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Identifying a sustainable operating window for seaweed aquaculture in the Global North: balancing expansion barriers and carrying capacity

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ABSTRACT

Seaweed aquaculture is a growing blue sector that provides many benefits to society (e.g. biomass provision for food, feed and cosmetics) and the environment (e.g. eutrophication mitigation, carbon uptake and habitat provision). Successful and sustainable production expansion requires that these activities are operated within limits of acceptable change (LAC) i.e. align with ecological and social carrying capacity. Emerging from a three-round Delphi study, this work presents, from a Global North perspective, the most relevant 1) limiting variables from the socio-environmental spheres that influence the cultivation unit (inputs), such as high operating costs or underdeveloped markets or uncertain impacts from climate change, and 2) the negative impacts of aquaculture on environment and society (outputs), such as overhyped and unrealistic expectation for seaweed cultivation, conflicts with fisheries or pollution. Consolidated lists of these inputs and outputs are accompanied by specific thresholds beyond which unacceptable changes are likely to occur. These results are placed into a globally applicable holistic framework for a multidimensional assessment of seaweed aquaculture including barriers and

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carrying capacity, which has been outlined for the first time for seaweed cultivation. Our results emphasize the need to include socio-economic aspects into ecosystem approaches, like profitability or social license to operate – and the need for broad stakeholder participation. This study provides thus a directly useable lists of aspects to consider for cultivators and decision-makers. And as is as such a crucial contribution for the ongoing discourse on sustainable growth of this emerging blue sector.

1. Introduction

Our climate, resources and biodiversity are under threat and Earth is well outside the safe operating boundaries for humanity (Richardson et al., 2023). Every year, our resource consumption and production still exceed the Earth's capacity on Earth Overshoot Day[2] (Wackernagel and Lin, 2023). As well as a reduction in resource use, there is also a need to produce sustainably in a way that stays within our planetary boundaries (Rockström et al., 2009; Steffen et al., 2015).

In recent years, there has been a shift in attitudes regarding aquaculture production. Lower trophic species cultivation, such as seaweed, have gained momentum and are increasingly studied and praised for their potential to be restorative and regenerative to the ecosystem (Alleway et al., 2023). The appreciation of seaweed as a sustainable source of biomass is increasing: Seaweeds can be used for food products (Birch et al., 2019; Khan et al., 2024), animal feed (Méité et al., 2024; Muizelaar et al., 2021), biodegradable packaging (Ayala et al., 2024; Carina et al., 2021; Wu et al., 2024), cosmetics (Santos et al., 2024), and biostimulants (Arias et al., 2024), among others. Thanks to its many applications, seaweed is currently living a renaissance, being called a "climate champion" by the United Nations Global Compact and studied as a key to restoring our oceans (Duarte et al., 2020). Seaweeds provide critical ecosystem services, such as habitat as nursery grounds and shelter for various species (Berger et al., 2024; Corrigan et al., 2024; Schutt et al., 2023; Theuerkauf et al., 2022), ocean eutrophication mitigation (Barrett et al., 2022; Chopin and Tacon, 2020; Kotta et al., 2022) and capacity to fix CO_2, and thus help mitigate ocean acidification and combat climate change (Filbee-Dexter et al., 2024; Krause-Jensen and Duarte, 2016; Pessarrodona et al., 2023; Pessarrodona et al., 2024). While the carbon sequestration potential of seaweed is still debated, science agrees that the highest climate change mitigation potential lies in substituting food and feed products that have a higher carbon footprint such as terrestrial products (Canvin et al., 2024; Pessarrodona et al., 2023; Thomas et al., 2024; van den Burg et al., 2023). Accordingly, seaweed aquaculture can directly advance a number of the United Nation's Sustainable Development Goals (SDGs), such as SDG 2 (zero hunger), 3 (good health and wellbeing), 13 (climate action) and 14 (life below water) (Duarte et al., 2020).

Seaweed aquaculture has the potential to reduce pressure on terrestrial agriculture (Spillias et al., 2023), provide proteins for human and animal consumption (Hossain et al., 2024; Pereira et al., 2024), serve as circular and climate-intelligent food production systems (Waqas et al., 2024), achieve large-scale production, etc. Expansion is being suggested by scientific research (van den Burg et al., 2021), explored by the industry itself, supported by the European Commission (European Commission, 2022), and funds are being invested in technology and research. Yet, in parallel with the call for expanding seaweed farming, concerns about the negative impacts of this growing activity become louder. Like any other industry, seaweed farming may cause a variety of impacts on the marine ecosystem, including the spread of invasive species, shading or nutrient depletion (Banach et al., 2022; Bhuyan, 2023; Campbell et al., 2019; Spillias et al., 2023; Tonk et al., 2021; van den Burg et al., 2023).

These risks need to be assessed, prevented and mitigated at any scale of seaweed cultivation. If not managed for any individual seaweed culture, these negative impacts will become more severe when expanding cultures. In order to minimize these risks, it should be known at which intensity of farming, or scale of cultivation, the tradeoffs or risks surpass the acceptable limits of the ecosystem, i.e. the carrying capacity (abbreviated to CC hereafter)(McKindsey, 2013). Therefore, unlike other frameworks, carrying capacity adopts a holistic approach by considering all farming activities at a spatial scale that is relevant for an ecosystem-level analysis. Impacts can be acceptable or even positive until a threshold is reached. For example, nutrient uptake can be considered an ecosystem service in eutrophic waters, but highly dense seaweed cultivation could directly compete with phytoplankton and cause trophic cascades (Jiang et al., 2020; Kotta et al., 2022; van der Meer, 2020). In addition to concerns regarding the effect of aquaculture on the ecosystem, spill-over effects on social and economic impacts also must be considered (Kluger and Filgueira, 2020). These spill-over effects vary from (eco)system to (eco)system depending on their social and economic parameters, such as the respectively different set of user groups (e.g. competing blue sectors) or a favorable market situation, and ecological conditions and parameters, such as nutrient availability or potential impacts on the local genetic diversity. The CC concept allows a holistic consideration of all these spill-over effects through the widely accepted four main 'types' of CC (Inglis et al., 2000; McKindsey et al., 2006):

1. physical (the area set by the physical space available for marine farms);
2. production (the stocking density to achieve maximum production levels);
3. ecological (the level of aquaculture above which unacceptable environmental impacts occur);
4. social (the level of farm development that causes unacceptable social impacts)

The importance of CC has been recognized as a tool for aquaculture management and has been studied for other marine species, such as bivalve aquaculture (Ferreira et al., 2008; Filgueira et al., 2015; Kluger et al., 2016; Silva et al., 2011) and finfish farming (Byron and Costa-Pierce, 2013; Weitzman et al., 2021). Some of the initial studies on the CC of seaweed aquaculture focused mainly on nutrient availability and competition (Bo et al., 2024; Jiang et al., 2020; Kotta et al., 2022), but thus far, other dimensions of CC have not been addressed.

By now, CC has been recognized as one of the major components of Ecosystem Approach to Aquaculture (EAA) (Byron and Costa-Pierce, 2013; Kluger et al., 2016; Ross et al., 2013), the FAO strategy for "*the integration of aquaculture within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems*" and as such embraces holistic thinking (Soto et al., 2008). However, the conceptual and logistical complexity of CC remains a challenge (Kluger and Filgueira, 2020). Research has not yet been put into practice on such holistic approaches to CC, but interdisciplinarity is identified as a central principle to guide such assessment (Weitzman et al., 2021). There are only a few studies aiming to quantify social limits to aquaculture (Needham et al., 2011; Thomas et al., 2018), and evidence suggests that very often, it is not about a maximum threshold but rather barriers to even unlock the potential expansion. Socio-economic

[2] Earth Overshoot Day is the calculated illustrative calendar date on which humanity's resource consumption for the year exceeds Earth's capacity to regenerate those resources that year. In 2024, it fell on August 1st (https://en.wikipedia.org/wiki/Earth_Overshoot_Day).

barriers, such as licensing processes of seaweed cultivation have also been identified (Franzén et al. (2024). The sector is under-researched, with the European and North American seaweed industry receiving significant investment in research but still being in its infancy, while the vast majority of the production happening in Asian countries, 98 % of the market share (The World Bank, 2023). A recent review concluded that there is a large gap in indicators of ecological CC for algae in comparison to finfish or bivalves cultivation (Byron et al., 2024). And, as yet there are no frameworks for the assessment of CC seaweed aquaculture, let alone frameworks that simultaneously consider barriers to expansion and the thresholds for sustainable expansion. This study addresses these knowledge gaps by developing a methodological approach for a holistic macroalgae CC assessment while incorporating barriers that preclude the expansion of the sector. Accordingly, the ultimate goal of this study is to define the sustainable production window that overcomes these barriers for production but ensures sustainability by embracing carrying capacity as a holistic approach to including relevant socio-economic and ecological components. The following research questions guide this work:

1) How would a framework that incorporates barriers and thresholds in a stepwise approach look like and how should it be used?
2) What are the relevant variables to consider in a cultivation site (inputs) and the impacts of a cultivation site (outputs)?
3) What are the best indicators to measure these inputs and outputs?
4) When expanding, what needs to be done to overcome barriers to production and to define the point at which we approach unacceptable changes?

Herein, we acknowledge the hierarchical approach to CC where first the physical CC and the production CC are determined before assessing the ecological and lastly the social CC (McKindsey et al., 2006). Yet, our study focuses on the ecological and socio-economic dimensions of CC with the particular aim to inform the ecosystem approach to seaweed aquaculture. This study does not aim to assess barriers or carrying capacity thresholds for a specific region; it provides a framework for assessing the sustainable production window. Complex holistic assessment with comprehensive available data would be needed to test these indicators, and the framework could thus be integrated into a more data driven approach.

2. Methodology

To gather knowledge for a comprehensive framework, a targeted literature review, with a Scopus search on ‘carrying capacity’ and ‘aquaculture’, was conducted as a first step, focusing on existing carrying capacity frameworks, seaweed-related impact assessments, and ecosystem services assessments. Based on this and the information provided by experts, a framework designated to barriers of expansion and carrying capacity of seaweed aquaculture is presented.

2.1. Delphi study

The core method of this work was a Delphi study (Dalkey & Helmer, 1963) consisting of three rounds aimed at consolidating knowledge on relevant limiting inputs to seaweed culture and negative outputs of seaweed culture as well as indicators. Here, *inputs* were conceptualized as an influence originating from the environment and society influencing the cultivation site (barriers for seaweed aquaculture expansion), and *outputs* were defined as negative impacts or pressures on the environment and society originating from the cultivation site (critical carrying capacity variables) (Fig. 1). Associated with each input and output, *indicators* were defined as metrics that can inform these inputs and outputs. Furthermore, associated with each indicator, a corresponding *barrier* and *threshold* were identified. A barrier was defined as the process that becomes a bottleneck for expansion, and a threshold was the limit (tipping point) that defines the carrying capacity of the system. Accordingly, barriers were associated with inputs and thresholds with outputs, defining the sustainable production window.

The recruitment of study participants followed a snowball sampling strategy with multiple entries. The first round of the Delphi study was launched at the Hobart International Seaweed Symposium (February 2023), aiming to recruit a maximum of international experts in the field of seaweed culture or CC experts working on lower trophic species. Additionally, it was sent to known experts in the field as obtained from professional networks of the first and last authors (e.g. individual experts, working groups, scientific networks on aquaculture development) and suggested by study participants. Participation was based on prior-informed written consent and completely anonymous and voluntary, with the option to leave the study at any time. Since the development of the seaweed aquaculture sector and thus the barriers and thresholds are vastly different from continent to continent, even country to country, participants were requested to consider one of the following scenarios (choosing the one they regarded as best representing their experience or expertise):

- Established seaweed industry (many barriers are solved, there is space and labor to upscale) in a country of the global South (developing country) with a developing economy.
- Established seaweed aquaculture industry (many barriers are solved, there is space and labor to upscale) in a country of the global North (developed country) where the economy is thriving on other high-tech goods and other aquacultures or fisheries.
- Nascent seaweed aquaculture industry (small sector facing policy and/or ecological and social barriers) in a country of the global South (developing country) with a developing economy.
- Nascent seaweed aquaculture industry (small sector) in a country of the global North (developed country) where the economy is thriving on other high-tech goods and other established aquacultures or fisheries.

In the first round, 54 % of participants were from academia, with the remaining being from (non-) governmental, industry or other organizations. A greater portion of experts from academia remained until the third round, making up 87 % of the experts in round 3. Only 2,34 % of the respondents were from the Global South.

The outline of each round is described in Fig. 2. Additionally, the first round of the study included the identification of positive inputs and favoring outputs of seaweed aquaculture (See Supplementary Materials). These were not further used or analyzed in the next rounds (second and third rounds), as they are considered not to be barriers or have thresholds of unacceptable change and thus, are not necessary for the framework. In the third round of the Delphi study, experts were also asked questions regarding the general use of indicators, which span beyond indicators for seaweed aquaculture per se. For example, they were asked if they considered it important to have many or just one indicator, if those indicators should be universally or locally applicable. The same questions were asked regarding thresholds, if thresholds should be universally applicable or locally, and if the methodology for assessing seaweed CC should consist of a single method or comprise a set of different methodologies.

2.2. Data analysis

The first round of the study employed the Microsoft survey tool ‘Forms’,[3] the second round used ‘lime survey’[4] and for the third round an editable pdf was used. The expert responses from each round were

[3] https://www.microsoft.com/en-us/microsoft-365/online-surveys-polls-quizzes

[4] https://www.limesurvey.org/de

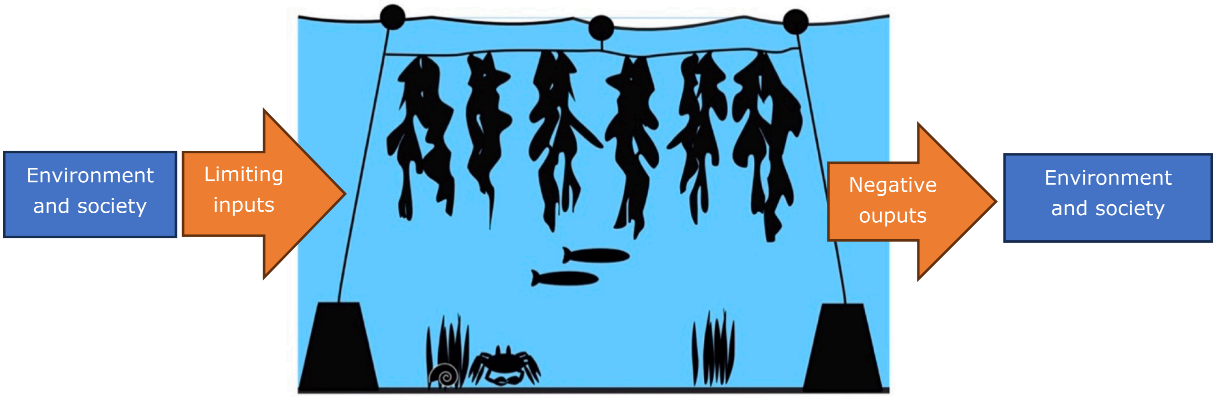

Fig. 1. Conceptual diagram of limiting inputs and negative outputs in regard to a seaweed cultivation site.

Steps of rounds	Content and purpose of rounds
Round 1: Collection of inputs and outputs Date: 24.02 - 11.04.2023 Respondents: 41 of 161 Response rate: 26%	Collection of... ... ecological or socio-economic inputs that are limiting or favouring seaweed industry and ... positive and negative ecological and socio-economic outputs of seaweed culture.
Round 2: Defining of indicators, barriers and thresholds Date: 15.09 - 31.10.2023 Respondents: 19 of 34 Response rate: 56%	Selection of the most relevant limiting inputs and negative outputs. Suggestions for indicators, barriers (local and internatinal) and thresholds (local and intenational).
Round 3: Sonsolidaton of results Date: 28.02 - 20.05.2024 Respondents: 15 of 16 Response rate: 94%	Consensus-reaching of most relevant and best fitting indicators, barriers and thresholds of a consolidated list of most relevant limiting inputs and negative outputs.

Fig. 2. Overview of the three rounds of our Delphi study. Please note that the number of respondents from a prior round does not necessarily represent the number of people included in the next round; this is because some participants opted out after round 1 or 2; or answered anonymously.

downloaded and organized in Excel[5] files. Results were analyzed by the lead author and synthesized to provide controlled feedback to the group about the previous round and inform the next one. The data were then coded, meaning standardized, the content of the answers was compared and grouped, concluding with a shorter list where similar answers were merged into the same topic. The inputs and outputs asked for in the first round were also coded, resulting in lists of the inputs to and outputs from seaweed cultivation. The grouping categories (ecological vs. socio-economic) were re-assigned by the study coordinators in those cases where a socio-economic factor had been answered in the ecological category and vice versa. The second round aimed at identifying the most prominent inputs and outputs, and assigning their potential indicators, barriers to overcome (for inputs) and thresholds to inform carrying capacity (for outputs). The study coordinators set the threshold of consensus for this round to be above 14 % for the limiting inputs and 20 % for the negative outputs, which is based on the average vote per limiting input – 2,7 votes - and negative output - 3,8votes. Thus the final lists provided for the participants in round three consisted of 18 out of 41 most relevant inputs and 18 out of 34 most relevant outputs. In round three, data on the selected highest voted and best-fitting indicators, corresponding barriers and thresholds were received for each of the most prominent inputs and outputs, respectively. Note that the participants could independently rate the relevance of the indicator, barrier and threshold; accordingly, the most relevant indicator and barrier could be associated with two different inputs, and similarly, the most relevant indicator and threshold could be associated with two different outputs. For the sake of simplicity, the final results consist of only the best-fitting indicator, barrier and threshold to each of the most prominent inputs and outputs. Given the potential mismatch in relevance between indicator, barrier and threshold as described above, the selection of corresponding barriers and thresholds for each of the most selected indicators was done following a decision tree (Fig. 3). The thresholds of consensus thus varied per input and output.

To have a compact version of the results, only one indicator, the highest voted one per input or output, was selected (Step 1 in Fig. 3). For the whole set of indicators and their corresponding barriers and thresholds please view the supplementary material. The decision of which barrier and threshold to pick is straightforward if the corresponding barrier and threshold to an indicator were also the highest voted one (upper path). However, if they were not the highest-voted ones, a decision has to be made (step 3). In this case, barriers and

[5] https://www.microsoft.com/de-de/microsoft-365/excel?market=de

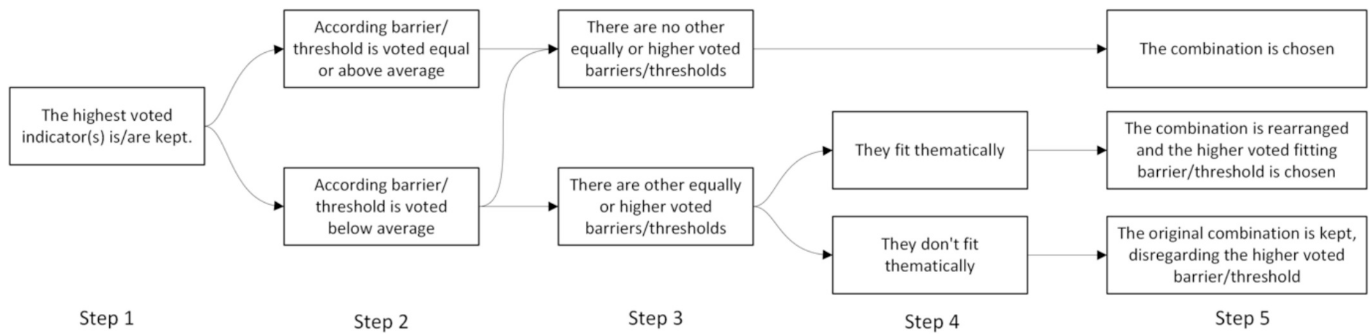

Fig. 3. Decision tree for the selection of final negative outputs, limiting inputs and their indicators, thresholds and barriers as emerging from the data of the third round of this Delphi study.

thresholds from other indicators were also considered (lower path). In step 4, the choice of a higher voted thematically fitting threshold or barrier, meaning it was on the same topic (to the indicator 'productivity loss' fits thematically the threshold 'crop loss' but not 'human illness'), or it did not fit thematically. If it fitted, the higher voted fitting barrier or threshold was taken (step 5, middle path). If it did not fit thematically, the original lower voted barrier or threshold was kept (lower path). In step 5, 'combination' refers to a combination of indicators and corresponding barriers and threshold for each limiting input and each negative output, respectively. Each step was noted in the metadata of the Excel file, providing a traceable outcome of the material.

Even though prepared for, not enough experts from the Global South or from an established seaweed industry responded to the study invite. We thus had to focus on the nascent seaweed industry in the Global North. Accordingly, no other inputs and outputs than the ones collected from the nascent seaweed industry in the Global North scenario were included in the analysis and thus this study did not capture the difference in priority setting that other nations with a more established seaweed industry would provide. The 63 % drop in participants from 41 initially agreed to take part in the first round, to 15 finishing the 3 rounds has to be considered and provides a potential bias in the results; but is potentially a consequence of the lengthy survey design (deemed necessary to answer the questions and challenges laid out). However, most dropped out after the first round, and 94 % remained between round two and three, where the essential inputs for consensus-reaching take place.

3. Results

3.1. Limiting inputs and negative outputs

The final compiled and standardized lists for limiting inputs and negative outputs are presented hereafter.

3.1.1. Limiting inputs

Some of the socio-economic limiting inputs (Table 1) were similar and grouped together to facilitate the digestion of the results. Three limiting inputs, the '*high operating costs*' ($n = 8$), '*seaweed cultivation being a costly practice with a low-value product*' ($n = 6$) and '*hesitant investors*' ($n = 4$) were grouped together as 'profitability' as they can all be measured with a cost-benefit analysis (indicator) and their barrier would be profitability. The other limiting inputs were grouped into issues concerning the '*market*', '*licenses and permits*', '*development needs*' and '*social license*'. As for ecological limiting inputs, '*the uncertainty businesses face regarding climate change*' received the most votes ($n = 5$), followed by '*epifaunal growth and fouling of the seaweed*' ($n = 4$). '*The temperature increase*' ($n = 3$) was rated into third position, which could both be due to climate change or the seasonal rising temperatures in the summer. Socio-economic inputs received overall higher selection rates, with the highest limiting input receiving 8 votes, (*high operating costs*' and an '*underdeveloped market*'), while ecological inputs were fewer and were less often selected, with the highest receiving 5 votes ('*uncertain impacts from climate change*').

Interestingly, 22 of the 41 (63 %) of the experts listed in the first round, that 'nutrient availability' is a limiting input, yet it was not selected as a relevant limiting input in round two. To be selected, it would have needed to be selected equal to or above the average selection number, which would have been 3 or more, but only 2 experts had selected the nutrient available as a relevant limiting input. This could potentially be due to the fact that the scenario we focused on was a nascent seaweed industry, without knowing the importance it might had received with more experts from the Global South or a more established seaweed industry. Another reason could be that sunlight, and nutrient availability had been grouped together in round two in an attempt to reduce the lists and thus lengthiness of the surveys. It is important to reiterate that even if limiting inputs (Table 1) and negative outputs (Table 2) are not representative of global seaweed aquaculture, the framework (Fig. 6) provides guidance that can be applied globally.

3.1.2. Negative outputs

The same grouping approach was carried out for the negative outputs. In this case, four socio-economic outputs, namely '*overhyped unrealistic view and expectation of seaweed cultivation*' ($n = 10$), '*opposition from fisheries*' ($n = 7$), '*potential monopolization*' ($n = 7$) and '*potential poor license*' ($n = 9$) were grouped as social acceptance as they can all be measured by social acceptance (indicator) and the communities should set control points (threshold) (Table 2). The remaining socio-economic limiting inputs concerned conflicts, economic viability, emissions and safety. The ecological outputs considered the most relevant by the experts were '*pollution*' ($n = 6$) and issues around the '*dispersal of genetic material (invasive species)*' ($n = 6$), '*genetically modified* ($n = 6$) or '*domesticated species causing retention of genetic diversity*' ($n = 5$)). Other outputs were related to diseases, resource competition, sedimentation changes, hydrological changes, organic matter, and the seabed. Similar to the limiting inputs (Table 1), the socio-economic outputs were selected more often, with the highest number ($n = 10$), being the '*overhyped unrealistic view and expectation of seaweed cultivation*', while the highest selection rate for ecological outputs, $n = 6$, was '*pollution*'.

3.2. Relationship between socio-economic and ecological answers

Of the list of inputs and outputs offered to the experts in the second round, 4 out of 14 (29 %) limiting ecological inputs, 14 out of 27 (52 %) limiting socio-economic inputs, 11 out of 22 (50 %) ecological negative outputs and 7 out of 12 (58 %) socio-economic negative outputs were chosen as relevant (Fig. 4). Percentage-wise, socio-economic inputs and outputs were chosen more often in relation to their initially suggested number in round 1, indicating a broader range of relevant topics.

Table 1
List of highest voted ecological (in green) and socio-economic (in purple) limiting inputs with the corresponding highest-voted indicators and barriers.

Thematic grouping	Limiting Input	Indicator	Vote	Barrier surpassed, when there is/are	Vote
Profitability	Operating costs are too high (not yet economically viable), need for costly infrastructure close by (hatchery, processing, harvesting, clean water, etc.) (n=8)	Cost-benefit and profitability monitoring and analysis (profit / loss) annually (n=5+3+2)	12	Profitability (n=2+2+2)	8
	Costly practice with low value product leading to possibly unprofitable businesses (n=6)		8		5
	Investors are hesitant as there are no established seaweed cultivation business cases (risks for capital), lack of capital for entrepreneurs (n=4)		6		5
	High price of seaweed products can't compete with cheaper seaweed form Asia or other sources of biomass that are cheaper (n=6)	Quality of products both domestic and international (n=1)	8	High quality local products are valued more (n=1)	8
Market	Underdeveloped market (not enough demand and high export host, too small or too large volumes, specific processing demands) (n=8)	Market size / maturity (n=2)	12	When the market grows and diversifies substantially (n=2)	8
Licences, permits	Difficulties with licenses, permits and certificates (administrative burden, expensive, cultivation license framework not in place) (n=7)	The process of acquiring permits (admin burden) (n=2)	8	Streamline process and clear guidelines (n=1)	9
	Limited permits, locations on coasts (n=3)	Available and suitable space(n=2)	8	Database establishment with suitable area that can be bought, leased, acquired (n=1)	8
Public support	Lack of investment for technology required for reaching large scale in an economical way (e.g. more automation of deployment, harvesting and processing) (n=6)	Public funds available for developing the technology (n=1)	9	Seaweed industry is a reputable and grown up industry here to stay (n=1)	5
	Lack of government support, no zoning for seaweed in marine spatial plans (n=4)	Government support or priorities (n=1)	8	Seaweed culture is incentivized (n=1)	9
Climate and weather	Uncertain impacts from climate change (adaptivity to warmer oceans, less meteorological predictability, less crop resilience and growth, more disease) (n=5)	Response of seaweed to climate variability (n=1)	7	Reduced response of seaweed to climate variability (n=1)	5
	Temperature increase (n=3)	Temperature monitoring (n=3)	11	NA	NA
	Access to sea in difficult weather conditions (n=3)	Number of at-sea days per season (n=2)	7	Larger/better boats and infrastructure to access farm sites in bad weather conditions (n=2)	2
Fouling	Epifauna, fouling, grazers (n=4)	Effect on growth rates (n=1)	9	No more fouling (n=1)	2
Farming design, technological readiness	Specific farming design needed (n=4)	Efficiency of current farming technologies to achieve high yields, incomes. (n=2)	8	Alternative or more efficient farming technologies available (n=3)	7
	Large scale farming not yet ready (needs proof of concept, has unknown impacts and risks) (n=4)	Carrying capacity of different environments for scaling up macroalgal farming (n=1)	7	Farming technologies are adjusted to carrying capacity of the environment (n=1)	8
Social acceptance	Social acceptance, social license to operate, lack of trust in the aquaculture industry (n=3)	Social acceptance and opposition (opinion) (n=2)	11	Community should set these control points (n=1)	6
	NIMBY, people are against the use of the sea (n=3)	Opinion (NIMBY, trust, engagement) (n=3)	7	People understand that negative impacts are outweighed (n=1)	6
				Seaweed is accepted as a priority crop (n=1)	6
Heavy metals	Heavy metal uptake leads to higher than acceptable levels (n=3)	Metal concentrations in seaweeds (n=1)	9	NA	NA

The table includes ‘n’ as the number of times the experts of the study selected the input or output in round 2 (brainstorming stage). Similarly, ‘n’ indicates the number of times an indicator and barrier or threshold were independently proposed by the experts in round 2. The numbers in the ‘vote’ column indicate often the experts have selected this indicator or barrier as the best fit for the input or output in round 3. Limiting inputs were grouped thematically and sorted according to the highest vote within a group.

Table 2
List of highest-voted ecological (in green) and socio-economic (in purple) limiting inputs with the corresponding highest-voted indicators.

Thematic grouping	Negative output	Indicators	Vote	Thresholds	Vote
Social acceptance	Overhyped unrealistic view and expectations of seaweed cultivation, with potentially being less profitable and less jobs created than expected (n=10)	Social acceptance, support and opposition (opinion) (n=3+3+1+5)	9	Community should set these control points (n=1+1+1+1)	7
	Opposition from fisheries if their fishing grounds are being converted to seaweed farms (n=7)		6		5
	Potential monopolisation by larger multi-national companies, leading to imbalance of benefit share (n=7)		6		5
	Potential poor social license and image due to over-promising/hype but under delivering of touted benefits (n=9)		8		6
		Transparency (n=1)	9	We can agree in the industry that an xxx size farm should yield xxx jobs, creating xxx biomass (plus or minus xxx) (n=1)	5
Conflicts	User space needed, potential conflicts with other economic activities (tourism, fishing) (n=7)	User needs, complaints, perception and opinion of local stakeholders in space conflicts (n=4)	6	Incompatible user needs (n=1)	4
		VMS, GIS and/or Satellite to gauge overlaps (n=1)	6	Marine spatial planning should be fixed (no change) except after consultation with stakeholders (n=1)	4
		NA	NA	Navigational safety, prior uses must be considered (n=1)	4
Pollution	Pollution (plastic, ropes) (n=6)	Plastic level, amount of plastic, that can be attributed to the source (n=1)	9	As low as possible (n=1)	8
Genetic material	Input of or spread of non-indigenous or invasive species (n=6)	Detecting any or increase of invasive species of non-indigenous species (DNA) (n=5)	8	0% tolerance (n=4)	6
	Input of or spread of genetically modified or selected bred species and translocation of native seaweed species (threat to genetic diversity) (n=6)	Gene flow, genetic fingerprinting of populations, genotyping, genetic diversity from native populations (n=4)	9	>0.01% (n=1)	3
	Release of reproductive material from domesticated seaweed species (and potential native local retention of reproductive material) (n=5)	Gene flow, genetic fingerprinting of populations (n=4)	8	No alteration of native gene pool (n=1)	4
Disease	Disease (Input of microbial pathogens and parasites and disease proliferation) (n=5)	Disease prevalence (n=3)	8	Below tolerable epidemiological levels (not yet established) (n=1)	7
Economic viability	Economically unviable compared to (unsustainable) productions from other regions (n=5)	Cost-Benefit value, including environmental and social costs (n=1)	7	Profitability loss (n=1)	5
Emissions	Fuel used and carbon emission from the boats (n=4)	Fuel consumption and carbon emissions (n=3)	9	As low as possible (n=1)	8
Safety	Consumer safety issues such as heavy metals or iodine content (n=4)	Level of heavy and iodine metals in products (n=4)	6	Levels as stated by food safety authority (n=1)	6
		Food safey parameters (n=1)	7	NA	NA

Resource competition	Sunlight competition (n=4)	Amount of shading/light (n=2)	6	Max 30% of shading compared to the surrounding areas (references site) (n=1)	3
	Nutrient competition (n=4)	Amount of nutrient removal (n=1)	6	Reduction of the concentration of water nutrients in the surrounding area by > 20% in oligotroph areas (n=1)	4
		Amount of Nitrate, Nitrite, Ammonia, Phosphate (n=2)	6	Significant attributable change when natural conditions are low in nutrient (n=1)	4
Organic matter	Input of organic matter (DOM and POM) (n=4)	DOC and POM concentrations (n=3)	8	Ambient seawater concentrations (n=1)	5
Sedimentation	Changes in siltation, sedimentation, turbidity (n=4)	Water turbidity change (3D mapping, up to 2km from the farm) (n=3)	7	Drop in Secchi depth of 20% (n=1)	3
				Max 10% change in 1 km range (n=1)	3
Hydrological changes	Impacts on hydrological processes (Water flow and wave energy changes) (n=4)	Changes in current and wave height before and after a seaweed farm (n=2)	6	Max 10% change in marine organisms (e.g. natural seaweed beds nearer shore, animals in the area, and biodiversity change) (n=1)	4
		ADCP, moorings with vertical array of sensors for temperature, salinity, turbulence. Account for seasonal variability (n=1)	6	No change in hydrography after some distance from farms (e.g. 500 m) (n=1)	4
Seabed	Physical disturbance to seabed (temporary or reversible) (n=4)	State of the benthic habitat (n=1)	5	Enter hypoxic conditions (n=1)	3

The tables include 'n' as the number of times the experts of the study selected the input or output in round 2 (brainstorming stage). Similarly, 'n' indicates the number of times an indicator and barrier or threshold were independently proposed by the experts in round 2. The numbers in the 'vote' column indicate often the experts have selected this indicator or threshold as the best fit for the input or output in round 3. Negative outputs were grouped thematically and sorted according to the highest vote within a group.

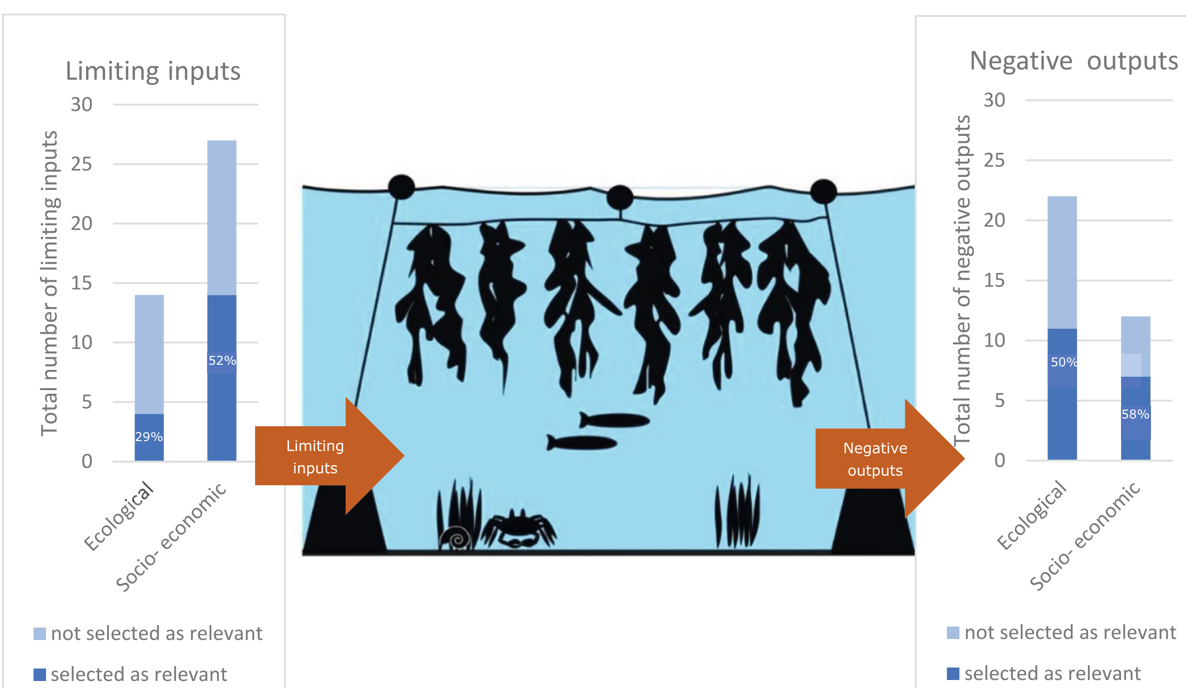

Fig. 4. Total number (y-axes) and percentage (within bars) of limiting inputs (i.e. those having an influence on a seaweed farm) and negative outputs (i.e. those having an influence on the environment) selected as relevant in the second round of the Delphi study.

3.3. Applicability of indicators, barriers and thresholds

Regarding the questions on the ideal number of indicators for seaweed cultivation and the optimum spatial scale at which indicators and thresholds should be applied, most participants (77 %) either disagreed or somewhat disagreed to have a single indicator for each input or output and thus also agreed and somewhat agreed (87 %) that a set of indicators should be selected for each input or output.

When asked whether indicators should be locally specific or as universal as possible, expert opinions diverged; with 63 % of experts voting for indicators to be as universal as possible, 67 % believed indicators should be locally specific (please note that these responses come from two independent questions). To support their vote, the experts had the chance to comment on it. Participants argued universal indicators "*would be more transparent*" (ID 11) and would facilitate cross-system comparison, i.e. that one has "*to compare (them) to other systems in order to make environmental claims*" (ID 9). Other participants acknowledged challenges for identifying universally applicable indicators as "*a good idea but may be hard in practice for some of them*" (ID 2) and "*some of them can be irrelevant for a specific context*" (ID 5). Expert's arguments in favor of locally specific indicators reiterated the need for indicators need "*to be context specific and matched to the value system of the people in that place*" (ID 1), with the "*value system of the people of the place determin(ing) appropriate indicators*" (ID 1). Challenges for identifying locally specific indicators were framed as "*not all indicators would be relevant for all sites*" (ID 11). A suggestion summed up nicely the discourse: to have "*universal (indicators) to start with, (and) locally specific (ones) if needed*" (ID 10).

Conflicting opinions were expressed regarding the thresholds; similarly to the discussion regarding indicators, 80 % of experts agreed or somewhat agreed that the thresholds should be locally specific, although 50 % believed they should be as universal as possible. It was argued that having universal thresholds is an "*oversimplification*" (ID 1), but "*for some (inputs and outputs) a universal threshold makes sense, for others only local*" (ID 10) and that "*a set (of locally specific thresholds) allows to have more complex outcomes reflecting better (the) reality*" (ID 11). 67 % of experts agreed or somewhat agreed that the methods for estimating seaweed CC will have to vary for each location, although 62 % agreed or somewhat agreed that we should aim at developing an accepted standardized method. Experts differentiated that the "*method is a general approach to assessing carrying capacity*" (ID 15) but then reiterated that this should not necessarily mean a fixed set of universal indicators and thresholds, repeating arguments from the questions above regarding general inputs and outputs.

Even though having several indicators seemed more agreeable for our results, we limited the results to one indicator per input or output to provide an exemplary overview. However, the full lists of all indicators for the relevant limiting inputs and negative outputs are provided in the supplementary material.

4. Discussion

4.1. Sustainable operating window

Our results provide a ranked list of limiting inputs to seaweed cultivation and barriers that would be overcome when these limiting inputs are considered in seaweed management. Also, the results include a list of ranked negative outputs of seaweed cultivation and suggested thresholds, above which there would be an unacceptable cost to the environment or society.

With these results, we are questioning the focus on only assessing the maximum possible production capacity, suggesting to find and aim for the sustainable window of cultivation for society and the environment (Fig. 5) based on the concept of the safe operating space or safe space of production (Kluger and Filgueira, 2020; Tett et al., 2011). We call operating window what Kluger and Filgueira (2020) and Tett et al. (2011) had termed operating space, because we believe this would reduce the association of a physical space. This concept of a sustainable window is particularly relevant for aquacultures that provide benefits, other than food provisioning, to the environment and society but face initial barriers. For example, the European Green Deal (European Union, 2019) calls for the production and use of alternative food and feed sources from the ocean and wants to promote and lead markets for climate-neutral and circular production, but in contrast to a large scale seaweed industry in many Asian countries, seaweed cultivation in the Global North is still facing many barriers before expansion could benefit the ambitions of the Green Deal's Goals. Our limiting inputs – from a Global North perspective -, such as '*operating costs are too high*', or '*underdeveloped market*' show that these barriers must first be addressed before many of the negative outputs, such as '*potential monopolization*' or '*hydrodynamic changes*' will reach a threshold of unacceptable change. However, both barriers and thresholds must be assessed to be in a safe and sustainable operating window where the environment and society can benefit from aquaculture while its impacts stay within acceptable limits. The relevance of these inputs and outputs changes for each region - over time, space and scale. For instance, socio-economic factors, like '*profitability*', might hinder the industry at the smaller scale level (van den Burg et al., 2021), while '*nutrient limitation*' or '*access to cultivation space*' might become more relevant once large-scale cultivation is established. The large-scale seaweed industries of China and Indonesia are an example, that barriers are locally specific: what is limiting in the Global North, for example an 'underdeveloped market' does not seem to be a limitation in Asian countries. It is a fine balance that has to be achieved from a multi-criteria and multidimensional perspective and that needs to stay adaptive (Kluger and Filgueira, 2020).

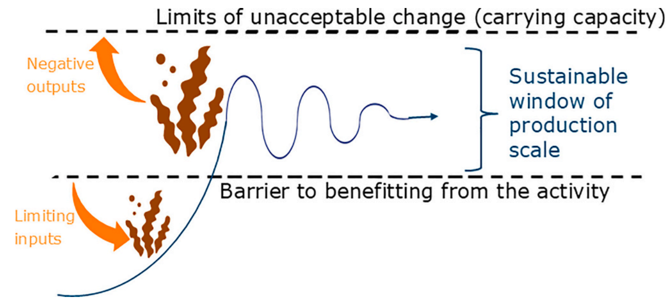

Fig. 5. Conceptual overview of the sustainable window of operation of seaweed aquaculture as proposed in this work. Seaweed culture should conducted in a way that benefits from the activity can arise, i.e. by operating at temporal, spatial scales that address limiting inputs while maintain negative outputs below limits of acceptable change.

4.2. The holistic framework for assessing the carrying capacity for seaweed cultivation

Our list of inputs and outputs (Tables 1 and 2) cannot be perceived as a universal assessment tool or check list. Similar to work on finfish carrying capacity assessment (Weitzman et al., 2021), also seaweed requires a multi-stakeholder governance approach before and after the assessment to discuss scope, limits, barriers and tradeoffs. Previous work describes the general approach to a CC assessment (Byron and Costa-Pierce, 2013; Kluger and Filgueira, 2020; McKindsey et al., 2006; Ross et al., 2013; Weitzman et al., 2021), but our works go further and include the barriers to expansion and adding detail, bridging theoretical frameworks with practical applications for seaweed aquaculture. Based on Weitzman et al. (2021)'s 8-step approach for finfish aquaculture, we propose a 12-step holistic framework for CC and barriers addressing the sustainable window for seaweed production (Fig. 6). This includes of ecosystem services, particularly relevant to lower trophic species such as seaweeds, as a holistic consideration to identify this sustainable production window.

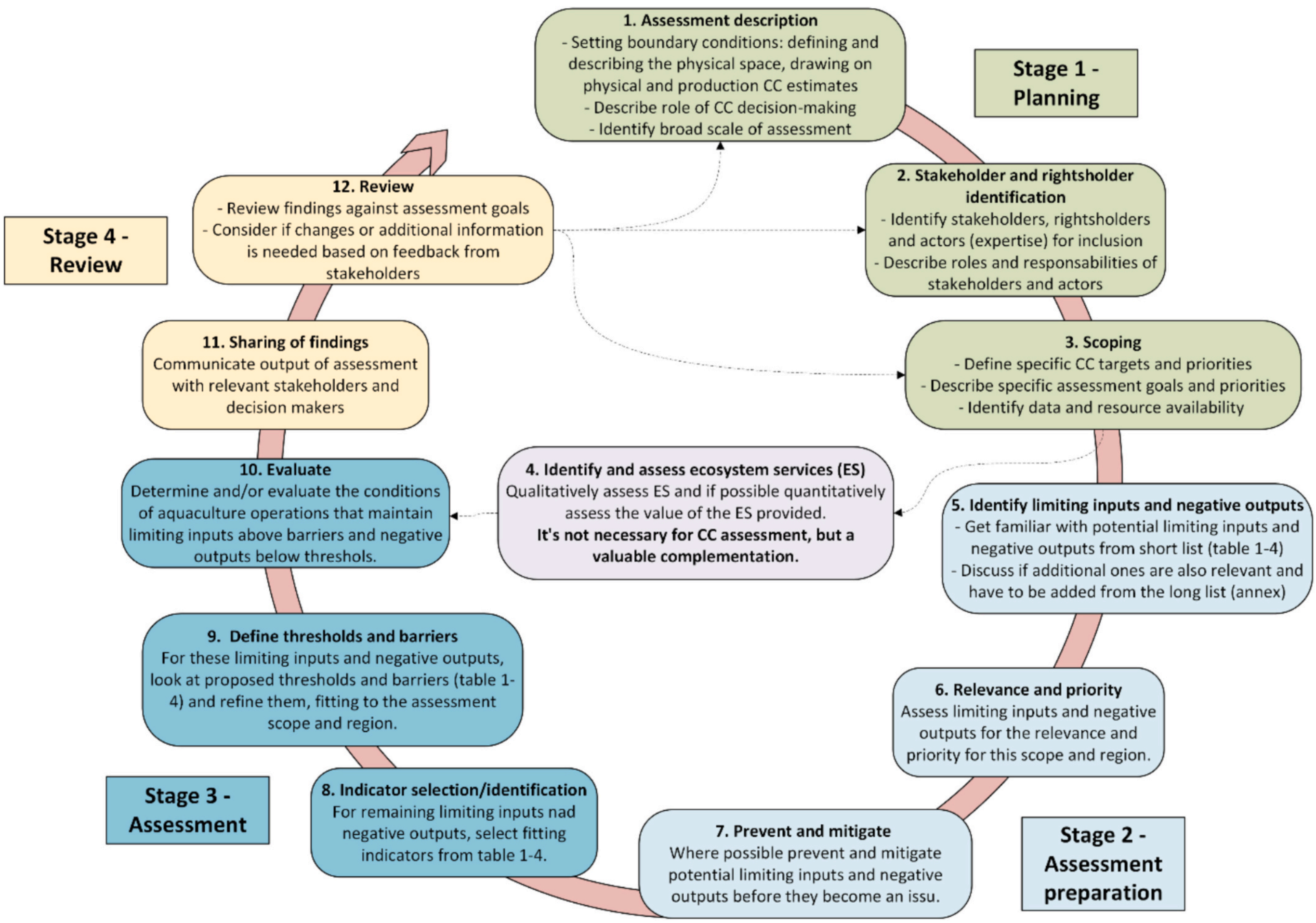

Fig. 6. Holistic approach to assess the sustainable window of seaweed cultivation, including barriers and carrying capacity. This figure is based on a stepwise approach to carrying capacity by Weitzman et al. (2021) and a generic protocol for safe seaweed cultivation from van den Burg et al. (2023).

The first stage is planning, which includes defining the assessment scope, including the integration of physical- and production CC (Step 1), identifying stakeholders and rightsholders(Step 2) and describing scopes (Step 3). Many of our socioeconomic limiting inputs and negative outputs involve stakeholders, for instance investors, administrators for permits, local inhabitants and other users such as the fishing industry. Stakeholders and rightsholders need to have a space to come together and exchange ideas in a planning phase, and again later to assess and review the goals of the assessment. Step 4 introduces the ecosystem service assessment- not essential to the identification of barriers or CC, but it is important for tradeoff discussions and social acceptance (view step 10).

We introduce a pre-assessment stage (Stage 2) to identify and prioritize the limiting inputs and negative outputs (Tables 1 and 2 and even more so in the supplementary material) (Step 5), noting that not all must be a concern for each region and can thus be excluded for an individual assessment (Step 6). Again, these can be entirely different for regions with an established seaweed industry, such as in Asian countries. Steps 6 and 7 are inspired by Van den Burg's generic protocol for safe seaweed cultivation and aim to reduce the list of variables to assess and to make the assessment more feasible. Monitoring the impacts (outputs) is expensive and time intensive, therefore reducing variables is practical. Some negative outputs, such as plastic pollution, or spills, could be prevented and mitigated (Step 7) and can thus be excluded from a full assessment (Stage 3). Site selection can also prevent many issues. The participating experts have highlighted several times the fact that doing a site assessment is necessary before starting a farm to avoid a site with many limiting inputs (ID 5), which is in line with recommendations by van den Burg et al. (2023).

The actual assessment begins with Step 8 in stage 3, where stakeholders select relevant indicators from Tables 1 and 2 and supplementary material. This framework is not meant to be a prescribed solution, but rather a guide. Our results (Tables 1 and 2) also provide suggestions for thresholds and barriers, which need to be refined and adjusted to the context, area and scope of the assessment (Step 9). Step 10 involves evaluating limits and barriers and facilitating a tradeoff discussion, including ecosystem services. This step demonstrates how all dimensions of CC are, in the end, dependent on the social CC, as limits and thresholds are defined by the stakeholders and what they are willing to accept (Kluger and Filgueira, 2020). In stage 4, the results will be communicated (Step 11) reviewed, and used to guide further assessments (Step 12), emphasizing the need for dynamic and adaptive management.

4.3. The importance of social aspects in determining thresholds

It has been suggested that CC can inform an EAA (Byron and Costa-Pierce, 2013; Kluger et al., 2017; Kluger et al., 2016; Ross et al., 2013). According to its definition, EAA requires aquaculture to be conducted in a sensible way for both ecosystem and society, without causing undue negative - unacceptable - outputs. This is where the concept of CC is theoretically so meaningful and where our study provides valuable inputs. Our results show that the limits are a result of a local discussion – and depend on respective priorities and necessary trade-off discussions (food security versus environmental concerns, for example). A multidimensional set of indicators – reflecting also socio-economic concerns - is needed to ensure that all stakeholders and rightsholders can contribute to the conversation (Kluger and Filgueira, 2020). Herein, we provide a set of indicators that can be drawn from to inform such a discussion.

Following the study participants choices between round one and two, allowed us to examine the importance given to the socio-economic inputs and outputs based on the prioritization given by the study participants (Fig. 4). In round one, more socio-economic limiting inputs were suggested than ecological ones, and in round two, socio-economic inputs and outputs were chosen more often in relation to their initially suggested number (percentage-wise). This is an important result, as most CC approaches so far have focused on production / ecological dimensions, not on the socio-economic dimension. Thus, the present work crucially advances the current research by providing example inputs to investigate. These results are in line with other work stressing the importance of socio-economic factors to be considered for a holistic CC assessment (Bizzaro et al., 2022; Kluger and Filgueira, 2020). As one of our study participants (ID 18) put it: "*It seems the socio-economic variables* (inputs) *are a bigger hurdle than the ecological ones at this stage of Western seaweed cultivation.*" This being said, it is important to keep in mind that study participants represented experts principally working in the Global North.

Kluger and Filgueira (2020) argued that any threshold is the result of a societal debate of what is acceptable. Understanding the stakeholders' needs, conflicts, and perceptions is considered essential to determining the CC (McKindsey et al., 2006). As such, all CC components reflect social values to some degree (for example, recreation) and therefore a CC framework should be more inclusive of the social aspects. For example, even if a decline in biodiversity is widely acknowledged as negative, how much decline a fjord, bay, coastline, or country will accept depends on how each specific community or society values the overall tradeoffs. It is also possible that biodiversity thresholds or concerns are deliberately left aside if aquaculture production for food security is of priority for a particular community or country (Kluger and Filgueira, 2020). This is reflected in regulations, legislation and directives, all potentially addressing ecological or production limits, but are defined by society (in the form of governance) as to what seems acceptable (Smaal and Van Duren, 2019). Integrating ecosystem services into trade-off discussions allows for the prioritization of aquaculture practices that provide greater ecosystem benefits, which could, in the long run, reduce pressure on coastal resources (Spillias et al., 2023) and thus benefit society on other dimensions rather than food security. Thresholds could be further accepted by being 'traded in' for other benefits coming from the cultivation site, or barriers might be lifted by an added value from the cultivation site. This holistic approach of assessing CC by considering socio-economic as well as ecological dimensions[6] allows for this discussion.

4.4. The need for stakeholder inclusion and just regulatory frameworks

Aquaculture is embedded in local, national and international governance schemes and legislative frameworks. Place-based priorities, constraints and concerns (i.e. the locally selected and applied thresholds) need to be also contextualized at global scales (Kluger and Filgueira, 2020). For instance, while an assessment including CC and barriers to expansion needs to capture and be rooted in local values, it needs to be acknowledged that there are international drivers, like a globalized seafood market. The coast has many user groups, and aquaculture practices produce social and ecological externalities at multiple scales. Thus, potential conflicts are not only a limiting input but also a negative output, as our results also show. Weitzman et al. (2021) argue that stakeholder participation, including government, is essential to the process of CC assessment. Decision makers need to consider that negative impacts and the potential overstepping of their thresholds may have impacts beyond political borders and should thus be open to cross-scale collaboration – further than the immediate surrounding or jurisdiction - to define and respect CC limits. At the same time, regulatory frameworks might act as facilitating or inhibiting to the development of a nascent industry. Government support for marine aquaculture is crucial (Davies et al., 2019) barriers within regulations need to be addressed (Lähteenmäki-Uutela et al., 2021) and possible social conflicts (with other marine sectors) have to be resolved (Camarena-Gómez et al., 2022; Cerca et al., 2023). The European Commission also identified fragmented governance frameworks as one of five main limitations to the expansion of seaweed aquaculture, the others being high production costs, low scale production, limited knowledge of the risk and environmental impacts of algae cultivation and limited knowledge of the market and consumers (European Commission, 2022). This is in line with barriers identified in our study and other publications by Kuech et al. (2023), Cerca et al. (2024) and Camarena-Gómez et al. (2022). Looking into the Asian context, 'limited knowledge of the market and consumers', was also a barrier identified in the Philippines in a study assessing the knowledge and willingness of fishers to engage in seaweed farming (Dumilag et al., 2023). A review on challenges in the Indonesian seaweed industry furthermore states that 'optimization of cultivation techniques', 'expansion of suitable farming areas', and 'digital technologies and genetic analysis' are identified research areas to boost productivity and sustainability (Sutrisno et al., 2024). This is why we argue that for such processes to address CC and barriers to expansion need to be addressed on a governmental, regional and national level.

Weitzman et al. (2021) showed that there is a 93,8 % agreement among consulted experts that actors involved with CC assessment should be from all diverse knowledge forms and disciplines. For instance, experts approached by Weitzman et al. (2021) suggested that the identification of indicators should be made by scientists, while thresholds should be set by the government (78,6 % high relevance) and public interest groups (64,3 % high relevance). This is aligned with our study results, as many of the barriers named and voted for by the experts include the consultation of local stakeholders. Of course, it can be debated that government isn't the deciding entity over thresholds; independently of the approach, all actors should have an opportunity to discuss these aspects in a meaningful way.

Another example of the necessity for multistakeholder discussions is the tradeoff debate which can be part of the CC and barriers to expansion assessment and will give ecosystem services, other than food provisioning, the chance to be considered. We show that these types of discussions need an understanding of the complex interactions of the socio-ecological system, going beyond one-dimensional goal, balancing goals on every dimension, considering drivers, barriers, pressures and benefits. Questions of social justice should also be considered since different societal actors have different economic means or power. For instance, in a trade-off discussion, a multinational or large aquaculture company can argue to bring jobs into a particular community, but a local professional fisher may lose their profession - that may seem like a solution on an economic level might not be on a social justice level.

5. Conclusion

To stay within the boundaries of our local (eco)systems – i.e. to operate aquaculture in the scope of EAA - understanding the carrying capacity of the given (eco)system is crucial. This work provides, for the first time, a framework to assess the carrying capacity of an ecosystem for seaweed aquaculture, which includes thorough planning, scoping definition, preparation of the assessment, the assessment and reviewing the findings (Fig. 6). The limiting inputs, their indicators and barriers as well as the negative outputs and their indicators and thresholds presented in this study, are practical lists to identify the sustainable operation window of seaweed aquaculture. These are focused on the Global North; a further enrichment of results by including voices and

[6] In our study, we considering that production and physical cc is already integrated

perspectives beyond the global North-South divide is recommendable.

Based on our results, we further develop the reason, that it is important to approach this from an interdisciplinary (considering ecological as well as socio-economic aspects) and transdisciplinary (i.e. involving not only scientists of different disciplines but multiple stakeholders) viewpoint. We have examined the socio-economic as well as the ecological dimensions and provided indicators, barriers and thresholds for a multidimensional approach to stay within this sustainable operation window. Our research shows that socio-economic aspects are key to an assessment, as many of these describe barriers to the growth of aquaculture industry long before it reaches its ecological threshold. With this, we learn that it is in fact about finding the sustainable operating window, and eliminating barriers hindering the growth of the sector, yet knowing how far one can expand without creating a cost that is evaluated as unacceptable for the environment and society. Seaweed is a new industry in the Global North, facing different challenges in different regions. This is also manifested by the study participants' differing opinions, resulting in the lack of consensus in the study.

Seaweed aquaculture, like other lower trophic species, provides regenerative stimulus to the aquatic system, cumulating in other benefits than mere biomass or food provisioning. Nature-based solutions and alternative biomass sources from the ocean are called for by the European Green Deal. Including these ecosystem services in trade-off discussions can potentially shift production priorities towards aquacultures of regenerative nature. Incorporating this in an adaptive, multi-stakeholder, multidimensional and multicriteria approach to identifying barriers and CC thresholds will enable expansion without surpassing the thresholds of unacceptable change; in other words, it will identify the sustainable operation window of seaweed aquaculture.

CRediT authorship contribution statement

Sophie J.I. Koch: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ramon Filgueira:** Writing – original draft, Validation. **Jóhanna Alberg:** Writing – review & editing, Validation. **Dror L. Angel:** Writing – review & editing, Validation. **Carrie J. Byron:** Writing – review & editing, Validation. **Mariana Cerca:** Writing – review & editing, Validation. **Leeann B. Ennis:** Validation. **Urd Grandorf Bak:** Writing – review & editing, Validation. **Frank Kane:** Writing – review & editing, Validation. **Jonne Kotta:** Writing – review & editing, Validation. **Stefan Kraan:** Writing – review & editing, Validation. **Myron Peck:** Writing – review & editing, Validation. **Marnix Poelman:** Writing – review & editing, Validation. **Petronella M. Slegers:** Writing – review & editing, Validation. **Kristian Spilling:** Writing – review & editing, Validation. **Jean-Baptiste E. Thomas:** Writing – review & editing, Validation. **Lotta C. Kluger:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2025.742907.

Data availability

No data was used for the research described in the article.

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