas milk solids would require continuing production on 37%–95% of current dairy land, but consuming seven times more diesel for the same food energy output as wheat.

No tillage farming may reduce fuel demands (Chen et al., 2015; Khaledian et al., 2014), as would prioritizing land use near to population centers to reduce transportation requirements.

Our findings suggest a theoretical capability to feed up to 43.2 million people (16.8 in the severe nuclear winter scenario), if existing arable land is used for optimal crops, with adequate fuel supplies. This production excess underscores the importance of ensuring the resilience of key global food-producing regions for potential catastrophes.

Consequently, in the precrisis phase, elements like wheat and canola seed, urban-adjacent arable land, harvesting and processing infrastructure, and biofuel refining facilities should be recognized as vital strategic national assets.

## 4.3 | Food selection

Although our analysis examined three crops in isolation for demonstration purposes, a mix of crops would realistically continue to be produced following any catastrophe (along with increased home and community gardening) to provide as nutritious a diet as possible. The point we demonstrate is that careful planning for what to grow (and where) in the aftermath is needed, along with planning to be able to provide the needed fuel. Decisions about which crops to scale-up, scale-back, or substitute will rest on the factors above (food energy density, liquid fuel consumption, and frost tolerance), plus other considerations such as versatility, seed availability, land optimization, demands on other imported commodities (e.g., fertilizer and agrichemicals), knowledge, or food wastage levels. Many of these factors could be enhanced in anticipation.

The optimal food production mix to minimize liquid fuel needs will vary by context. For example, potatoes would be a superior crop to wheat for home or community gardens in an urban setting. Overall, horticulture is likely much more efficient than dairy production. This has significant implications for a country like New Zealand where most of the food production is dairy.

## 4.4 | Biofuels

Producing biofuels can lower carbon emissions and aid in decarbonizing hard-to-electrify transport/machinery. In our case study nation of New Zealand, a 2018 national report used a bioenergy value chain model to examine various pathways to increasing biofuel use (Scion, 2018). This revealed that canola oil, though costlier as a feedstock, has benefits: low capital costs in conversion, high yield, and substantial coproduct sales. Canola oil is a human food and canola seed meal serves as livestock feed. Canola biodiesel is a mature technology with local feedstock growth. Notably, canola is frost resistant, and its biodiesel works well in cold weather. Tallow's use in biodiesel is also established, but exploring other feedstocks, such as forestry by-products, willow, and agricultural waste, is context dependent.

There are some standard objections to developing biofuel capacity. Many feedstocks displace food, potentially increasing food insecurity, or require clearing additional land, potentially worsening climate change or reducing biodiversity. However, in a post-catastrophe situation, the production of biofuel might be needed to prevent a devastating collapse in agricultural yield and mass starvation. Although canola often competes with food in some regions, in a catastrophe affecting New Zealand, its use for food would compete with its ability to allow the production of much greater volumes of food. Policy needs to strike a balance between preparing to be able to produce fuel in an emergency and optimizing food production in normal times. Robust analysis should weigh the expected benefits of catastrophe preparedness and commercial revenues from canola products against the removal of it from use as a food.

Though biodiesel blends with fossil diesel, higher blend ratios might necessitate engine modifications and risk damage. Producing renewable diesel from canola oil or other sources could surpass blend limits, making this "drop-in" fuel more suited for discussed scenarios. Renewable diesel production, distinct from biodiesel, requires a hydrogenation process. Any post-catastrophe biofuel scaling would need additional industrial inputs, like hydrogen or methanol, which New Zealand already produces.

Factors that might limit local uptake of biofuels if not a part of self-sufficiency plans (e.g., in New Zealand) include lack of cost-competitiveness with fossil fuels, international demand for feedstock, financial and technical barriers to producing drop-in sustainable biofuels, coordination challenges among production entities, and the fact many diesel engines cannot run on higher blends, and a lack of incentives and uncertainty around biofuel policies (Ministry of Transport, 2021).

Addressing these challenges would be assisted if governments recognized biofuel feedstocks and refineries as essential "resilience infrastructures" for mitigating global crises. Encouraging more biofuel production could involve guaranteeing purchase volumes for canola growers and refiners. Investments in renewable diesel refineries and research could resolve blend and engine concerns.

## 4.5 | Policy implications for trade vulnerable nations

New Zealand would benefit from an ability to maintain essential transport and food production services in the event of a catastrophe. Were subsequent analysis of comparable options to result in selection of canola biofuel production as part of the optimum response, New Zealand (or other island nations facing similar circumstances) could do the following:

1. Expand the cultivation of canola to provide for biofuel needs in a no trade scenario as well as stockpiling additional canola seed, sowing and harvesting machinery, and other industrial agricultural inputs to allow for further expansion of production post-catastrophe.
2. Develop a logistics plan for how to deploy these stockpiled resources within weeks to months, should a catastrophe strike and pilot test this plan.
3. Consider modifying any existing food oil refineries so they can pivot to producing biodiesel at short notice and without the need for additional imported parts.

4. Invest in additional processing and refining capacity for biodiesel to the point that it is cost-effective to do so, on a risk-weighted basis (accounting for the expected value of harms).

However, we acknowledge that building resilience to catastrophe is more nuanced than a single intervention. So, we recommend the following approaches to food and fuel security that the Government of New Zealand (or other countries likely to suffer similar problems) could take.

- Conduct a systematic National Risk Assessment to identify potential catastrophe scenarios and their consequences.
- Develop or amend a National Fuel Plan that includes off-road agricultural use as a critical consumer, quantifies how much liquid fuel is required to provide "basic needs" for the population, and establishes what rationing or adaptation is needed to provide these fuel volumes or alternative energy sources.
- Identify the best mix of fuel options for sustaining agricultural production, such as electrification, storing more petroleum fuel, producing domestic biofuel, and pivoting to more fuel-efficient crops.
- To the extent that biodiesel production forms a part of the ideal mix of fuels, then identify the optimum mechanisms for ensuring early construction or conversion of sufficient biorefinery capacity, availability of sufficient harvesting equipment, adequate seed stocks and stocks of any other inputs and spares required. This could involve market mechanisms, direct government investment, or a combination of these.
- Designate systems for producing high food-calorie yield, low fuel-demand food products, biofuel feedstock, and biofuel as critical national infrastructure.
- Develop a Food Resilience Plan—as well as planning for general food/trade/climate trends. This should include analysis and plans for pivoting agriculture at short notice to produce biofuel feedstock, frost resistant crops, and crops with high food-energy density, and low on-farm and transport fuel demands.
- Undertake a "how to" analysis of how to scale biofuel production from a baseline level that would be commissioned early on to that capable of supplying minimum fuel needs in less than the time that it takes stored diesel to be consumed or degraded.
- Consider investing in research to establish the most efficient pathways, resource needs, and communities of practice, for scaling biofuel production assuming only local resources if no preparation ahead of time.
- Investigate government support for strategic expansion of frost resistant crops like wheat and the associated expertise and logistics.

## 4.6 | Study limitations

Our analysis has several limitations, which could be addressed through a future government risk assessment of these issues. Furthermore, several factors might pose barriers to the efficiency of food production, and as such, our results should be interpreted as likely bare minimum fuel requirements.

### 4.6.1 | Nuclear war and nuclear winter

The impact of a future nuclear war is inherently uncertain (Hess, 2021). It would depend on such factors as arsenal sizes and proportions used, weapon yields, burst heights, the countries attacked, the extent of any firestorms in cities and forests, and so on. Although the results we used for New Zealand from the nuclear winter modeling by Xia et al. considered impacts on "surface air temperature, precipitation and downward direct and diffuse solar radiation," this modeling itself still involved limitations and substantial uncertainty. For example, it did not consider potential damage to agriculture from increased ultraviolet light after a nuclear war (Bardeen et al., 2021). The uncertainty around nuclear winter means that any preparations to ensure food supply must contemplate potentially severe climate impacts in addition to other substantial agricultural and societal disruptions, including changes in population sizes from refugee movements. Therefore, in this study, we have assumed total trade disruption and analyzed a relatively severe nuclear winter scenario (150 Tg soot) to try to avoid underestimating the level of preparation needed to mitigate the impacts.

### 4.6.2 | Food

We have not included an adjustment for food wastage. We have analyzed just three agricultural products in isolation. A more comprehensive analysis would include additional crops and identify a more plausible dietary mix when establishing minimum fuel requirements, including the potential for meat from culled livestock. We are developing an interactive model (v0.9 is available from the authors on request). With this model, users will be able to adjust the population to determine calorie needs, provide alternative yield reductions for nuclear winter scenarios, enter data for alternative crop types, or vary transport distances, to explore results under different assumptions. Most mixed crop approaches probably increase land or fuel requirements given the impressive efficiency of wheat and potatoes as food sources. Particular attention could be paid to other frost resistant cereals and vegetables (Wilson, Payne et al., 2023) and projected population.

### 4.6.3 | Other agricultural inputs

We did not account for potential inability to access fertilizer, herbicides, fungicides, and pesticides. Previous modeling of agriculture without industrial inputs estimated wheat yield reduction of 39% for the Oceania region, with heavily industrialized farming suffering more (Moersdorf et al., 2024). Another study estimated a 60% yield reduction without industrial inputs (Cole et al., 2016). However, these studies assumed no electric powered irrigation and no mechanization (contrary to our scenarios for New Zealand). Nevertheless, the impact of losing imported (though not necessarily locally produced) fertilizers and agrichemicals should be studied further. Optimal crop rotations could be investigated to reduce requirements for fertilizer and pesticides. Crops in the rotation could include legumes for food or livestock feed that fix nitrogen. If soya beans are used in the rotation, these can also be used for biofuel.

### 4.6.4 | Diesel

Our analysis is somewhat simplistic in that it did not consider the use of diesel stocks for transporting seed, fertilizer, and pesticides to farms. We assumed efficient use of trucks (always full in one direction). We did not account for fuel needed to transport fossil diesel from storage facilities to farms (or the supplies already on farms). Our assumptions of 20, 50, and 100 km round trip travel distance and diesel efficiency of heavy trucks were simplistic, and obviously, there would be variation. A more robust analysis would be complex and context dependent. In New Zealand, although trucks would be used in the South Island, existing hydro powered electrified railways could be used in parts of the North Island. We did not analyze the liquid fuel required to distribute food from processing facilities to retail outlets (although this could be partly achieved with repurposing the existing electric vehicle fleet). Significant additional fuel or a complete reworking of the post-processing distribution chain might be needed.

### 4.6.5 | Other energy

Our calculations are isolated calculations that assume an ongoing electricity supply (and fossil coal where this is used, e.g., for drying milk solids), the existence of an appropriate biofuel refinery, and so on. We also assumed electric powered irrigation. We excluded non-diesel liquid fuel use on farms, such as petrol-powered vehicles/machinery (chainsaws, ATVs, and farm motorcycles), for example, this amounts to 11 million L per annum for dairy production in New Zealand (an additional 11.6% by volume of the diesel consumption).

Policymakers will need to deal with the above uncertainty via: (i) commissioning further targeted research; (ii) planning to deal with the more severe scenarios—if it is found cost-effective to do so.

## 4.7 | Further research

Our findings underscore the importance of thoroughly assessing national food and fuel security amid catastrophic risks. It is recommended that government funded scientists replicate this study, delving deeper into additional crops, clarifying transport needs, and exploring other biofuel sources and other energy options. Although previous New Zealand models contemplated transition to renewables in standard scenarios (Scion, 2018), a shift in focus toward minimum requirements in a catastrophe is essential. Other nations should adapt this approach using their local yield and nutritional data.

Subsequent research should

1. **Assess the scale-up**: Determine the time frame and logistics for increasing canola feedstock and optimal food sources' production.
2. **Audit equipment needs**: Identify the required food oil processing equipment and inputs such as solvents, exploring the potential for post-catastrophe local biofuel refinery construction.
3. **Explore alternatives for transport to processing site**: Not all food transport relies on diesel-powered road trucks. The feasibility of electric rail as an alternative, contextual to each region, should be analyzed. For instance, although New Zealand's freight predominantly uses roads (93%), there are electrified rail sections.
4. **Analyze food distribution**: Examine food distribution from processing units to consumers, accounting for the energy mix required (e.g., electric, hydrogen, and liquid fuel). Additionally, analyze fossil diesel distribution to farms, considering the fuel consumed in the process.
5. **Assess impact of agricultural inputs**: Model the effects of diminished availability of fertilizers, fungicides, herbicides, pesticides, and seeds, accounting for what can be produced locally. Trials for local yields under nonindustrial conditions would be beneficial. Where possible, redirecting domestic production or existing imported supplies toward essential human food production could be explored.
6. **Assess impact of trade disruption**: Examine the repercussions on essential parts for maintenance, the potential decline of agricultural machinery, and evaluate existing stockpiles and spare part sources.
7. **Understand potential for machinery conversion**: Explore the potential of biogas-operated farm machinery and electrifying certain farming processes.
8. **Assess scaling of resilient foods**: Explore resilient food supplies such as seaweed; rabbits; leaf protein concentrate from agricultural residues; and mushrooms grown on leaf protein concentrate wastes, animal waste, and logging residues, etc. (Denkenberger & Pearce, 2014).
9. **Evaluate fuel self-sufficiency options**: A comprehensive review is needed on fuel independence, considering costs, timeframes, and multiple alternatives, such as
   - Esterification/biodiesel versus hydrogenation/renewable diesel.
   - Alternatives like electricity, hydrogen, and natural gas.
   - Wood gasification-powered machines, as used during the Second World War.
   - Replacing machines with human or farm animal labor.
   - Amplifying urban food production to minimize diesel reliance in industrial farming.

Ultimately, an effective strategy should weigh the chances of a global catastrophe against the investment costs in mitigation and the consequent benefits for food security and overall well-being during crises. Effectiveness may also depend on whether the allocation of land to crops is done on a centralized basis (e.g., analogs to the Defense Production Act in the United States, under a situation of emergency) or a decentralized basis (with landowners choosing what to plant). If decentralized, it is possible that the allocation of land to crops may not be optimal. However, such considerations are beyond the scope of this article.

## 5 | CONCLUSIONS

A major global catastrophe would almost certainly disrupt trade in liquid fuels. Some countries could be left without imports of oil products including diesel required to operate agricultural machinery and transport food. Island nations that import 100% of their refined fuels may be particularly vulnerable. Our case study of New Zealand suggests that although the country has sufficient stored diesel to sustain agriculture through the initial period of a catastrophe, this supply would need distribution and could be exhausted relatively quickly, even with strict rationing. One way to extend the effective diesel supply would be to farm the most diesel-efficient crops. We found that wheat is far more liquid fuel efficient than potatoes or dairy farming and has the advantage of being frost resistant in case of a nuclear or volcanic winter. New Zealand could transition to the production of canola feedstock sufficient to produce the biodiesel required for wheat production with a modest expansion of canola cropping to approximately 1%–7% of all currently grain-farmed land. Provided investment was made in sufficient canola biodiesel or renewable diesel refineries, biodiesel could provide the bare minimum of New Zealand's agricultural liquid fuel needs. Given potential supply chain disruptions in a catastrophe, such refining capacity would need to be developed in anticipation. The biodiesel produced would also help the nation meet its emissions reduction targets and increase business-as-usual energy security. Canola cropping should be expanded in advance of such a disruption to minimum levels required during a crisis period. This would provide greater assurance of biofuel delivery when needed. Mechanisms in normal times that encourage canola cropping and increased biorefining capacity should be considered. Given the implications of global catastrophic risk more broadly, other countries should conduct these sorts of analyses to help prepare for whichever types of disasters may be most relevant to their situations.

### AUTHOR CONTRIBUTIONS

Matt Boyd and Nick Wilson conceived and designed the research, performed the analysis, and wrote the manuscript; Sam Ragnarsson performed the analysis, designed the interactive model, and contributed review of drafts; Simon Terry contributed review of drafts and provided important intellectual input; Ben Payne contributed review of drafts and provided important intellectual input.

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### CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

### DATA AVAILABILITY STATEMENT

All data analyzed in this study are described in Table 2 with source citations. A prototype (v0.9) interactive model (called "Flagri") that users might find a useful supplement to the article, and where they can vary assumptions, is available from the authors on request.

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