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RESEARCH

Seaweed cultivation: a cost-effective strategy for food production in a global catastrophe

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Abstract

An event such as a large volcanic eruption, nuclear winter, and asteroid/comet impact has the potential to seriously reduce incoming sunlight, impacting the global climate, and crop yields. This could have catastrophic impacts on human nutrition, unless the food system can adapt. One possible answer is seaweed, where growth is projected to be less impacted (or even enhanced) by the climate shock; however, this requires seaweed to be cost-effective, which has not yet been assessed. Here, we estimate the economic viability of producing Gracilaria Tikvahiae seaweed under the climatic conditions of a severe 150 Tg nuclear winter, as a benchmark. To do this, we incorporate projected yields and estimated costs under either a capital-intensive or labor-intensive model, including drying, assuming sales only occur in the initial 7 years when food prices would be highest. Overall, we find that seaweed costs would range between $ 400 and 450/dry tonne for the lowest cost clusters, and could potentially be produced in significant quantities, up to 250 million tonnes annually. Given the rise in food prices expected post-disaster a scaleup in seaweed would likely be justified, and could support global nutrition, either via direct consumption or when used as animal feed.

Keywords Seaweed · Production costs · Global catastrophic risk · Resilient food · Food security · Nuclear winter

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Introduction

An abrupt sunlight reduction scenario (ASRS) refers to an event that disrupts incoming sunlight, resulting in a serious shock to the climate for several years. Potential causes include large volcanic eruptions (Rampino and Self 1992; Newhall et al. 2018), nuclear conflict leading to nuclear winter (Coupe et al. 2019), or even a large asteroid or comet impact (Chapman and Morrison 1994). In each, particulate material injected into the stratosphere absorbs or reflects incoming sunlight, resulting in reduced solar radiation, temperatures, and precipitation worldwide.

These events vary in their magnitudes and duration; however, any ASRS would have a catastrophic impact on the global food system (Xia et al. 2022), with the shock potentially lasting for over a decade. Food prices are expected to rise sharply as a result (Hochman et al. 2022), and unless conventional agriculture can adapt at short notice or additional food sources are found there is the risk of mass starvation, presenting a clear global catastrophic risk. At their extreme, this could present an existential risk to humanity—especially when other threats that could occur simultaneously are considered (Denkenberger et al. 2022; Jehn 2023).

One potential answer is seaweed. In contrast to conventional agriculture located on the land, seaweed growth is expected to be far less impacted (Jehn et al. 2024). In addition, seaweed cultivation is relatively “no-frills”: requiring simple technologies likely to be locally available in coastal areas during catastrophic scenarios where international trade has been cut or infrastructure has been severely disrupted.

Seaweed is eaten extensively over parts of the world, predominantly in East Asia, where a variety of species are included into diets via many different products (Delaney, Frangoudes, and Ii 2016). Seaweed has also been used in past periods of food insecurity in order to bridge deficits in traditional staples, for example, blended into noodles (Collingham 2013, 305).

As a result, it can make an important contribution to nutrition, particularly as a source of protein (Pham et al. 2022). The seaweed species analyzed in Jehn et al. 2024 (*Gracilaria tikvahiae*) ranges from 10 to 19% protein by dry matter (Johnson et al. 2014), and the genus as a whole is a good source of many micronutrients (McDermid and Stuercke 2003). It could also be used as animal feed, meeting some of the shortfall in other parts of the food system (Rivers et al. 2022), and beyond direct consumption provides opportunities for carbon sequestration and offsetting eutrophication (Gao et al. 2022). Furthermore, the species is resilient to a broad range of temperature swings from 20 to 30 °C (Gorman et al. 2017), important under the conditions of an ASRS, and seaweed in general is resilient to PH differentials, and can even offset imbalances (Xiao et al. 2021).

However, for this to be possible, seaweed must be able to be produced in both significant enough quantities and at a low enough cost to make a meaningful contribution to the food system. There are also challenges with iodine content, as well as high levels of dietary fiber, which must be considered when assessing the viability of its mass inclusion into diets.

This paper seeks to estimate the cost of cultivating seaweed on a large scale, following a severe 150 Tg injection of stratospheric soot following a nuclear winter (the largest scale nuclear winter scenario studied (Coupe et al. 2019)). However, this is also relevant for smaller scale climate shocks, as the primary strength of seaweed cultivation—that its yields are largely unaffected by the climate shock over large areas of the tropics—would still apply.

Cultivation is assumed to occur on newly constructed aquaculture plots, as a dramatic expansion in output is assumed, and can make use of either high or low capital systems. To reduce transportation costs as well as the necessary capital, we have restricted cultivation to areas close to the coast and existing ports, and in shallow waters (taken to be a maximum 46 km from a port and a maximum depth of 100 m (Rubino 2008), and then adjusted downwards to account for other limitations on developing the full area). In addition to cultivation, we have included analysis of the viability of different drying systems, which are necessary in many cases to produce marketable seaweed and which would also be disrupted by the ASRS conditions. Costs are broken out into their constituent elements (labor, fuel, inputs, capital expenditure (capex), etc.) where it has been possible to do all.

All calculations, assumptions and our results are included in the attached supplementary spreadsheet.

Methods

In order to estimate the cost of seaweed production post-disaster, we adopted the following steps. Firstly, seaweed yields were calculated for all areas inside a country's exclusive economic zone suitable for seaweed development, calculated using geographic information systems (GIS) data. Next, production costs were estimated on a cell-by-cell basis, based on selecting the lowest cost method of seaweed cultivation and drying. Finally, output was estimated by multiplying yields with the available area. This process is summarized in Fig. 1 below, which lays out the flow from input data to final cost and output estimates.

Our cost estimates are presented for dried *Gracilaria tikvahiae* seaweed, at the point of drying. As a result, they neglect any further transportation, post-drying processing and retailing costs. All costs are adjusted to 2023 USD, unless otherwise indicated, based upon inflating or deflating USD costs via the US Consumer Price Index ('U.S. Bureau of Labor Statistics' 2024).

Seaweed properties and growth

The dry mass of the *Gracilaria tikvahiae* seaweed is around 11% of the total mass (Penniman and Mathieson 1987). We took seaweed growth rates as presented in Jehn et al. (2024), which models growth worldwide following an injection of 150 Tg soot into the stratosphere, and is to date the only published study that estimates seaweed growth under ASRS conditions. Daily growth varies significantly even within countries, with maximum rate exceeding 20%; however, most growth is lower than this, with the upper quartile of cells reaching around 5–15% daily.

Also, in line with Jehn et al. (2024), we assumed 20% of the seaweed is lost prior or during the harvesting process (harvesting losses, losses to animal grazing, and storms for example), while a further 15% is lost in general post-harvesting transportation and processing. Growth rates were mapped to the area dataset via matching each cell to its nearest direct partner, making use of the latitude and longitude values.

In line with past studies on best practice (Lapointe and Ryther 1978), plots were assumed to have 12 tonnes wet per hectare of seaweed at time of seeding, and are harvested once they reach 36 tonnes, with growth rates calculated on this basis. Self-shading was taken into account using the empirical observations of James and Boriah (2010), meaning

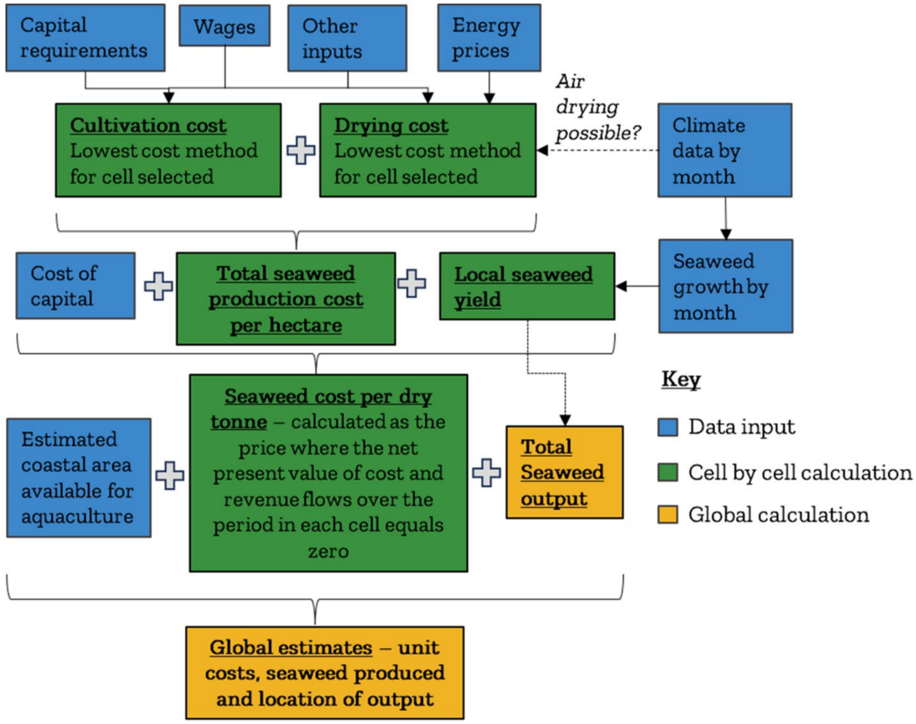

Fig. 1 Flow chart of our methodology

growth slows as the seaweed increases in density across the plots above the optimal measured density of 0.4 kg m^{-2} equal to factor reported at exp (−0.513(current density − 0.4)). Seaweed yields were calculated by month based on the growth rates in the cell in question, assuming an even continuum of plots across days required to reach maturity after seeding. This takes into account the fact that seaweed farms can (and do) operate on a rolling basis, with some plots harvesting while others are being re-seeded. The seasonality of yields by month is also accounted for by this method, which can lower capital utilization and therefore increase costs. Example yield calculations are provided in the attached supplementary spreadsheet online.

Based upon these assumptions, we estimate that an average daily growth rate of around 5% would translate into an effective annual harvest of 10 dry tonnes per cultivated hectare (corresponding to a harvest cycle of around 96 days before maturity), and a 15% growth rate would translate into around 33 dry tonnes annually (corresponding to a harvest cycle of around 29 days before maturity). We consider all cells in this study, even those where growth is negligible; however, in reality, only the higher yielding and faster growing plots would likely be viable, as we later discuss.

Potential area

To estimate the area suitable for seaweed cultivation, we started with a GIS dataset of the viable coastal zones (Flanders Marine Institute 2019) at a resolution of 200 NM, based upon reported coastal areas at a maximum depth of 100 m, and maximum distance from port of 25 NM (46.3 km). A seaweed floating line farm at a 100-m depth was shown to be suitable in a prior simulation (Olanrewaju et al. 2017), which gave us our maximum depth, and a kelp farm at a 100-m depth has also been modeled (Coleman et al. 2022). Forty-six kilometers have been suggested to be the maximum economic distance outside a catastrophe (Rubino 2008), and is supposed to ensure our assumption of low transportation costs is reasonable versus our benchmark studies. Cultivation beyond this threshold however would likely still be possible, although at a higher cost.

All data on yields, growth and the suitable area are available online.

Available and usable area

Not all of the area suitable for seaweed cultivation would be available for seaweed farms. Some would be reserved for the circulation of boats, recreational uses, bioconservation, and some would not be available due to local currents or wave dynamics. We set the available area to 2/3rds (66.7%) of the suitable area.

In addition, not all of the seaweed farm area would be usable. Some would be reserved for harvesting lanes and there would be gaps between plots. We set the usable area at 85% of the total, in line with the assumptions of Jehn et al. (2024).

Cultivation and drying methods

We analyzed two methods of seaweed cultivation, and two methods of seaweed drying.

The two cultivation methods were a labor-intensive method based on Indonesian style floating plots worked by hand from small boats, and a capital-intensive system based upon floating grids managed by specialized planting and harvesting machinery attached to larger vessels. Indonesian cultivation costs were taken from Valderrama et al. (2015), excluding the cost of drying, and scaled to 2023 levels. Capital intensive costs were calculated as the average reported costs from DeAngelo et al. (2022). Yields were assumed to be equal for both systems.

The two drying methods were air drying and industrial drying via a high-capacity fluid bed system. Costs for air drying were once again taken from Valderrama et al. (2015), based on Indonesian style systems. Industrial drying costs were estimated assuming a fluid bed dryer benchmarked on costs taken from the Handbook of Industrial Drying (Mujumdar 2006). These were then adjusted to local labor costs and energy prices. Energy use per kg of dry seaweed produced was calculated to be around 10 kWh, based upon the mass of water required to be removed. This gives a similar result to the drying of algae for biofuels (Bagchi et al. 2022), which assumes similar levels of water reduction.

We deemed air drying to be feasible within a cell during months where the seaweed can reach an equilibrium of 18.5% moisture based upon the surrounding humidity. Equilibrium moisture of the seaweed was calculated based on the relative humidity in each cell by month and the Brunauer–Emmett–Teller (BET) model, making use of the estimated model constants for the *Gracilaria* genus as reported by Sappati, Nayak, and Van Walsum (2017), as *Gracilaria tikvahiae* specific constraints were not available. During periods where air drying is not viable, we assume that producers are forced to use fuel based drying.

We used air relative humidity from Coupe et al. (2019) referring to an injection of soot into the stratosphere of 150 Tg. We estimated the maximum moisture content on a dry basis of 22.0% from the Philippine National Standard (Bureau of Agriculture and Fisheries

Standards—Philippines 2021) corresponding to a value on a wet basis of ~18%. Overall, this results in a much higher threshold for air drying being viable compared to the present day, due to a combination of the stringent moisture content requirement assumed (versus over 30% for *Kappaphycus* spp.) combined with the higher relative humidity during nuclear winter.

Installed drying capacity was assumed to cover the maximum monthly harvest. This raises costs for countries with a strong seasonality, via reduced rates of utilization.

The break-even cost of each of these methods was calculated based upon the price needed for a positive net present value (NPV), assuming a 10% required return on capital (discount rate), a 1-year construction period, and 6 years of operation after this date (as the length of the disaster was assumed to be ~7 years). The lowest break-even cost per dry tonne for cultivation and drying were then chosen separately for each cell, and then added to create a cost of cultivating, harvesting, and drying seaweed. These assumptions, formulas, and calculations are also available online, in the attached document. Cost sensitivities are provided at the end of this paper, in the discussion section, alongside further details in the supplementary spreadsheet.

Capital costs

We assume capital costs in a nuclear winter of 150 Tg are 47% higher than in normal conditions, as it has been proposed for the increased construction cost of scaling a single-cell protein (García Martínez et al. 2022). This is a pessimistic assumption copied from the paper, based upon building labor costs increasing by 47% when doing 24/7 construction, which is conservative but allows for the scale of expansion required. Capital costs here refer to the all-plant machinery, construction, and direct infrastructure necessary for each method.

Operational costs

Labor costs were estimated at the hourly requirements of each system multiplied by the local wages. We obtained country monthly rates from the International Labor Organization (ILO) for agriculture, forestry and fishing (‘International Labor Organization Statistical Database (ILOSTAT)’ 2023). We then converted monthly wages to hourly rates based on a workload of 44 h/week (mean between the 40 and 48 h/week used by ILO (‘Wages and Working Time Statistics (COND Database)’ 2023)) and 4.33 week/month (used by ILO (‘Wages and Working Time Statistics (COND Database)’ 2023)), and assumes full-time employment. We accounted for changes in wages between the last year for which data is available and 2022, assuming wages are proportional to gross national income (‘World Bank Open Data’ 2023). We predicted the wages in the countries for which data from ILO were not available via a linear regression of wages on real gross domestic product per capita (‘World Bank Open Data’ 2023). This method has an R^2 of 0.54, however, only enters into our model for smaller countries, and is not used for any of our top 10 producers. We stipulated the labor cost to the employer is 1.325 times the wages, the average of the lower and upper bound of 1.25, and 1.4 from the United States Small Business Administration (Weltman 2023).

Our sources do not estimate the exact percentage of labor that is fixed (tasks whose duration is independent of the harvested volume) and variable (tasks that scale with volume, such as harvesting and cleaning seaweed). We have assumed that half of the tasks are variable and the rest are fixed for the purposes of this study, with higher variable costs benefiting lower yield zones and higher fixed costs benefiting high yield ones.

Non-labor-operating costs were estimated based on the reported costs for each system scaled by inflation to 2023. Energy prices came from a variety of sources. Electricity prices were taken from online data for industrial consumers by country ('Electricity Prices' 2023). The price of coal, fuel wood, and natural gas was taken from the UN COMTRADE database, as the average of export and import prices by country in 2023 ('UN Comtrade' 2023). Countries without reported data had a price set at the world average plus 50%, to account for their isolation and limited trade flows; however, all of our top producers have data available. Industrial drying uses the lowest cost source of energy; although, we discuss the sensitivities of this assumption in the discussion section (Table 1).

Caloric assumptions

For the purposes of estimating demand in the future sections, we used a caloric requirement of 2100 kcal/person/day (FAO 2020), and considered the population in 2023 ('World Bank Open Data' 2023). We supposed a caloric density of dry seaweed of 2232 kcal/kg in agreement with the mean of the varieties studied in Gamero-Vega, Palacios-Palacios, and Quitral (2020).

Results

Globally, following a 150 Tg ASRS, we estimate that up to around 250 million dry tonnes of *Gracilaria tikvahiae* could be produced annually at a cost of US$500 per dry tonne or less, or around 750 million dry tonnes could be produced at a cost of US$1000 per dry tonne or less (Fig. 2 below). Around half of this cost comes from the cultivation of seaweed, while the rest is the cost of drying.

Table 1 Cost elements by cultivation and drying method

Element	Units	*Labor intensive*	*Capital intensive*
Seaweed cultivation—excluding drying		**Indonesian style plots**	**Capital intensive plots**
Initial CAPEX	$/ha	$4,005	$124,261
Operational non-labor cost	$/ha/year	$691	$5,499
Labor requirement	hours/ha/year	2477	65
Seaweed drying		***Air drying***	***Fluidized bed drying***
Initial CAPEX	$/unit	$1154	$6,858,366
Capacity	Dry tonnes/unit/year	33	44,474
CAPEX per installed capacity	US$/dry tonne of installed capacity	$35	$154
Energy requirement	MWh/dry tonne	n/a	10.06
Other operational non-labor cost	$/dry tonne	n/a	$9
Labor requirement	hours/dry tonne	64	1.6

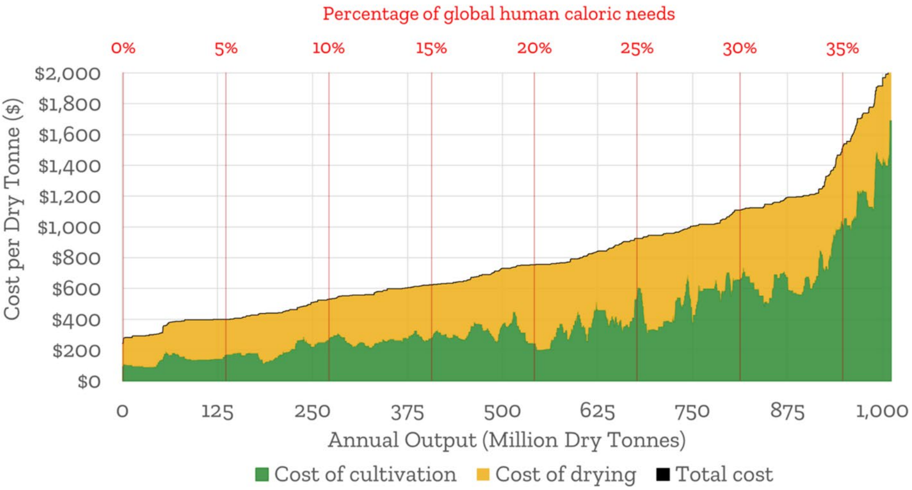

Fig. 2 Marginal production costs versus annual output—global total under US$2000—years 1–7 post 150 Tg nuclear winter. *Note: costs of cultivation and drying are cumulative, and their sum is the total cost of production*

The distribution of this production is summarized in Figs. 3 and 4, while the top 10 producing countries at cost of US $1000 or less are summarized in Table 2 below. Overall, the lowest cost countries tend to be located in the tropics, and are concentrated in a few zones where climate and nutrient conditions are best, as well as low labor and capital costs.

High yields tend to be concentrated between the −25 and 25° of latitude worldwide—with only limited opportunities to cultivate north or south of this band.

All of our lowest cost producers make use of the labor-intensive systems for seaweed cultivation, with Indonesia, Nigeria, Southern India, Thailand, and Kenya expected to be the most suitable. However, within many countries, there is significant regional variance in costs, driven primarily by the estimated yields in each zone.

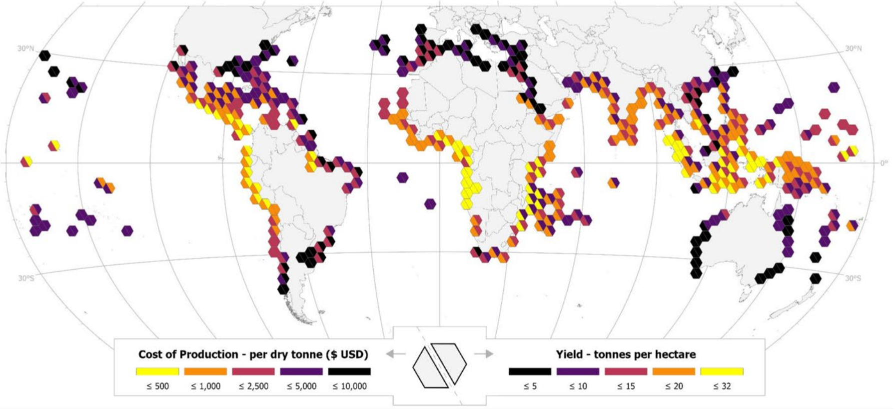

Fig. 3 Distribution of seaweed yields and production costs post disaster, average of years 1–7

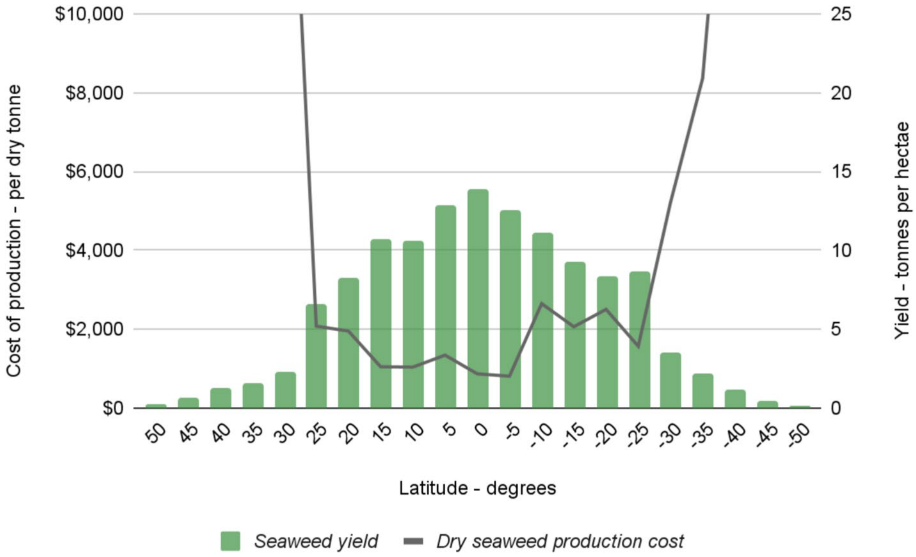

Fig. 4 Average seaweed yields and production costs versus latitude in our model, 50° to − 50°

Table 2 Top 10 countries by production, at a cost of US $1000 per dry tonne or less

Country	Production *thousand dry tonnes/year* (% of total)	Area *thousand ha*	Yield *dry tonnes/ha/year*	Average cost *US$/dry tonne*	Required capital investment *US$ billion, (% of GDP)*
Indonesia	115,656 (15.34%)	9278	12.5	$470	$136 (10.3%)
Nigeria	85,919 (11.39%)	4405	19.5	$411	$60 (12.6%)
India	80,685 (10.7%)	7288	11.1	$647	$122 (3.5%)
Angola	51,044 (6.77%)	2284	22.3	$295	$33 (29.4%)
Philippines	44,587 (5.91%)	4205	10.6	$706	$68 (16.9%)
Peru	43,059 (5.71%)	1966	21.9	$761	$38 (15.5%)
Mexico	30,610 (4.06%)	3739	8.2	$649	$54 (3.7%)
Cameroon	27,328 (3.62%)	1151	23.7	$954	$15 (33.3%)
Vietnam	21,408 (2.84%)	1163	18.4	$585	$18 (4.4%)
Madagascar	17,427 (2.31%)	1754	9.9	$642	$25 (166.4%)
Other	115,656 (15.34%)	17,961	13.2	$727	$295 (0.3%)
TOTAL	**754,102 (100%)**	**55,197**	**13.7**	**$614**	**$569 (0.6%)**

While air drying is typically the least expensive drying method, it would not be viable for most high yielding zones for the length of the disaster under our assumptions. This means that at least some supplementary fuel is expected to be needed, significantly raising costs due to the high-water content of seaweed.

Discussion

Benchmarking post-disaster costs to the present day

Overall, we estimate seaweed cultivation costs to be around US$170–220 per dry tonne in the most efficient clusters making use of the Indonesian techniques, while seaweed drying costs are around US$230—primarily making use of industrial drying techniques.

This compares to a cultivation cost of around US$180/tonne in Valderrama et al. (2015) on which our study is benchmarked—which looks at the cultivation of *Kappaphycus* seaweeds. These are typically lower yielding compared to our estimates for *Gracilaria tikvahiae*—which is an advantage of switching to edible, higher yielding varieties; however, a number of our other cost assumptions are more pessimistic—including the higher capital costs and wage/input cost inflation since the study occurred.

Meanwhile, our estimate of drying costs is much higher than those in the same study, which had a drying cost of around US$51/dry tonne. This is due to the need for supplementary fuels and the additional drying requirements of *Gracilaria tikvahiae* versus *kappaphycus*, which is a significant disadvantage. As the seaweed industry grows, suitable and cost-effective methods of seaweed drying remain an open topic of debate (Santhoshkumar et al. 2023; Santiago and Moreira 2020; Suherman et al. 2018), and one key result of our study is that drying may be just as important viability of seaweed in ASRSs as its cultivation.

There is no universally reported world price for *Gracilaria tikvahiae*—and available trade data for seaweed aggregates a number of products at many different levels of processing and therefore cost. However, reported prices for dry seaweed ex farm gate in Indonesia and China ranged from US$300/dry tonne to US$350/dry tonne respectively according to farmer interviews (Seaweed Insights, 'Sales—Gracilaria' 2022). This price will certainly see high variation year to year; however, it suggests that our projected costs in Indonesia are certainly higher than prices/costs the present day, but not massively so.

Overall, the lowest cost producers in our model have the following characteristics. Firstly, low wages, secondly, high yields. Finally, other factors such as having a low degree of seasonal variance are also useful, so that capital is not underutilized, and low energy costs for drying.

This means that all of our highest producing regions are located close to the tropics, and in lower or middle-income countries. Many of them are already significant seaweed producers, including Indonesia and South-East Asia more broadly, as well as India to a lesser extent. However, other areas that see significant production today, most notably China and other East Asian countries, are expected to struggle under our modeled conditions due to much lower yields.

One challenge of deploying seaweed more extensively in our model is formulating a solution that can cultivate seaweed in high yielding environments where wages are high. In our model, there is no location that can produce seaweed for less than US$1000/dry tonne with wages over US$10/h.

Capital-intensive solutions today tend to be higher cost compared to labor intensive solutions, but our scenario magnifies this result. Firstly, we assume capital costs rise due to the scale of the expansion. However, capital-intensive systems have a second challenge in that we assume that the disaster lasts for 7 years, while the typical lifespan of the equipment in question is 20. This results in a high effective amortization of investments, further raising the cost for high capital systems.

However, there are ways this could change. In order to increase the effective lifespan of investments, governments could guarantee sales for a period after the disaster at a fair guaranteed price, which would lower that price at which companies would need to receive over the disaster itself in order to break even. This would reduce the price needed to break even under capital-intensive cultivation to around US$600–750/dry tonne for the higher yielding zones. This is still expensive in present day terms—but could be affordable many consumers.

In addition, current capital-intensive systems are not at the frontier of what is possible with more research and development. Kite-Powell et al. (2022) estimated that large-scale capital-intensive plots with specialized equipment have potential for cultivation costs of around US$200–300 per dry tonne even in high wage environments and up to 200 km from the coast, and this could fall to US$100 per dry tonne for the highest yielding zones—a range in which seaweed could possibly be cost-effective as a biofuel input. Their numbers are partially speculative, but highlight that the industry has not reached the frontier of cost effectiveness, and that the frontier is continually shifting.

With this in mind, our cost estimates may be pessimistic for capital intensive systems. However, given the speed of response needed in the crisis it cannot be guaranteed that improved systems could be ready in time, unless they were piloted pre-disaster. Here, there is an opportunity for a co-development project: a capital-intensive farm with conventional output in normal conditions that could rapidly pivot to producing edible products in a disaster. This could raise resilience to these forms of shocks for the countries in question, ideally earning a commercial return to ensure viability as well as piloting technologies in order to reduce costs over time.

Implications for diets and food security

While our analysis above focuses on a severe nuclear winter scenario, as yields are broadly unaffected, seaweed has the potential to be a low-cost food source following a range of ASRSs.

When expressed in terms of total human dietary needs, we estimate that there is the potential to produce enough seaweed to meet around ~10% of global dietary caloric needs at a cost of under US$524/dry tonne, or US$0.63/2730 kcals (the approximate average daily caloric requirement of 2100 kcals adjusted for 30% waste in distribution and retail). While the final retail price would be, this suggests seaweed could be an affordable source of nutrition under nuclear winter conditions. Furthermore, this cost should be considered in the context of a shock that would disrupt the majority of global caloric production—significantly raising the prices and costs of other foods.

It is uncertain how much seaweed could be incorporated into diets, and while there are opportunities, there are also nutritional and cultural factors to consider. As an upper limit, direct seaweed consumption at levels significantly above 10% would be difficult without additional processing due to its high fiber and iodine content (Pham et al. 2022); although, the latter can be minimized by cooking (Zava and Zava 2011). In addition, some populations where seaweed is not often consumed have less developed gut flora for seaweed digestion (Pudlo et al. 2022), and uptake is likely to be slower for cultures where it is less prominent in present diets, such as those outside of East and South-East Asia. This may limit seaweed's deployment, for example, across parts of Africa where it is not currently extensively consumed.

However, seaweed could make contributions to the food system beyond direct consumption, for example, by being fed to animals, particularly ruminants (Al-Shorepy et al. 2001), or even by being processed into biofuels. Seaweed can even be used as a fertilizer, and can help crops tolerate harsher conditions and lower temperatures (Ali et al. 2021), which could also be of great value in an ASRS. Collectively, this would produce edible or useful outputs, cover part of the shortfall in grasses and other residues that would also occur in an ASRS and would free up human edible feeds for direct consumption. This would be more cost-effective in high yield zones and for end users which are able to make use of wet dry seaweed (removing drying costs).

In addition, further processing to remove iodine, fibers, and to raise palatability and digestibility of seaweeds would allow far more to be incorporated into diets. There are existing methods to remove iodine (such as boiling, or chemical processing); however, these can also reduce the nutritional content of the seaweed itself (FAO and WHO 2022). Meanwhile, separation of proteins from seaweeds and algae is possible via mechanical and chemical processes (Good Food Institute IN 2021), and further technologies might be developed. There is little incentive to do so in the present day, as seaweeds are typically more expensive than other sources of nutrition. However, post-disaster solving such issues has the potential to greatly raise the utility of seaweed, meaning that any work pre-disaster on these issues has the potential to save lives.

Other considerations

Our modeling suggests there would be very significant regional variations in the cost of producing seaweeds worldwide. This suggests that extensive trade would be necessary if seaweed is to make a significant global impact on nutrition.

While low capital seaweed farms themselves are fairly low cost to construct, installing the required drying capacity would represent a significant initial investment, and would likely be required even in areas currently air drying. Table 2 in the results section presents the total CAPEX needed to produce seaweed at US$1000/tonne or less, which is just over US$860 billion in order to achieve ~750 million dry tonnes of output. Collectively this is less than 1% of global GDP, and not all of this expansion may be required.

However, at a country level, the investment needed in some cases exceeds 10–20% of their total GDP—a heavy burden, and in the case of Madagascar (Table 2 above) there would be no way for domestic resources to come close to the expansion required. As a result, international movement in machinery and investments would also likely be required to allow large-scale drying as well as trade in the seaweed itself, which may present a challenge under the conditions of the catastrophe that created the ASRS, such as a large nuclear exchange or volcanic eruption.

There is great uncertainty in how well global supply chains will endure under a serious disaster that results in an ASRS. Especially concerning are scenarios in which ASRS might coincide with a global catastrophic infrastructure loss, as could be the case for a nuclear war involving high-altitude electromagnetic pulse attacks. Other potential causes of mass infrastructure disruption could include solar storms, cyber-attacks, or extreme pandemics involving mass absenteeism (Moersdorf et al. 2024). However, seaweed cultivation has a number of advantages in its potential simplicity in cultivation—where cost-effective production can occur with access only to ropes, poles, boats, and a few other items of locally produced capital. Therefore, even if international trade breaks down, seaweed could still make a contribution to local or regional diets, and the local surpluses in output that could result from areas maximizing output would have a strong incentive to be exported even in a severe food crisis.

We have assumed that industrial drying is available and deployed as a technology wherever it is lowest cost; however, this may not be the case. While a number of drying configurations could be suitable (Santhoshkumar et al. 2023), they typically share the requirement of needing coal, electricity, or natural gas to operate, and rely on access to machinery which comes at a cost of hundreds of thousands to millions of dollars. Furthermore, access to energy may be disrupted by the disaster, forcing production to adopt more simple solutions. This may limit the ability to scale seaweed production unless international trade can be maintained, and is another factor to consider.

Wood kilns are far simpler, and can run on local fuel sources, offering one possible local solution should international trade in equipment be restricted. However, their cost is likely to be higher due to their lower efficiency and the higher average cost of wood as an energy source. While detailed peer reviewed costs for wood kilns were not available to us, one proxy would be to restrict our industrial drying to only utilizing wood as a fuel. This restriction would raise the cost of drying from US$200–250 to US$350–550/dry tonne, meaning seaweed could still be viable as a food source—although more expensive.

Overall, we estimate that it would take around 350 million tonnes of coal annually to dry enough seaweed to meet 10% of global caloric needs. This is in the context of global coal production of around 9 billion tonnes in 2023 (Energy Institute 2024). This suggests that while the energy requirements would be significant and expensive, they would not be impossible to meet in the context of the total energy market.

While it would only require approximately one quarter of the area able to produce seaweed at US$1000/dry tonne or less in order to meet the equivalent of 10% of calories, developing this at short notice would be a huge challenge. Total cultivated seaweed area was estimated to be around 160,000 ha in 2015 (Duarte et al. 2017), while we estimate it would require over 15 million ha to reach this 10% threshold, an increase of over 90-fold. The technology required to cultivate seaweed is known, already deployed in many of the promising regions, and readily modular and scalable. However, it would still require international investment and mobilization to achieve this kind of area expansion.

Conclusions

Seaweed has the potential to be a cost-effective source of calories during severe ASRS, even where other food sources are disrupted, and should be considered in the preparedness and response planning when considering such shocks. The lowest cost locations are estimated to be able to produce seaweed at US$400–450 per dry tonne, and there are potentially over 100 million coastal ha that are readily suitable for development, even before cultivation further offshore is considered. This could make an important contribution to diets in such disasters, with seaweed able to meet 10% of direct human needs within a price range of US$525/dry tonne. However, this low-cost output is concentrated across a few key producers located in the tropics, meaning there would need to be international trade in machinery and the finished seaweed, which is likely to require planning across both the public and private sectors. Furthermore, incorporating this volume of seaweed into diets would be challenging, which needs to be considered in any response planning by governments. High capital seaweed production systems were also reviewed but resulted in much higher costs, between $1500 and 2000/tonne. Our results also emphasize the importance of the drying process in the cost, as 40–75% of the total product cost comes from drying equipment capital and operational costs—with the cost of energy being a very important factor. Further research could assess other seaweed species that could be suitable, methods of processing to raise palatability, and strategies to develop seaweed in the present day, all of which would raise its potential in any future disasters.

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Declarations

Competing interests The authors declare no competing interests.

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