Seaweed Cultivation: A Cost-Effective Strategy for Food Production in a Global Catastrophe

Michael Hinge [a] [*], Vasco Amaral Grilo [a], Florian Ulrich Jehn [a], Juan B. Garcia Martinez [a], Farrah Jasmine Dingal [a], Michael Y. Roleda[c], David Denkenberger [a,b]

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

[b] *Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand*

[c] The Marine Science Institute, University of the Philippines Diliman, Quezon City, Philippines,

* Corresponding author: Michael Hinge, mike@allfed.info

* *Present address: ALLFED Institute, 603 S. Public Rd #57, Lafayette, CO 80026, U.S.A.*

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Highlights

- During events that disrupt sunlight seaweed may be a source of nutrition.
- We estimate the cost of producing *Gracilaria Tikvahiae* seaweed under a severe sunlight reduction scenario.
- Costs are likely to be affordable even in the most severe climate scenarios.
- Low cost areas have competitive wages, high yields and low energy costs.

Abstract

An event such as a large volcanic eruption, nuclear winter or asteroid/comet impact has the potential to seriously reduce incoming sunlight, impacting both the global climate and conventional 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 due to overturning of the ocean bringing nutrients to the surface. We assess the expected cost of producing dry edible seaweed under the climatic conditions of a severe 150 Tg nuclear winter, using *Gracilaria Tikvahiae* as a benchmark species. To do this we incorporate projected yields and estimated costs under either a capital intensive or labor intensive model, covering both the cost of cultivation and drying. Overall, we find that seaweed costs would range between $ 400-450/dry tonne for the highest yielding/lowest labor cost clusters, and could potentially be produced in significant quantities even when constrained to shallow waters close to ports. This cost is higher than the current reported ~$300-350/dry tonne price of *Gracilaria tikvahiae*, reflecting additional capital costs and additional drying requirements during the catastrophe. The cost is also higher than current staple cereal prices on a caloric equivalent. However, given the sharp rise in food prices expected post disaster, it is likely a large scaleup would be justified, offering an important contribution to global nutrition, either via direct consumption or when used as animal feed.

Keywords

Seaweed; Production costs; Global catastrophic risk; Existential risk; Resilient food; Food security; Nuclear winter.

1. 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, Self, and Robock 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, these ASRSs could even present an existential risk to humanity - especially when interactions with other threats that would likely 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). A recent analysis by Jehn et al. estimates that seaweed yields may even rise across the tropics during severe ASRSs in early years, as ocean circulation patterns are disrupted and more nutrients are brought to the surface. This means that while sections of higher latitude coastlines may be unable to support cultivation, many of the most productive aquaculture areas today, such as Indonesia, could maintain or even raise their seaweed output. 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 and other nutrients (Pham et al. 2022). It could also be used as animal feed, meeting some of the shortfall in other parts of the food system (Rivers et al. 2022). 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.

This paper seeks to estimate the cost of cultivating seaweed on a large scale, following a 150 Tg injection of stratospheric soot following a nuclear winter (the largest scale nuclear winter scenario studied (Coupe et al. 2019)), in order to establish a baseline for viability even under the harshest potential conditions of this plausible worst case. However, this analysis is also relevant for smaller scale nuclear winter shocks, as well as volcanic events, 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 100m (U.S. Department of Commerce and National Oceanic & Atmospheric Administration 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.

2. 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 immediately suitable for seaweed development, calculated using geographic information systems (GIS) data for the potential area within each grid cell. Next, production costs were estimated across each cell, based on selecting the lowest cost method of seaweed cultivation and drying. Finally, output was estimated by multiplying yields with the available area, in order to estimate the total volume able to be produced at each price point and a global estimate of output. This process is summarized in figure 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).

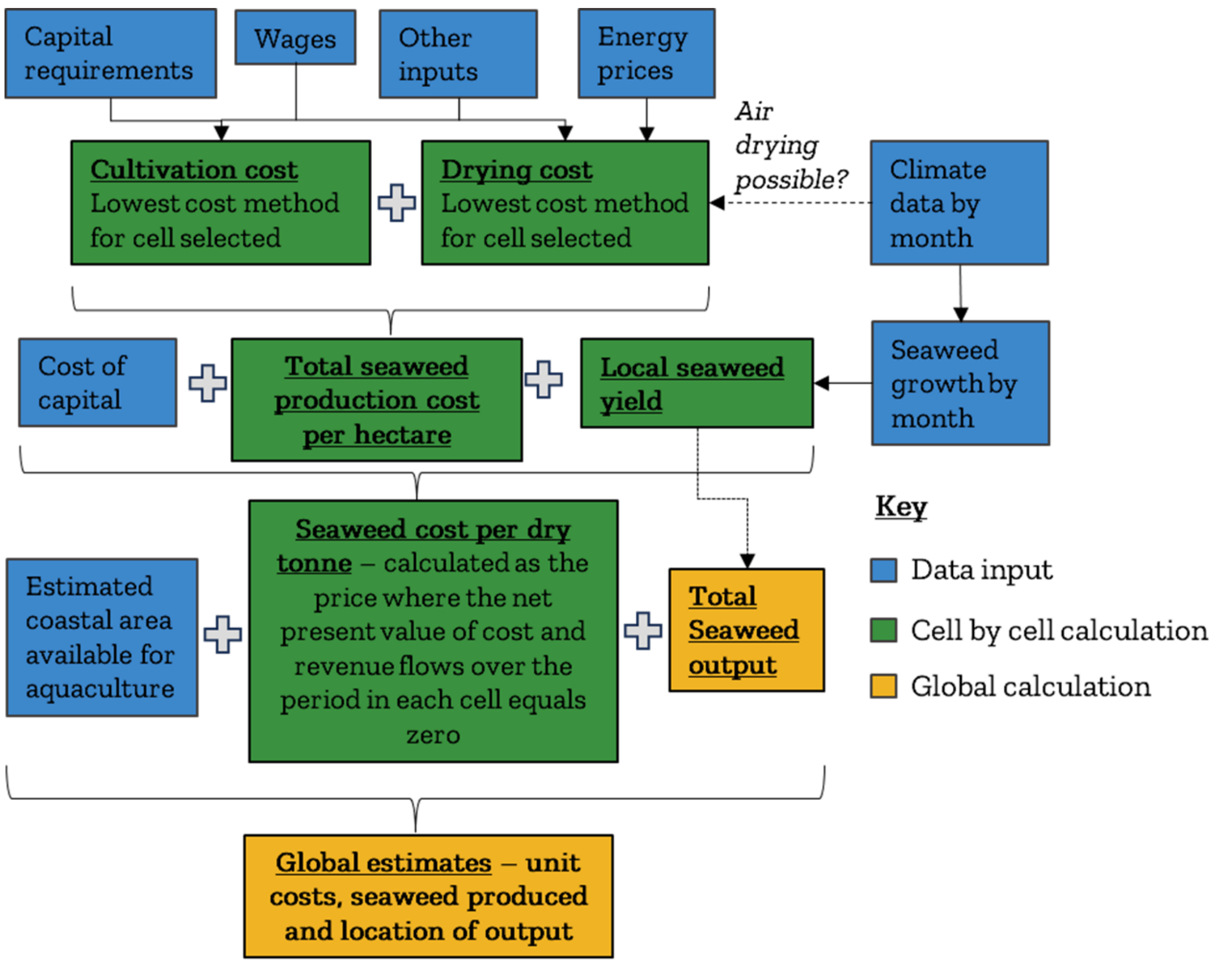

Figure 1: Flow chart of our methodology

2.1 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 following an injection of 150 Tg soot into the stratosphere. 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 modeling results of James and Boriah 2010, meaning growth slows as the seaweed increases in density across the plots. 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.

2.2 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 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 100 m depth has also been modeled (Coleman et al. 2022). 46 km has been suggested to be the maximum economic distance outside a catastrophe (U.S. Department of Commerce and National Oceanic & Atmospheric Administration 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.

2.3 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, and discuss later the implications of further restrictions.

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

2.4 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 attached via ropes to the seafloor and 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, which assesses the cost of a number of high capital cultivation systems on a wet basis. Yields were assumed to be equal for both systems, with the same grid density and harvesting losses.

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 reported information for 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 per final dry kilo and the energy per kilo of water 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 *Gracilaria* as reported by Sappati, Nayak, and Van Walsum 2017. During periods where air drying is not viable we assume that producers are forced to use fuel based drying, even if this has a higher cost.

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.

Drying capacity was assumed to be installed 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 one year construction period, and 6 years of operation after this date (as the length of the disaster was assumed to be ~7 years, and the drying facility operators were assumed to be uncertain of profitable operation beyond this point). 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.

2.5 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 single cell protein (García Martínez et al. 2022). This is a pessimistic assumption 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.

2.6 Operational costs

Labour costs were estimated at the hourly requirements of each system multiplied by the local wages. We obtained the hourly rate for each country based on monthly wage data from the International Labour Organization (ILO) referring to agriculture, forestry and fishing ('International Labor Organization Statistical Database (ILOSTAT)' 2023). We 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)). 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). 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 were assumed to have 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 is assumed to use the lowest cost source of energy in each country, although we discuss the sensitivities of this assumption in the discussion section of the report.

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-labour cost	$/ha/year	$691	$5,499
Labour requirement	hours/ha/year	2477	65
Seaweed drying		***Air drying***	***Fluidized bed drying***
Initial CAPEX	$/unit	$1,154	$6,858,366
Capacity	Dry tonnes/unit/year	33	44,474
CAPEX per installed capacity	US$/dry tonne of installed capacity	$35	$154
Energy requirement	MWh/dry tonne	n/a	10.06
Other operational non-labour cost	$/dry tonne	n/a	$9
Labour requirement	hours/dry tonne	64	1.6

2.7 Caloric assumptions

For the purposes of estimating demand in the future sections, we used a caloric requirement of 2,100 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 2,232 kcal/kg in agreement with the mean of the varieties studied in Gamero-Vega, Palacios-Palacios, and Quitral 2020.

All input data and results can be consulted in an online Google Sheet.

3. 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 (Figure 2 below). Around half of this production cost comes from activities related to the cultivation of seaweed, while the rest is the cost of drying. Production is biased towards the earlier years of the disaster, as many of the areas of lowest costs actually see higher growing yields due to the nuclear winter conditions, meaning availability could be higher in the earlier years.

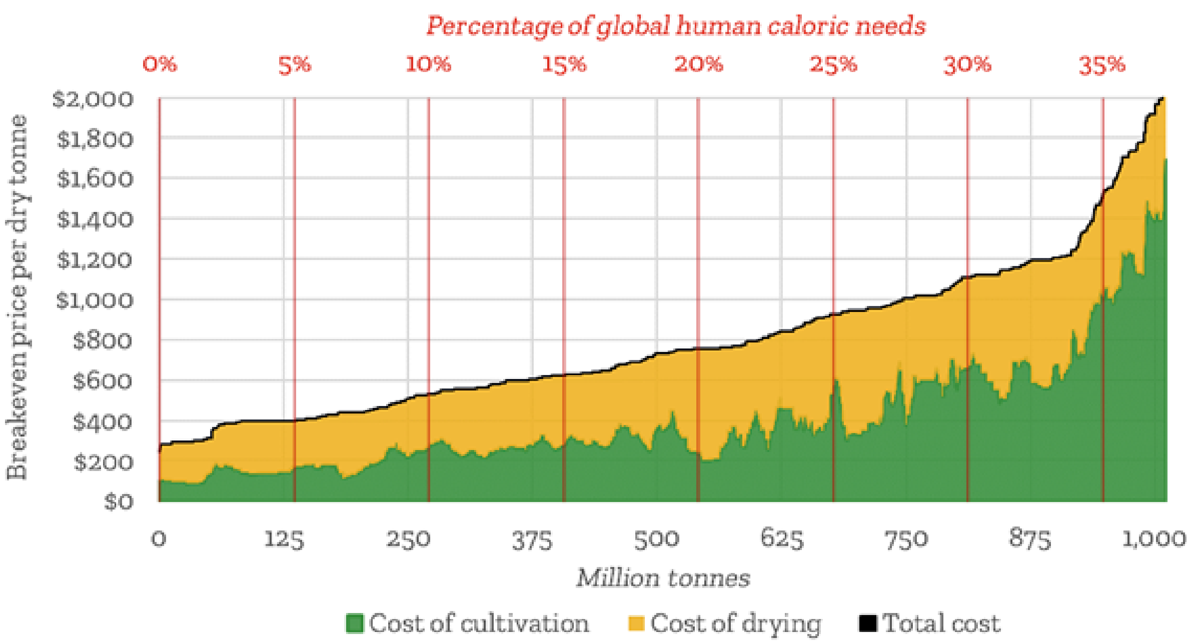

Figure 2: Marginal production costs versus annual output - global total under US$2000 - years 1-7 post 150 Tg nuclear winter.

The distribution of this production is summarized in Figures 3 and 4, while the top ten 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 to 25 degrees of latitude worldwide - with only limited opportunities to cultivate north or south of this band.

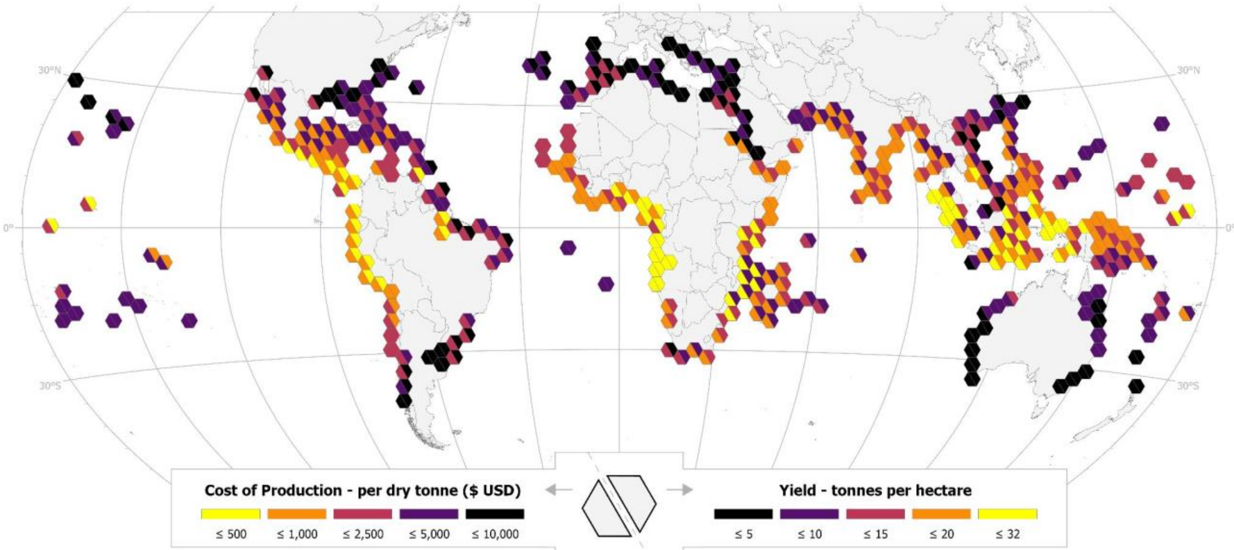

Figure 3. Distribution of seaweed yields and production costs post disaster, average of years 1-7

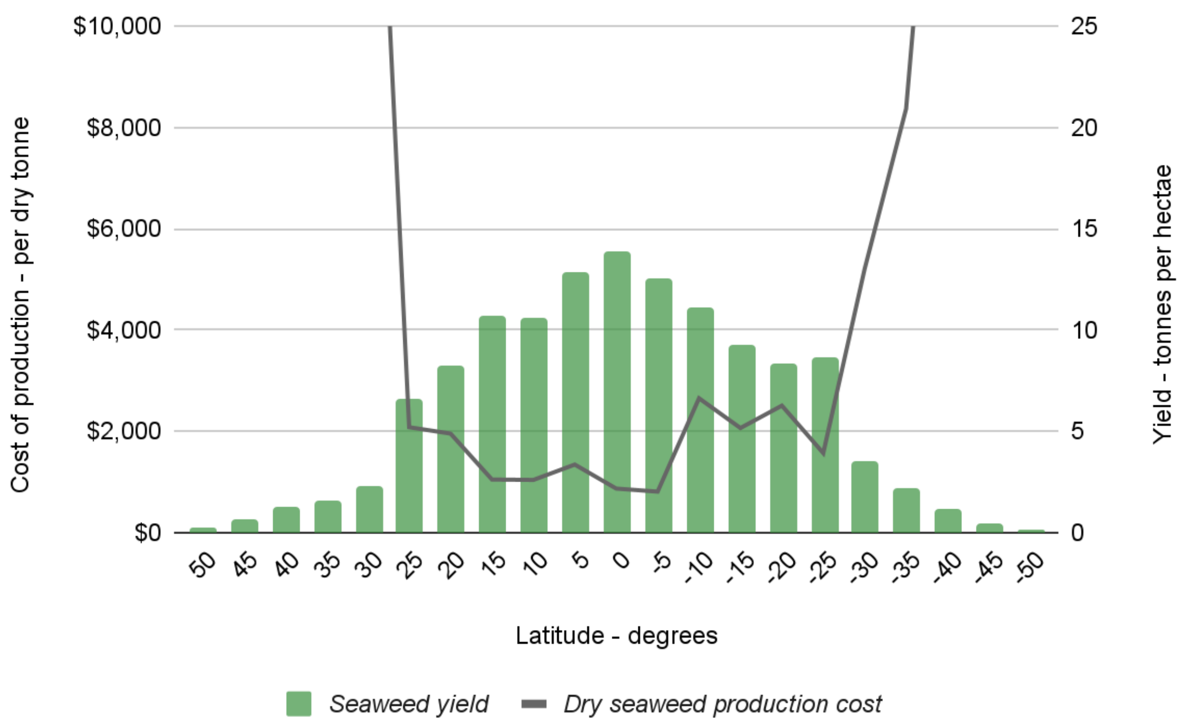

Figure 4. Average seaweed yields and production costs versus latitude in our model, 50 degrees to -50 degrees

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. This matches the present day, where the largest and lowest cost seaweed aquaculture systems make use of these methods. However, within many countries there is significant regional variance in costs, driven primarily by the estimated yields in each zone.

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, where the relative humidity is higher than in the present day. This means that at least some supplementary fuel is expected to be needed, significantly raising costs due to the high water content of seaweed.

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

Country	Production	Area	Yield	Average cost	Required capital investment
	thousand dry tonnes/ year	thousand ha	dry tonnes/ ha/year	US$/dry tonne	US$ billion, (% of GDP)
Indonesia	115,656	9,278	12.5	$470	$136 (10.3%)
Nigeria	85,919	4,405	19.5	$411	$60 (12.6%)
India	80,685	7,288	11.1	$647	$122 (3.5%)
Angola	51,044	2,284	22.3	$295	$33 (29.4%)
Philippines	44,587	4,205	10.6	$706	$68 (16.9%)
Peru	43,059	1,966	21.9	$761	$38 (15.5%)
Mexico	30,610	3,739	8.2	$649	$54 (3.7%)
Cameroon	27,328	1,151	23.7	$954	$15 (33.3%)
Vietnam	21,408	1,163	18.4	$585	$18 (4.4%)
Madagascar	17,427	1,754	9.9	$642	$25 (166.4%)
Other	236,380	17,961	13.2	$727	$295 (0.3%)
TOTAL	**754,102**	**55,197**	**13.7**	**$614**	**$569 (0.6%)**

4. 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 that maintain product quality remain an open topic of debate (Santhoshkumar, Yoha, and Moses 2023; Santiago and Moreira 2020; Suherman et al. 2018), and one key result of our study is that drying may be just as important to the economic viability of seaweed in severe ASRS as its direct cultivation. In particular, methods to reduce the reliance on fuels would be of great importance, for example better combining solar/air drying systems with supplementary fuels, mechanical separation of water, dehumidifying, or other drying techniques that are slower but less energy intensive.

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, with a high yield to wage ratio being key to low costs. 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/hour.

Capital intensive solutions today tend to be higher cost compared to labor intensive lower tech solutions, but our scenario magnifies this result for several reasons. Firstly, we assume capital costs rise due to the need for rapid construction and the scale of the expansion needed, raising the cost of investments versus the present day. However, capital intensive systems have a second challenge in that we assume that the disaster lasts for seven years, while the typical lifespan of the equipment in question is twenty. This results in a high effective depreciation and 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. There may also be other proposals that could have a similar impact, and a correct investment environment such that farmers and processors would have the confidence to develop the necessary infrastructure is also a vital part of any future seaweed expansion. This would reduce the price needed to breakeven under capital intensive cultivation to around US$600-750/dry tonne for the higher yielding zones. This is still expensive in present day terms, (partly as the capital cost is still inflated in our scenario due to the assumptions around rapidly scaling the industry) - 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 when it comes to capital intensive systems. However, given the speed of response needed in the crisis it cannot be guaranteed that these more efficient systems could be developed and deployed in time, unless they were piloted and deployed pre-disaster. Here, there is an opportunity for a co-development project: a capital intensive farm producing extracts such as carrageenan, feed products, fertilizers or potentially biofuels 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 earn a commercial return to ensure long term viability as well as pilot and develop technologies to improve seaweed cultivation and reduce costs over time.

Implications for diets and food security

While our analysis above focuses on a severe nuclear winter scenario, the result that yields are broadly unaffected throughout the tropics suggests that seaweed has the potential to be a low cost food source following a range of ASRSs, and one that could make an important contribution to nutrition and diets, saving lives.

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$0.63/2,730 kcals (the approximate average daily caloric requirement of 2,100 kcals adjusted for 30% waste in distribution and retail). While the final price would be higher for the end consumer, reflecting the additional processing, packaging, transportation and retail costs, this suggests seaweed could be a low cost and broadly affordable source of nutrition at the margin even 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 a number of 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 content and presence of micronutrients such as iodine in high quantities (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).

However, seaweed could still make contributions to the food system beyond the amount that can be directly consumed, for example by being fed to animals, particularly ruminants (Al-Shorepy, Alhadrami, and Jamali 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, Ramsubhag, and Jayaraman 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.

The cost effectiveness of animal feed/biofuel activities has not been evaluated under the conditions of an ASRS, and more work is needed here before its viability is determined, and in what quantity. However, it would be more cost effective in high yield zones and end users are able to receive deliveries of wet rather than dry seaweed (removing a significant source of 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 and other heavy metals, however, these can also reduce the nutritional content of the seaweed itself (FAO and WHO 2022). Meanwhile, the separation of proteins from seaweeds and algae is possible (Good Food Institute IN 2021), and further technologies or techniques could 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.

This study selected *Gracilaria tikvahiae* as a benchmark species as it is edible, fast growing, resilient to ASRS conditions, and data were available on projected yields from past work. However, in reality many different varieties would be cultivated, much as in the present day. These would be chosen based upon suitability for local conditions, nutritional profile/taste, ease of processing and other factors. As a result, it is possible that seaweed could be cultivated outside of the zones we have identified as best for *Gracilaria tikvahiae*, and it is also possible that varieties that are lower yielding could also be viable for inclusion in our identified zones, if they come with other advantages. These could include a better nutritional profile, lower drying requirements, or greater ease of processing.

Other considerations

Our modeling suggests there would be very significant regional variations in the cost of producing seaweeds worldwide, with low cost output focused in a few distinct regions across the tropics. This results in output significantly above local needs in these regions, suggesting 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 making use of air drying, due to the colder and more humid climate in a catastrophe (Coupe et al. 2019). 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, which would present a heavy local burden.

As a result, international movement in machinery and investments would also likely be required 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, as this is almost certain to involve extensive destruction to infrastructure following an event such as a serious volcanic eruption or full scale nuclear exchange. 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.

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). Fortunately, the simplicity of the technologies involved in seaweed cultivation makes it a viable option for scenarios involving infrastructure disruption. However, there could be a significant challenge in producing significant quantities of synthetic fiber and twisting it into ropes in the most extreme cases of infrastructure disruption (Jehn et al. 2024), which would complicate deployment. One potential option is utilizing already woven fibers such as in clothing.

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, Yoha, and Moses 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 that caused the ASRS itself, forcing production to adopt more technologically simple solutions.

Wood kilns are far simpler, and can run on local fuel sources such as wood and agricultural residues, offering one possible local solution should international trade in equipment be restricted. However, their cost per unit of dried seaweed 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 - an additional US$150-200. This is a serious increase - however 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, especially given the central importance of raising food output in such a scenario.

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 represent a serious logistical and social challenge. Total cultivated seaweed area was estimated to be around 160,000 hectares in 2015 (Duarte et al. 2017), while we estimate it would require over 15 million hectares 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 future lowest cost regions, and readily modular and scalable. However, it would still require a massive international investment and mobilization to achieve this kind of area expansion, as well as coordination between farmers and seaweed dryers within countries.

Our analysis here focused on the reasonable worst case nuclear winter scenario recently published (150 Tg) (Xia et al. 2021) on the basis of assessing it under a worst case scenario for the food system. However, it is likely that seaweed would also be cost effective in smaller nuclear winters and ASRSs more generally, as much of its primary areas of cultivation are located far from nuclear states, and the yields of seaweed are estimated to be far less influenced by the climate shock versus other food sources (Jehn et al. 2024) - which was why we chose it as a potential resilient food source. More moderate shocks would see a reduced disruption to the conventional food system versus the 150 Tg scenario. However, seaweed could still be a vital source of nutrition in these cases, and has the potential to save lives across a broad range of magnitudes at the costs we calculate above, especially considering that all published scenarios (Xia et al. 2022) could lead to unprecedented food shocks with potential price increases unlike anything in recent history.

Conclusions

Seaweed has the potential to be a cost effective source of calories during severe ASRS, even where other food sources would be heavily disrupted. The lowest cost locations are estimated to be able to produce seaweed at around US$400-450 per dry tonne, and there are potentially over 100 million coastal hectares that are readily suitable for development, even before cultivation further offshore is considered. Together, this could make an important contribution to diets in such disasters, with seaweed able to meet 10% of direct human needs on a caloric equivalent basis within a price range of US$525/dry tonne, with the potential for far more production. However, this low cost output is concentrated across a few key producers located in the tropics, and as such there would likely need to be extensive trade in both the capital needed to dry seaweed and in the finished products themselves. Furthermore, incorporating this volume of seaweed into diets could be challenging. High capital seaweed production systems were also reviewed but resulted in much higher costs, between $1,500-2,000/tonne. However, they might still be competitive with other foods in developed countries in the case of trade restrictions, due to crop price rises. 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.

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