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Key Points:

- Abrupt sunlight reduction from events such as nuclear war or volcanic eruptions can affect agriculture
- Seaweed is a promising resilient food source due to its ability to grow quickly in a range of conditions
- A global simulation shows that seaweed could provide a significant contribution to global food security in 9–14 months

Supporting Information:

Supporting Information may be found in the online version of this article.

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Seaweed as a Resilient Food Solution After a Nuclear War

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Abstract Abrupt sunlight reduction scenarios such as a nuclear winter caused by the burning of cities in a nuclear war, an asteroid/comet impact or an eruption of a large volcano inject large amounts of particles in the atmosphere, which limit sunlight. This could decimate agriculture as it is practiced today. We therefore need resilient food sources for such an event. One promising candidate is seaweed, as it can grow quickly in a wide range of environmental conditions. To explore the feasibility of seaweed after nuclear war, we simulate the growth of seaweed on a global scale using an empirical model based on *Gracilaria tikvahiae* forced by nuclear winter climate simulations. We assess how quickly global seaweed production could be scaled to provide a significant fraction of global food demand. We find seaweed can be grown in tropical oceans, even after nuclear war. The simulated growth is high enough to allow a scale up to an equivalent of 45% of the global human food demand (spread among food, animal feed, and biofuels) in around 9–14 months, while only using a small fraction of the global ocean area. The main limiting factor being the speed at which new seaweed farms can be built. The results also show that the growth of seaweed increases with the severity of the nuclear war, as more nutrients become available due to increased vertical mixing. This means that seaweed has the potential to be a viable resilient food source for abrupt sunlight reduction scenarios.

Plain Language Summary An abrupt sunlight reduction scenario like nuclear winter could reduce sunlight and harm agriculture. Seaweed is a promising food source for such events because it can grow quickly in many conditions. We studied the growth of seaweed globally using a model based on one type of seaweed, and found that it could provide an equivalent of up to 45% of the world's food in 9–14 months. The main challenge is building new seaweed farms quickly enough. The growth of seaweed actually increases after a nuclear war, because more nutrients become available in the ocean. This means seaweed has the potential to be a reliable food source in case of abrupt sunlight reduction.

1. Abrupt Sunlight Reduction Scenarios as a Risk to Global Food Security

How can we avoid a global famine if Earth's surface is suddenly receiving significantly less sunlight? The main mechanisms to cause such a reduction of sunlight are either nuclear war (Coupe et al., 2019; Toon et al., 2008), asteroid/comet impacts (C. R. Chapman & Morrison, 1994; Tabor et al., 2020) or large volcanic eruptions (Rampino, 2002; Rougier et al., 2018). Those three mechanisms are grouped together as abrupt sunlight reduction scenarios. These scenarios could lead to a massive injection of particles into the upper atmosphere, where they have long residence times, limiting sunlight reaching the Earth's surface, in turn disrupting global climate and causing a significant drop in temperature. For example, after a large nuclear war, mean global temperature could drop up to 9°C below current values (Coupe et al., 2019; Turco et al., 1983). In the historical and paleo records, large volcanic eruptions lead to reductions of global average temperature on the order of 1°C (Otto-Bliesner et al., 2016; Sigl et al., 2015), with higher reductions on land and in the Northern Hemisphere, associated with famines, disease outbreaks, political instability, and regime changes (White, 2013).

Extreme changes in temperature, sunlight, and precipitation due to nuclear winter might reduce currently practiced global agriculture by up to 90% in the worst year after an all out war between Russia and the US if no extensive precautions and adaptations are taken (Xia et al., 2022). The ultimate effects of the nuclear war on the food

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system strongly depend on global trade continuing and the scale of the war. There will also be strong differences regionally, with some regions still being able to produce food even in extreme scenarios (e.g., Australia).

The effects of abrupt sunlight reduction scenarios scale with the size of the impacting event, but it is argued that even smaller events like a regional nuclear war could have a large negative impact (Jägermeyr et al., 2020; Mills et al., 2014) in both combatant and non-combatant countries (Robock et al., 2007). Therefore, a much larger effect has been found in simulations of a full-scale nuclear war and other large abrupt sunlight reduction scenarios. The effects could differ strongly between countries, due to differences in national food production and storage, as well as spatially heterogeneous effects of the abrupt sunlight reduction scenario on the climate (Coupe et al., 2019; Rivers et al., 2022).

If such an abrupt sunlight reduction scenario occurred today, it would hit a largely unprepared world. Wheat is the most widely stored food, and global storage would only last for a few months at current consumption (Do et al., 2010), while the cool climate after an abrupt sunlight reduction scenario can persist from years to over a decade (Coupe et al., 2019; Rampino, 2002; Turco et al., 1983). Other sources of food including wild captured fish could decrease quickly, especially if they are not managed sustainably before the abrupt sunlight reduction scenario (Scherrer et al., 2020). This means that alternative food sources are needed to avoid a global famine. These alternative foods need to reliably produce food over several years, even if there is less sunlight available, and the temperature is lower. We will refer to such alternative food sources as resilient foods in the following.

2. Why Seaweed?

Research has described a range of resilient foods (Tzachor et al., 2021; Winstead & Jacobson, 2022), especially for abrupt sunlight reduction scenarios (Denkenberger & Pearce, 2015; Denkenberger et al., 2019). Resilient food solutions include leaf protein concentrate (J. M. Pearce et al., 2019), greenhouse crop production (Alvarado et al., 2020), single cell protein from natural gas (García Martínez, Pearce, et al., 2022) and hydrogen (García Martínez et al., 2021), sugar from lignocellulosic biomass (Throup et al., 2022), synthetic fat from petroleum (García Martínez, Alvarado, & Denkenberger, 2022), and wild edible plants (Winstead & Jacobson, 2022). One modeling study concluded that these resilient foods could provide enough calories to avoid anyone starving after the nuclear war scenario (Rivers et al., 2022). However, many of the resilient foods are in a very early stage of technological development. It could be difficult to ramp up production on very short notice to produce enough food to avoid a global famine. Other well-developed resilient foods are needed that can be used in low tech settings.

One promising candidate is seaweed (D. Denkenberger et al., 2019; Tzachor et al., 2021). It is fast growing and highly scalable (John et al., 2011; Yarish et al., 2016), and has been highlighted as a valuable addition to the global food supply by the FAO for decades (DeBoer, 1981; Ferdouse et al., 2018; McHugh, 2003), since it is not competing with conventional agriculture when it comes to freshwater, land, fertilizers or pesticides (Fedoroff et al., 2010). It also has been an important part of human food for millennia and was used in its dried form for long voyages hundreds of years ago (Mouritsen et al., 2013). Seaweed gives good yields even in low tech settings (Yarish et al., 2016). Such low tech farms mainly consist of ropes, held in place by anchors and buoys. In addition, a nuclear conflict and large volcanic eruptions might lead to a higher intensity of UV radiation at the Earth's surface, as the ozone layer could be depleted (Bardeen et al., 2021; Mills et al., 2008; Xu et al., 2019). In contrast to land-based agriculture, seaweed is partly shielded from this by the water it grows in. Moreover, seaweed is a potential biofuel solution (John et al., 2011; Lehahn et al., 2016). Recent research established that seaweed could contribute up to 100% of the human protein need (Greene et al., 2022) and that globally around 20–48 million km^2 are suitable for seaweed production (Froehlich et al., 2019; Liu et al., 2023). However, the places best suited for seaweed production today are likely to differ in an abrupt sunlight reduction scenario, due to changes in temperature and nutrient availability caused by changes in climate and the ocean state (Harrison et al., 2022).

This paper has two aims. The first aim is to establish where and how well seaweed could grow in an abrupt sunlight reduction scenario. We base this on nuclear winter Earth system simulations, as this kind of abrupt sunlight reduction scenario has been studied most, and detailed data sets are available (Coupe et al., 2019; Harrison et al., 2022). While there are ongoing discussions about the likelihood and severity of nuclear winter effects (Hess, 2021), we still think it is prudent to focus on nuclear war, as it is the only one with where modeling data is available and the results are likely transferable to volcanic and impact winter due to their similar consequences

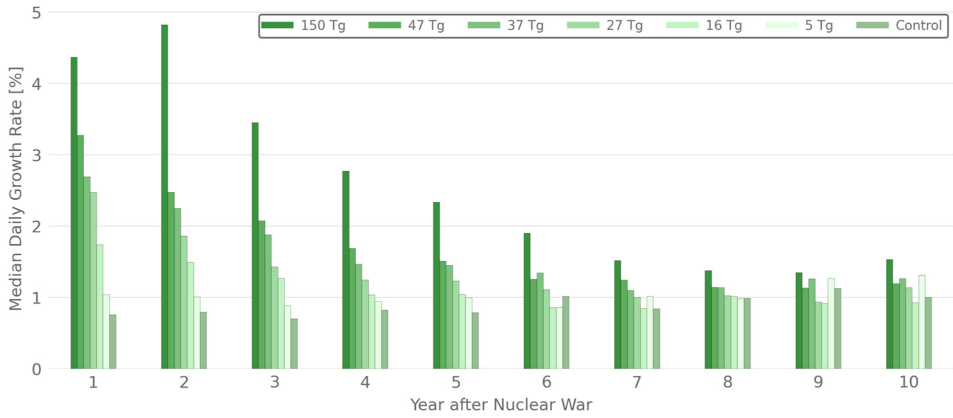

Figure 1. Comparison of global median daily seaweed growth after nuclear war of different magnitude and a control run. Colors indicate the severity of the nuclear war in teragrams soot ejected. Control is a scenario without soot injection. Growth rates shown only include areas between −45° and +45° of latitude, as the areas north and south of this are unsuitable for *Gracilaria tikvahiae* even before the nuclear war. The rightmost bar indicates the range of the results of the control run to show the variability of the model without a soot injection.

for climate and agriculture. To evaluate the feasibility of seaweed as a resilient food we use a global, empirical seaweed growth model based on *Gracilaria tikvahiae* (Bird et al., 1979; Lapointe & Ryther, 1978), which is used for human consumption (Abbott, 1978), is grown globally (e.g., in Brazil and China) (Buschmann et al., 2017) and shows growth behavior and resource needs in the range of many other seaweed (Xiao et al., 2019), with growth rates of up to 30% per day under optimal conditions (Parker, 1982). The second aim is to explore how quickly seaweed can be scaled up to meet an equivalent 45% of the global human food demand. This would be enough seaweed enough to substitute 15% of human food by seaweed, 10% of animal feed and 50% of the global biofuel production. This scale-up calculation is based on the growth rates from the seaweed growth model. Taken together, this will evaluate the feasibility of seaweed as a resilient food in an abrupt sunlight reduction scenario.

3. Growing Seaweed After Nuclear War

3.1. Global Effects

Running the seaweed growth model for the first ten years after nuclear war calculates seaweed growth rate for all oceans globally. This model uses nuclear winter ocean simulation and calculates the fraction of the optimal growth rate for seaweed based on factors for nutrients, salinity, temperature and illumination. This total growth factor is the product of those factors. Looking at those growth rates in aggregate has two clear results (Figure 1). First, that seaweed growth rate is directly proportional to nuclear war severity, with faster growth under more extreme forcing. Second, the growth of seaweed is fastest at the beginning of the ten years (with a peak at year two) and slows down over time. This seems counterintuitive, as one would expect that seaweed growth would be more limited the more climate is impacted. The climate impact of the nuclear winter is strongest in the first few years (Coupe et al., 2019). However, the main factor to limit growth is not temperature or illumination, but nutrients (Figure 2). The ocean surface is generally nutrient poor. This changes after a nuclear war, as global ocean circulation patterns are disrupted and nutrients are brought to the surface due to increased vertical mixing during the cooling event, creating a new ocean state with enhanced surface macronutrients that lasts for decades (Harrison et al., 2022). This vertical mixing process is proportional to the severity of the nuclear war and happens mainly in the first few years (Harrison et al., 2022), which in turn leads to the improved seaweed growth after more severe nuclear wars.

3.2. Spatial Distribution of Seaweed Growth Patterns

The following results and discussion focus on the US-Russia 150 Tg (trillion grams = million tons) of soot scenario, as in such a case seaweed is most important as an addition to food security, while also having the highest growth of all nuclear winter scenarios considered. Currently, we produce 2.5 times the food needed for humans, with a substantial portion going to animals and fuel. In a severe nuclear war (150 Tg) scenario with a

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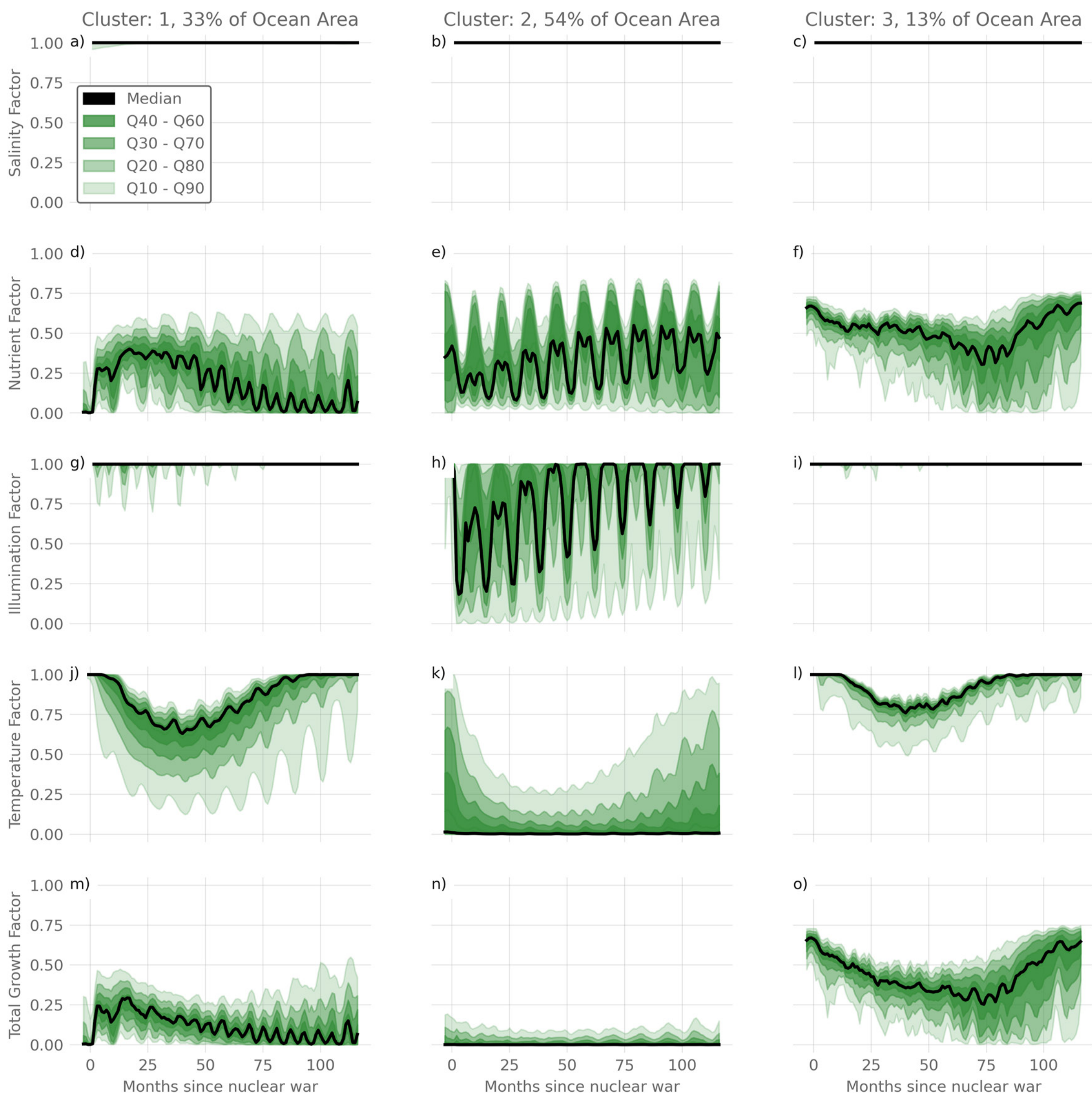

Figure 2. Time series of the growth factors (salinity, nutrients, illumination, temperature) for the three *Gracilaria tikvahiae* growth regime clusters and the overall total growth factor (which is the product of the four factors). The black line indicates the median in the cluster. Q refers to quantiles. Green shaded areas show how much of all the time series of the cluster is contained within the range. The darkest green contains the 20% of the time series that are closest to the median, while the next shade of green contains 40%, up to a value of 80% of the data set for the lightest green. All calculations are weighted by area of covered ocean regions.

90% reduction of food production (Xia et al., 2022), we would have only 0.25 times the food needed. If seaweed provides 45% of human food, we could bring this up to 0.7 again. In a less severe nuclear war with 47 Tg of soot, production is reduced by around 50% (Xia et al., 2022). This means even without further interventions 100% of the human need would be produced. Therefore, seaweed is most important in the most severe scenarios.

We determined 3 distinct geographical clusters in which growth rates differ substantially from the global mean presented in Figure 1. The growth regimes were differentiated using k-means clustering, which groups regions (Figure 3) together that have a similar growth pattern over time (Figure 2). In the following, we describe the differences in cluster behavior and location:

- Cluster 1 (Figure 2 left panels): This cluster is unsuited for *Gracilaria tikvahiae* before the nuclear war, due to limited nutrients. This changes shortly after the onset of the cooling event (Figure 2d) as nutrient limitation decreases and thus the seaweed can grow faster. This effect continues throughout the nuclear winter, but becomes more seasonal and weaker over time. After the first 1–2 years, this nutrient effect is countered by increased temperature limitation as the ocean cools (Figure 2j), leading to overall declining growth. Also, the

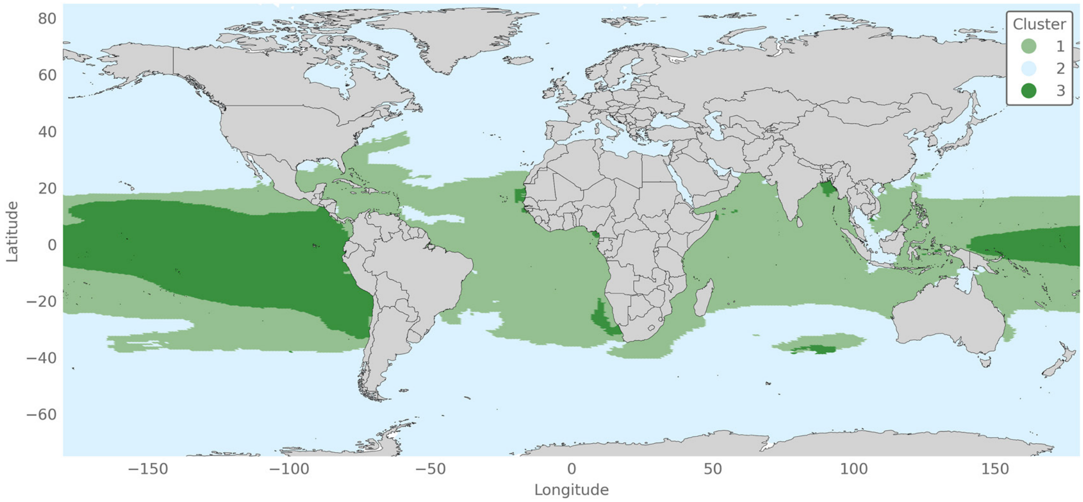

Figure 3. Global locations of the *Gracilaria tikvahiae* growth regime clusters for a 150 Tg nuclear war scenario. Colors indicate the different clusters. White areas indicate missing data.

growth declines after the third year even more, due to increased nutrient limitation, though this varies regionally, with some portions of the cluster (lighter green) having relieved nutrient stress and elevated growth after more than 100 months (Figure 2m). This cluster can be found globally near the equator ±30° latitude and covers one third of the global ocean area (Figure 3).

- Cluster 2 (Figure 2 center panels): This cluster is characterized by its very low overall total growth factor (Figure 2n). The median growth factor is close to zero for the entire 10 years of the time series. However, different regions in this cluster are growth limited for different reasons. While a large portion of the regions are limited by being located in very high or very low latitudes and thus in water too cold and dark to grow seaweed, another portion is located in warm, but nutrient poor environments closer to the equator and marginal seas where the ocean model does not simulate nutrient dynamics well (Figure 3). These regions are nutrient poor, due to little exchange of water with other parts of the ocean. However, this might also be partly an artifact of the resolution of the forcing simulated data, as this area is only represented by few data points, and nutrients from rivers are not included. Cluster 2 accounts roughly for half of the global ocean area.
- Cluster 3 (Figure 2 right panels): The regions in this cluster show the highest overall growth factor, with an average of almost half of the optimal growth rate (Figure 2o). They are also very suitable for seaweed even before a nuclear war. Still, those regions experience a drop in their productivity after the nuclear war. The overall growth factor declines slowly for the first 6–7 years, before it starts to rise again. This drop is driven by declining temperature and declining nutrient availability (Figures 2f and 2l). The temperature reaches its pre-war values after 5–6 years, while the nutrients follow 1–2 years after that. After recovery, the nutrients even reach values higher than during the pre-war period. Most of the regions with this growth pattern are located in the Pacific Ocean and far away from human settlements (Figure 3). Still, there are several areas with this growth pattern that are located near coasts (e.g., in Chile and Peru). It covers 13% of the global ocean area. In addition, there are also occurrences of this growth pattern where major rivers meet the ocean (e.g., Ganges Delta, Bight of Biafra, Senegal River Delta). The cluster is strongly influenced by the so-called Nuclear Niño (Coupe et al., 2021). This means that the shift in ocean currents due to the nuclear winter creates El Niño like weather and ocean conditions for several years with warmer water in much of the ocean west of Central America. Finally, this cluster partly overlaps with the regions that have been identified as being best for low cost, large scale seaweed farming (DeAngelo et al., 2022).

Overall, cluster 1 and especially cluster 3 are most suited for seaweed cultivation after nuclear war, while cluster 2 should be mostly avoided. Additional figures showing the seaweed growth patterns for a selection of large marine ecosystems (Figures S1 and S2) and an example of the global distribution of growth rates (Figures S3–S5) can be found in Supporting Information S1. Our results highlight that the main factors for reduced growth are nutrients and to a lesser extent temperature.

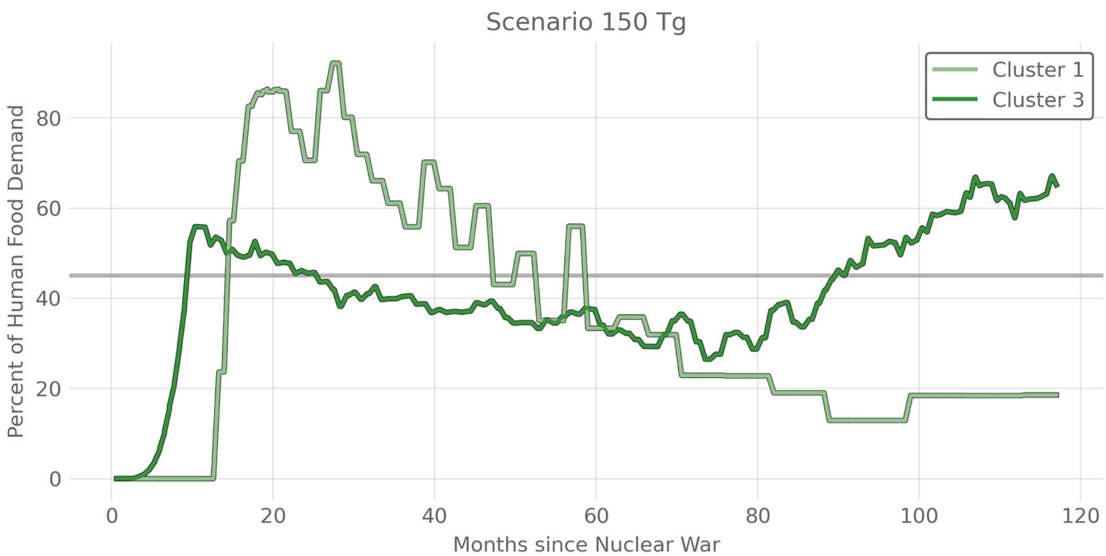

Figure 4. Seaweed production as percent of human food demand for suitable seaweed growth clusters (150 Tg nuclear war scenario and 30% per day as optimal growth rate). This is optimized for meeting an equivalent of 45% of the global human food demand on average for the whole 10 years (gray line).

4. Scaling up of Seaweed Production

After calculating the growth rates after nuclear war, we use a scale-up model to calculate how quickly seaweed farming can be scaled up to a level needed to produce an equivalent of 45% of the global human food demand. The model assumes that seaweed farms are built until the area needed to fulfill 45% of the global human food demand can be satisfied on average over the 10 years of the simulation. The yield is used to stock existing farms until those are saturated. Thereafter, all yield is used for food, feed and biofuel. This is under the assumption that enough other food resources are available until the seaweed is scaled up and therefore seaweed is only distributed for consumption once the target yield is reached (Rivers et al., 2022). This way the overall availability of food for the years after the nuclear war is maximized.

The model assumes an initial global seaweed stock of 10,000 t on an area of 100 km^2. Currently, around 35,000,000 t of seaweed are produced annually (Buschmann et al., 2017) on an area of around 1,600 km^2 (Duarte et al., 2017). This means the starting parameters of the model are considerably less than the area used and amount produced today, and were chosen to have a conservative estimate that reflects the possible disruptions by a nuclear war. This includes inability to grow tropical seaweed species after nuclear war and transporting suitable seaweed species to their new growing areas.

Cluster 2 has such a low overall growth rate that it is excluded from further analysis, as it could be ineffective to grow seaweed there. Clusters 1 and 3 are productive enough to produce enough seaweed to satisfy 45% of global human food demand on average over the entire 10 years of the abrupt sunlight reduction scenario (Figure 4). However, the clusters differ considerably in how quickly they can provide seaweed, when they have their peak productivity and how much growing area is needed.

Cluster 1 is the least productive of the viable clusters suited for seaweed production. Due to its lower productivity it takes considerably longer to reach saturation and produce yields (~14 months; Figure 4). Also it needs a very large area (1,572,000 km^2), as the growth rates decline over time. It still might be a worthwhile investment to create seaweed farms here, as many countries only have this cluster available (e.g., Australia, United States) and it allows food production in the first few years of the nuclear winter, when food security is most under threat (Xia et al., 2022). Given a dry weight of 11% of wet weight for Gracilaria tikvahiae (Penniman & Mathieson, 1987), this results in an average yield of 8.91 tons dry/year/hectare for cluster 1 (mean growth rate 3.4% per day before considering self-shading and transport lanes).

As cluster 3 is located in highly productive areas, it can be quickly scaled up, with daily growth rates reaching 25% (and above) of the optimum around half of the time (Figure 2). Thus, after around 9 months, enough seaweed is grown that it can be used to feed people instead of saturating new seaweed farms. Due to this high yield, around

416,000 km^2 of ocean are needed to produce the seaweed with this cluster, which is about the size of Colombia. In comparison, the exclusive economic zone of Peru alone, which consists mostly of cluster 3 has a total size of around 900,000 km^2, of which a considerable fraction has shallow depths and thus allows low-tech seaweed farming (though not all is near ports), while also being a low cost area for seaweed production (DeAngelo et al., 2022). This means that enough area is available to grow seaweed on such a global scale. Given a dry weight of 11% (Penniman & Mathieson, 1987), this results in an average yield of 33.63 tons dry/year/hectare for cluster 3 (mean growth rate 13.1% per day before considering self-shading and transport lanes).

5. Potential Challenges and Their Implications

5.1. Scaling up Seaweed Farm Infrastructure

Our study demonstrates that seaweed can play a significant role in meeting human food demands following a severe nuclear war. Our findings indicate that a scaled-up seaweed production of 45% of human food demand is possible in as little as 9 months. However, the results also show that the global median of seaweed growth is smaller in less severe nuclear exchanges, as fewer nutrients reach the surface waters of the ocean, limiting seaweed growth (Figure 1). However, this does not mean that scale-up might be slower in those cases (Figure S6 in Supporting Information S1), as in all nuclear war scenarios there are wide areas in the oceans with high growth rates. The limiting factor is the speed of the global scaleup in the construction of new seaweed farms and not the growth rate. For the more severe scenarios a slightly longer scale-up is needed, to account for the fact that the growth rate experiences a lower dip in year three, which was to be compensated with a bigger area. Still, this means that seaweed could be a viable addition to global food security now and in severe abrupt sunlight reduction scenarios, but also in smaller nuclear exchanges and volcanic eruptions.

To fully take advantage of the fast growing seaweed, hundreds to thousands of km^2 of seaweed farms would have to be built each day. However, seaweed farms can be quite low tech and still provide good yields (Yarish et al., 2016) (Figure S7 in Supporting Information S1). It also has been proposed to build 100 km^2 floatable seaweed rafts (Notoya, 2010). If those could be mass produced it could be possible to cover even much more area per day, thus allowing production of even more seaweed than proposed here. The creation of those seaweed farms would be a global priority in the case of nuclear war. It might be possible to create farms of this magnitude, especially as past work has shown that there are enough resources to scale up greenhouse production by a larger amount than needed for seaweed farms here (Alvarado et al., 2020). Analysis of the scale up of the infrastructure is beyond the scope of this paper, but will need to be studied in future research.

With decreasing productivity the seaweed needs increasingly large areas to meet a production equivalent to 45% of global human food demand. Still, the 1,572,000 km^2 needed for the less productive areas are a very small fraction of the global ocean area and only around 7.5% of the area that is likely suitable for seaweed production now (Liu et al., 2023). Australia alone has an estimated 2,000,000 km^2 suitable for seaweed production (Liu et al., 2023). This means that even in the case that seaweed production is much more unproductive than estimated here, globally there are much larger areas available for growing seaweed than are needed in even the most pessimistic cases. Still, the results show that areas that are currently seen as resilient in a nuclear winter like New Zealand (Boyd & Wilson, 2022) might not be able to further improve their resilience with seaweed, as their coastal waters are either too cold or nutrient poor.

The seaweed farm design in this study assumes a very low tech approach, which mainly consists of ropes that are kept in place by anchors and buoys (Hurtado et al., 2014; Yarish et al., 2016). This is done to assess the feasibility of seaweed production after nuclear war under the worst conditions. However, this also means that higher yields and lower labor requirements could be accomplished by using more modern, offshore approaches to seaweed production (Soto & Wurmann, 2019). This also opens up the possibility to grow more of the seaweed in cluster 3, to ensure the highest growth rates possible. As such, productive offshore cultivation is possible with current and near-future technologies (Olanrewaju et al., 2017); however, such high tech solutions may not be accessible to all in an abrupt sunlight reduction scenario. Therefore, low-tech options such as small scale vessels for transport are a viable alternative, as more people have the skills to use them and they have lower energy requirements.

Still, even though the technology exists and there is potentially enough area available for building the seaweed farms and growing the seaweed, this will be a very difficult project to implement. Factors that could hinder the implementations as described here are the availability of seaweed spores, which can be used to seed ropes and

make distribution easier. Other factors include a possible lack of maintenance of seaweed farms due to insufficient specialized labor after nuclear war, and imperfect offshore cultivation technology. Most of these problems would require preparations now, and would be difficult to implement after the catastrophe happens. Some possible solutions that could increase the chances of a successful implementation are discussed in the section "Preparations to ensure successful seaweed production after a nuclear war."

In addition, the scale-up model used here is a simple logistic growth curve. This means it does not specifically account for important factors that would influence the results in the aftermath of a nuclear war, such as marine pollution, infrastructure damage or inhibited trade. Therefore, the results here are likely very optimistic and further modeling is needed to better understand the impact of the difficult environment after a nuclear war.

5.2. Nutrient Availability for Seaweed Growth

In many regions of the ocean net primary production is strongly limited by iron availability, both before and after a nuclear war (Harrison et al., 2022). However, the research on this is mainly based on phytoplankton and not on seaweed (e.g., (Fung et al., 2000)). While there is some evidence that seaweed growth can be inhibited by iron deficiency (Kakita & Kamishima, 2006), this does not seem to be a major limiting factor. Iron is mainly needed for the reduction of nitrate (Suzuki et al., 1995), but also needed in low concentrations as a micro nutrient (Lobban & Harrison, 1994). Therefore, if the nitrogen is available as ammonium, seaweed can also grow in iron sparse environments. The seaweed growth model considers ammonium, nitrate and phosphate and limits the growth with the nutrient that is least available. In the case of this study, ammonium is usually the limiting factor (Figure S8 in Supporting Information S1). Still, the ammonium is enough to support the growth rates shown here. This also means that the growth rates could be further enhanced by making more iron available, as this could allow the seaweed to also use nitrate. Therefore, iron fertilization might be a good way to increase growth rates further. Such large scale ocean fertilization with iron would be an unprecedented project, yet it has also been proposed as a climate change solution (Bertram, 2010). Therefore, research into potential ocean fertilization could both help mitigate risks from climate change and nuclear winter. Still, additional research is needed to analyze how global iron fertilization might impact marine ecology, especially in combination with the extreme circumstances of an abrupt sunlight reduction scenario. Finally, the nutrient concentrations could be quickly depleted locally given a large enough area for seaweed farming. How quickly local nutrients would be replenished would depend strongly on local conditions, likely limiting the area for optimal seaweed growth. Across the subtropics and tropics where iron is not limiting (Figure 3, Cluster 1), nutrient stress is relieved after the war due to the deep mixing during global cooling (Harrison et al., 2022). These are regions that see increased productivity after the war, making them ideal candidates for seaweed production.

5.3. Potential Effects of High Seaweed Consumption

Seaweed can have high concentrations of essential elements such as iodine and heavy metals such as arsenic, which are associated with health risks (Bouga & Combet, 2015). The United States defines the tolerable upper intake level of iodine for almost all individuals as 1.1 mg per day. However, other countries with a diet richer in iodine tolerate higher limits (e.g., Japan (Zava & Zava, 2011)). There has also been research showing that humans can tolerate extremely high levels of iodine of around 50 mg per day for a prolonged period of time, without suffering permanent damage (E. N. Pearce et al., 2002). This means that, at least for a few months, high iodine levels in the food due to a large intake of seaweed could be tolerable. Also, iodine concentration in seaweed varies considerably and changes with season, location, preparation and species (Mageswaran & Sivasubramaniam, 1984; Teas et al., 2004). Therefore, iodine concentrations and other potentially harmful substances would have to be monitored. Another potential problem is digestibility. Most countries do not consume seaweed in larger quantities and there has been preliminary evidence that a certain microbiome is needed to digest some seaweed species properly (Hehemann et al., 2010). While it seems to be possible to feed humans iodine in levels that account for roughly 20% of the food from seaweed (Pearce et al., 2002), this results in health problems. We therefore settled to 15% for food to have a wider safety margin. Similar, but possibly stricter limits can be found in animals (Lewis, 2004). However, there are also reports of animals being fed almost exclusively seaweed (Hansen et al., 2003).

Radioactive fallout, that is, the deposition of radionuclides, is characterized by uneven distribution, which highly depends on scale of and targets in a nuclear war. Radionuclide concentration and behavior has been explored in some depth in the aftermath of events such as the Fukushima nuclear accident (Chen, 2013). The main risks

come from consuming fish, as those accumulate environmental contaminants. However, it remains unclear how the much larger emission of radioactive particles during a nuclear war could play out. Continuous surveillance might be necessary to define high-risk foods. One particular concern is the fact that seaweeds tend to be high in iodine, and radioactive iodine could be incorporated instead. However, since the half-life is only hours to days (depending on the isotope) (E. M. Chapman, 1983), it should not be a significant problem as the seaweed needs to be scaled up first and could only be consumed after several months. The iodine in seaweed would also be a health benefit in the aftermath of a nuclear war, as it prevents the body from absorbing radioactive iodine 131. In addition, sodium alginate can combine with ingested toxic chemical particles and various heavy metals in the digestive tract (Abd Elnabi et al., 2023), which could be used to address exposure to such substances due to fallout.

5.4. Harvest, Distribution and Preparation for Consumption

The seaweed scale-up model assumes a constant loss of 20% of yields to grazers such as fish, epiphytes (plants growing on the seaweed) and diseases. This is the upper bound commonly found in marine fisheries (Gopal et al., 2012). However, values in extremely large seaweed farming might differ considerably. Therefore, adaptations will have to be made to ensure healthy conditions for seaweed. One promising way to ensure this is seaweed diversification (Gachon et al., 2010). This simply means that seaweed should not be grown in monoculture.

It is unclear which seaweed species could be overall best suited for food production after a nuclear war. However, it is likely that a variety of different seaweed species could be used to make food production more resilient, adapt it to the local environment, and provide diet diversity. Still, this work makes a contribution to our understanding of food production after nuclear war, as it shows how much seaweed production might shift due to the changed climatic conditions. Species selection must focus on how well they cope with potential environmental stressors including low temperature, nutrients, grazing pressure and pathogens. In addition, this selection of seaweed species can be used to optimize the nutrient content (e.g., making sure that enough fat and protein is available).

Seaweed spoils quickly once harvested. Therefore, most of it has to be preserved to get it to consumers. There are a variety of preservation methods including salting, canning, freezing and drying. Drying has the further advantage of reducing shipping mass and cost. Currently, seaweed is often dried by solar drying (Santiago & Moreira, 2020). However, this might generally not be feasible in the colder, higher relative humidity, lower sunlight conditions of nuclear winter. While seaweed can also be dried by freeze drying, vacuum drying and convective air drying (Santiago & Moreira, 2020), none of these techniques have been used to dry seaweed on the scale needed after nuclear war. The logistics of distributing seaweed on such a scale are potentially challenging. To our knowledge no research exists about how global logistics will be affected in detail by a nuclear war. This also strongly depends on which nuclear armed states went to war against each other, and how much of their arsenal was used. Therefore, additional research is needed to demonstrate the feasibility of drying and logistics in this condition.

5.4.1. Potential Negative Impacts of Large-Scale Seaweed Farming on Global Marine Ecology

Building seaweed farms on a scale as envisioned here would be an unprecedented global intervention into marine ecology. While seaweed farms have a relatively low environmental impact in comparison with other aquaculture like fisheries, they can still influence local marine ecology negatively (Kelly et al., 2020). This mainly happens via competition with other local species. Seaweed can overgrow coral reefs and seagrass beds, which degrades local ecosystems for other species, especially fish (Kelly et al., 2020). The ultimate effects on marine ecology of a global seaweed scale-up are unknown, but might be a more severe version of the negative effects of seaweed farming we can see today. However, as the context of this proposed scale-up is an abrupt sunlight reduction scenario, global marine ecosystems would already be massively disrupted (Scherrer et al., 2020). More research is needed to determine how negative or even positive the influence of large scale seaweed farming would be in such an event.

6. Preparations to Ensure Successful Seaweed Production After a Nuclear War

The challenges that have to be overcome to produce seaweed on such a large scale as proposed in this paper are considerable. However, there is also much that could be done today to elevate the chances of success:

- In many seaweed farm designs, seaweed is either inserted into twisted rope by hand or seaweed spores are allowed to grow on seedling lines in so-called hatcheries (Forbord et al., 2012; Yarish et al., 2016). The latter

is more efficient, but needs some infrastructure set up in preparation. The infrastructure to allow this could be deployed in regions that could have high seaweed growth rates after nuclear war.

- Creating such a large number of seaweed farms will likely consume a considerable amount of working hours and materials. If plans are made beforehand that outline how this can be accomplished, the response could be quicker.
- This study focuses on *Gracilaria tikvahiae*, because it has an empirical growth model available (James & Boriah, 2010). It is likely that successful food production with seaweed in an abrupt sunlight reduction scenario needs a wider variety of species. This means there is a need to model additional species, so that the best species combination for every region can be identified. For example, kelp could be a good species for further research, as it is grown in many spaces globally (e.g., Brazil and China) and is used for food. Good research to build on here would be a recent paper by van Oort et al. (2023) where they discuss the potential of seaweed species to contribute to global scale food production.
- Iodine is the main limiting factor when it comes to using seaweed for human consumption. The amount of iodine in seaweed varies strongly depending on species, preparation and environmental factors. If the amount of iodine could be reduced cost-effectively on large scales, humans and animals could be fed with more seaweed. Promising avenues of research here are using microorganisms (Councell et al., 1997) or low tech solutions like soaking the seaweed in water before consumption (Nielsen et al., 2020) to reduce iodine content.
- The ocean model used has a resolution of $\sim 1°$ (latitude and longitude). This means that marginal seas like the Red Sea cannot be modeled in a sufficient resolution. If data with a finer resolution becomes available this study could be repeated to discover how suitable marginal seas are for seaweed production after nuclear war.
- Seaweed is not only a good source of food after nuclear war, but also now (Ferdouse et al., 2018). This means that food security could be improved both today and after nuclear war, if seaweed would be used more today. This could also improve the pool of skilled labor and improve the technology available. Especially promising are places that have a high productivity both now and after nuclear war (e.g., west coast of South America).
- There are also calls to action to use seaweed as a way to sequester carbon from the atmosphere to combat climate change (Greene et al., 2022). A recent global analysis has identified a suitable global ocean area of 48 million km^2 suitable for seaweed production (Froehlich et al., 2019). Even if only a fraction of this potential could be realized this could provide both climate change benefits (even if the storage is only temporary (Matthews et al., 2023)) and increase civilizational resilience in abrupt sunlight reduction scenarios.

7. Conclusion

Seaweed has a high potential to be an important pillar of global food security. Not only now, but also after a nuclear war. This study shows that, especially in the case of a severe nuclear war, large ocean areas exist that have high growth rates. Partly, these are also located in areas where seaweed production is feasible today, highlighting important areas to facilitate seaweed production now. Given enough preparation and using the most productive areas available, seaweed could start producing an equivalent of 45% of global human food demand after a scale-up period of only 9 months. While a pure seaweed diet is not possible, this intervention could have an expected value of averting up to ~1.2 billion deaths from starvation (15% of human food demand times 8 billion people). The main bottleneck to produce enough seaweed to make a significant contribution to global food security is the speed at which the construction of new seaweed farms can be scaled up. Therefore, investments into increasing such capacity could help to avoid a global famine in an abrupt sunlight reduction scenario. In addition, global carbon sequestration with seaweed has a similar demand in inputs as the scale proposed here to use seaweed as a resilient food after a nuclear war (DeAngelo et al., 2022). This means that seaweed farming at a much larger scale than today could combat climate change, while also making the food system much more resilient in abrupt sunlight reduction scenarios.

8. Methods

The analysis in this paper is done in a two step approach (Figure 5). First, we use an empirical seaweed model to calculate global seaweed growth after nuclear war. Second, we use the resulting growth rates to calculate how quickly global seaweed production can be scaled up to meet 45% of the global human food demand need.

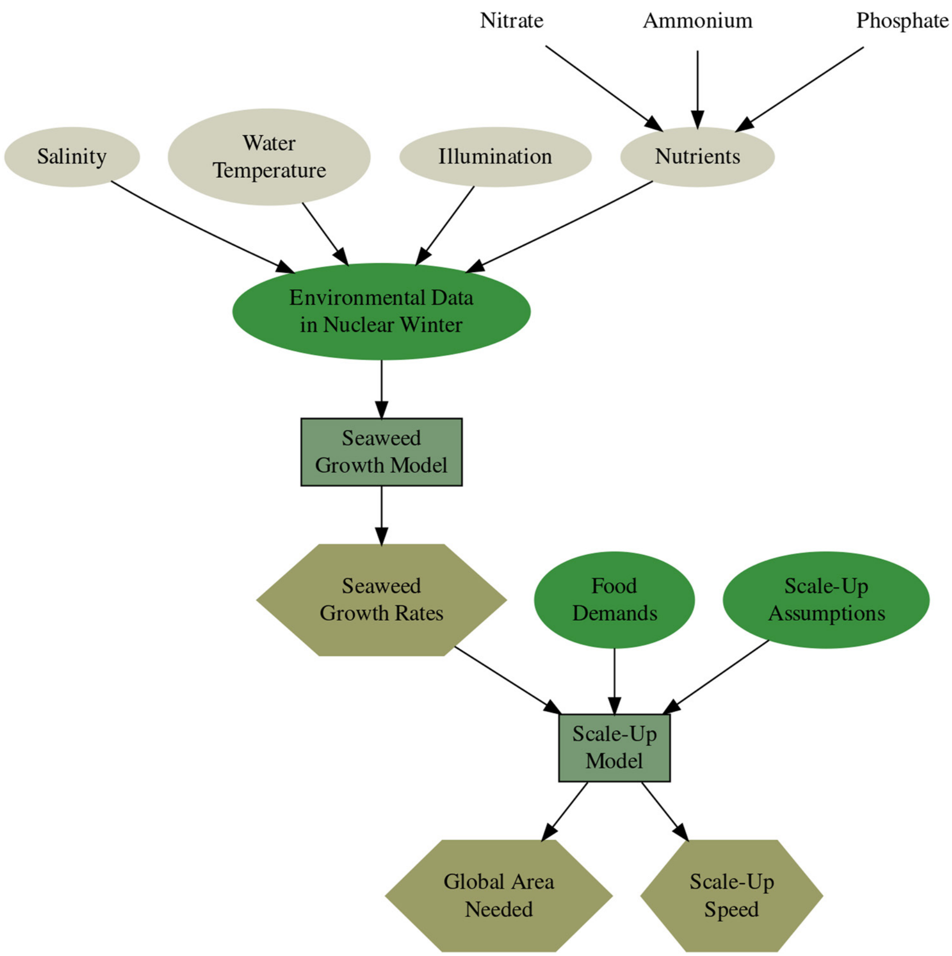

Figure 5. Workflow for modeling set-up and simulation. The seaweed growth model calculates seaweed growth rates based on nuclear winter environmental simulation. Based on those growth rates, the scale-up model estimates how quickly 45% of the global human food demand could be satisfied with seaweed and how much area could be needed for this. Hexagons highlight resulting data, ellipses inputs (forcing and assumptions) and squares the models.

8.1. Seaweed Species Selection for Modeling

Seaweeds exhibit a wide range in their properties including morphology, nutrient content and their preferred environmental conditions. A seaweed species was chosen that could be successful in the conditions of a nuclear winter. The growth model is based on the species *Gracilaria tikvahiae* (Bird et al., 1979; Lapointe & Ryther, 1978), a morphologically variable red macrophytic algae (*Rhodophyta*) (Figure S9 in Supporting Information S1). It is commonly found in the Atlantic estuarine environments and the Western North Atlantic Ocean, with extremes of its geographic range may be found in the environmental regimes of Canada and southern Mexico (Gurgel et al., 2004).

Gracilaria tikvahiae was chosen for its persistence in the vegetative condition so that it can be continuously trimmed as well as its growth rate and dry weight yield (Lapointe & Ryther, 1978) under a wide variety of environmental conditions, is used for human consumption (Abbott, 1978) and is grown commercially in countries around the world (e.g., China and Brazil) (Buschmann et al., 2017). Its current growing conditions are similar to those found near the equator in the case of nuclear winter (Harrison et al., 2022) and its environmental constraints for growth are well known (James & Boriah, 2010). It has also been proven to be suitable for offshore cultivation (Lehahn et al., 2016). It has growth rates, as well as nutrient, illumination and temperature needs which are in a typical range for seaweeds (Eggert, 2012; Xiao et al., 2019). This choice is not meant to imply that Gracilaria tikvahiae is the only viable species after a nuclear war, but merely that it was a good species due to its current use, environmental flexibility and availability of a good empirical growth model.

8.2. Seaweed Growth Model

The analysis to assess the feasibility of seaweed as a resilient food source is split into two steps (Figure 5). First, we calculate the growth rate of the seaweed on a global scale. To do this we use the empirical model for the growth of *Gracilaria tikvahiae* based on James and Boriah (James & Boriah, 2010). The model uses growth limitations. It starts with the optimal growth rate of 30% per day, which is conservative (Kim & Yarish, 2014; Parker, 1982), as cases with up to 60% per day have been reported in controlled experiments for *Gracilaria tikvahiae* (Lapointe & Ryther, 1978). The optimal growth rate is multiplied by limiting factors for illumination, temperature, nutrients, salinity and self-shading, which results in the actual growth rate. For a detailed description of the factors see Figures S10–S14 in Supporting Information S1. The code (Jehn et al., 2023a) and data (Jehn et al., 2023b) for the growth model can be found at the corresponding repositories. We excluded the self-shading factor in our adaptation of the growth model and only looked at it in the scale-up model, as it is more relevant for continuous harvesting and less so for assessing if seaweed can grow after nuclear war at all. This means that in the scale-up model, the seaweed is regularly harvested to maximize yield subject to a reasonable harvest frequency.

The growth model uses as its forcing Earth system model simulation (Coupe et al., 2019; Harrison et al., 2022), which models the impact of a range of nuclear wars on the global ocean state. This ocean model simulation component contains information about salinity, sea surface temperature, illumination, and nutrients (ammonium, nitrate, phosphate). The original data set reflects the effects of a nuclear war on the atmosphere and oceans. The scenarios consists of soot injections of 5, 16, 27, 37, 47 and 150 Tg of soot into the atmosphere and a control run. The ocean model has a resolution of ∼1° grid cells. Due to this resolution, processes near coasts underestimate nutrient fluxes and thus overall productivity near coasts. We model the first ten years after a nuclear war, as after those ten years conventional agriculture largely recovers (Coupe et al., 2019).

When the seaweed model is run, it results in a time series for all the growth factors and the total growth factor, for each grid cell in the ocean. The total growth factor is simply the product of the single growth factors. To find patterns in the total growth factors between different grid cells, we clustered the time series of the total growth factor using k-means clustering with dynamic time warping (Müller, 2007) as the distance measure, as implemented in tslearn (Tavenard et al., 2020). Dynamic time warping allows the similarity of two time series to be detected, even if they happen at different speeds. In the case of this paper, two regions will be counted in the same cluster if they have the same overall growth pattern, even if the pattern is slightly shifted in both timing and amplitude. The optimal number of clusters was determined by using the elbow method (Figure S15 in Supporting Information S1) and resulted in three distinct clusters, which represent the main growth regimes in seaweed that can be found after nuclear war.

8.3. Seaweed Scale-Up Model

The second step in our analysis is a scale-up model (F. U. Jehn & Dingal, 2023). This model uses the modeled seaweed growth rates to calculate how quickly society could scale up global seaweed production to account for an equivalent 45% of global human food demand. This could be enough to substitute 15% of human food by seaweed, 10% of animal feed and 50% of the global biofuel production (though it may not be feasible for seaweed to provide bio diesel, the conversion of efficiency of seaweed to ethanol may be lower than that for grains, necessitating a greater seaweed supply (Milledge et al., 2014)).

The model scales up the seaweed in such a way that over the whole time period of ten years 45% of global calories can be produced on average. The amount of new seaweed farms built each day is represented by a logistic curve (Figure S16 in Supporting Information S1), which models the scale-up of seaweed farm production by comparing it to the scale-up of aircraft production in World War II in the United States (Automobile Manufacturers Association, 1950). In each time step the model grows the seaweed by using the modeled seaweed growth rate for that day. This accounts for self-shading (James & Boriah, 2010) (Figure S14 in Supporting Information S1) and how much area is available to grow seaweed. The model assumes 85% of the area of a seaweed farm are suitable for seaweed production (United Nations Environment Program, 2023). The rest is needed for harvesting lanes and infrastructure. The growth values mentioned are all referring to only the used area if not mentioned otherwise. The seaweed grows until it has reached a density of 3.6 kg per m^2 and is then cut back to 1.2 kg per m^2, the optimal trimming threshold to minimize self-shading (Lapointe & Ryther, 1978; Lehahn et al., 2016). Once the whole seaweed farm area is saturated with seaweed, all yield thereafter can be used to produce food, feed and biofuel.

This is based on a low tech seaweed farm design. Such designs consist mainly of seedling lines to attach the seaweed, longlines to attach the seedling lines, buoyant to keep the longlines afloat and anchors to fix the farm in place (Yarish et al., 2016). See Hurtado et al. (2014) for a selection of low tech seaweed farm design schematics. We are assuming 262 kcal per 100 g of dried seaweed (Gamero-Vega et al., 2020).

8.4. Seaweed Farm Building Scale-Up

To estimate how quickly seaweed farms could be built, we mainly looked at rope production, as this is the main component and most complex part of low-tech seaweed farming (Yarish et al., 2016). The other main components being anchors and buoys, which can be substituted through rocks and black plastic bottles (Steenbergen et al., 2017). Currently 60.5 million tonnes of polyester fibers are produced per year (Statista, n.d.), Out of this synthetic fiber category at least polyamide (Nylon), polypropylene and polyethylene are suitable for seaweed farms. Conservatively, we are assuming no additional scale-up of fiber production and that only 50 million tonnes of global polyester production are suitable for seaweed farms. Given the 2 types of ropes (0.025 kg/m for seedling lines and 0.11 kg/m for longlines) in the farm design 33.9 tons of suitable rope are needed to create 1 km^2 of seaweed farm in a low tech setting. This means that around 4,000 km^2 of seaweed farms can be built per day with current global fiber production. However, the current production of ropes is much lower than that and will need to be scaled up. To estimate the possible speed of this scale-up we use the switch of the American automobile industry to producing aircraft (and other war machinery outputs) in the Second World War (Automobile Manufacturers Association, 1950). This shows that a considerable scale up can be done in around 9 months. To finally estimate the seaweed farm production over time, we use the scale up speed from the Second World War with 4,000 km^2 as the maximum production and fit a logistic growth curve to it (Figure S12 in Supporting Information S1). We do not include logistics (like transport boats) or the availability of knowledgeable personnel, as this was no major problem in the Second World War scale-up. As the scale-up we are proposing here is smaller, we assume that this should be no major problem here as well.

We further assume that the distribution and installation of the seaweed farms will be possible if the needed amount of rope is provided. Overall, the seaweed farm production is a considerably smaller effort than the American war effort in World War Two alone, and should thus be possible to accomplish now as well.

Data Availability Statement

All data and code used for this study is openly available. The code is made available at Github and is published under the Apache-2.0 license. The data can be directly downloaded from Zenodo. The code repositories also contain instructions for installing and using the models.

- Python code for the Seaweed Growth Model: Jehn et al. (2023a).
- Python code for the Seaweed Scale-Up Model: Jehn and Dingal (2023).
- Nuclear winter ocean data: Jehn et al. (2023b).

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References

Abbott, I. A. (1978). The uses of seaweed as food in Hawaii. *Economic Botany*, *32*(4), 409–412. https://doi.org/10.1007/BF02907938

Abd Elnabi, M. K., Elkaliny, N. E., Elyazied, M. M., Azab, S. H., Elkhalifa, S. A., Elmasry, S., et al. (2023). Toxicity of heavy metals and recent advances in their removal: A review. *Toxics*, *11*(7), 580. https://doi.org/10.3390/toxics11070580

Alvarado, K. A., Mill, A., Pearce, J. M., Vocaet, A., & Denkenberger, D. (2020). Scaling of greenhouse crop production in low sunlight scenarios. *Science of the Total Environment*, *707*, 136012. https://doi.org/10.1016/j.scitotenv.2019.136012

Automobile Manufacturers Association. (1950). *Freedom's Arsenal: The story of the automotive council for war production*. Automobile Manufacturers Association.

Bardeen, C. G., Kinnison, D. E., Toon, O. B., Mills, M. J., Vitt, F., Xia, L., et al. (2021). Extreme ozone loss following nuclear war results in enhanced surface ultraviolet radiation. *Journal of Geophysical Research: Atmospheres*, *126*(18), e2021JD035079. https://doi.org/10.1029/2021JD035079

Bertram, C. (2010). Ocean iron fertilization in the context of the Kyoto protocol and the post-Kyoto process. *Energy Policy*, *38*(2), 1130–1139. https://doi.org/10.1016/j.enpol.2009.10.065

Bird, N. L., Chen, L. C.-M., & McLachlan, J. (1979). Effects of temperature, light and salinity on growth in culture of Chondrus crispus. Furcellaria lumbricalis, Gracilaria tikvahiae (Gigartinales, Rhodophyta), and Fucus serratus (Fucales, Phaeophyta). *Botanica Marina*, *22*(8). https://doi.org/10.1515/botm.1979.22.8.521

Bouga, M., & Combet, E. (2015). Emergence of seaweed and seaweed-containing foods in the UK: Focus on labeling, iodine content, toxicity and nutrition. *Foods*, *4*(4), 240–253. https://doi.org/10.3390/foods4020240

Boyd, M., & Wilson, N. (2022). Island refuges for surviving nuclear winter and other abrupt sunlight-reducing catastrophes. *Risk Analysis*, *43*(9), 1824–1842. https://doi.org/10.1111/risa.14072

Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M. C., et al. (2017). Seaweed production: Overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology*, *52*(4), 391–406. https://doi.org/10.1080/09670262.2017.1365175

Chapman, C. R., & Morrison, D. (1994). Impacts on the Earth by asteroids and comets: Assessing the hazard. *Nature*, *367*(6458), 33–40. https://doi.org/10.1038/367033a0

Chapman, E. M. (1983). History of the discovery and early use of radioactive iodine. *JAMA, the Journal of the American Medical Association*, *250*(15), 2042. https://doi.org/10.1001/jama.1983.03340150084036

Chen, J. (2013). Evaluation of radioactivity concentrations from the Fukushima nuclear accident in fish products and associated risk to fish consumers. *Radiation Protection Dosimetry*, *157*(1), 1–5. https://doi.org/10.1093/rpd/nct239

Councell, T. B., Landa, E. R., & Lovley, D. R. (1997). Microbial reduction of iodate. *Water, Air, and Soil Pollution*, *100*(1), 99–106. https://doi.org/10.1023/A:1018370423790

Coupe, J., Bardeen, C. G., Robock, A., & Toon, O. B. (2019). Nuclear winter responses to nuclear war between the United States and Russia in the whole atmosphere community climate model version 4 and the goddard institute for space studies ModelE. *Journal of Geophysical Research: Atmospheres*, *124*(15), 8522–8543. https://doi.org/10.1029/2019JD030509

Coupe, J., Stevenson, S., Lovenduski, N. S., Rohr, T., Harrison, C. S., Robock, A., et al. (2021). Nuclear Niño response observed in simulations of nuclear war scenarios. *Communications Earth & Environment*, *2*(1), 1–11. https://doi.org/10.1038/s43247-020-00088-1

DeAngelo, J., Saenz, B. T., Arzeno-Soltero, I. B., Frieder, C. A., Long, M. C., Hamman, J., et al. (2022). Economic and biophysical limits to seaweed farming for climate change mitigation. *Nature Plants*, *9*, 1–13. https://doi.org/10.1038/s41477-022-01305-9

DeBoer, J. A. (1981). *The marine plant resources and their aquaculture potential in the Bahamas: A report to the fisheries training and development project*. FAO. BHA/78/001, Nassau, Bahamas.

Denkenberger, D., Pearce, J., Taylor, A. R., & Black, R. (2019). Food without sun: Price and life-saving potential. *Foresight*, *21*(1), 118–129. https://doi.org/10.1108/FS-04-2018-0041

Denkenberger, D. C., & Pearce, J. M. (2015). Feeding everyone: Solving the food crisis in event of global catastrophes that kill crops or obscure the sun. *Futures*, *72*, 57–68. https://doi.org/10.1016/j.futures.2014.11.008

Do, T., Anderson, K., & Brorsen, B. W. (2010). *The World's wheat supply*. Oklahoma Cooperative Extension Service.

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00100

Eggert, A. (2012). Seaweed responses to temperature. In C. Wiencke & K. Bischof (Eds.), *Seaweed biology: Novel insights into ecophysiology, ecology and utilization* (pp. 47–66). Springer. https://doi.org/10.1007/978-3-642-28451-9_3

Fedoroff, N. V., Battisti, D. S., Beachy, R. N., Cooper, P. J. M., Fischhoff, D. A., Hodges, C. N., et al. (2010). Radically rethinking agriculture for the 21st century. *Science*, *327*(5967), 833–834. https://doi.org/10.1126/science.1186834

Ferdouse, F., Holdt, S. L., Smith, R., Murúa, P., & Yang, Z., & Food and Agriculture Organization of the United Nations. (2018). *The global status of seaweed production, trade and utilization* (Vol. 124). Globlefish Research Programme.

Forbord, S., Skjermo, J., Arff, J., Handå, A., Reitan, K. I., Bjerregaard, R., & Lüning, K. (2012). Development of Saccharina latissima (Phaeophyceae) kelp hatcheries with year-round production of zoospores and juvenile sporophytes on culture ropes for kelp aquaculture. *Journal of Applied Phycology*, *24*(3), 393–399. https://doi.org/10.1007/s10811-011-9784-y

Froehlich, H. E., Afflerbach, J. C., Frazier, M., & Halpern, B. S. (2019). Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biology*, *29*(18), 3087–3093.e3. https://doi.org/10.1016/j.cub.2019.07.041

Fung, I., Meyn, S. K., Tegen, I., Doney, S., John, J., & Bishop, J. (2000). Iron supply and demand in the upper ocean (vol 14, pg 281, 2000). *Global Biogeochemical Cycles*, *14*, 697–700.

Gachon, C. M. M., Sime-Ngando, T., Strittmatter, M., Chambouvet, A., & Kim, G. H. (2010). Algal diseases: Spotlight on a black box. *Trends in Plant Science*, *15*(11), 633–640. https://doi.org/10.1016/j.tplants.2010.08.005

Gamero-Vega, G., Palacios-Palacios, M., & Quitral, V. (2020). Nutritional composition and bioactive compounds of red seaweed: A mini-review. *Journal of Food and Nutrition Research*, *8*(8), 431–440. https://doi.org/10.12691/jfnr-8-8-7

García Martínez, J. B., Alvarado, K. A., & Denkenberger, D. C. (2022). Synthetic fat from petroleum as a resilient food for global catastrophes: Preliminary techno-economic assessment and technology roadmap. *Chemical Engineering Research and Design*, *177*, 255–272. https://doi.org/10.1016/j.cherd.2021.10.017

García Martínez, J. B., Egbejimba, J., Throup, J., Matassa, S., Pearce, J. M., & Denkenberger, D. C. (2021). Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios. *Sustainable Production and Consumption*, *25*, 234–247. https://doi.org/10.1016/j.spc.2020.08.011

García Martínez, J. B., Pearce, J. M., Throup, J., Cates, J., Lackner, M., & Denkenberger, D. C. (2022). Methane single cell protein: Potential to secure a global protein supply against catastrophic food shocks. *Frontiers in Bioengineering and Biotechnology*, *10*. https://doi.org/10.3389/fbioe.2022.906704

Gopal, N., Srinath, K., Gr, U., Hvl, B., & Tauqueer, A. (2012). *Harvest losses in marine fisheries*. Society of Fisheries Technologists (India). Retrieved from http://epubs.icar.org.in/ejournal/index.php/FT/article/view/16526

Greene, C., Scott-Buechler, C., Hausner, A., Johnson, Z., Lei, X. G., & Huntley, M. (2022). Transforming the future of marine aquaculture: A circular economy approach. *Oceanography*, 26–34. https://doi.org/10.5670/oceanog.2022.213

Gurgel, C. F. D., Fredericq, S., & Norris, J. N. (2004). Phylogeography of Gracilaria Tikvahiae (gracilariaceae, Rhodophyta): A study of genetic discontinuity in a continuously distributed species based on molecular evidence. *Journal of Phycology*, *40*(4), 748–758. https://doi.org/10.1111/j.1529-8817.2004.03070.x

Hansen, H. R., Hector, B. L., & Feldmann, J. (2003). A qualitative and quantitative evaluation of the seaweed diet of North Ronaldsay sheep. *Animal Feed Science and Technology*, *105*(1), 21–28. https://doi.org/10.1016/S0377-8401(03)00053-1

Harrison, C. S., Rohr, T., DuVivier, A., Maroon, E. A., Bachman, S., Bardeen, C. G., et al. (2022). A new ocean state after nuclear war. *AGU Advances*, *3*(4). https://doi.org/10.1029/2021AV000610

Hehemann, J.-H., Correc, G., Barbeyron, T., Helbert, W., Czjzek, M., & Michel, G. (2010). Transfer of carbohydrate-active enzymes from marine bacteria to Japanese gut microbiota. *Nature*, *464*(7290), 908–912. https://doi.org/10.1038/nature08937

Hess, G. D. (2021). The impact of a regional nuclear conflict between India and Pakistan: Two views. *Journal for Peace and Nuclear Disarmament*, *4*(sup1), 163–175. https://doi.org/10.1080/25751654.2021.1882772

Hurtado, A. Q., Gerung, G. S., Yasir, S., & Critchley, A. T. (2014). Cultivation of tropical red seaweeds in the BIMP-EAGA region. *Journal of Applied Phycology*, *26*(2), 707–718. https://doi.org/10.1007/s10811-013-0116-2

Jägermeyr, J., Robock, A., Elliott, J., Müller, C., Xia, L., Khabarov, N., et al. (2020). A regional nuclear conflict would compromise global food security. *Proceedings of the National Academy of Sciences*, *117*(13), 7071–7081. https://doi.org/10.1073/pnas.1919049117
James, S. C., & Boriah, V. (2010). Modeling algae growth in an open-channel raceway. *Journal of Computational Biology*, *17*(7), 895–906. https://doi.org/10.1089/cmb.2009.0078
Jehn, F. U., & Dingal, F. J. (2023). allfed/seaweed-scaleup-model: Release for publication (Version 1.4) [Software]. Zenodo. https://doi.org/10.5281/zenodo.10216432
Jehn, F. U., Dingal, F. J., Mill, A., Ilin, E., Harrison, C., Roleda, M. Y., & Denkenberger, D. (2023a). Seaweed in nuclear winter data repository (version 1.0) [Dataset]. Zenodo. https://doi.org/10.5281/ZENODO.7553874
Jehn, F. U., Rivers, M., & Ilin, E. (2023b). allfed/seaweed-growth-model: Release for submission (Version 1.1) [Software]. Zenodo. https://doi.org/10.5281/ZENODO.7575050
John, R. P., Anisha, G. S., Nampoothiri, K. M., & Pandey, A. (2011). Micro and macroalgal biomass: A renewable source for bioethanol. *Bioresource Technology*, *102*(1), 186–193. https://doi.org/10.1016/j.biortech.2010.06.139
Kakita, H., & Kamishima, H. (2006). Effects of environmental factors and metal ions on growth of the red alga Gracilaria Chorda Holmes (Gracilariales, Rhodophyta). *Journal of Applied Phycology*, *18*(3), 469–474. https://doi.org/10.1007/s10811-006-9047-5
Kelly, E. L. A., Cannon, A. L., & Smith, J. E. (2020). Environmental impacts and implications of tropical carrageenophyte seaweed farming. *Conservation Biology*, *34*(2), 326–337. https://doi.org/10.1111/cobi.13462
Kim, J. K., & Yarish, C. (2014). Development of a sustainable land-based Gracilaria cultivation system. *ALGAE*, *29*(3), 217–225. https://doi.org/10.4490/algae.2014.29.3.217
Lapointe, B. E., & Ryther, J. H. (1978). Some aspects of the growth and yield of Gracilaria tikvahiae in culture. *Aquaculture*, *15*(3), 185–193. https://doi.org/10.1016/0044-8486(78)90030-3
Lehahn, Y., Ingle, K. N., & Golberg, A. (2016). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: Feasibility and sustainability. *Algal Research*, *17*, 150–160. https://doi.org/10.1016/j.algal.2016.03.031
Lewis, P. D. (2004). Responses of domestic fowl to excess iodine: A review. *British Journal of Nutrition*, *91*(1), 29–39. https://doi.org/10.1079/BJN20031017
Liu, Y., Cao, L., Cheung, W. W. L., & Sumaila, U. R. (2023). Global estimates of suitable areas for marine algae farming. *Environmental Research Letters*, *18*(6), 064028. https://doi.org/10.1088/1748-9326/acd398
Lobban, C. S., & Harrison, P. J. (1994). *Seaweed ecology and physiology*. Cambridge University Press. https://doi.org/10.1017/CBO9780511626210
Mageswaran, R., & Sivasubramaniam, S. (1984). Preliminary studies on the iodine content of some marine algae from coastal areas of Jaffna Peninsula. *Journal of the National Science Foundation of Sri Lanka*, *12*(2), 173. https://doi.org/10.4038/jnsfsr.v12i2.8355
Matthews, H. D., Zickfeld, K., Koch, A., & Luers, A. (2023). Accounting for the climate benefit of temporary carbon storage in nature. *Nature Communications*, *14*(1), 5485. https://doi.org/10.1038/s41467-023-41242-5
McHugh, D. J. (2003). *A Guide to the seaweed industry*. Food and Agriculture Organization of the United Nations.
Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-derived biofuel: A review of methods of energy extraction from seaweed biomass. *Energies*, *7*(11), 7194–7222. https://doi.org/10.3390/en7117194
Mills, M. J., Toon, O. B., Lee-Taylor, J., & Robock, A. (2014). Multidecadal global cooling and unprecedented ozone loss following a regional nuclear conflict. *Earth's Future*, *2*(4), 161–176. https://doi.org/10.1002/2013ef000205
Mills, M. J., Toon, O. B., Turco, R. P., Kinnison, D. E., & Garcia, R. R. (2008). Massive global ozone loss predicted following regional nuclear conflict. *Proceedings of the National Academy of Sciences*, *105*(14), 5307–5312. https://doi.org/10.1073/pnas.0710058105
Mineault, P., & Nozawa, K. (2021). The good research code handbook (Version releases). *Zenodo*. https://doi.org/10.5281/ZENODO.5796872
Mouritsen, O. G., Dawczynski, C., Duelund, L., Jahreis, G., Vetter, W., & Schröder, M. (2013). On the human consumption of the red seaweed dulse (Palmaria palmata (L.) Weber & Mohr). *Journal of Applied Phycology*, *25*(6), 1777–1791. https://doi.org/10.1007/s10811-013-0014-7
Müller, M. (Ed.) (2007). Dynamic time warping, *Information retrieval for music and motion* (pp. 69–84). Springer. https://doi.org/10.1007/978-3-540-74048-3_4
Nielsen, C. W., Holdt, S. L., Sloth, J. J., Marinho, G. S., Sæther, M., Funderud, J., & Rustad, T. (2020). Reducing the high iodine content of Saccharina latissima and improving the profile of other valuable compounds by water blanching. *Foods*, *9*(5), 569. https://doi.org/10.3390/foods9050569
Notoya, M. (2010). Production of biofuel by macroalgae with preservation of marine resources and environment. In J. Seckbach, R. Einav, & A. Israel (Eds.), *Seaweeds and their role in globally changing environments* (pp. 217–228). Springer Netherlands. https://doi.org/10.1007/978-90-481-8569-6_13
Olanrewaju, S. O., Magee, A., Kader, A. S. A., & Tee, K. F. (2017). Simulation of offshore aquaculture system for macro algae (seaweed) oceanic farming. *Ships and Offshore Structures*, *12*(4), 553–562. https://doi.org/10.1080/17445302.2016.1186861
Otto-Bliesner, B. L., Brady, E. C., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., et al. (2016). Climate variability and change since 850 CE: An ensemble approach with the community earth system model. *Bulletin of the American Meteorological Society*, *97*(5), 735–754. https://doi.org/10.1175/BAMS-D-14-00233.1
Parker, H. S. (1982). Effects of simulated current on the growth rate and nitrogen metabolism of Gracilaria tikvahiae (Rhodophyta). *Marine Biology*, *69*(2), 137–145. https://doi.org/10.1007/BF00396893
Pearce, E. N., Gerber, A. R., Gootnick, D. B., Khan, L. K., Li, R., Pino, S., & Braverman, L. E. (2002). Effects of chronic iodine excess in a cohort of long-term American workers in West Africa. *The Journal of Clinical Endocrinology & Metabolism*, *87*(12), 5499–5502. https://doi.org/10.1210/jc.2002-020692
Pearce, J. M., Khaksari, M., & Denkenberger, D. (2019). Preliminary automated determination of edibility of alternative foods: Non-targeted screening for toxins in red maple leaf concentrate. *Plants*, *8*(5), 110. https://doi.org/10.3390/plants8050110
Penniman, C. A., & Mathieson, A. C. (1987). Variation in chemical composition of Gracilaria tikvahiae McLachlan (Gigartinales, Rhodophyta) in the Great Bay estuary. *New Hampshire*, *30*(6), 525–534. https://doi.org/10.1515/botm.1987.30.6.525
Rampino, M. R. (2002). Supereruptions as a threat to civilizations on Earth-like planets. *Icarus*, *156*(2), 562–569. https://doi.org/10.1006/icar.2001.6808
Rivers, M., Hinge, M., Martínez, J. G., Tieman, R., Jaeck, V., Butt, T., & Denkenberger, D. (2022). Deployment of resilient foods can greatly reduce Faminein an abrupt sunlight reduction scenario (preprint). *Review*. https://doi.org/10.21203/rs.3.rs-1446444/v1
Robock, A., Oman, L., Stenchikov, G. L., Toon, O. B., Bardeen, C., & Turco, R. P. (2007). Climatic consequences of regional nuclear conflicts. *Atmospheric Chemistry and Physics*, *7*(8), 2003–2012. https://doi.org/10.5194/acp-7-2003-2007
Rougier, J., Sparks, R. S. J., Cashman, K. V., & Brown, S. K. (2018). The global magnitude–frequency relationship for large explosive volcanic eruptions. *Earth and Planetary Science Letters*, *482*, 621–629. https://doi.org/10.1016/j.epsl.2017.11.015

Santiago, A., & Moreira, R. (2020). Chapter 5 - drying of edible seaweeds. In M. D. Torres, S. Kraan, & H. Dominguez (Eds.), *Sustainable seaweed technologies* (pp. 131–154). Elsevier. https://doi.org/10.1016/B978-0-12-817943-7.00004-4

Scherrer, K. J. N., Harrison, C. S., Heneghan, R. F., Galbraith, E., Bardeen, C. G., Coupe, J., et al. (2020). Marine wild-capture fisheries after nuclear war. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(47), 29748–29758. https://doi.org/10.1073/pnas.2008256117

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., et al. (2015). Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, *523*(7562), 543–549. https://doi.org/10.1038/nature14565

Soto, D., & Wurmann, C. (2019). *Offshore aquaculture: A needed new frontier for farmed fish at sea* (pp. 379–384). Brill Nijhoff. https://doi.org/10.1163/9789004380271_064

Statista, (n.d.). Global textile fiber production by type 2021. Retrieved from https://www.statista.com/statistics/1250690/global-textile-fiber-production-type/

Steenbergen, D. J., Marlessy, C., & Holle, E. (2017). Effects of rapid livelihood transitions: Examining local co-developed change following a seaweed farming boom. *Marine Policy*, *82*, 216–223. https://doi.org/10.1016/j.marpol.2017.03.026

Suzuki, Y., Kuma, K., Kudo, I., & Matsunaga, K. (1995). Iron requirement of the brown macroalgae Laminaria japonica, Undaria pinnatifida (Phaeophyta) and the crustose coralline alga Lithophyllum yessoense (Rhodophyta), and their competition in the northern Japan Sea. *Phycologia*, *34*(3), 201–205. https://doi.org/10.2216/i0031-8884-34-3-201.1

Tabor, C. R., Bardeen, C. G., Otto-Bliesner, B. L., Garcia, R. R., & Toon, O. B. (2020). Causes and climatic consequences of the impact winter at the Cretaceous-Paleogene boundary. *Geophysical Research Letters*, *47*(3), e60121. https://doi.org/10.1029/2019GL085572

Tavenard, R., Faouzi, J., Vandewiele, G., Divo, F., Androz, G., Holtz, C., et al. (2020). Tslearn, a machine learning toolkit for time series data. *Journal of Machine Learning Research*, *21*(118), 1–6.

Teas, J., Pino, S., Critchley, A., & Braverman, L. E. (2004). Variability of iodine content in common commercially available edible seaweeds. *Thyroid*, *14*(10), 836–841. https://doi.org/10.1089/thy.2004.14.836

Throup, J., García Martínez, J. B., Bals, B., Cates, J., Pearce, J. M., & Denkenberger, D. C. (2022). Rapid repurposing of pulp and paper mills, biorefineries, and breweries for lignocellulosic sugar production in global food catastrophes. *Food and Bioproducts Processing*, *131*, 22–39. https://doi.org/10.1016/j.fbp.2021.10.012

Toon, O. B., Robock, A., & Turco, R. P. (2008). Environmental consequences of nuclear war. *Physics Today*, *61*(12), 37–42. https://doi.org/10.1063/1.3047679

Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B., & Sagan, C. (1983). Nuclear winter: Global consequences of multiple nuclear explosions. *Science*, *222*(4630), 1283–1292. https://doi.org/10.1126/science.222.4630.1283

Tzachor, A., Richards, C. E., & Holt, L. (2021). Future foods for risk-resilient diets. *Nature Food*, *2*(5), 326–329. https://doi.org/10.1038/s43016-021-00269-x

van Oort, P. A. J., Verhagen, A., & van der Werf, A. K. (2023). Can seaweeds feed the world? Modelling world offshore seaweed production potential. *Ecological Modelling*, *484*, 110486. https://doi.org/10.1016/j.ecolmodel.2023.110486

White, S. (2013). *The climate of rebellion in the early modern Ottoman Empire*. Cambridge University Press.

Winstead, D. J., & Jacobson, M. G. (2022). Food resilience in a dark catastrophe: A new way of looking at tropical wild edible plants. *Ambio*, *51*(9), 1949–1962. https://doi.org/10.1007/s13280-022-01715-1

Xia, L., Robock, A., Scherrer, K., Harrison, C. S., Bodirsky, B. L., Weindl, I., et al. (2022). Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection. *Nature Food*, *3*(8), 1–11. https://doi.org/10.1038/s43016-022-00573-0

Xiao, X., Agusti, S., Lin, F., Xu, C., Yu, Y., Pan, Y., et al. (2019). Resource (Light and Nitrogen) and density-dependence of seaweed growth. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00618

Xu, L., Wei, K., Wu, X., Smyshlyaev, S. P., Chen, W., & Galin, V. Y. (2019). The effect of super volcanic eruptions on ozone depletion in a chemistry-climate model. *Advances in Atmospheric Sciences*, *36*(8), 823–836. https://doi.org/10.1007/s00376-019-8241-8

United Nations Environment Program. (2023). Seaweed farming: Assessment on the potential of sustainable upscaling for climate, communities and the planet. Nairobi. Retrieved from https://www.unep.org/resources/report/seaweed-farming-assessment-sustainable-upscaling

Yarish, C., Brummett, R., Hansen, S., Bjerregaard, R., Valderrama, D., Sims, N., et al. (2016). *Seaweed aquaculture for food security, income generation and environmental health in tropical developing countries (Seaweed aquaculture No. 107147)*. World Bank Group. https://doi.org/10.1596/24919

Zava, T. T., & Zava, D. T. (2011). Assessment of Japanese iodine intake based on seaweed consumption in Japan: A literature-based analysis. *Thyroid Research*, *4*(1), 1–7. https://doi.org/10.1186/1756-6614-4-14

References From the Supporting Information

Carruthers, T. J. B., Longstaff, B. J., Dennison, W. C., Abal, E. G., & Aioi, K. (2001). Chapter 19 - Measurement of light penetration in relation to seagrass. In F. T. Short & R. G. Coles (Eds.), *Global seagrass research methods* (pp. 369–392). Elsevier Science. https://doi.org/10.1016/B978-044450891-1/50020-7

DeBoer, J. A., Guigli, H. J., Israel, T. L., & D'Elia, C. F. (1978). Nutritional studies of two red algae. I. Growt rate as a function of nitrogen source and concentration. *Journal of Phycology*, *14*(3), 261–266. https://doi.org/10.1111/j.1529-8817.1978.tb00296.x

D'Elia, C. F., & DeBoer, J. A. (1978). Nutritional studies of two red algae. II. Kinetics of ammonium and nitrate uptake. *Journal of Phycology*, *14*(3), 266–272. https://doi.org/10.1111/j.1529-8817.1978.tb00297.x

Hansiak, M. D. (1987). Cultivation of Gracilaria and other macroalgae in Florida for energy production. In K. T. Bird & P. H. Benson (Eds.), *Seaweed cultivation for renewable resources*. Elsevier.

Lapointe, B. E., & Hansiak, M. D. (1985). Productivity and nutrition of marine biomass systems in Florida. *Energy from Biomass and Waste*, *9*.

Mulder, C., & Hendriks, A. J. (2014). Half-saturation constants in functional responses. *Global Ecology and Conservation*, *2*, 161–169. https://doi.org/10.1016/j.gecco.2014.09.006

van der Ploeg, R. R., Böhm, W., & Kirkham, M. B. (1999). On the origin of the theory of mineral nutrition of plants and the law of the minimum. *Soil Science Society of America Journal*, *63*(5), 1055–1062. https://doi.org/10.2136/sssaj1999.6351055x

Thorndike, R. L. (1953). Who belongs in the family? *Psychometrika*, *18*(4), 267–276. https://doi.org/10.1007/BF02289263