Cropland expansion in a nuclear winter with loss of industry

Luísa L. Monteiro[1,2,*], Michael Hinge[1], Simon Blouin[1], and David Denkenberger [1,2]

[1]Alliance to Feed the Earth in Disasters (ALLFED) Lafayette, CO 80026, USA

[2]Department of Mechanical Engineering, University of Canterbury, Private Bag 4800 Christchurch 8140, New Zealand;

*****Correspondence: analuisa.monteiro@pg.canterbury.ac.nz (L.L.M.)

This is a non-peer reviewed preprint submitted to EarthArXiv and has been submitted to the Global Environmental Change journal for peer review.

Abstract: A nuclear war has the potential to cause an abrupt-sunlight-reduction scenario and the collapse of electricity/industry, disrupting food production and distribution worldwide and creating widespread food insecurity. In this work, we explore the potential of using animal draught as a power source to cultivate current cropland and expand cropland area during a nuclear winter with loss of industry. For a 150 tera-grams soot injection with no fertiliser application, the current animal count would be able to cultivate over 700 million hectares (Mha) of current cropland, and expand cropland area by 100 Mha. The grain produced from these areas would be used partly to feed the working animals, and the remaining wheat would be enough to feed more than half of the global population by the fourth year of the catastrophe, making outdoor agriculture and cropland expansion viable methods to mitigate starvation in such a scenario.

Keywords: food security, resilient foods, existential risks, crop area expansion, nuclear war, animal power.

1. Introduction

Modern agricultural systems have increased in size, complexity, and interconnectedness, largely thanks to global trade. As such, production depends increasingly on external factors, including fertiliser and pesticide production, and provision of equipment, labour, and fuel (Ahvo *et al.*, 2023; García Martínez *et al.*, 2025). However, this dependence has increased the food system's vulnerability to shocks, and local disruptions can trigger cascading failures and threaten global food supply (Moersdorf *et al.*, 2024; Wescombe *et al.*, 2025).

Food systems are also vulnerable to global catastrophes. A nuclear war or supervolcanic eruption could release large volumes of aerosols into the stratosphere, triggering an abrupt sunlight reduction scenario (ASRS) and altering global climate (Coupe *et al.*, 2019; Rivers *et al.*, 2024). An ASRS could last for several years and reduce crop yields around the globe, as many crops would be unable to withstand the harsh conditions. Climate and crop models suggest an ASRS could reduce global calorie production by up to 90% and require a decade for full recovery (Jägermeyr *et al.*, 2020; Xia *et al.*, 2022).

The detonation of nuclear weapons at high altitude could also cause electromagnetic pulses (HEMPs), which would cause long-term catastrophic damage to the electricity system (Oak Ridge National Laboratory, 2010; Cole *et al.*, 2016). This damage would propagate widely, causing a global catastrophic industry loss (GCIL), which would impair supply of fuel and agricultural inputs, such as fertilisers and pesticides (Kinney *et al.*, 2005; Foster *et al.*, 2008; Oak Ridge National Laboratory, 2010; Bernstein *et al.*, 2012; Blouin *et al.*, 2024; Blouin, Jehn and Denkenberger, 2024). While strategies such as decentralisation of industrial infrastructure, and Faraday-cage shielding of electrical components could prevent GCIL, they are currently uncommon, making the world vulnerable to a GCIL (Blouin, Jehn and Denkenberger, 2024).

A 50% reduction in agricultural inputs supply (fertiliser, pesticide, and equipment) could reduce wheat production by 21%, which could be further reduced by larger shocks (Ahvo *et al.*, 2023). A nuclear exchange between US and Russia could reduce global industrial output by 25%, which would reduce wheat yields by 15% and cause shortages in countries targeted by the exchange and those dependent on food imports (Blouin, Jehn and Denkenberger, 2024; Wescombe *et al.*, 2025). The loss of electricity and transport networks would affect food storage and distribution, leading to food spoilage and shortage (Davis, Downs and Gephart, 2021). Combined, an ASRS and GCIL could trigger a food shock large enough to cause widespread famine, malnutrition, and even the collapse of modern civilisation (Denkenberger *et al.*, 2021, 2022; Wescombe *et al.*, 2025).

Therefore, ensuring survival in an ASRS requires resilient food solutions. One such solution is the expansion of agricultural land to counteract reduced yields of existing crops. Previous research showed cropland expansion would constitute a plausible food source in nuclear winter, assuming mechanised equipment could be used for land conversion and cultivation (Monteiro *et al.*, 2024). However, damage to mechanised equipment was not considered, meaning this research did not account for the effects of GCIL. Thus, the potential to prevent starvation by expanding cropland area in an ASRS without industrial function is currently unknown.

This paper explores the potential to prevent global starvation by cultivating and expanding cropland during a nuclear winter with global catastrophic industry loss. A crop model is used to determine the current cropland and non-cropland area suitable for winter wheat growth during a nuclear winter with 0% fertiliser input, to simulate industry loss. The possibility of cultivating current cropland and of expanding and cultivating new cropland area using animal draught is assessed, to estimate the possible wheat produced. The animal feed requirements for animals cultivating and expanding the land, and the global human calorie demand met with the produced wheat were also calculated.

2. Materials & Methods

A crop model is used to simulate crop growth in a combined ASRS and GCIL scenario and determine crop yields, with its parameters and assumptions detailed in section 2.1. An explanation of the utilisation and allocation of draught animals is described in section 2.2. The yields are used to determine the current cropland and non-cropland areas that could be cultivated, with the tasks required to cultivate and expand cropland area presented in section 2.3. The wheat production cycle and the utilisation of said wheat to meet energetic requirements of draught animals and humans are described in sections 2.4 and 2.5, respectively.

2.1. Crop model

The Mink global gridded crop model, based on the Decision-Support System for Agrotechnology Transfer (DSSAT) physiological crop model, is used to assess winter wheat crop yields in both current cropland and non-cropland areas of 158 countries (Robertson, 2017; Blouin *et al.*, 2025). A single winter wheat cultivar, selected for its tolerance of low temperatures and drought, short vernalisation period, and energy density, is modelled based on the crop growth parameters of winter wheat grown in northern Europe. The model provides details on land coverage, focusing on land classified as current cropland (CC), herbaceous vegetation (H), barren land (B), and shrubland (S). Bodies of water, forest, and ice were excluded when assessing viable areas for cropland expansion.

The detonation of the nuclear weapons in this model occurs in May (Coupe *et al.*, 2019), which is considered the start of year 1 of nuclear winter, offset from calendar years. The model considers a 150 Tg soot injection to simulate severe nuclear winter conditions for seven years, and the crop yields are calculated optimising the best planting month for each of the years. The model also considers 0% of current nitrogen application levels for rainfed cropland, since historically nuclear attacks target critical industrial infrastructure, which would halt fertiliser and pesticide production (Blouin, Jehn and Denkenberger, 2024).

To improve prediction accuracy, a correction factor of 80% is applied to all yields to match current global wheat production on current wheat cropland and under current climate conditions. Additionally, factors of 65%, 80% and 90% are applied to the first three years of nuclear winter (Plastina and Edwards, 2017), respectively, to account for farmer inexperience when growing a new crop, inexperience from planting on newly cleared area (Müller *et al.*, 2019), and the lack of mechanised equipment. These factors would make yield estimations slightly pessimistic in regions where wheat is already cultivated, but the effect is considered negligible given the size difference between current wheat cropland and the area modelled.

The results of the Mink gridded crop model are interpolated with the 90m Digital Elevation Data provided by the NASA Shuttle Radar Topographic Mission (SRTM) to determine the slope of the area of each grid cell ("SRTM 90m DEM Digital Elevation Database," 2018). Only areas with a slope under 10% were considered, as most cattle reside in low slope terrains and could get hurt working in land with too steep a slope (Donovan, 2022).

Areas over a grid cell are considered fit for cropland expansion and cultivation if the average predicted yield over 7 years of ASRS is equal or larger than 1,000 kg/ha, and they are referred to as productive areas. While a comprehensive economic analysis would be needed to determine precise viability thresholds, this is considered plausible because (1) wheat yields below 1,000 kg/ha were common in pre-industrial Europe; and (2) many countries' current wheat yields do not surpass this threshold, representing a viable minimum for agricultural production (Ritchie, Rosado and Roser, 2022).

2.2. Animal distribution

A HEMP would disrupt electric power and fossil fuel production, which could render mechanised equipment non-functioning. Alternative power sources such as wood gasification or above-ground fuel reserves could be considered, but not guaranteed (Nelson, Turchin and Denkenberger, 2024). Therefore, all mechanised equipment is assumed to be out of use in this model.

In case of a nuclear winter, many animals would be culled, since their feed sources would be diverted for human consumption (Rivers *et al.*, 2024). The remaining animals could be used as draught animals to cultivate and expand land. In this model, draught cattle and horses are the main draught animals used because of their heavier weight compared to other draught animals. Dairy cows have historically been used as draught animals, but it could be more advantageous to use dairy cows for milk production in ASRS, so two scenarios are considered to accommodate both potential uses of dairy cows (Matthewman, 1987; Cole *et al.*, 2016):

- **Dairy-cows scenario (DCS):** dairy cows are used alongside draught cattle and horses as draught animals;

- **No-dairy-cows scenario (NCS):** dairy cows are excluded from draught work, and only horses and draught cattle are used.

For each country, the number of existing cattle and horses and the number of cattle slaughtered are extracted from the FAO statistical database (FAO, 2023), and the number of dairy cows is calculated based on the milk yield and milk output of each country. The fraction of slaughtered cattle and dairy cows is then subtracted from the total number of cattle in each country (representing those too young for draught right away) to obtain the number of draught cattle (oxen, heifers, and steers) that can be used.

The difference in average draught power of horses, oxen, and cows is large enough to reflect on the area these draught animals can work on. Horses have a draught power of nearly 700 W, and are capable of ploughing 2 ha per day (Davidson, 1950), but oxen and dairy cows can only achieve 60% and 30% as much power, respectively (Smil, 2017, p. 67). These factors were used to normalise the number of draught cattle and dairy cows into horse equivalents, thus facilitating the distribution of animals for cultivation (2 ha per animal). Ploughing and harrowing are dependent on animal power, and both require an animal pair to be executed. Therefore, an animal pair and two guiding people can cultivate 4 hectares.

Given the scarcity of resources in an ASRS, the model prioritises animal allocation for the cultivation of current cropland areas over cropland area expansion. Therefore, area expansion only occurs in countries where there is an excess of animals. The number of animals allocated for expansion becomes smaller every year because as more area becomes available, the animals are allocated to cultivate the expanded cropland.

2.3. Tasks

Land clearing

The number of hours per hectare of each equipment and technique is adapted from Smil's calculations for the labour requirements in traditional farming (Smil, 2017, p. 61), depicted in **Table 1**. A working day of 8 working hours, 7 days per week is assumed.

Table 1 - Labor requirements of techniques employed in cropland expansion (Smil, 2017, p. 61).

		Hours per hectare		
Task	**People/Animals**	*Minimum*	*Median*	*Maximum*
Controlled burning	-/-	0.12	0.30	0.60
Mowing	1/-	33	42	50
Hoeing	1/-	100	110	120
Ploughing	1/2	120	150	180
Harrowing	1/2	18	39	60

Ploughs and harrows are pulled by draught animal pairs to prepare soil for farming, and ploughing/harrowing should be performed at least 3 times, to level and aerate the soil, producing an even seedbed (Smil, 2017, p. 54). In this model, land clearing begins with barren land, then proceeds to herbaceous vegetation, then shrubland, in increasing order of difficulty. Barren land can be ploughed and harrowed immediately, while herbaceous vegetation and shrubland are first cleared of existing vegetation plants. Herbaceous vegetation is cleared by mowing with scythes, and shrubland is first burnt, then burnt remnants removed with hoes.

Land clearing rates

In this model, cropland expansion rates depend on each country's number of excess draught animals, land type, and amount of area to clear. The land is cleared sequentially, with a rate corresponding to the land type being cleared at a given time. Therefore, the land clearing process as a function of time can be described by a curve split into 3 sections: barren land, herbaceous vegetation, and shrubland.

Each section can be described by the following equations:

$$For\ 0 < t \leq t_B :\ A\ (t) = m_B \times t \tag{1}$$

$$For\ t_B < t \leq (t_B + t_H): A\ (t) = m_H \times t + b \tag{2}$$

$$For\ (t_B + t_H) < t \leq (t_B + t_H + t_S): A\ (t) = m_S \times t + c \tag{3}$$

Where m_B, m_H, and m_S correspond to the land clearing rates in ha/day for B, H, and S, respectively, and t_B, t_H, and t_S correspond to the time in days required to clear the full areas of B, H, and S, respectively. The constants *b* and *c* in ha correspond to the points where the land type changes, and are the described by the following equations:

$$b = t_B \times (m_B - m_H) \tag{4}$$

$$c = [(t_B + t_H) \times (m_H - m_S)] + b \tag{5}$$

Since the number of animals used in land clearing changes every year, the land clearing rates, times and constants are different for every year of clearing. Since the first month of the ASRS is spent allocating animals and equipment, cropland expansion begins in the second month of the catastrophe and it stops at the end of year 3 of nuclear winter, so the land can be cultivated several times in the years while the climate is still highly degraded, aligning with previous resilient food analysis (Alvarado *et al.*, 2020; García Martínez *et al.*, 2020; Throup *et al.*, 2022).

Cultivation

Cultivation is modelled to happen once a year, after ploughing, harrowing and drilling in the soil. The number of hours per hectare of each task is adapted from Smil's calculations for the labour requirements in traditional farming (Smil, 2017, p. 61), depicted in **Table 2**. The current and expanded cropland areas are cultivated within 60 days (Smil, 2017, p. 65), and a working day of 8 working hours, 7 days per week is assumed.

Table 2 - Labor requirements of techniques employed in traditional farming (Smil, 2017, p. 61).

		Hours per hectare		
Task	**People/Animals**	*Minimum*	*Median*	*Maximum*
Ploughing	1/2	40	50	60
Seed drilling	1/2	6	7	8
Harrowing	1/2	6	13	20

2.4. Wheat production

In this model, the area expanded by the end of a year of nuclear winter is cultivated at the start of the next year, while the current cropland is cultivated for the first time on the second month of nuclear winter. Wheat is harvested 9 months after cultivation, and then replanted in the typical regional cropping pattern. The yields decline through years 1-3, but then improve as the soot concentration in the atmosphere decreases. The amount of wheat produced monthly for each country is calculated by multiplying the area cleared 9 months prior by the average annual wheat yield of that country during an ASRS.

Annual wheat residue production is also estimated. Approximately 49% of the final dry matter wheat weight is residue, 65% of which is stem, 22% chaff, and 12% leaves (*The main components of yield in wheat*, no date). Bran production is also estimated by considering 13% of kernel weight is bran (Ranhotra *et al.*, 1994).

2.5. Animal and human feed

In baseline conditions, draught animals are fed primarily with grass and non-edible crop residues (Dijkman and Lawrence, 1997; Mottet *et al.*, 2017), but feed utilisation in an ASRS would need to be adjusted to accommodate the reduced feed availability and still provide the animals with the energy required for draughting.

In this model, the working animals in year 1 are fed with crop residues and grain produced before the ASRS, but starting from year 2, the animals are fed with the wheat and residues produced from the current and expanded cropland. The animals are fed with wheat to meet their work energy requirements during working days, and on non-working days, the animals are fed wheat crop residues to meet their maintenance energy needs. When the maintenance energy requirements cannot be fully met with residues, the shortfall is met by feeding additional wheat to the animals.

Feed requirements were based on the daily energy requirements for a working horse (Smil, 2017, p. 111); working horses fed every day with grain, concentrate, and straw for roughage would obtain 28 Mcal of energy (assuming grain and concentrate are wheat and roughage is wheat straw). Since draught can expend up to 1.8 times the maintenance energy requirements of working animals (Pearson, 1993), the energy requirements for working horses are 15 Mcal for maintenance and 12 Mcal for work.

The energy provided by a given residue feed is calculated by multiplying the amount of residue produced annually by its digestible energy (DE) for horses, depicted in **Table 3**. That energy is then divided by the number of animals working in the year after the feed has been produced to deduce how much of the energy demand can be met by the produced residues. From that, it becomes possible to calculate the amount of wheat required to meet the demands of the animals.

Table 3 - Energetic values of wheat and its residues for horses.

Feed	**Gross energy (kcal)**	**Digestible energy (kcal/kg)**	**Ref.**
Chaff		2,476	(*Golden Horse Feeds Lucerne Chaff 20kg*, no date)
Leaves	4,460	2,529	(*Grass, dehydrated* | *Tables of composition and nutritional values of feed materials*, no date)
Wheat	4,350	3,715	(*Wheat, soft* | *Tables of composition and nutritional values of feed materials*, no date)
Wheat bran	4,520	3,019	(*Wheat bran* | *Tables of composition and nutritional values of feed materials*, no date)
Wheat straw	4,410	1,341	(*Wheat straw* | *Tables of composition and nutritional values of feed materials*, no date)

The remaining wheat is directed into meeting the energy requirements of the global population, by assuming a daily intake of 2,100 kcal/person and 12% food waste, which is expected to be lower than current levels due to increased food scarcity (García Martínez *et al.*, 2020; Throup *et al.*, 2022).

2.6. Assessments

Since three levels of labour requirements are used, the average of the three is reported for the animal distribution, cropland expanded, cropland cultivated, wheat produced, and fraction of global human and animal caloric demand met. The area suited for winter wheat growth and expanded cropland area are calculated for every country, and presented aggregated by continent. Animal distribution, wheat produced, and wheat used to meet animals' energetic requirements are also calculated for every country, but the global sum is presented in the results. The wheat used to meet global human calorie demand is based on the global amounts of wheat produced and wheat used to feed to meet animals. Cropland expansion is modelled only for the first 3 years of the catastrophe, but wheat production and consumption are shown for 7 years of the catastrophe.

3. Results & Discussion

3.1. Crop model

The productive non-cropland area covered in the selected land types spreads over 545 million hectares (Mha), distributed across 73 countries. There are approximately 860 Mha of productive current cropland area distributed across 99 countries, 26 of which do not possess any productive non-cropland area. **Figure 1** shows the total productive area available per continent, according to land type.

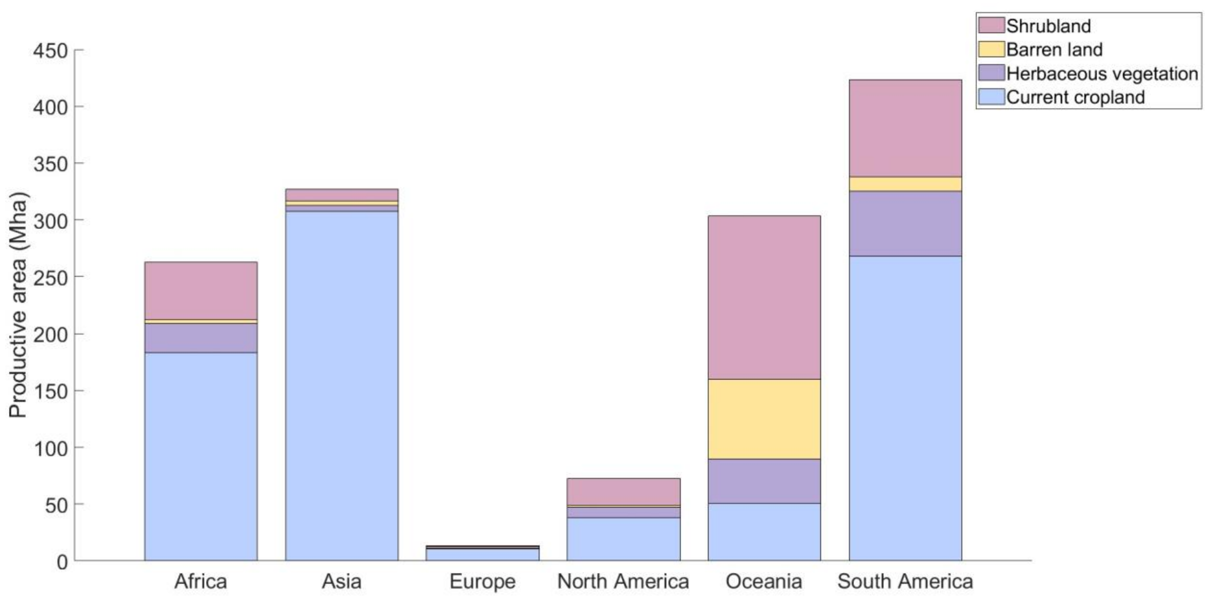

Figure 1 - Productive current cropland and non-cropland areas in a combined nuclear winter and industry-loss scenario according to land cover type

Asia, Europe, and North America show the lowest amount of non-cropland area, showing the Northern Hemisphere extratropical countries are the most affected by the temperature drop.

The temperature drop is not as severe in countries in the tropics, which is why Africa, Oceania, and South America have the most non-cropland area suited for expansion. Except for Europe, shrubland is the most common non-cropland land type, and it constitutes nearly 60% of the global non-cropland productive area, followed by herbaceous vegetation and barren land.

Except for Oceania, all continents have more productive current cropland than non-cropland area. When compared to baseline conditions, Oceania shows the smallest drop in productive current cropland area (only 3%), while Europe shows a drop of approximately 97%. Considering these areas would also have lower yields in ASRS conditions, expansion to non-cropland areas becomes crucial to make up for the drop in cultivable area.

3.2. Animal distribution

According to the FAO statistical database, there were approximately 55 million horses and 1.8 billion cattle in 2023, and 307 million slaughtered cattle (FAO, 2023). Through the milk production statistics and by subtracting the number of slaughtered cattle, we calculated there would be approximately 252 million dairy cows and 1.2 billion draught cattle. The number of draught animals used in DCS and NCS is 1.2 billion and 970 million, respectively, since NCS does not consider dairy cows. These animals are then distributed for cultivation of current cropland and clearing and cultivation of BHS, as detailed in **Table 4**.

Despite widespread mechanisation, some countries still default to draught animals as their primary power source in agriculture, either because of terrain constraints, reduced funds, lack of skill, poor access to maintenance services and/or oil prices (Copland, 1987, pp. 64–68; Mota-Rojas *et al.*, 2021). Although the number of draught animals per area has decreased over time, there would be a large number of animals today that could be trained and used in drought (Zhou, Ma and Li, 2018).

Table 4 - Number and type of draught animals employed in each scenario (in millions of horse-equivalents).

	Dairy cow scenario				**No dairy cow scenario**			
Year	1	2	3	4 - 7	1	2	3	4 - 7
CC								
Cultivation	414	414	414	414	396	396	396	396
BHS								
Clearing	202	110	90	0	158	82	71	0
Cultivation	0	92	112	202	0	76	87	158

In both scenarios, there are 97 countries with animals allocated to cultivate current cropland, of which 84% have enough animals to meet cultivation demands. Some countries do not have enough animals to meet their cultivation demands or do not have area to expand cropland to, therefore their full animal draught force is allocated to current cropland. The more animals are used, the easier it is to meet current cropland cultivation and cropland expansion demands, so horses and oxen are used in both scenarios.

Given their inclusion in draught in the past century, the DCS assesses the impact of dairy cows in meeting draught demands. Since dairy cows can be used for draught and milk production, using cows in draught would be seen as a more economical use of feed in baseline conditions (Copland, 1987, pp. 69–77; Matthewman, 1987). But in a catastrophe, meeting human energy requirements becomes the priority, and animals should only be fed enough for maintenance and for their designated purpose.

If dairy cows cannot be used, the NCS assesses how losing a fraction of the draught force affects wheat production during the catastrophe. There are many reasons as to why dairy cows should not be used for draught while producing milk: cows cannot do work for months after calving, which would lead to inconsistent draught work, and they would need more feed than other draught animal for both milk production and draught, which would decrease feed availability for humans (Copland, 1987, pp. 64–68; Matthewman, 1987). If cows are used exclusively for draught, animal population would decrease over time and there would be yet another food source people would be deprived from. Therefore, it becomes important to analyse both scenarios, in case dairy cows would need to be used for milk production or calving exclusively.

3.3. Cropland expansion

There are 73 countries with non-cropland area suitable for expansion, but only 47 and 43 countries (in DCS and NCS, respectively) with an excess of draught animals that can be used for cropland expansion. **Table 5** shows the annual increase of expanded area by continent for both scenarios, and **Figure 2** shows the global land clearing process for both scenarios in 3 years.

Table 5 - Average cumulative expanded cropland area in Mha by year for the DCS and NCS.

	Dairy cow scenario			**No dairy cow scenario**		
Year	1	2	3	1	2	3
Africa	26	29	31	23	26	27
Asia	11	12	12	8	8	8
Europe	2.5	2.6	2.6	2.5	2.6	2.6
North America	13	15	17	13	15	17
Oceania	0.9	0.9	0.9	0	0	0
South America	57	59	61	57	59	61
Total	109	119	125	102	111	116

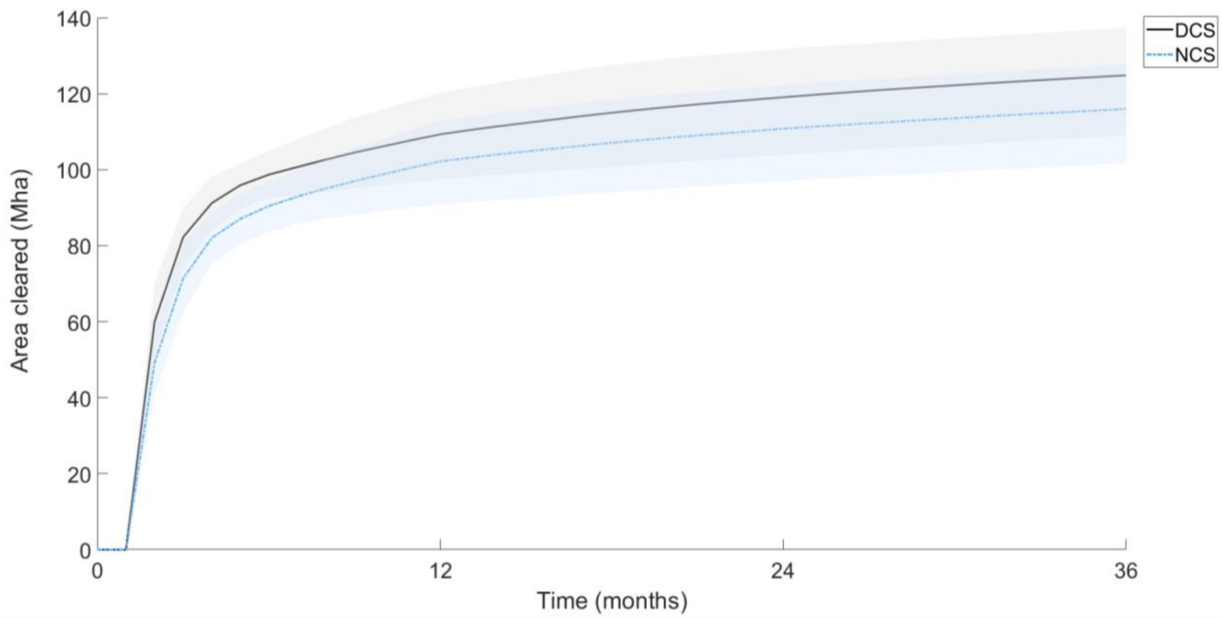

Figure 2 - Comparison of the average area cleared as a function of time in different scenarios.

In 3 years, approximately 23% and 21% of the productive BHS area is cleared in DCS and NCS, respectively. In DCS, expansion of cropland area happens continuously in Africa, Asia, North America, and South America, but it halts in Europe and Oceania after years 2 and 1, respectively. This is because at the end of every year, the animals used for expansion are redistributed to cultivate the freshly expanded cropland, and some countries will not have enough remaining animals to continue expansion. Since Europe has the least amount of productive non-cropland area, the full area is cleared in both scenarios, but in the NCS, Africa and Asia expand 12% and 32% less area, respectively, than in DCS. North and South America experience little variation in the area cleared in both scenarios because the removal of dairy cows from the draught force represents a loss of less than 6% of the draught force. Additionally, there is no cropland expansion in Oceania in the NCS, as removing dairy cows from the draught force reduces the number of draught animals by 2 million in horse equivalents, and therefore all the animals get allocated to cultivate current cropland area in Oceania.

While the exclusion of dairy cows from draught can represent a big drop in area expanded on a country level, it only represents a 7% drop in area expanded globally; using dairy cows in draught could make a substantial difference in countries that are more dependent on inputs from other nations and/or geographically isolated if trade cannot be recuperated. Countries could also consider breeding more animals post disaster to add to their animal draught force, to either cultivate current cropland and/or expand cropland area, as long as enough food could be produced to both raise the animals and meet human calorie demand.

3.4. Cultivation of current and expanded cropland areas

Approximately 61% and 65% of the global number of draught animals in DCS and NCS, respectively, are used in current cropland cultivation. In countries where cropland expansion happens, all the expanded cropland area can be cultivated within the specified timespan because the animals only expand the area they can cultivate.

Every year, there are 732 and 711 Mha of current cropland cultivated in DCS and NCS, respectively. In both scenarios, over half of every continent's current cropland area is cultivated, (except for Oceania), with South America cultivating over 260 Mha (nearly a third of the productive global current cropland area and 98% of the continent's current cropland area). The drops in cultivated productive current cropland area from DCS to NCS are minimal, with the biggest one being a 4% drop in Asia, showing that the utilisation of dairy cows in draught would not make a big difference in cultivation of current cropland area.

Figure 3 shows the annual wheat production from the current cropland and expanded cropland. In DCS, the area cultivated is 3% higher than in NCS, which is reflected in the amount of wheat produced in each scenario. The expanded cropland area produces little over 10% of the annual wheat production, with most of the wheat being produced in the current cropland area. Wheat production increases steadily over time as the yields increase, but particularly in years 1-3, which are the years when expansion happens and that have inexperience factors applied to them, which are no longer present by year 4.

In DCS, current and expanded cropland areas respectively produce a cumulative total of 9.3 billion and 1.2 billion tons of wheat by the end of year 7, making average annual wheat production over 7 years 92% higher than current annual wheat production. This corresponds to an average annual wheat of 1.75 t/ha, nearly half of current annual wheat yields. In NCS, the cumulative total of wheat produced from current and expanded cropland areas drops by 3% and 6%, respectively, making average annual wheat production 86% higher than the current one, and average annual wheat yield 48% of current annual yield. While the temperature drop in ASRS causes yields to drop, more wheat is produced on average compared to baseline conditions because the crop model simulates wheat growth in every hectare of cultivated land, even for land that is not currently used to grow wheat. This presents growing cold-tolerant crops in an ASRS, even with lower yields, as a plausible solution to mitigate starvation, as making use of existing and expanded cropland area to grow these crops would allow increased production of the chosen crop compared to baseline levels.

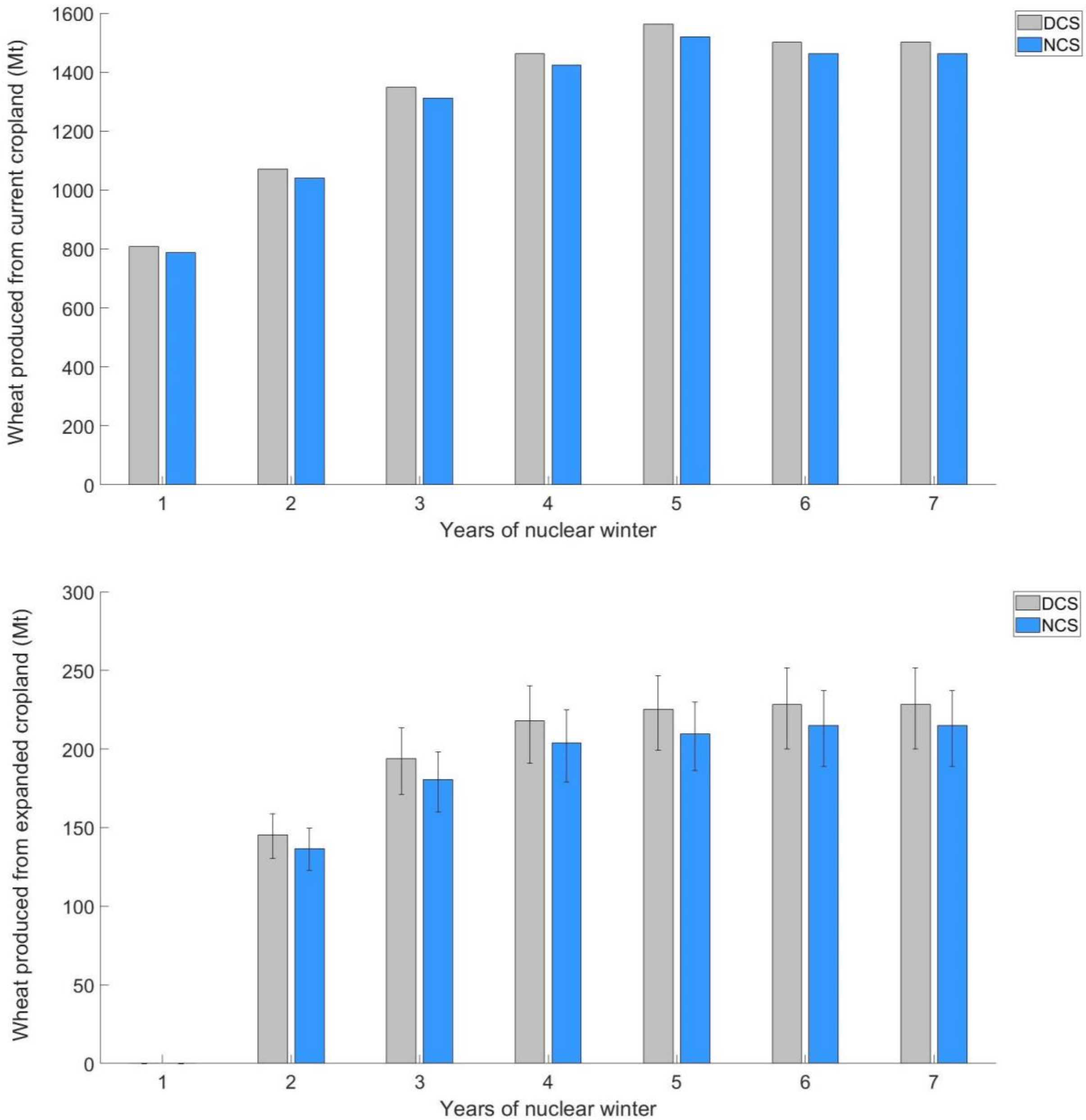

Figure 3 - Annual average wheat production from current cropland (top) and expanded cropland (bottom) in million tons (Mt).

Wheat residue production was also estimated based on annual wheat production, and is depicted on **Figure 4**.

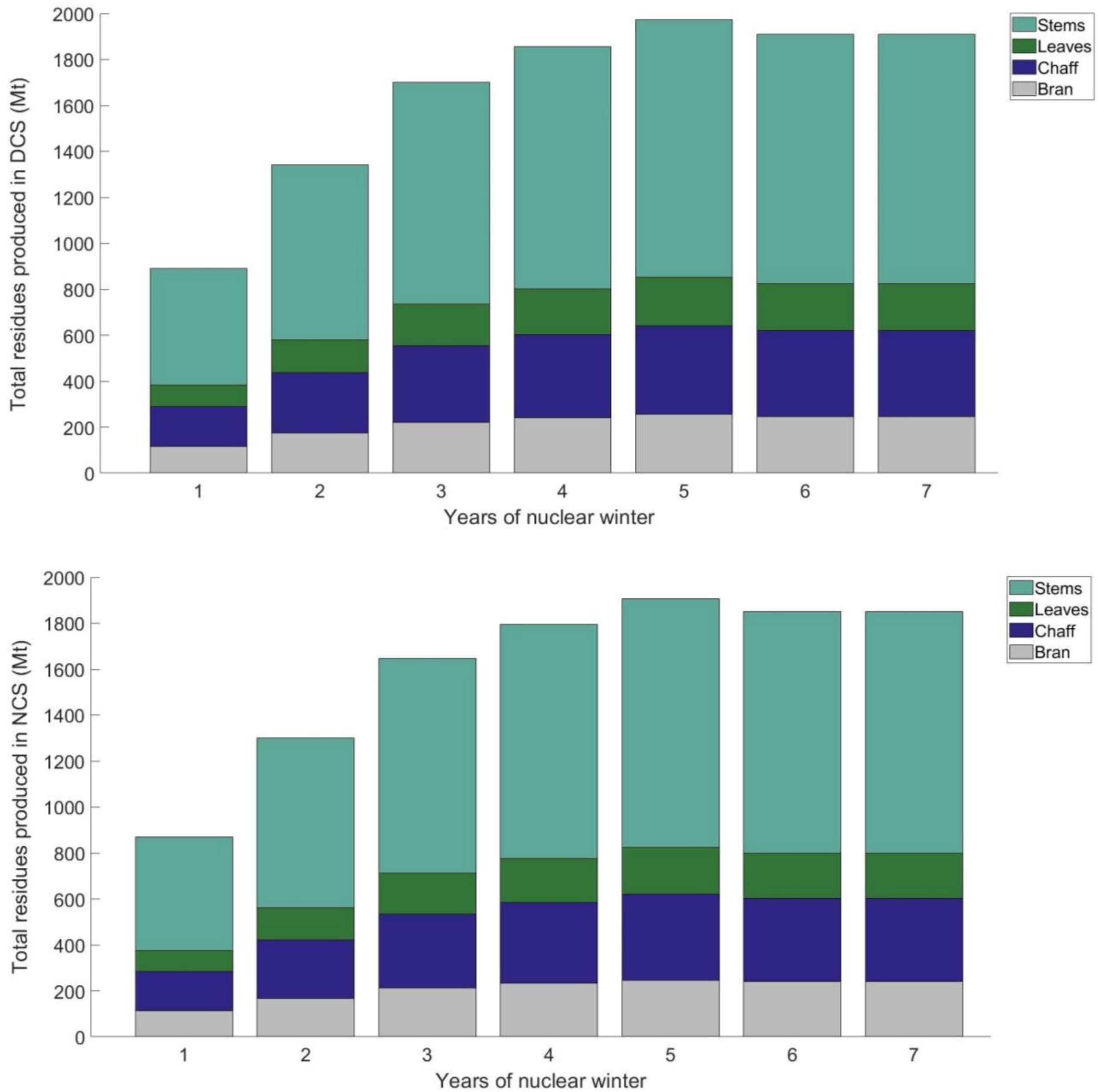

Figure 4 - Annual average wheat residue production (in Mt) in the dairy-cow scenario (top) and in the non-dairy-cow scenario (bottom, discriminated by residue type.

3.5. Meeting caloric demand of animals and humans

While grass and crop residues would help supplement animal diets, their intake would not be enough to fulfil energy requirements. Grass production in an ASRS would not match the baseline animal grass demand, so other feed sources would need to be ramped up to help meet demand. Currently, global cattle and buffaloes' feed requires 1.3 billion ha of land, with only 70.7 Mha dedicated to growing cereal grains (Mottet *et al.*, 2017). Assuming a 3.63 t/ha yield of wheat in baseline conditions (*Production of wheat worldwide 2024/25*, 2025), this corresponds to an annual consumption of nearly 260 Mt of grain. Since animals would be used for draught during the catastrophe, their grain intake would likely be bigger compared to baseline levels.

Figure 5 shows the amount of wheat used to supplement the animal's diets to fulfil their energy requirements. Initially, residue production is not enough to fulfil the animal's energy requirements, so a large fraction of the wheat produced is directed to supplement these animals' diets. As wheat production increases annually, so does residue production, and less wheat will need to be directed to feed the animals. The second year shows the biggest wheat demand, since area expansion and cultivation of current and expanded cropland areas is happening simultaneously. While cropland expansion also happens during year 3, the number of animals used in expansion is the lowest (see **Table 3**) and the rate of area expansion is lower. Since the animals working on land expansion during year 3 do not work as many days as the animals doing cultivation, the amount of wheat consumed by the animals in year 3 is lower than in year 2. From the fourth year onwards, the amount of wheat fed to the animals becomes constant, as the production of residues becomes constant and is at its highest (see **Table 6**).

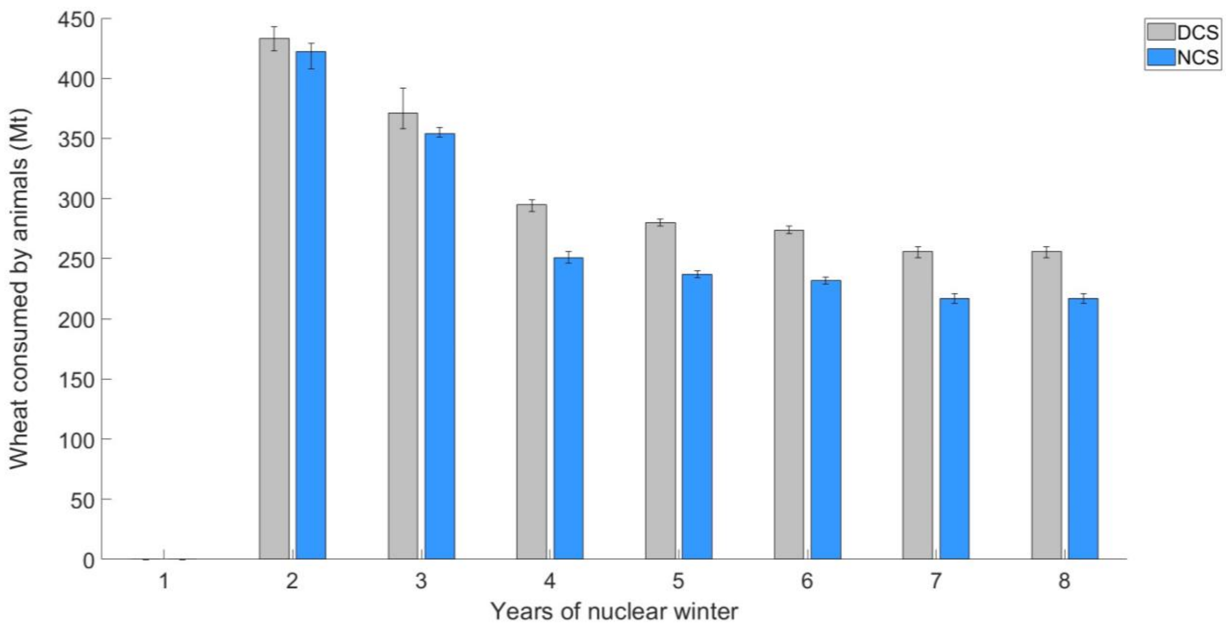

Figure 5 - Global amount of wheat consumed by working animals in a combined nuclear winter and industry-loss scenario

Animals allocated to cropland expansion consume less than 35% of the annual animal wheat requirements, but consume a major fraction of the wheat produced from the expanded cropland area. In DCS, over 90% of the wheat produced from the expanded cropland area in year 2 is used to feed animals, which gradually decreases as wheat production increases annually, and by year 7 only 48% of produced wheat is fed to animals. In NCS, although less wheat is produced, only 74% of the wheat produced in year 2 from the expanded cropland is used as animal feed and, by year 7, less than 40% of the wheat produced from the expanded area is used as animal feed. Since there is net positive wheat production from expanded area, cropland expansion can be seen as a viable food source to mitigate starvation during a nuclear winter.

With the exception of the first year of the catastrophe, animals working in a given year are fed wheat and residues produced the year before, and the remaining wheat is used to meet global human caloric demand. **Figure 6** depicts the global human caloric demand met by both the full amount of wheat produced from current and expanded cropland and by the wheat remaining after feeding the animals.

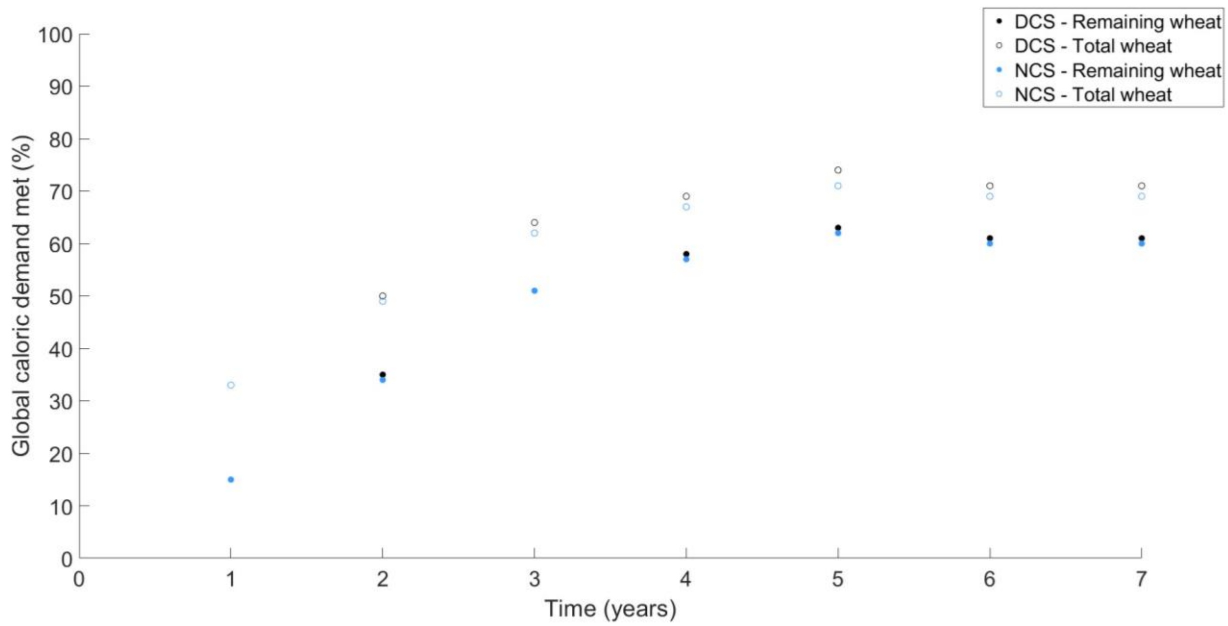

Figure 6 - Human caloric demand met by the total amount of wheat produced in a given year and the remaining wheat after feeding the working animals.

The wheat produced by the end of year 1 is enough to meet the calorie requirements of a third of the global population. By feeding the animals in year 2 with the residues produced in year 1, over half of the wheat produced that year is used to feed the animals, which leaves enough wheat to feed 15% of the global population. In contrast, animals working in year 3 would only require a third of the wheat produced in year 2, and the animals would require progressively less as the climate improves and production increases. By year 7, there would be enough remaining wheat to feed 60% of the global population, as only 16% of the wheat produced that year would be directed to the animals working in year 8. Since the global food demand is not entirely met by the wheat produced from current and expanded cropland, other resilient foods would need to be developed in tandem to help meet the shortfall of the calorie demand.

Previous research looked into the possibility of cultivating 3 billion ha of tropical land area in a combined ASRS and GCIL scenario, which showed that, at least in the first years of the catastrophe, the global food requirement would not be met. As the climate recuperates and the UV effect is reduced, it becomes possible to feed the entire global population with the grain produced from that area (Denkenberger *et al.*, 2017). In our study, more than 700 Mha of land are cultivated every year, producing enough wheat to feed a small fraction of the global population at worst or a third at best in the first years of the catastrophe. Even if no wheat was fed to the animals, it would be possible to feed 74% of the global population at best by year 7, showing the potential of cropland expansion as a food-providing system during an ASRS.

4. Limitations and future work

Our crop modelling has several limitations. First, and most importantly, a single winter wheat cultivar is simulated as a proxy for cold-tolerant crops, when in reality farmers would plant a mix, and our wheat proxy could over- or under-estimate calories that a realistic portfolio would deliver. Methodologically, the Mink/DSSAT framework and the same set-up as in Blouin et al. (2025) is used, which carries the same caveats, such as the fact that DSSAT is applied outside its normal calibration range (cool temperatures, low-light levels), and the assumption that farmers can plant during the optimal month each year. Pest and disease, ozone/UV-B effects, or model organic N fertiliser application are not included in the simulation. Finally, the 80% global scaling used to match modelled wheat to current production (under present nitrogen inputs and planted area) is a coarse approach that likely conceals regional biases.

This study assumes there would be enough animal-drawn cultivation equipment to equip all the animals. Currently, animal-drawn equipment is more often found in smallholders and in developing countries. The mechanised equipment would need to be retrofitted into animal-drawn equivalents, but the feasibility of doing this in a scenario of industry collapse is unknown. Alternatively, animal-drawn equipment could be fabricated from scratch from wood and metal scraps, but the capacity to do this would vary across the globe and depend on resource availability and skill. The time of production of animal-drawn equipment in these conditions is also unknown, but it would likely mean wheat production would be lower in the first years of the catastrophe.

There is some uncertainty regarding the cropland expansion aspect of this study; land clearing tasks could require animals to work every day or at any given period throughout the year. This constitutes an optimistic assumption, as there would be months where the harsh climate conditions would make working outdoors difficult, which would decrease cropland expansion rates. On an opposite note, expansion rates would improve if the animals allocated for cultivation of current cropland participated in cropland expansion in the days when they are not required for cultivation. Although this would increase the expanded area, it would also increase the animals' feed requirements. Since the first 3 years of nuclear winter are the most critical for crop production, it would be better to save as much of the wheat produced for human consumption, thus only feeding the animals for the minimum time required.

Although there is no fertiliser application, the crop model simulations show that there would still be many areas worth cultivating in an ASRS. Wheat output could potentially be improved by using animal and human manures to fertilise crops. The human manure would need to be pasteurised, which could plausibly be done in large piles even in nuclear winter.

The number of animals is considered constant throughout the 7 years of nuclear winter, assuming that births occur at a rate that allows for the replacement of dead animals. Factors that may cause mass animal death such as diseases, lack of veterinarian care, scarcity of feed to maintain the animals alive and culling of animals for human consumption are not considered, but all are likely to happen during a catastrophe.

The number of dairy cows could have been underestimated since it is calculated based on annual milk production, since it does not consider cows in small farms or owned by families. Similarly, there is uncertainty in the number of draught cattle that can be used, as it is assumed that all male cattle would have the power of oxen and does not distinguish between gender or age, which could factor into the work rates, energy requirements and amount of feed required.

While results show that there would be enough feed produced globally to feed all the animals, if there is no international trade, animals in a given country could only be fed with their country's production, which may not be enough to feed all the animals depending on how much land can be cultivated. Neighbouring countries could potentially supplement stocks of countries with smaller annual wheat outputs, but depending on the geographical distribution of the animals and the land cultivated, this could be an arduous task.

To facilitate calculations, the number of animals fed is kept in horse-equivalents, and the digestible energy of the different feeds is that for horses. Cattle are capable of digesting crop residues better than horses can, (Falvey and Chantalakhana, 1999, chap. 7) and given there are more cattle than horses, the wheat animal requirements (see **Figure 5**) could be lower, reducing the need to feed them wheat during the non-working days (Copland, 1987, pp. 64–68, 1987, pp. 69–77; Falvey and Chantalakhana, 1999, chap. 7).

Since the wheat animal requirements are so high, particularly in the first 4 years of nuclear winter, alternative feeds could be used to supplement animals' rations, so as to use as much of the produced wheat as possible for human consumption. Instead of cultivating all the productive land, some cropland area next to the animals' working place could be transformed into pasture. Alternatively, wood and paper pulp could be processed, and it has already been shown that its incorporation in small amounts into the diets of ruminants is possible (Millett *et al.*, 1973; Coombe and Briggs, 1974; Peavy *et al.*, 1980; Abo Omar, 2001).

This study also does not consider the intricacies of mobilising animals, humans, and food during the catastrophe. Getting animals and humans to the places where they are needed could prove difficult if the places are too far or hard to access. Animal's speed of transport and susceptibility to injuries could indefinitely delay the supply of food to people and animals, which would pressure them to rely on stored food and/or food scraps. The best possibility would be recuperating trade, so that countries would not be limited to their own wheat production, but the possibility of doing this in a GCIL scenario with heavy geopolitical tensions at work is uncertain.

5. Conclusions

Expansion and the cultivation of cropland using animal draught seems to be a viable food-providing system in a nuclear winter with industry collapse. When horses, draught cattle and dairy cows are used in draught, approximately 730 Mha of current cropland are cultivated, and cropland area is expanded by 125 Mha. This leads to a cumulative production of 10.5 billion tons of winter wheat over 7 years, 20% of which is directed for animal consumption. When dairy cows are not used in draught, 710 Mha of current cropland area are cultivated, and area is expanded by 110 Mha. Approximately 10 billion tons of winter wheat are produced over 7 years, with 18% being used to feed the animals. In both scenarios, wheat production is eventually enough to feed over half of the global population, if international trade resumes. Utilising dairy cows in draught makes a difference in cropland expansion, but not very large as the power per cow is small compared to horses or other cattle. Future work would include uncertainty and sensitivity analysis for different input parameters (annual yield, equipment numbers, other crops and cultivars) and model parameters, test more draught animal combinations, and overcome the additional stated limitations.

List of Abbreviations

ASRS	Abrupt sunlight-reduction scenario
B	Barren
BHS	Barren land, herbaceous vegetation, and shrubland
CC	Current cropland
DE	Digestible energy
DCS	Dairy-cow scenario
DSSAT	Decision-Support System for Agrotechnology Transfer
FAO	Food and Agriculture Organisation
FAOSTAT	Global Food and Agriculture Statistics of FAO
H	Herbaceous vegetation
HBS	Herbaceous vegetation, barren land, and shrubland
IFPRI	International Food Policy Research Institute
NCS	No-dairy-cows scenario
S	Shrubland
SRTM	Shuttle Radar Topographic Mission

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supplementary materials

The authors declare there are no supplementary materials.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

The crop model was a product of International Food Policy Research Institute and the Consultative Group on International Agricultural Research (IFPRI/CGIAR) and Alliance to Feed the Earth in Disasters (ALLFED) collaboration (https://github.com/allfed/mink). The authors would like to thank Ricky Robertson at IFPRI, Benjamin Poulter at NASA, Nicholas Lam, and Baxter Kamana-Williams. This research was funded by the Department of Mechanical Engineering at the University of Canterbury and by ALLFED.

Author contributions

L.L.M.: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, visualisation, writing - original draft; M.H.: formal analysis, investigation, supervision; S.B.: data curation, investigation, methodology, software, writing - original draft; D.D.: conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, writing - original draft.

Funding sources

This research was funded in part by the Alliance to Feed the Earth in Disasters (ALLFED). Luísa L. Monteiro was funded as a PhD student by the Department of Mechanical Engineering at the University of Canterbury.

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