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Deployment of Resilient Foods Can Greatly Reduce Famine in an Abrupt Sunlight Reduction Scenario

Morgan Rivers [a], *Michael Hinge* [a], *Juan B. García Martínez* [a], *Ross J. Tieman* [a], *Victor Jaeck* [b], *Talib E. Butt* [a,c], *David C. Denkenberger* [a,d]

Abstract

In a nuclear war, volcanic eruption, asteroid or comet impact that causes an abrupt sunlight reduction scenario (ASRS), agricultural yields would plummet. Global society is currently unprepared for such an event, implying an urgent need for evaluation and prioritization of solutions. We show effective deployment of resilient food solutions appears sufficient to fulfill global energy and macronutrient food requirements, potentially saving billions from famine. A Monte Carlo analysis of resilient food outcomes, using a linear optimization model, shows a 95% probability of global food availability between 2,300 and 3,900 Kcals per capita per day in a nuclear winter scenario involving 150 Tg of soot in the stratosphere. Our analysis indicates nutritionally sufficient diets from resilient foods would be widely affordable, costing US$1.73 daily, though subsidization could be needed across Southern Asia and Sub-Saharan Africa. Post-disaster conflict or insufficient international cooperation could increase costs and reduce output, hampering effective resilient food deployment.

1 Main

The global population is unprepared for several food-related global catastrophic risks (GCRs). We classified a subset of extreme food-related GCRs under the label *abrupt sunlight reduction scenarios* (ASRS), in which a catastrophic event causes a widespread, rapid reduction in sunlight reaching the surface of the Earth. At least three mechanisms for ASRS have been identified in the literature: extreme volcanic eruption, large bolide (asteroid/comet) impact, and nuclear war[1,2]. In these scenarios, an enormous sudden ejection of aerosol material such as sulfates or soot (black carbon) takes place, causing multi-year reductions in global temperature, solar irradiation, and precipitation, leading to a global catastrophic food shock (GCFS). Nuclear war has a likelihood of ~1% per annum[3], while large bolide impact has a likelihood of ~0.0001% and supervolcano eruption has a likelihood of ~0.001%[4]. Global conflicts such as the 2022 Russo-Ukrainian crisis may increase the annual probability of nuclear war above these levels.

Prevention of an ASRS is unambiguously the best outcome. However, this may be impossible, and according to the "three layers of defense" model of existential risk, a comprehensive strategy ought to include prevention, response and resilience[5]. The current work investigates the feasibility of response and resilience approaches to an extreme ASRS, in line with the recent United Nations calls for "Defining, identifying, assessing and managing existential risks"[6,7].

Xia et al.[8] have estimated a global fatality rate of 75% due to starvation in an ASRS catalyzed by a nuclear winter involving 150 Tg of soot in the stratosphere ("150 Tg scenario"), but did not evaluate scenarios involving effective global measures taken to bridge the food production shortfall. In this work, we investigate a subset of foods and food production methods known as *resilient foods* or *resilient food solutions*, which could allow for significant food production in the face of an ASRS[9]. Resilient food solutions must be scalable and amenable to rapid production ramp-up. Solutions must also be low cost, as affordability is a key factor for adequate access to food during an ASRS, just as it is today[10].

In this study we investigate the reduction in global famine in scenarios involving a globally coordinated response and approximately $30 million to $300 million in preparation prior to a 150 Tg scenario. The primary difference between a 150 Tg nuclear winter scenario and a comparable volcanic eruption is the higher-altitude lofting in the stratosphere of soot emanating from firestorms induced from the nuclear blast, prolonging the duration of a nuclear ASRS[11].

We begin our analysis by analyzing two 150 Tg scenarios: one involving no response, and another involving plausible outcomes of the deployment of a suite of resilient food solutions. Based upon these estimates we find that resilient foods could feed everyone throughout the 150 Tg scenario. A Monte Carlo simulation of 10,000 different scenarios confirms our results. The relative caloric contribution of each resilient food is compared in a separate set of 1,000 scenarios. Finally, we compare resilient food costs and overall nutritive contributions to common low-cost foods in 2020. Expectations of the performance of some resilient foods are still preliminary. However, as new research refines expected resilient food outcomes, and as the food system changes over time, updated or new data can be included in the open source model for scenario analysis and easily run online using the publicly available Jupyter notebook Colab interface.

2 Results

2.1 Feasible Global Macronutrient Production

150 Tg Scenario, Without Resilient Foods

In the face of an ASRS such as a 150 Tg scenario or an equivalent volcanic eruption, human edible food from agriculture would undergo near-complete collapse, with a minimum production of only 11% of current levels after three years, given current behaviors[4]. Here we evaluate the degree of food availability in a scenario assuming continued global trade, not including disruptions due to the ongoing or additional conflicts, and assuming a relatively rapid reduction in human edible foods fed to livestock.

In the event of continued coordination, several aspects of the food system would allow for more food availability than implied from an 11% baseline. As a result of the readily apparent severity of the disaster, even with no planning we would expect that the majority of biofuel production would halt quickly, due to the rapid expected rise in food prices relative to fuels. Because continuation of livestock at present-day levels would imply fewer animals would starve than humans, and economic incentives would increase the cost of feed, we estimate the majority of human edible feed fed to animals would be redirected. As the disaster progresses, livestock would also become a key source of macronutrients, as most livestock would be consumed rather than maintained with expensive human edible food. Finally, in part due to soaring food prices relative to incomes, we estimate that waste (which includes "overconsumption" beyond minimum healthy levels) would be reduced sharply. Based on an estimated tripling of food prices, and a consumer response to this based upon individual incomes, we estimate post-harvest waste would fall to approximately 13% of production[12]. See Supplementary Information section I for the food system baseline before catastrophe.

Assuming some continued food waste, a two-month delay before shutoff of biofuel production, and a three-month delay before human edible animal feed is redirected to humans, only 1,600 Kcals per capita per day are available throughout **(Figure 1)**. The simulation indicates that a full 6.5 years (78 months) is required to increase food availability significantly above this level. The models indicate that calories are the primary nutrient limitation throughout, and that sufficient dietary fat and protein would be available to meet the needs of those who could obtain enough calories with a mixed diet. A rough estimation of the survival rate obtained by dividing the proportion of available calories by the minimum recommended caloric consumption (of 2,100 Kcals[13]) indicates approximately 24% of the global population would starve even if food were allocated optimally over time.

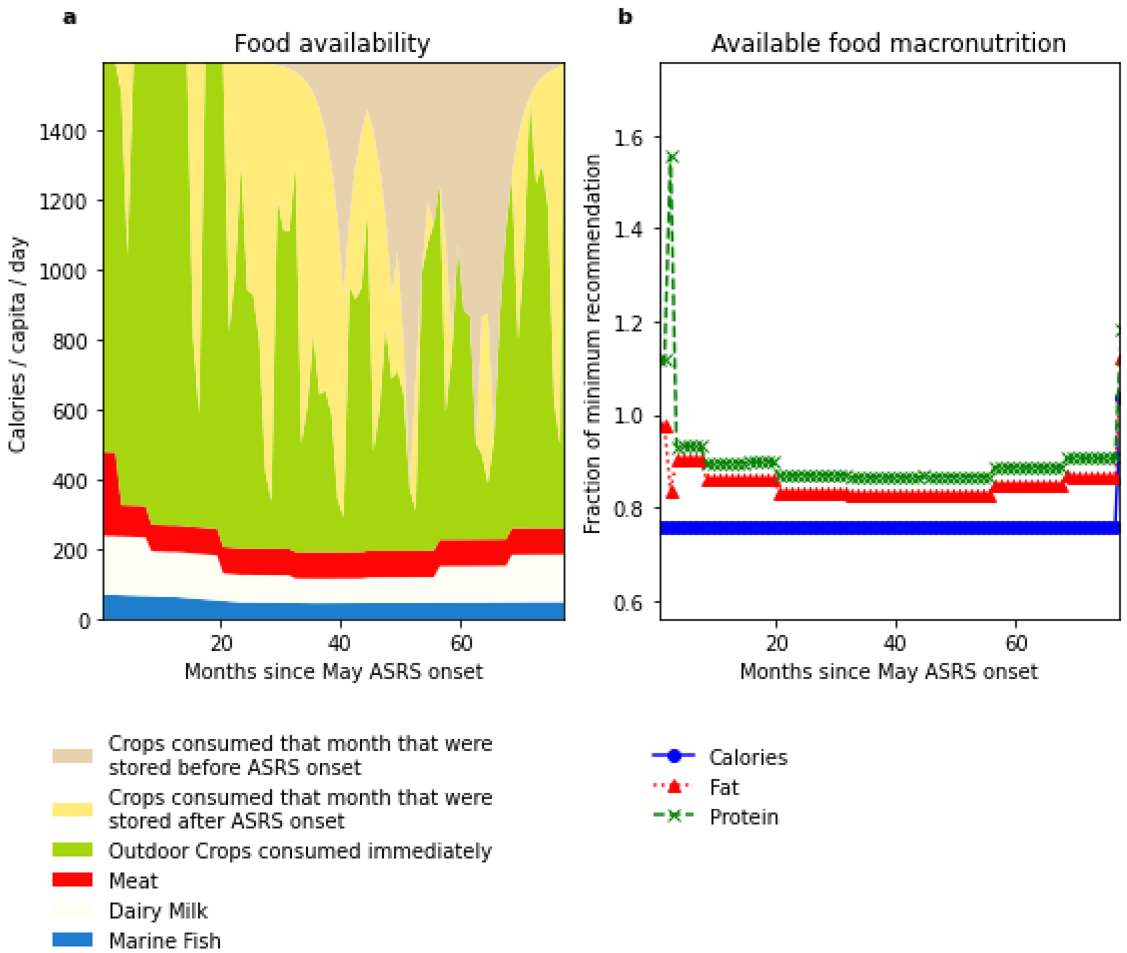


Figure 1 | Food availability after accounting for waste and a delayed halt of non-human consumption, without resilient foods. a, Expected per capita caloric availability by food source in a 150 Tg scenario with no resilient food deployment. 13% waste is assumed, with a two month delayed biofuel shutoff and a three month delay before human-edible animal feed is redirected to humans. **b,** Fraction of macronutrients on average available during the 150 Tg scenario with no resilient foods. Recovery of available food past 1,600 Kcals only occurs after 6.5 years under a wide range of assumptions, and in all cases quickly recovers past minimum present global needs. Waste was estimated using the probable reduction in waste if there were a 3:1 ratio of food price to 2020, as described in more detail in the methods section. The change in percentage waste was not delayed in the model. See Supplementary Information for detailed information on each food source.

150 Tg Scenario, With Resilient Foods

The successful implementation of resilient foods would make some coordination assumptions in the previous section more plausible. With food production combined with waste well above minimum human requirements throughout, stored food would not be in as extreme demand in the worst years of the 150 Tg scenario. Preparedness plans for resilient foods would imply a situation in which the industrial producers and decision makers are aware of the critical urgency of rapidly culling and storing livestock and reducing human edible food fed to animals and used for biofuel production. It is therefore assumed to take one month to halt biofuel production and two months to redirect substantial fractions of animal feed to humans. International action to coordinate deployment of these foods, combined with strong international food subsidies for the world's poor, could allow sufficient nutrition in all areas able to trade and receive food. In this scenario, conflicts from food riots and resource competition would thus be greatly reduced.

The resilient food solutions with maximum life-saving potential in a 150 Tg scenario were identified as a combination of the following:

- The optimal release and equitable distribution of all forms of stored food, both nationally and internationally.
- Outdoor crops with high levels of fertilizer applied to croplands in the tropics and with rotations altered to accommodate the colder climate.
- Continued dairy output near present-day levels via prioritization of grasses, fodder crops and residues for dairy cattle.
- Continued meat production where output does not conflict with human consumption, while prioritizing grazing of ruminants on any available pasture beyond those needed for dairy.
- A seaweed industry that is rapidly scaled up to approximately 70x present-day farm area and production quantities.9d
- Rapid expansion of low-tech greenhouses in the tropics[14].
- The rapid repurposing of paper and pulp factories into cellulosic sugar factories, (an "industrial food").
- The rapid establishment and deployment of single cell protein (SCP) factories[15,16], an ("industrial food").
- Continued commercial marine fishing with reduced catch yields as the ASRS progresses[4].

For this scenario, the food production potential of resilient food solutions implemented successfully plus traditional agricultural production is estimated at approximately 2,700 Kcals per capita throughout the 150 Tg scenario after incorporating waste, feed, and biofuel production **(Figure 2)**.

The primary contribution to maintain fat and protein requirements involved a selection of rotations involving increased planted area for wheat as a protein source, rapeseed for fat, and sugar beets or potatoes for caloric supply. In this scenario, caloric demand is the most important limiting factor. Seaweed met significant protein demand, due to the use of *Porphyra amplissima* with its high protein to calorie ratio. Protein was also significant from Methane SCP.

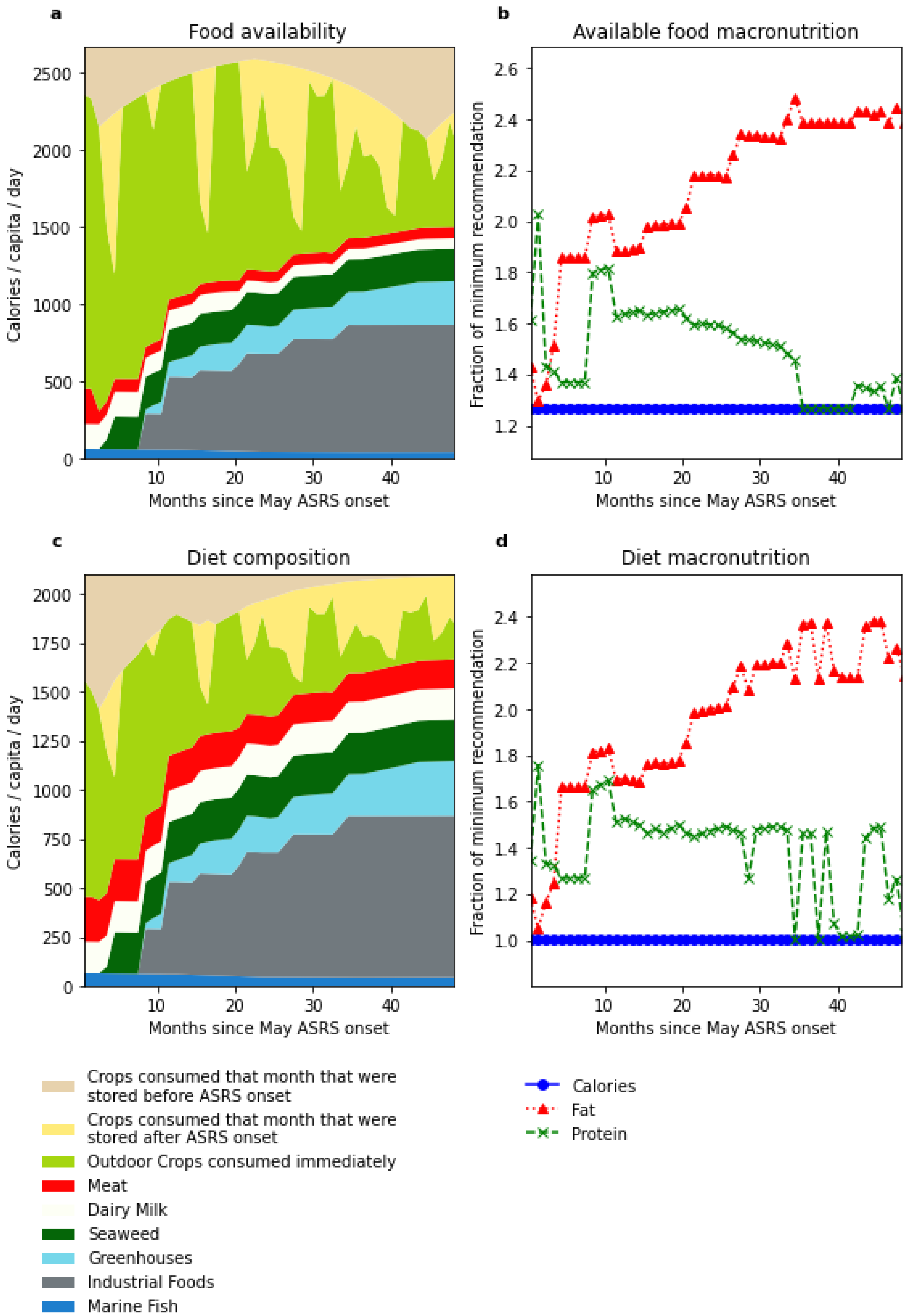


Figure 2 | Food availability after accounting for waste and a delayed halt of non-human consumption assuming resilient food scaling up in a 150 Tg scenario. a,b: Availability of food by food source, incorporating approximately 18% food waste, including overconsumption and excluding on-farm waste, and with current biofuel production continued for one month and current animal feed usage continued for two months. **c,d:** An approximate average ASRS-resilient diet composition determined by feeding excess production from outdoor crops to livestock. In this scenario, dairy could be fully maintained, and other animal products could be maintained at significant volumes by prioritizing the most efficient feed systems. The change in percentage waste was not delayed in the model. See Supplementary Information for detailed information on each food source.

By month 48 after the ASRS onset, resilient foods would be fully scaled up, and traditional crop yields would pass their minimum point and begin to recover to normal levels over the coming years. This would allow diets to slowly revert to more traditional foods. Finally, the average human diet shown could include less seaweed and industrial foods if these foods were fed to animals rather than humans, although this has not been investigated.

Monte Carlo Simulations

We performed a set of Monte Carlo simulations to estimate the variability in resilient food outcomes. A random sampling of 10,000 scenarios over the parameter space was selected. The 2.5th percentile outcome scenario produced 2,300 Kcals per capita per day after waste, and the 97.5th percentile produced 3,900 Kcals per capita per day after waste. Calories remained the limiting factor in the majority of Monte Carlo scenarios. See the Supplementary Information, section II for details.

We also ran a separate set of 1,000 scenarios with either only one resilient food scaled up or only one resilient food removed. These scenarios reveal that if fat and protein minimum requirements are enforced, each individual resilient food is less effective than when scaled up in combination with other resilient foods. Relocation contributed to meeting macronutritional needs most when scaled in combination with other foods.

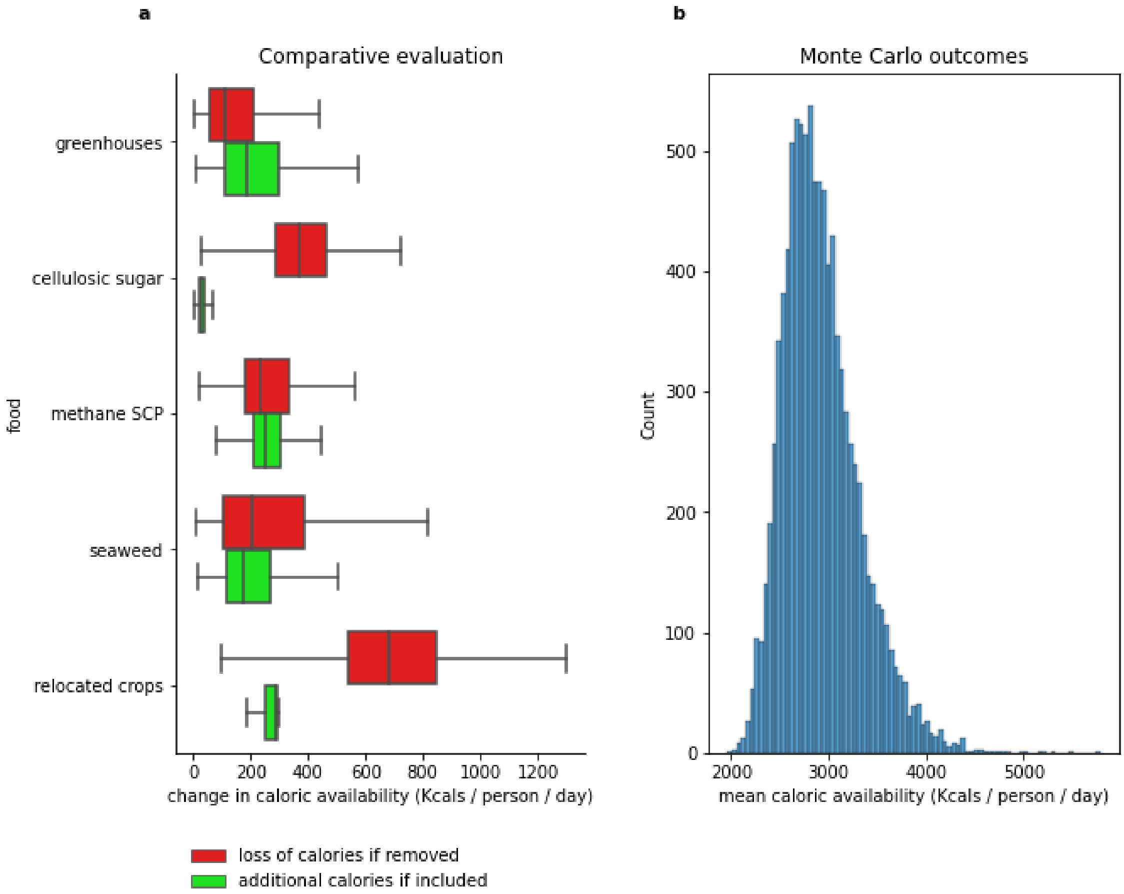


Figure 3 | Food available after accounting for delayed shut off and waste. a Estimated caloric contribution per person for each resilient food over 1,000 scenarios. Scenarios where the resilient food is removed from the full suite of resilient foods are shown in red. Scenarios where only one resilient food is scaled up is indicated in green. Only calories used as part of a balanced macronutrient profile are shown. Reduced variability is observed when adding foods, as evaluating the variability of scenarios in the non-resilient food case is outside the scope of this paper. Red bars are relative to scenarios similar to **Figure 2a** while green bars are relative to scenarios similar to **Figure 1a**. **b** Estimated caloric availability in 10,000 scenarios after incorporating a constant level of reduced waste of 18% due to increased food price, delayed biofuel and feed, and differences in the production and scaling up of resilient foods. While caloric availability is shown, fat and protein limitations are often influential in determining the change in number of useful calories for a scenario.

While many challenges remain before they are ready for rapid deployment at scale, solutions such as industrial foods and seaweeds could possibly scale to 2x or more of current global human minimum caloric requirements within the first few years after a 150 Tg scenario onset, given sufficiently large portions of global industrial and economic resources[15–19].

2.2 Affordability of Macronutrient Consumption

Economic as well as physical access to foods is required in order to meet the criteria of food security, as defined by the Food and Agriculture Organization of the United Nations (FAO) in the 1996 World Food Summit[20]. While a detailed analysis of price equilibria is beyond the scope of this paper, here we present an analysis of the cost of producing resilient foods post-disaster under a median production resilient food production scenario. This analysis allows us to determine the minimum cost of diets, as prices must exceed costs to be sustainable over the duration of the ASRS, especially with rapid capacity expansions. See Supplementary Information, section III for details.

Figure 4 shows the estimated costs three years subsequent to the disaster when outdoor crop production is at its highest cost, including an allowance for a return on capital and depreciation. Costs have been normalized onto a US$/day, or 2,100 Kcal, basis. Our results indicate significant variation in the cost of foods in the ASRS. This ranges from around US$0.30/2,100Kcal for cellulosic sugars, up to US$0.60-0.90 for outdoor grown grains (wheat and maize), US$0.95 for rapeseed oil, around US$2.70 for seaweed and potatoes, and around US$6.00 for milk vs US$7.50-15.00 for chicken/pork and ruminant meat respectively.

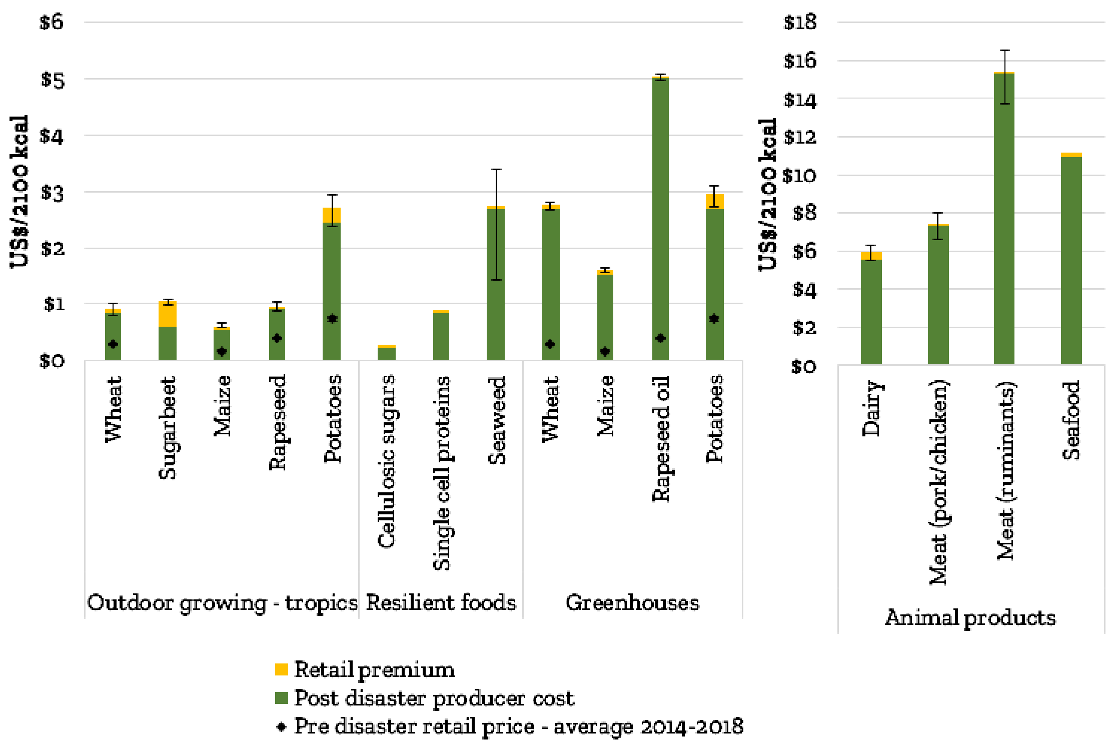


Figure 4: Cost of production on a retail basis for a sample of foods, before and after disaster. Costs are listed as US$ per 2,100 Kcal, estimated three years after 150 Tg scenario onset. These costs represent a significant rise when compared to current retail prices, with increases in bulk grain prices such as wheat and maize by around 250% and vegetable oils by 300%. This suggests a significant decline in food affordability post-disaster, pushing billions into food insecurity unless additional support is provided. Sources of foods that generate more calories per unit area, such as potatoes and greenhouse crops, are less affordable, ranging from US$1.5-3 per 2,100 Kcal, versus around

US$0.2-0.3 for the cheapest grains today. The retail premium refers to the estimated cost of moving foods from farm/factory gate to a shop available for sale to consumers, as well as a retail margin. Error bars indicate the range of high/low production costs based upon the variance in minimum and maximum yields over the period of calibration (see Supplementary Information, section III).

In order to provide an estimate of affordability post-disaster, we constructed four representative diets out of the proposed set of foods subject to meeting the constraints listed below. While diets typically do not match well to richer consumers, they are much closer to the choices made by consumers facing significant budgetary constraints[21], and are therefore useful when considering affordability and diets for those in or close to global poverty. We compared the cost of these diets to global poverty thresholds by region[22], based upon market exchange rates and spending no more than 63% of total income on food[23] (see Supplementary Information, section III).

Potential diets have been presented on four different levels of affordability:

- A "minimum cost caloric" diet costing US$0.51 per day, based upon sourcing 30% of calories from cellulosic sugars and the remaining 70% from the next lowest-cost source, maize. However, this would be well below other macronutrient and micronutrient intake recommendations.

- A "minimum cost macronutrient" diet for protein and fat as well as carbohydrates costing US$0.80 per day, achieved by substituting some grains and sugars for single cell proteins, seaweed and vegetable oils in the diet above.

- A micronutrient-complete diet as laid out in Pham et al.[9], which presents diets constructed out of foods projected to be available following a ASRS. These satisfy minimum and maximum micronutrient (vitamin/mineral) bounds as well as macronutrients. There are a number of diets in the study, and we have chosen the period III diet (once resilient foods are scaled), excluding greenhouses, to get the lowest-cost diet satisfying full nutrient requirements in year three. In total, this diet is projected to cost $1.73 daily. However, while the paper examined low cost diets post-disaster it did not minimize costs, and as such it is possible micronutrient requirements could be met at a lower cost than this estimate.

- An average "basket of foods" diet costing US$2.56 per day, weighted evenly on a caloric basis by its share of the total, including higher-cost foods such as animal products and greenhouse cultivated crops. This diet meets minimum calories, protein and fat requirements. It however has not been assessed for micronutrients.

The affordability of each of these diets is presented in Table 1. While most could afford the diets on their pre-disaster income, at least 1.1 billion would be unable to afford a basic caloric diet at cost post-disaster, 1.35 billion would be unable to afford adequate macronutrients, just over 3 billion might struggle to consume enough vitamins and minerals without supplementation/fortification and over 3.7 billion would be unable to consume the average basket of foods produced.

Table 1: Affordability of dietary benchmarks post disaster - Year 3 - US$ international exchange rates

	Cheapest calories	Cheapest macronutrients	All nutrients met	Average diet

		met		
Daily cost per capita	$0.51	$0.80	$1.73	$2.56
Necessary income per day at 63% of budget	$0.81	$1.28	$2.75	$4.07

Region	**Unable to afford calories**		**Unable to afford macronutrients**		**Unable to afford micronutrients**		**Unable to afford average diet**	
	million people	%	*million people*	%	*million people*	%	*million people*	%
East Asia and Pacific	17	0.7%	31	1.3%	422	17.9%	790	33.5%
Europe and Central Asia	19	2.1%	22	2.3%	49	5.3%	83	9.0%
Latin America and the Caribbean	17	2.6%	21	3.3%	84	12.8%	140	21.5%
Middle East and North Africa	6	1.2%	10	2.1%	122	26.3%	195	41.9%
Other high Income	4	1.0%	4	1.0%	6	1.6%	8	2.3%
South Asia	644	34.7%	822	44.3%	1,557	83.9%	1,634	88.0%
Sub-Saharan Africa	372	32.7%	440	38.7%	813	71.5%	892	78.5%
World Total	**1,078**	**13.9%**	**1,348**	**17.4%**	**3,053**	**39.3%**	**3,742**	**48.2%**

This affordability issue suggests that extensive support involving income transfers, food coupons or price subsidies would be needed post-disaster in order to ensure sufficient nutrition for a section of the global poor. International support post-disaster would be necessary across Sub-Saharan Africa and South Asia, particularly for the urban poor.

Affordability on a cost basis is an important first step in determining economic access to food, as it sets the minimum prices paid by consumers. Prices could however be significantly higher than this level, as described in the Discussion section. Meanwhile, in the case of a complete or partial nationalization of the food system, costs are still a relevant consideration for the capital, labor and inputs needed to produce each form of nutrition.

The same method to calculate affordability as is used above applied to current prices suggests that around 169 million people would not be able to afford sufficient macronutrients from 2015 to 2019. This compares to an average of 642 million people reported to be in severe food insecurity over the same period by the FAO[10], with the difference due in large part to factors beyond direct macronutrient affordability on a cost basis, including conflict-induced food insecurity and failures in infrastructure. As such, these additional factors have significant implications for food security post-disaster, and more analysis is needed to understand how they would apply.

3 Discussion

Maintaining sufficient production of nutritious and affordable foods is a commonly identified element of food security[24], but some have challenged the centrality of production to modern food systems thinking[25]. Global food shock analyses typically involve only a few percentage points lower production than expected trends in global output[26,27,28]. In many ASRS outcomes, even with optimal allocation and distribution, sufficient access for the world's population would be impossible. Thus, we focus on food production and affordability as our primary form of analysis in this paper, while still acknowledging the vital importance of broader factors such as equitable food allocation and distribution in both ASRS and other food shocks[25].

Key future work to prevent global famine from lack of production in an ASRS includes but is not limited to: 1) research on food production methods, production ramp-up and technology deployment, as well as nutritional qualities of the foods, 2) further development of technologies and techniques conducive to a faster response such as fast construction and rapid repurposing, and 3) policy outcomes such as the creation and distribution of effective disaster response plans. Arguably, these areas of work can also inform preparedness and resilience against less-extreme global catastrophic food risks, such as a multiple bread-basket failure due to other forms of climate, or weather shocks, or crop diseases and pests.

While convenient for modeling purposes, the assumptions of continued global trade and other forms of international cooperation may not hold in a world where billions more people are at risk of starvation. Export bans, food riots, resource competition, and ensuing global conflict are potential outcomes, which would significantly increase famine compared to our analysis above. In a 150 Tg scenario, denial of the severity of the ASRS would likely be limited after several months, as the sky would appear dark globally in the months following the global catastrophic event[29,30], and outdoor crop production is estimated to fall to roughly half of present-day levels after only 12 months without relocation. This could lead to widespread panic without a credible response, significantly complicating the prospect of efficient global rationing and allocation of food stocks. By contrast, demonstrating that widespread starvation post-disaster is not a guaranteed outcome could prevent panic and counterproductive negative-sum actions.

It may also be that rapid shutoff of non-human sources of demand such as biofuels and large scale animal feed systems would not occur without sufficient regulatory legislation in advance of the ASRS. We therefore recommend including contingencies in biofuel legislation to quickly phase out food-based biofuel production in case of a GCFS.

The sociotechnical systems which constitute the global food system are complex in nature and will exhibit nonlinear dynamics as system variables change[31,32]. Complex systems often exhibit tipping points – thresholds which once surpassed result in a conformational change of the system to another state through positive feedback loops[33–35]. Aggregate food availability below the global population's nutritional needs may represent such a tipping point.

The Monte Carlo analysis implies that with a coordinated resilient food production response there is a low likelihood for output to dip below this hypothetical tipping point over a wide range of resilient food outcomes. Strengthening food resilience and response capabilities prior to an ASRS could thus be critical to prevent positive feedback loops. The results of our analysis demonstrate that it is possible that the current global population could be fed even in a severe ASRS, although at a higher cost compared to current resources devoted to food production. As a result the world could continue global trade in order to reduce the severity of the crisis.

Global GDP dedicated to agriculture, forestry and fishing was in excess of 9% as recently as the 1970s[36], and while accurate estimates of GDP further back are hard to make, employment in agriculture was dominant for much of human history[37]. Meanwhile, agriculture, forestry and fishing is only 3.5-4% of GDP in the present day by World Bank World Development Indicator estimates[38]. We estimate an expansion of resilient foods would require an additional 3.7% of global GDP based on their capital and operating costs (see the supplementary information for details), raising the total of GDP dedicated to agriculture, forestry and fishing to around 7-7.5%. As a result, while GDP dedicated to food production would need to increase sharply during an ASRS, such an increase may still be feasible and could still be within the upper bounds of living memory.

Despite this potential to meet nutritional needs, it is far from certain that cooperation would actually be secured or maintained, and other social and economic factors could also impact the post disaster response. Producing surplus nutrition is a necessary but not sufficient step in securing global cooperation and meeting individual needs. Expectations for the outcome of a severe ASRS incorporating these considerations are the topic of future work. As a result it is possible that as understanding of the relevant resilient food solutions and systems improve, the conclusions listed may change.

Additional modeling challenges are involved when considering social instability and calculating price equilibriums where output of vital staples are disrupted and future production is highly uncertain. Accordingly, full modeling of food markets and prices under such a scenario are left to future work. However, standard financial systems could experience severe disruption and could potentially collapse under such a scenario, even with continued trade. In addition, there are a number of factors that could alter our cost results, including import and consumption taxes as well as breakdowns in infrastructure. In addition, conflict and continued demand from biofuels or animal feed have the potential to raise prices further post-disaster, especially in the early months.

The ability to coordinate between trading blocs is uncertain following a GCFS and will significantly impact global capacity to respond. In certain types of ASRS, infrastructure could be affected such that countries may no longer be able to communicate and trade internally or externally after the GCFS[39]. In a nuclear exchange, international trust may have eroded as well. In the context of outdoor crop production, this would reduce the ability to send agricultural inputs located in the Global North to tropical regions which could best use them, and for excess yields to be distributed to deficit zones.

Finally, transitioning to inherently more resilient food production systems prior to shocks (e.g., closed-environment systems and modular designs) would also be conducive to warding off the impacts of ASRS[15,16] as well as other food system[40] risks. In a similar vein, expanding use of seaweed as a food and feed[41] source could directly draw down CO_2, and reduce cattle methane emissions, improve food security around the world today by its use as a low-cost food source[42], and reduce the food security impacts of trade restrictions[40], pests[40], ASRS[43], and a loss of electrical and/or industrial function[44,45].

While pathways for prevention of massive volcanic eruption[46] or bolide impact[47] require more research, there is an urgent and well-established need for large-scale global nuclear arms reduction to small fractions of the current global arsenal[48], in part because nuclear war continues to pose a risk for large-scale societal collapse or human extinction. We encourage work along these lines, in parallel with ongoing research and preparations for a GCFS should the worst occur.

We recommend business continuity managers and decision makers working in disaster risk management to promote policies for the creation of preparedness and response plans against GCFS, as has been done for other high-impact low-probability risks, both natural (e.g., tsunamis)[49] and anthropogenic (e.g., nuclear plant accidents)[50], even at the international level[51]. These regional preparedness arrangements could complement systems such as the international "emergency platform" proposed by the UN Secretary-General for responding to GCRs[7] such as those characterized in this work.

4 Methods

The model presented was designed to determine the feasibility of feeding everyone through deployment of resilient foods. Details of the linear optimization model can be found in the Supplementary Information, section IV. All resilient food production methods evaluated here have been deployed at a large scale at the time of writing. As low-cost foods are included preferentially, economic considerations are then applied to estimate how many people could likely afford the food produced. Resilient foods were selected according to anticipated resource constraints (e.g., industrial capacity, availability of production inputs) and the value of the food output – roughly macronutrient content (i.e., calories, fat, protein) per unit cost.

Previously estimated growth rate models are used for estimating the growth rate of industrial foods[18,15]. We account for the management of food reserves and livestock carried in from before the onset of a 150 Tg scenario, as well as redirection of crops away from biofuel production and animal feed. Food waste and estimated reductions of waste at each stage (production, distribution, retail, and consumption above minimum requirements) are also accounted for.

Key assumptions used in the model include:

- Continued global trade - Trade is maintained and production activities are coordinated to maximize total output.
- No hoarding or looting of food at the household, retail or wholesale level.
- Financial stability is assumed
    - Second order analyses and economic effects of the likely financial system disarray are not considered.
    - Income is assumed to be in line with current levels and distributions.
- Infrastructure intact - No direct destruction of infrastructure/industry is considered.
- Population maintained - Reductions in population due to direct or indirect effects are not considered in the results.

Key additional assumptions for the resilient foods section include:

- Sufficient preparation and knowledge in appropriate sectors on how to implement resilient foods.

- Key relations between organizations being put in place early after onset and remaining functional throughout the food shortage.
- Appropriate supporting industries are spun up starting early after the onset.

Future work in scenario analysis will study the effect of varying these assumptions.

Population Energy and Macronutrient Requirements

Energy and macronutrient requirements represent the minimum recommended daily intake for an average weight adult (62 kg): Energy - 2,100 Kcal/day[13], Protein - 51 g/day and Fat - 47 g/day[52]. This is in line with previous assessments of GCFS[9,15–18]. Quality of protein (i.e., the full complement of amino acids in sufficient proportions), and quality of fat (i.e., sufficient unsaturated fat, and omega-3 and omega6 fatty acids) are beyond the scope of this paper, although baskets of the same resilient foods as discussed in this paper have been calculated to provide a protein-complete diet[9]. Resilient food diets appear to be able to largely meet key macronutrient and micronutrient requirements at a population scale with adequate nutritional planning[9]. Therefore, meeting specified daily quantities of macronutrients is considered nutritionally sufficient within the model. Future work will combine food availability and nutrition analyses.

Waste

Waste information was determined using the FAOSTAT Supply Utilization Accounts database between 2014 and 2018[53]. Over one third of current agricultural production on a caloric basis goes to waste before coming to any use. Agricultural waste consists of harvest losses, distribution losses, and retail/household waste. Harvest losses are already accounted for in the estimates of current-day agricultural production and were not adjusted in the ASRS, which is pessimistic as there would be effort to reduce harvest losses given the higher prices. Distribution losses refer to losses in processing, transit and storage, post-farm but before they are delivered to the retail level. Distribution losses are largely a function of existing quality of storage and transport infrastructure[54], and are assumed to be maintained. Distribution losses vary widely by crop/food variety, and so the percentage loss appropriate for each agricultural category in FAOSTAT is assumed[53]. Retail/household waste refers to food damaged or not consumed at the retail level onwards, such as shops rejecting or failing to sell products or households discarding food once purchased.

In order to estimate waste in the "no resilient foods" case, a tripling of food prices is assumed, a conservative reduction given the estimated rise in costs. In the "no resilient foods" case, applying empirical linear extrapolation between food price and waste[12] and aggregating over all countries, retail and household waste were estimated to be reduced from 24% to 14% globally post-catastrophe in the resilient foods scenario, and from 24% to 10% in the scenario without resilient foods.

Stored Food

Available stored food at the time of the disaster has been estimated based upon reported crop year end stocks from the United States Department of Agriculture's Production, Supply and Distribution (USDA PSD) Database[55]. These have been adjusted onto a calendar year basis (as crop years and calendar years do not typically align), and takes the month of May as its starting point: the month of the abrupt sunlight reduction in the climate model (see Supplementary Information, section V for details of this process).

This gives total stored food of around 1.65 billion tonnes, dry caloric value. This considers storage of all bulk grains, sugar, soybeans and other oil crops, as well as any vegetable oils. Data on storage for fruits, vegetables and tubers are not available in the database and so have not been included; however, these are likely to be small by comparison due to their higher perishability, and this presents a more conservative view of stored foods. In order to match production and consumption in the present day, stored food was assigned the same dietary fat and protein percentages as outdoor crop production.

Allocation of Output

In the cases of validation of the run model and 2020 data, once nutrient flows have been optimized, they are allocated to an end use, firstly direct human consumption, followed by any surplus outdoor crop production going to animal feed. Human consumption is assumed to equal the total population, multiplied by the dietary needs per person and taking into account distribution and retail/household waste discussed above.

Any surplus above this threshold is assigned to animal feed systems (see Supplementary Information, section VI). In our allocation, we have assumed that long-term use of foods for other uses such as biofuels is negligible. Prices of crops would be high post-disaster, likely making the use of biofuels highly uneconomical, and it would be expected that biofuels policy would also adjust to reflect the new reality of food scarcity.

4.1 Resilient Food Modules and Interactions

Relocated Outdoor Growing

The severity of a 150 Tg scenario with no resilient foods was estimated by scaling down year 2020 production in yields using the analysis of Xia et al[4]. Because it is expected that the majority of crop production in a 150 Tg scenario would come from currently tropical areas, the seasonality of production in the tropics (defined as 24° north to 24° south) was used as a proxy for monthly variation in global production throughout the time period.

For the relocated case simulation, sugar beets and potatoes produced the most calories per hectare, rapeseed produced the most fat per hectare, and wheat produced the most protein per hectare. An 80% reduction in planting area of crops outside of these staples was assumed, and the remaining area would be planted with a combination of potatoes, rapeseed, wheat, and sugar beet. Under the assumption that global fertilizer production would be largely unchanged and allocated efficiently to tropical crop growing regions without the need for increased fertilizer production, crop models were run with a uniform 100 kg/ha of elemental nitrogen equivalent applied to all cropland, implying low nitrogen stress growing conditions. While these crops would not be the only crops able to be grown outdoors post-disaster, they represent a reasonable high yield, cold-tolerant rotation for macronutrients, which would be likely combined alongside some ongoing cultivation of maize, rice, pulses and vegetables where possible. As a result, the one standard deviation lower bound is the current global distribution applied to the tropics existing cropland, while the one standard deviation upper bound assumes full adoption in existing food cropland. Expanding arable land would in principle be feasible over the course of 150 Tg scenario, but it was conservatively not included in the analysis.

The varieties and types of relocated crops were instrumental in meeting fat and protein requirements. Rapeseed was found to be an efficient source of fat for a 150 Tg scenario. It is assumed that the protein from rapeseed meal would not be used to feed humans, as rapeseed meal is not deemed to be safe for human consumption[9] and it is not guaranteed a technological solution would be achieved in a reasonable timeframe. Wheat was the largest contributor of protein per hectare in the relocated crop model, closely followed by soybean. However, soybean produced many fewer calories per hectare in the relocated case and its area was reduced compared to the present day to allow for other crops to be grown.

The improvement in yields was used to linearly scale the reduction in crop yields over time, such that the biggest improvement in rotation was three years after the GCFS, but the fully recovered yields would remain unchanged from the 2020 crop yields projection. Outdoor growing yields remain exogenous to the optimization model, although excess production from any month is stored and redistributed in months after the excess production occurs. More details on outdoor growing can be found in Supplementary Information, section VII.

Greenhouses

While greenhouses today feed a negligible number of people, low-tech polymer-based greenhouses have been estimated to provide a large fraction of calories as a resilient food source in a 150 Tg scenario at an affordable price in past work[14]. While these low-tech greenhouses reduce the CO_2 levels, air circulation, and incoming photosynthetically active radiation (PAR) for crops, they increase the average temperature, humidity, and thus increase available *growing degree days*. Greenhouses would also allow for growth in some regions which would otherwise be unable to grow significant quantities of food. To avoid overly optimistic outcomes, we have assumed that newly constructed greenhouses would be built only on the available outdoor growing cropland area, and subtracted this fraction of area from available outdoor cropland.

Greenhouses are estimated to produce a 50% yield increase versus outdoor growing post-disaster in a 150 Tg scenario, based on a *growing degree day* evaluation of maize and potatoes (see Supplementary Information, section VIII).

Seaweed

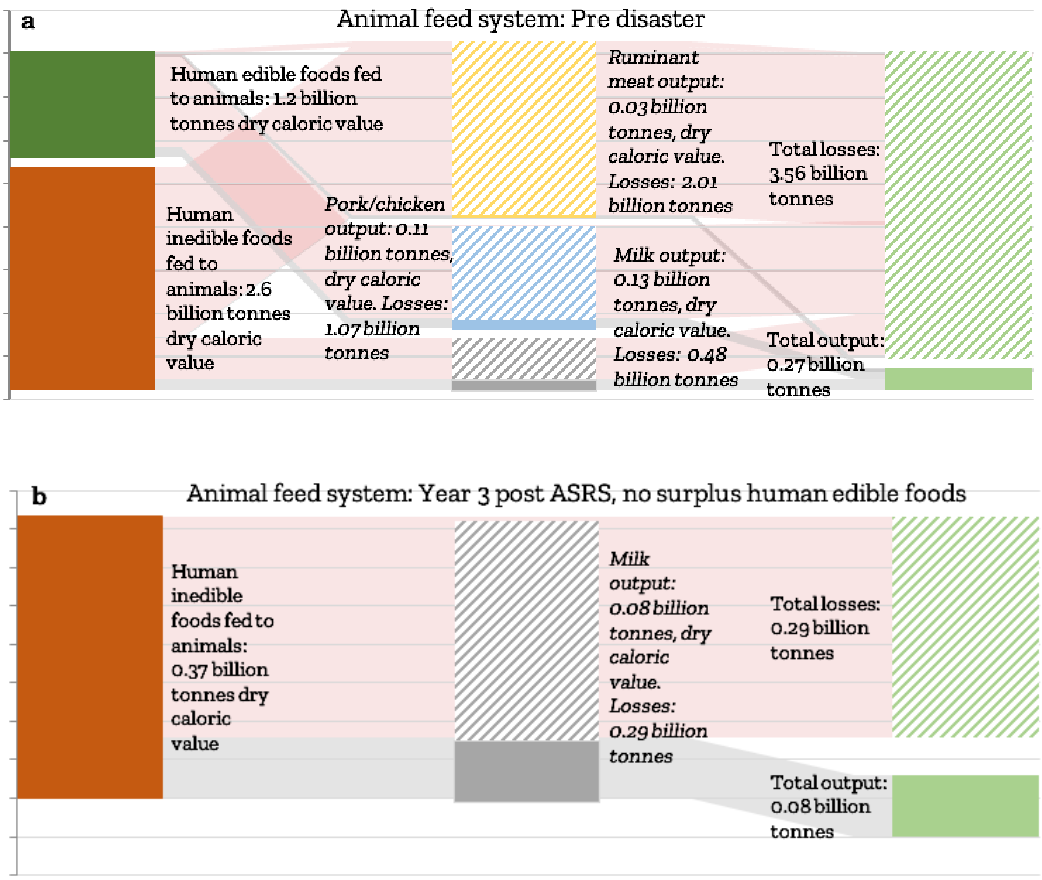
Low-tech marine seaweed farm designs hold potential to be a low-cost, rapidly scaleable, and nutritious food source. Seaweed tolerates low sunlight conditions and cold temperatures[56], and can quickly scale to high productivity[42]. For these reasons, seaweed is an especially promising food source in an ASRS. We selected *Porphyra amplissima* as a representative example for its cold tolerance and high protein content[57]. Species of Porphyra are also widely consumed in Southeastern countries today[58]. However, other varieties would also be suitable, such as those in the *Gracilaria* family. Due to nutritional and palatability concerns, seaweed has been capped at a maximum of 10% of daily calories. The linear optimization model used to estimate seaweed growth and deployment of new farms is listed in Supplementary Information section IX.

Dairy and Meat Output

While crop yields would be severely reduced in an ASRS, efficient allocation of agricultural residues could be used to maintain a significant amount of dairy production. Prioritizing maintenance of dairy is justified by the favorable feed and protein conversion efficiency of dairy as compared to beef[59], with around 400 kcal and 21 g of protein per kg of inedible feed for milk and 22 kcal and 2 g of protein per kg of inedible feed for beef (see Supplementary Information, section VI for a detailed breakdown).

For technical feasibility calculations, it was estimated that livestock was reduced to levels that could be maintained by a combination of grasslands, agricultural residues, fodder crops and excess human edible food for the 150 Tg scenario. An iterative market equilibrium was used to estimate that feed would be maintained such that approximately 50% of current-day meat production on a caloric equivalent (mostly chicken and pork) could be maintained from Year 2 given the central assumptions of the resilient food model (see Supplementary Information, Section VI). This system is summarized below, in **Figure 5**.

In both resilient and non-resilient 150 Tg scenarios, the meat obtained by culling livestock populations was allocated uniformly until stored food is no longer being used up in the model. This takes 48 months after ASRS onset for the resilient foods case, and 78 months for the non-resilient food case. Livestock slaughter capacity scaling up might be needed but was not considered.



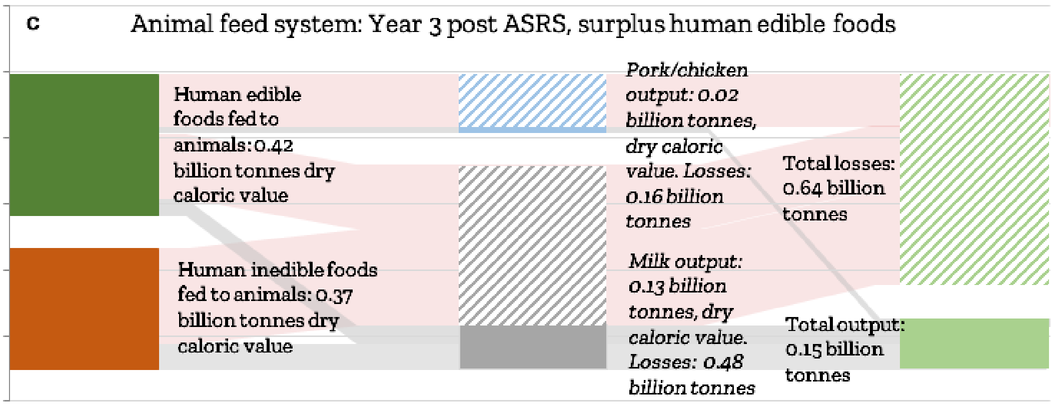


Figure 5: Examples of animal feed system modeling, before and after the disaster. We assume feed is applied to the most efficient use in terms of calories/protein, up to the limit set by output in the present day. This allows for significant output of animal products despite a sharp decline in feed output. Plot C detailing Year 3 with surplus human edible foods is based upon the resilient food scenario under base assumptions. All values are in dry caloric tonnes (normalized to 4,000,000 kcal/metric tonne) to allow comparison between different foods.

Marine Fish

The catching of marine fish could continue at a diminished rate during the 150 Tg scenario[4]. This accounts for roughly half of current aquatic caloric production. Meanwhile, aquaculture systems typically use human edible food and were assumed to cease post-disaster. Marine fish was treated as an exogenous variable.

Industrial Foods

The ramp-up of industrial resilient food production in the 150 Tg scenario was modeled as a combination of the two options with highest technology readiness at the current time of writing. The first one is sugars from lignocellulosic biomass assuming rapid repurposing of pulp and paper mills to sugar biorefineries[18]. The second one is single cell protein (SCP) production from natural gas based on fast construction of large-scale fermentation facilities[15]. The rate of growth of industrial foods in the current model was hard-coded from the results of the cited papers, and is thus treated as an exogenous variable. First a large wave of paper factory repurposing is assumed (~two thirds of the current global pulp and paper capacity), from then onwards the available industrial resources are assumed to be invested in methane SCP production. SCP can serve as a useful food product due to its high-quality protein content and micronutrient profile, despite the higher resource intensity and unit costs compared to lignocellulosic sugar. Fast repurposing for sugar production can help bridge the sudden gap in food production, but after the most promising facilities have been repurposed, a switch to more nutritionally rich products appears reasonable.

In the 150 Tg scenario, multiple industrial responses would likely develop in parallel at different paces and with varying degrees of success, as happened during the COVID-19 pandemic[60,61], potentially including others not considered in this model such as foods from CO_2 (other SCPs[16], carbohydrates[62], electrosynthesized foods[17], etc.) or synthetic fats[19]. However, this is arguably a realistic representation of the potential of leveraging industrial resources for increasing resilient food production from inedible raw materials.

The ramp-up values from the literature used in this work were estimated based on the capital expenditure budget of chemical and related industrial sectors. There is some chance that qualified labor, material resources, equipment construction capacity and supply chains of other industries could also be quickly and efficiently diverted to food production, resulting in values ~10 times higher than the ones used in this work for industrial foods, but this is speculative and might require preparedness plans to be in place prior to an ASRS. Further research should be conducted to properly characterize the potential of agriculture-independent industrial food production for GCFS response.

5 Data Availability

Supplementary Information includes more detail on methodology, while the supplementary spreadsheet at https://github.com/allfed/allfed-integrated-model/blob/main/Supplemental_Data.xlsx contains quantitative assumptions used by the model.

6 Code Availability

The Python code used and associated Jupyter notebook is available at https://github.com/allfed/allfed-integrated-model.

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Author Information

Affiliations

[a] *Alliance to Feed the Earth in Disasters (ALLFED), Fairbanks, AK, USA.*

[b] *ETH Zürich, Department of Mathematics, 8092 Zurich, Switzerland*

[c] *Northumbria University, Faculty of Engineering and Environment, City Campus, Newcastle-upon-Tyne, NE1 8ST, United Kingdom*

[d] *University of Alaska Fairbanks, Mechanical Engineering and Alaska Center for Energy and Power, Fairbanks, AK, 99775 USA*

*Corresponding author: morgan@allfed.info

Ethics Declarations

Competing interests

The authors declare no competing interests.

Supplementary Information: Deployment of Resilient Foods Can Greatly Reduce Famine in an Abrupt Sunlight Reduction Scenario

Morgan Rivers [a], *Michael Hinge* [a], *Juan B. García Martínez* [a], *Ross Tieman* [a], *Victor Jaeck* [b], *Talib E. Butt* [a,c], *David C. Denkenberger* [a,d]

Affiliations:

[a] *Alliance to Feed the Earth in Disasters (ALLFED), Fairbanks, AK, USA.*

[b] *ETH Zürich, Department of Mathematics, 8092 Zurich, Switzerland*

[c] *Northumbria University, Faculty of Engineering and Environment, City Campus, Newcastle-upon-Tyne, NE1 8ST, United Kingdom*

[d] *University of Alaska Fairbanks, Mechanical Engineering and Alaska Center for Energy and Power, Fairbanks, AK, 99775 USA*

*Corresponding author: morgan@allfed.info

I. Model validation with 2020 food production

We define primary food production as any food production which results in net-positive creation of calories amenable to human consumption (and is not converted to another source of food). This definition excludes animal products, eggs, fish farms, and dairy milk that are not based on inedible inputs i.e. grazing and agricultural residues. Total primary food availability of foodstuffs suitable for human consumption aggregate to approximately 5500 calories per capita in 2020, excluding retail and distribution waste but including production losses. This is significantly higher than human needs because foods go to uses other than direct consumption, such as animal feed and biofuels. In particular, foods such as meat, dairy, and eggs almost always use more human edible calories than they produce in aggregate.

A global diet of 2100 calories per capita was then predicted, which accounts for the satisfaction of global dietary and macronutrient consumption. This diet prediction accounts for distribution waste, retail (including household) waste, and overconsumption summing to approximately 28%, and reflects the estimated present-day average intake of 61 grams of fat and 59.5 grams of protein associated with baseline metabolic caloric needs.

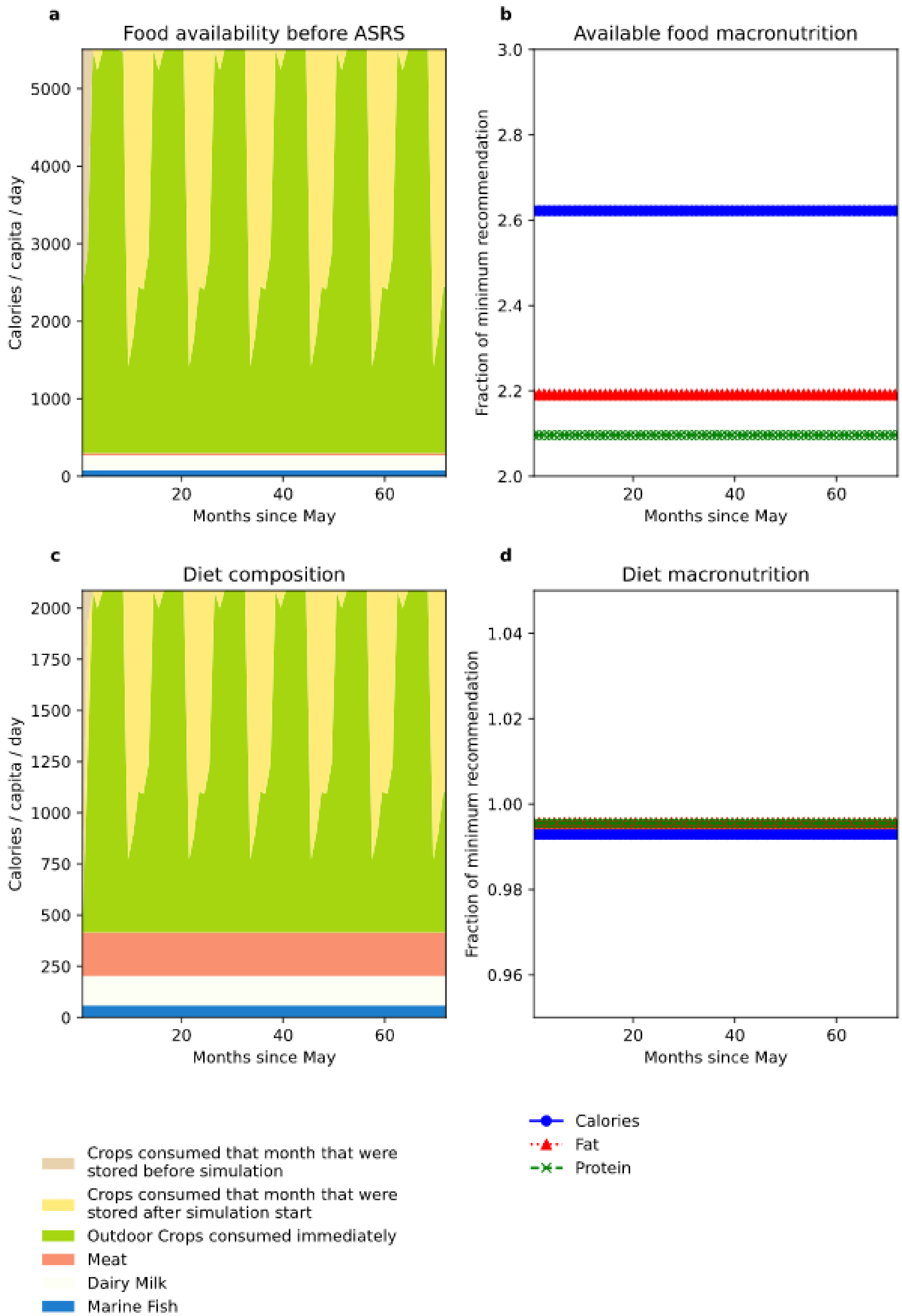
a
Food availability before ASRS
Calories / capita / day
Months since May
b
Available food macronutrition
Fraction of minimum recommendation
Months since May
c
Diet composition
Calories / capita / day
Months since May
d
Diet macronutrition
Fraction of minimum recommendation
Months since May
Calories
Fat
Protein
Crops consumed that month that were stored before simulation
Crops consumed that month that were stored after simulation start
Outdoor Crops consumed immediately
Meat
Dairy Milk
Marine Fish

Figure S1 | Production in 2020: a Year 2020 agricultural primary food availability by source **b** Macronutrition of primary production **c** Dietary composition, excess calories are fed to livestock and used for biofuels at 2020 levels **d** Macronutrition of average 2020 diet.

Production and consumption are for the 2020 global population of 7.8 billion and a linear projection of food utilization statistics from 2014 through 2018[1]. Matching estimated consumption and production for year 2020 projections required adjustment factors of 0.96 for stored food before simulation, 0.94 on caloric production, 1.02 on fat production, and 0.93 on protein production.

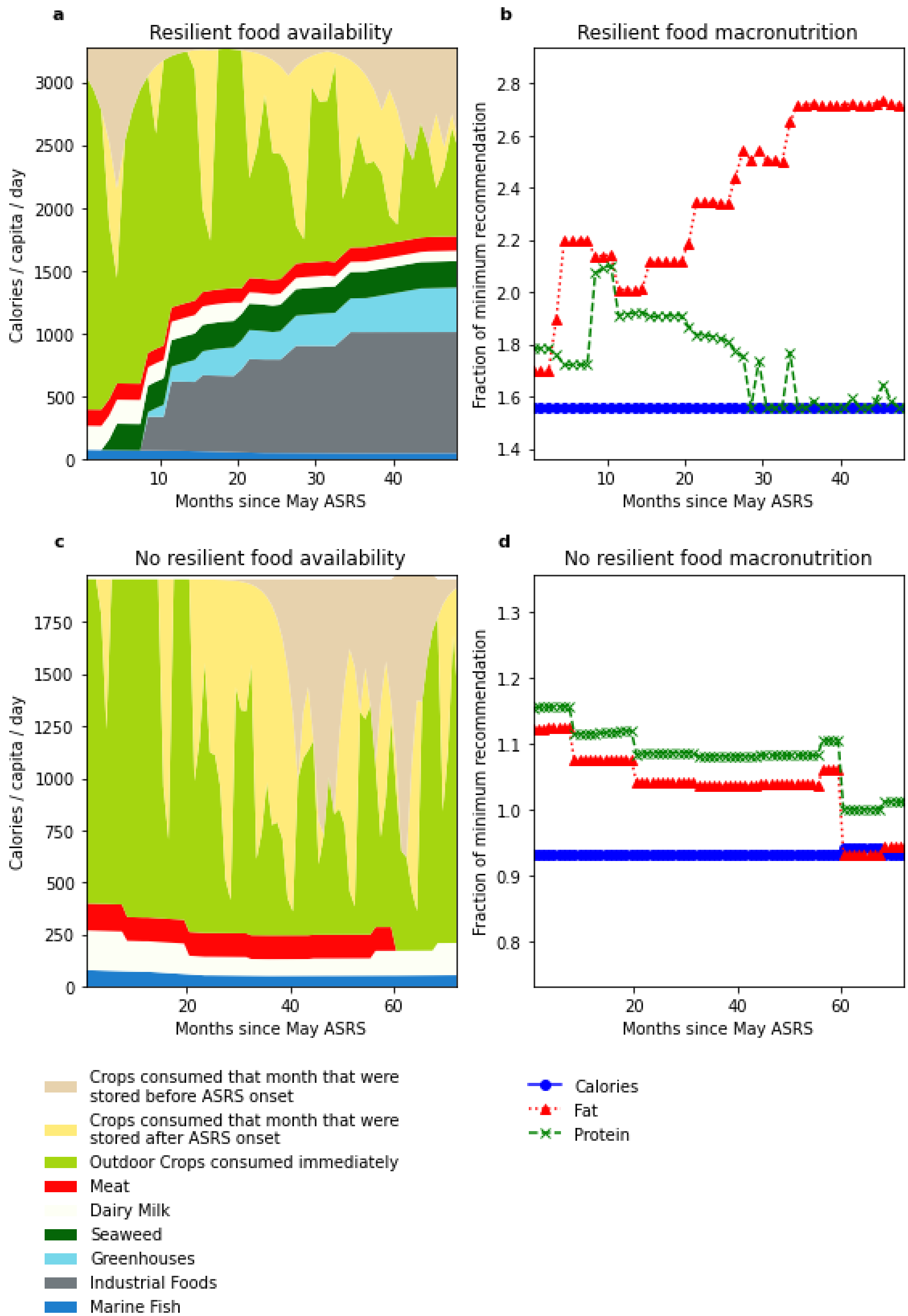
a
Resilient food availability
Calories / capita / day
Months since May ASRS
b
Resilient food macronutrition
Fraction of minimum recommendation
Months since May ASRS
c
No resilient food availability
Calories / capita / day
Months since May ASRS
d
No resilient food macronutrition
Fraction of minimum recommendation
Months since May ASRS
Crops consumed that month that were stored before ASRS onset
Crops consumed that month that were stored after ASRS onset
Outdoor Crops consumed immediately
Meat
Dairy Milk
Seaweed
Greenhouses
Industrial Foods
Marine Fish
Calories
Fat
Protein

Figure S2 | Primary production in 150 Tg scenarios: a Primary food availability in a 150 Tg scenario with resilient foods before waste, feed and biofuels. Primary food availability can be maintained at approximately 70% of current levels in the resilient food case **b** Macronutrition for resilient food case **c** Primary food availability before waste, feed and biofuels for no resilient food 150 Tg scenario. Primary food availability can be maintained at approximately 35% of current levels in the no resilient food case **d** Available macronutrition in no resilient food 150 Tg scenario for primary production.

II. Details on the Monte Carlo Model

The Monte Carlo model was run using the sensitivity_analysis.py script under a range of assumptions. The model was constrained to reasonably likely best-case and worst-case variable values. The exact values chosen can be found in the "sensitivity_analysis.py" in the src folder in the associated github code repository. Upper and lower bounds refer to 1 standard deviation probability interval. Justification for values chosen are:

- "seaweed max calories" is the maximum percentage of calories produced which are assigned to seaweed. Although in past disasters in Japan, seaweed has substituted approximately 10% of the diet, concerns about the feasibility of reducing iodine concentration from boiling the seaweed, limited bio digestibility, and the unappealing nature of the food may limit seaweed to 5% of calories. While difficult to estimate, it is plausible that in a 150 Tg scenario up to 30% of calories may come from an iodine-reduced, powderized form of seaweed for increased palatability.
- "seaweed growth per day" is determined based on the daily growth rates as a percentage of mass for a variety of seaweed species. The range was chosen to be between 5%, and 15%. Growth rates observed in current aquaculture vary between 9 and 12% growth per day[2]. The main factor for reduced growth is likely a lack of phosphorus[3]. Nitrogen does not typically limit growth, but can be a limiting factor[4]. Growth can further be inhibited by a temperature below 13 °C[5].
- "seaweed area built" is determined assuming that today's production of synthetic rope needed for seaweed farms is less than, equal to, or exceeding current global production capacity. Scaling up rope twisting capacity greatly would enable the twisting of 70,000 tonnes of rope per day, enough to construct 2,100 km^2 of seaweed farms per day. Half and double this number were assumed as lower and upper bounds for the Monte Carlo, incorporating the possibility of the use of repurposing of other machines for rope production, or a slower scaleup. Double this number implies the use of close to all of current global synthetic fiber production for rope twisting. Rapid seaweed expansion continues to occur today. For example, the expansion of the seaweed industry in the south China sea underwent a multiplier of farmed area increased by 12,000-fold from 0.13 ha in 2000 to 1500 ha in 2011[6].
- "seaweed yield gain" was estimated at 50% using increased growing degree days as a proxy for productivity gain. More work is needed to evaluate the typical yield increases in simple low-tech large-area greenhouses under the climate conditions in an ASRS.

- "greenhouse area scale factor" scales the area covered by greenhouses to between 62.5, 125, and 250 million hectares over a period of 36 months of construction. While 250 million hectares are estimated to be technically feasible[7], the relatively high cost of greenhouses per unit production may reduce production due to lower demand for costlier foods. Consequently, greenhouse construction was estimated as between ½ and ¼ of the expected maximum construction rate.
- "industrial foods scale factor" was determined using a scale factor between 0.71 to 1.40 in the overall production over time for the upper and lower bound. The upper bound accounts for the increased rate of possible conversion between existing facilities and economic complications may increase costs, while the lower bound accounts for resistance to the conversion process on the part of existing paper factories, and the possibility of increased cost of methane SCP large-scale production. While a large amount of human and material resources of adjacent industries could potentially be redirected to greatly increase industrial foods production[8–12], this remains speculative and could increase costs.
- The "delay" variables were assigned to biofuel shutoff, feed shutoff, seaweed construction starting, industrial food conversion construction starting, greenhouse construction starting, and changes to the planted crops. These were assumed to be perfectly correlated. Longer delays were assumed for industrial foods and greenhouses due to the technical complexity. A longer delay as assumed for rotation switching due to the possibility of delayed climate effects on growing conditions delaying the adoption of improved rotations, and the likelihood of resistance to altering crops from small-holder farmers. Biofuels shutoff was assumed to be a smaller delay than feed shutoff on average. While feed shutoff would not likely have to be a complete shutoff in resilient food scenarios due to the excess food production beyond human needs possible with resilient foods, this was not considered in the Monte Carlo. In the case of relocated crops, improvements from the rotation change were applied as an addition to the average 7 month delay between planting and harvesting the new rotation.
- Upper and lower bounds for "ratio to baseline calories" are discussed in Section VII of this document.

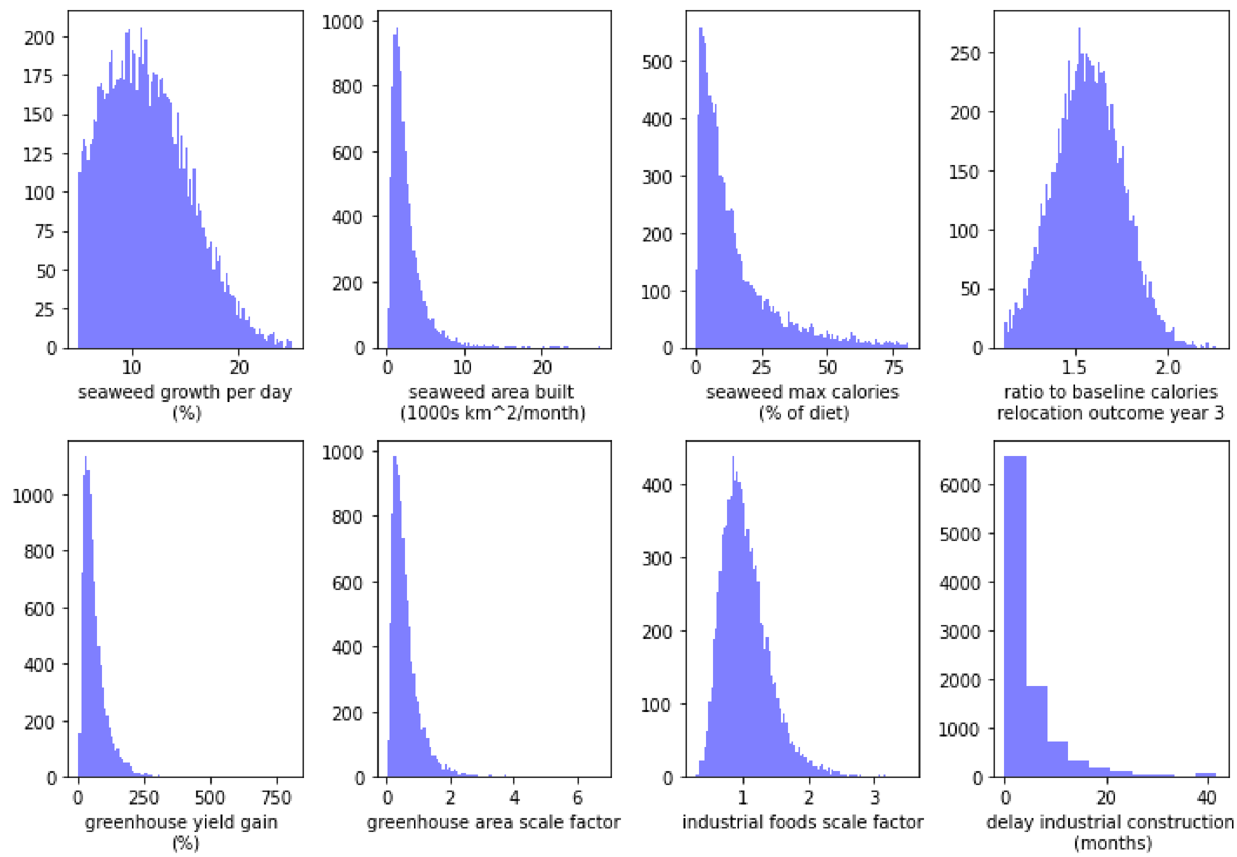

Figure S3: Inputs to the 1000 monte carlo simulation results. The y axes of the histograms represent the number of scenarios at the given input variable value.

Input	95% confidence interval	Median Value (If Untruncated)	Distribution Type
Seaweed max calories	1.7% - 60% (truncated at 80%)	10%	Truncated Lognormal
Seaweed area built	0.52 - 8.32	2.08	Lognormal
Greenhouse area scale factor	⅛ - 1	1/2	Lognormal

Seaweed growth per day	5%-25% (truncated at these values)	10%	Truncated Normal
Industrial Foods scale factor	0.51 - 1.96	1	Lognormal
Ratio to baseline calories relocation outcome year 3	1.3 - 1.8 (lower bound truncated at 1)	1.57	Truncated Normal
Ratio to baseline Fat and Protein 3 years after relocation (not shown in figure)	1.7-3.05 (fat) 1.58-1.85 (protein)	2.33 (fat) 1.73 (protein)	Truncated Normal
Delay industrial construction	0 - 9	3	Lognormal Integer
Months delay after ASRS onset, non industrial foods (not shown in figure)	0-8 (greenhouse, feed shutoff, rotation change) 0-4 (seaweed, biofuel shut off)	2 (greenhouse, feed shutoff, rotation change) 1 (seaweed, biofuel shut off)	Lognormal Integer

Table S4: Value ranges and probability distributions used to generate input variables used for the Monte Carlo simulations. Lognormal distributions were selected for input variables that are likely determined by a multiplication of many independent variables, normal distributions were selected for variables best approximated by additive random processes. All delay values were assumed to be perfectly correlated, and ratio to baseline kcals, fat, and protein after relocation were assumed to be perfectly correlated.

III. Details on costs modeling

In order to analyze costs versus income, we have adopted the following method:

Costs for **industrial resilient food sources** have been estimated based on prior work on the topic[13,8], which assessed the producer costs on an ex factory basis. These calculated totals include operating costs, an allowance for depreciation based upon the projected lifespan on investments, as well as an allowance for a return on capital, which we have set at 12%. Costs have been normalized onto a dry caloric basis at 4,000 kcal per kg (for example a food with 2,000 kcal per kg would have its price doubled and one at 8,000 kcal per kg would have its price halved in order to make them directly comparable on a caloric basis).

For **outdoor growing**, costs have been estimated based upon the farm revenues (prices multiplied by yields for each key crop) reported by FAOSTAT in Northwest Europe (defined here as France, The Netherlands, Belgium, the United Kingdom, Republic of Ireland, Germany and Denmark) for the period of 2015-2019 (the last year available in detail). On top of this, we have added subsidies per hectare net of taxation as reported by the European Union's Farm accountancy data network, as these subsidies are also considered in a farmer's revenue, depreciation and a return on capital. Over the medium to long run (where capital and labor resources invested into agriculture can rise and fall), revenues per hectare would be expected to equal the costs of crop cultivation per hectare, including a return on capital and labor for the farmer, and while this may overestimate the actual cost of cultivation, it provides a conservative estimate of the cost of producing crops per hectare under some of the most intensive commercial systems currently adopted worldwide. Finally, this revenue needed to grow a specific crop per hectare has then been converted to a crop cost basis by dividing the cost per hectare with the expected yields post disaster across the tropics in Year 3 post disaster. This is an overestimate of crop cost as some inputs may decrease, such as fertilizer. Finally, for rapeseed we have added a processing cost, based on the average price premium between rapeseed oil prices ex works and the cost of seeds required to produce it (this implicitly includes transport costs from farm to plant). These have been taken from the FAO FPMA database[14], with oil taken from Netherlands ex works prices and rapeseed using Hamburg producer prices as a benchmark.

For **greenhouses**, we have assumed capital costs in line with the estimates reported in the estimated cost of establishing a simple greenhouse in Indonesia[15], excluding the cost of the geomembranes (as the greenhouse would not need to be water tight under the soil). Overall, the cost of installation is around US$5.9/$m^2$, and has a projected lifespan of five years. This is a low cost construction, and has a cheaper cost of labor compared to a high income country, but should provide a reasonable estimate of the cost of the simplest greenhouse possible across the tropics. In reality costs may fall post disaster due to economies of scale, but this estimate should provide a conservative benchmark.

For **seaweed** cultivation, costs per hectare have been estimated based upon cultivating *Porphyra amplissima* varieties, in line with the seaweed growth model laid out below. Our costs per hectare have been calibrated based upon larger scale Indonesian farming systems[16]. These represent best practice at a simple level of technology and scale (typically covering 0.75 hectares each) as well as achieving good labor and capital efficiency. These costs per unit area have been divided by the expected seaweed yield in open waters off China[17] to calculate a projected cost per tonne of wet and dried seaweed produced, assuming an average of 45 tonnes of wet matter produced per hectare per year, or 9.9 dry tonnes per hectare per year. This is a conservative estimate of costs as pond cultivation and cultivation close to the shore achieves higher yields at lower costs, and significantly higher yields are also achieved in other species[18] and in locations such as Chile[2]. However, broad expansions in seaweed production would push cultivation into open waters and areas in the tropics, meaning the higher cost benchmarks are more suitable for this cost calculation.

For **animal products**, we have taken the average producer prices of ruminant meats from FAOSTAT as well as the average cost of dairy products, weighted by production. This has been inflated by the change in wheat prices between the pre and post disaster scenarios, multiplied by the feed intensity of dairy[19] and meat in semi intensive systems,[20] respectively**.**

Seafood has been priced at the weighted average of current producer prices, reported by FAOSTAT[1], inflated by the reduction in projected output. This assumes that the resources devoted to fishing remain approximately equal before and after the disaster, but the rate of catches deteriorates in line with the projected fall in seafood.

This analysis suggests that the cost of producing foods will rise post disaster for a number of reasons. Firstly, crop yields will decline sharply globally, while the intensity of inputs used compared to global averages prior to the disaster will rise. This will raise the cost of crops per tonne of output produced, with a higher cost per unit area divided by a smaller output.

On top of this, additional capital will be needed in order to raise yields, such as extensive investments in greenhouses. While this will be partly offset by the gain in crop output, this capital cost is expected to further raise the cost of production on a per tonne basis.

Finally, the resilient foods needed to meet demand will require an extensive capital investment as well as ongoing spending on their operating costs. This includes the necessary feedstocks, energy, labor and ongoing maintenance needed to produce food.

To translate these costs from a producer price ex-factory/ex farm gate to a retail basis ready to be purchased in shops, we have added a flat cost per tonne, to cover the cost of distribution, wholesaling and retail margin. This has been estimated from the FAO Food Price Monitoring and Analysis (FPMA) database, where we have averaged the wholesale and retail premium above producer prices for the period of 2015-2019 for bulk grains (wheat and rice) across developing markets. This gives us an average of US$76 per tonne to move from a producer price to a wholesale price, and an average of US$36 to move from wholesale to retail for bulk grains, for a total of US$112/tonne.

This would be at the low end for higher income countries; however, it provides a useful estimate for developing countries, where affordability is the highest concern for this paper. This transport cost is expressed per tonne of food moved, meaning that low energy density foods experience a higher transport cost per calorie.

Estimates for people in poverty at various thresholds have been taken from the World Bank's PovcalNet Database[21], based upon the June 2021 dataset. Each region uses the most recent estimate available (2018 for all regions other than South Asia, which uses 2014 results), converted from 2011 to 2020 via the growth in US CPI, and we have assumed a diet is affordable if it takes up no more than 63% of total daily income (the threshold for food poverty set by the FAO in 2020[22]).

As we assume the majority of food is either traded or priced against global market prices (the basis for our cost calculations above), we have adjusted from Purchasing Power Parity (PPP) to market exchange rates, using World Bank figures for 2011 once again. The majority of the costs of food are likely to be on an international basis post crisis as the inputs needed, and the finished foods, will be extensively traded. However, some costs such as distribution (and more with locally produced food) would be at local market prices (where PPP is more appropriate). As such, using only PPP would present a too optimistic picture for affordability, while market exchange rates are too pessimistic. As a result, to ensure our estimates are conservative we have therefore chosen to use market exchange rates.

In total, we estimate that the total capital cost of developing the additional greenhouse, seaweed and industrial food capacity to be around US$8.6 trillion, split by around US$7.4 trillion for the greenhouse expansion based on the costs above, US$242 billion for the cellulosic sugar investments, US$370 billion for single cell protein and US$540 billion for seaweed expansions. In addition, there would be ongoing replacement parts, depreciation and operational costs of around US$2.1 trillion/year following the ramp up period, based around the lifespan of the factories and equipment. This is broken down into around US$1.5 trillion annually for greenhouses, US$110 billion for cellulosic sugar plants, US$105 for single cell protein and US$365 billion for seaweed farms. In total, this implies a total increase to world GDP assigned to agriculture, forestry and fishing of approximately 3.7% annualized over the first seven years of the crisis.

IV. Optimization model

In order to estimate possible macronutrient production in the 150 Tg scenario, a linear optimization was run to maximize the minimum production of global human caloric, fat, or protein demand in any month. The python package PuLP version 2.50 was used to perform the linear optimization.

Key files defining the simulation are located in the src/ folder in the github directory. The four python files which can be used to generate the results shown in this paper are:

- run_model_before_catastrophe.py which runs the production scenarios and diets for the 2020 baseline.
- run_model_no_resilient_foods.py which runs the scenario with no resilient foods expected maximum food availability
- run_model.py which runs a scenario involving the estimated food production, availability, and predicted diet if resilient foods are deployed
- monte_carlo.py which runs the best and worst case maximum food availability and produces the histogram over some number of scenarios chosen from a combination of upper and lower variable bounds, as well as the comparison for resilient foods added and removed.

All simulations were run using python version 3.7.3 on Debian 10, with 20Gb of memory and an Intel® Core™ i7-7500U quad core CPU at 2.70GHz. A typical optimization scenario took 0.2 seconds to run. The entire software repository uses 18 megabytes of storage space.

Both traditional agriculture and resilient food modules were included in the food production estimates.

V. Details on global food stocks modeling

In order to estimate total food stocks by month, we have started with the USDA PSD (United States Department of Agriculture Production, Supply and Distribution) database[23], which presents detailed estimates of crop year ending stocks by country. These were taken for all key grains (wheat, barley, rice and maize), centrifugal sugar, oilseeds (primarily soybeans) and vegetable oils, for the period 2014-2018. Data on storage for fruits, vegetables and tubers are not available; however, these are likely to be small in caloric terms by comparison, and their exclusion will not significantly bias our total stock estimations downwards.

Crop years refer to the cycle of harvest, stock buildups (where stored food rises around harvests), consumption and stock drawdowns (where stocks fall during the off crop periods) which characterize agricultural markets, with the crop year end referring to the last month before harvests begin. Because of this, crop year end values represent the minimum level stocks reach before harvests/processing begins again, and do not line up with a standard calendar year unless harvests begin in January. As a result, simply adding crop year end stocks will give a significant under estimate of total global stocks in a given month, as harvests and therefore crop year ends do not align.

To correct for this, crop years have been downloaded for each crop and each country globally (also reported in the PSD database). We have assumed that harvests start at the beginning of their crop year, last 4 months, and stocks build over this period based upon reported production. Meanwhile consumption/exports/other disappearance is flat month to month, with crops drawn down to their crop year end value reported in the database. On a country by country basis this may not hold, as for example key exporters may see higher shipments in the months during and just after harvest, however on a global basis this methodology will average out any seasonality between importers and exporters.

By carrying out this analysis for all crops and all countries by month it is possible to calculate an estimate of total stocks for each crop by month. This total volume was then multiplied by the nutritional values for each crop/product as reported by the FAO, in order to convert them onto a total calorie, protein and fat basis.

From this total we have subtracted an allowance for stocks in transit, as food moving from farm/factory to plate is included within the methodology above but is not able to be drawn down. Average minimum transit/storage times have been assumed to be two months. This is conservative, given that bulk shipment times between Asia and Europe average around 15 days via the Suez canal, and Europe to the US East Coast averages around 8-10 days, depending upon the ports[24], however the two month assumption allows for handling, processing, logistics to and from the port and other factors. Therefore, stocks in transit have been set at two months of consumption, based upon the caloric, protein and fat requirements listed in the paper, a population of 7.8 billion and retail/distribution losses/waste in line with pre-disaster levels.

VI. x Details on calculating animal products

In order to model total meat and dairy output (eggs are ignored) post disaster, we have split systems into those based on human inedible feeds (grasses, crop residues and some fodder crops such as alfalfa), and those based on human edible feeds (primarily grains, oilseeds and oilseed meals). Post disaster, it is always optimal to make use of human inedible feeds when available, while after a few month delay from the disaster onset, human edible feeds are assumed to be fed to animals only once human caloric needs have been met. Edible feeds were assumed to only be redirected from the outputs of outdoor growing and stored food, even in the case of resilient food deployment. We have included edible organs in our analysis, all under the title of meats.

Human inedible feeds prior to the disaster have been estimated based upon reported values taken from the Global Livestock Environmental Assessment Model (GLEAM) database with a reference year of 2010[20]. Yields per hectare of grasses, residues and fodder crops have assumed to remain constant up to the present day (a conservative estimate given growth across the broader agricultural system). In addition, the changes to crop areas and areas under grasses between 2010 and 2018 (the latest year available) have also been considered, however the change here was negligible (4.65 billion hectares total in 2010 vs 4.58 billion in 2018). Overall this gives the following results pre disaster:

Grass yield = 0.822 dry tonnes/ha under grass, total output = 2,624 million tonnes/year

Residue yield = 0.804 dry tonnes/ha under all crops, total output = 1,113 million tonnes/year

Fodder crop yield = 0.338 dry tonnes/ha under all crops, total output = 446 million tonnes/year

To calculate yields post disaster we have applied the impact to crop output to residues and fodder output per hectare, and the impact to grasses output to grasses outputs, while assuming area remains constant (in line with the reported assumptions of Xia et al.)[25]. This is modeled for each year post disaster, to give a total output of inedible feeds. The yields are considered per unit total area, not per unit area planted for the uses referenced.

Inedible feeds are assumed to be fed first to dairy cattle (the most efficient conversion ratio of feed to calories available), followed by any surplus feed going to beef cattle grazing. Ratios are listed below:

The ratio of human inedible feed dry value to milk wet value is 1.44[26]*. We have assumed dairy is constrained by the level of output in 2018 (the latest available full year of data on FAOSTAT*[1]*), at 879 million tonnes wet value.*

The ratio of inedible feed dry value to dry cattle meat is assumed to be 92.6, based upon reported grazing values[20] *and converting the small amount of edible feed used in grazing systems to inedible equivalent at a ratio of 11.5 inedible:edible (calculated from the regression of grazing vs feedlot systems). This includes the production of some small ruminants such as sheep, and absorbs the remaining output of inedible feeds.*

Edible feeds are calculated at the surplus over human consumption, and are fed to animals based upon the following assumptions and ratios:

The ratio of human edible feed dry value to milk is assumed to be 0.7[19]*. This absorbs any available edible feed up to 879 million wet tonnes of output, including the milk produced from inedible feed.*

The assumed ratio of human edible feed dry value to dry value chicken/pork monogastric (single stomach) systems is averaged at 4.8[20]*. This has an allowance for converting the small amount of inedible feed used in monogastric systems to edible equivalent at a ratio of 25.5 inedible:edible (calculated from the regression of backyard vs industrial systems). This has a maximum of 250 million tonnes of wet output, based on 2018 FAOSTAT figures for pork and chicken combined.*

Ratio of edible feed dry value to dry value cattle meat is 9.8[20]*. This includes an allowance for converting the small amount of inedible feed used in feedlot systems to inedible equivalent at a ratio of 11.5 inedible:edible (calculated from the regression of grazing vs feedlot systems). This includes the production of some small ruminants such as sheep, and absorbs the remaining output of edible feeds. This absorbs any remaining edible feed surplus.*

In order to estimate the required excess feed in the case of resilient food deployment, first the scenario involving the delayed complete shutoff to feed is run. If this does not produce an excess beyond 2020 global nutritional requirements, an error is thrown and the program exits. If the program predicts an excess, then an additional quantity of excess food is assigned to meat and dairy production. The subroutine is rerun to determine the resultant total population fed, and the process repeats until the minimum total people fed in any month reaches below 7.81 billion, at which point the program exits. The entire iterative process of average global diet estimation completes after approximately 30 seconds.

The ratio of output pre to post disaster is used to estimate the population of chickens, pigs and ruminants maintained following the disaster.

Culling of cattle provides an important source of calories and fat post disaster.

VII. Details on Estimating Crop Yields

Present-day crop yields were determined from FAOSTAT yield data for the years 2014-2018, and due to data unavailability in 2019 and 2020 for calories, fat, and protein, a linear trend was extrapolated to the year 2020. Present-day production used the average global seasonal production variation based on crop years listed in the USDA PSD database[27], assuming a 4 month average harvest period. The no resilient foods ASRS case was estimated by scaling down year 2020 production by the annual reduction in yields for a 150 Tg scenario from the analysis of Xia et al[25]. Because their analysis concludes that the majority of crop production in an ASRS would come from currently tropical areas, the seasonality of production in the tropics (defined as 24 north to 24 south) was used as a proxy for monthly variation in global production throughout an ASRS.

Improvements in crop rotations were determined using a single run of the DSSAT based MINK global gridded model[28]. The crop model was run for one year averaging over many runs of a random weather generator using the climate average of 1994-2016, centered on 2005, and run with 400 ppm atmospheric CO_2[29]. The model was then run again but was modified to reflect the worst year of the ASRS period which starts 36 months after onset, with a 60% reduction in photosynthetically active radiation (PAR), reduction in average daily highs of 14°C, reductions in average daily lows of 12°C, and 68% reduction in average rainfall. Planting dates were selected such that emergence would occur no later than 30 days after planting and maturity would occur no later than 241 days after planting. Application of 100 kg/ha elemental nitrogen equivalent was modeled in all cropped areas to simulate the increase in available fertilizer per hectare viable cropland in an ASRS assuming continued present-day fertilizer production. The increase in yields was found for maize, paddy rice, wheat, soybeans, barley, rapeseed, potatoes, sorghum, sugar beet, sunflower seed, and chickpeas, which account for 63% of cropland and approximately 80% of the caloric production in 2005.

The comparison was made between the same crops in 2005 weather conditions using the same crop model. In the ASRS, the yield of per hectare of the crop was estimated as the total production if planted uniformly over all current cropland, divided by the total area of all cropland. The crop rotation percentage for each crop was then multiplied by the yield per hectare of that crop if planted on all considered crop areas to determine total production of that crop. Double or triple cropping was not considered. The relative crop production determined by this method was then used as a reduction factor for 3 years after the onset of the ASRS. While the nutritional content was assumed to remain constant ratio to calories produced after improved rotation harvest begins as predicted by the crop rotation considered, the total caloric improvement was determined according to the equation:

```
kcals_improved_rotation[m] =
      2020_baseline_kcals[m]
      * (1 - rotations_boost_year_3 * nuclear_winter_baseline_reduction[m])
```

where `2020_baseline_kcals` is the average calories produced in approximately 2020 for each month, `rotations_boost_year_3` would be 1 if there was no improvement compared to an unchanged crop rotation and 2 if there was a doubling in yields due to the crop rotation, and `nuclear_winter_baseline_reduction` would be 1 in that month for no agricultural production in an ASRS, and 0 if there was no reduction compared to baseline in that month due to the ASRS.

Even with the full 100kg/ha of nitrogen, the estimated reduction for the crops considered remained within 6% of the estimate from Xia et al which used an estimate of present-day nitrogen in its crop model. We expect this is because nitrogen stress is not a key limiting factor for yields, unless relocation is used to grow crops in more appropriate climate conditions. Other factors which may account for the difference include the lack of time-dependent temperature reductions in our crop model and our simplification of uniform climate alterations in the 150Tg case averaged over all land area in the tropics.

For the relocated case and for the limited crops considered, sugar beets and potatoes produced the most calories, rapeseed produced the most fat, and wheat produced the most protein. These four crops were considered "important" and prioritized in allocating relocated cropland. In current global food cropland, these crops consist of approximately 34% of cropland area. The lower bound for the Monte Carlo was selected as this number, implying these crops would have to be relocated to the tropics in the lower bound scenario to maintain a similar percentage of important crops in the tropics as now exists globally. In order to produce the upper estimate, it was assumed 100% of current cropland area would be planted with important crops. However, this does not consider the planted area of non-food crops. The average caloric production in the nuclear winter scenario involved approximately a 50% reduction in planting area of unimportant crops, which was selected as the median scenario for our analysis. Because the crop model attempted planting in all current cropland, many planted areas did not produce any yield. The alterations in crop area percentages due to this effect were not considered in the analysis. Furthermore, a lower bound for planting as a function of crop yield was not considered.

The associated spreadsheet tabs "Crop_Model_Relocation_Lower", "Crop_Model_Relocation_Estimate", and "Crop_Model_Relocation_Upper" contain specific percentages chosen manually to produce improved dietary fat and protein production while maintaining some crop diversity, and to minimize the overall caloric production per hectare.

Numerical optimization of the crop rotations is anticipated in future work. In order to prevent excessive mono-cropping, the fraction of area used for individual crops was not set in excess of 1/3 of 2005 total cropland area.

The varieties and types of relocated crops were very important in meeting fat and protein requirements. Protein from rapeseed meal was not included as a food, as more research as to the safety of consumption of rapeseed meal for human consumption needs to be performed[30]. Wheat was the largest contributor protein per hectare in the relocated crop model, closely followed by soybean. However, soybean produced much fewer calories per hectare in the relocated case and was reduced to allow for other crops to be grown.

VIII. Greenhouse yield estimate details

To estimate greenhouse yield improvements, the average temperatures for every month for Miami as a representation in tropical regions. Yearly growing degree days (GDDs) were calculated for an average day in each month and multiplied by the number of days in that month, then summing over all months. An average 4°C increase over the 12.5°C reduction in year 3 gave us an estimate of 46% for potatoes and 54% for maize, for an average of 50% yield improvement. More research is ongoing to estimate production incorporating changes in precipitation, reduction in solar radiation, CO_2 levels, and humidity in a greenhouse.

IX. Details on Seaweed Growth Modeling

Seaweed growth rate bounds are discussed in Section VI. Other variables required to model seaweed include harvest losses, initial area, and maximum and minimum density. Harvest losses from the harvest process and natural losses, e.g. from grazing fish, are highly dependent on seaweed species, environment, and applied methods and have a high uncertainty, but are likely close to 15%[31]. Initial area was selected at 1000 hectares. This is less than the current total area in the South China Sea, although some of the current seaweed area would no longer be suitable for seaweed cultivation due to reduced sunlight. Maximum wet-on-farm density of the stock was 0.8 kg/m^2 , while minimum density after harvest was estimated as 0.4 kg/m^2 based on harvests of the species *Gracilaria tikvahiae*[32]. The density was kept low to minimize self-shading effects due to low-light conditions in an ASRS.

The linear equation for the seaweed module in the optimization model is as follows:

```
for d in days from 0 to NDAYS:
  if(d==0):
    wet_on_farm[0] = INITIAL_SEAWEED
    used_area[0] = INITIAL_AREA
  else:
    assign wet_on_farm[d] to be less than used_area[d]*MAXIMUM_DENSITY
    also assign wet_on_farm[d] =
      wet_on_farm[d-1]*DAILY_GROWTH
```

```
- ((used_area[d]-used_area[d-1])
  * MINIMUM_DENSITY
  * HARVEST_LOSS)
- food_produced[d]
```

The optimization algorithm is then used to determine the total food produced per day from seaweed using the *food_produced[d]* variable.

Several challenges would need to be overcome in order to scale seaweed to large percentages of human consumption. Our research indicates the two primary challenges to quickly scaling seaweed would involve twisting sufficient synthetic fiber, and the feasibility of drying the seaweed in a humid, cold ASRS. Future work will analyze potential scale up issues in drying the seaweed. Seaweed farms require approximately 34 T/km^2 of synthetic rope. At 2,100 km^2 of seaweed per day, seaweed farms would require approximately 70,000 tons of rope per day, in order to produce sufficient rope. Current production is only 223.5 metric tons per day in 2016[33], requiring a factor of approximately 300 increase in industrial production of synthetic rope.

Due to concerns around digestibility[34,35] and excessive iodine consumption, seaweed has been capped at a maximum of 10% of daily calories. Experts suggest 1-2 mg is a safe level of iodine, although empirically higher consumption does not typically cause health issues[36]. Based upon the selection of *Porphyra amplissima* as a cultivar, 10% of calories would imply an intake from seaweed of around 1.52 milligrams of iodine daily. In comparison, the average Japanese diet consists of 1-3mg of iodine daily largely due to seaweed consumption. Boiling and washing the seaweed has also been shown to reduce iodine content in similar seaweeds[37].

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