



## Full Length Article

# Advancing a restorative blue Economy: A DPSIR–Ecosystem services framework for sustainable seaweed aquaculture

Marianne Thomsen <sup>a,b,\*</sup> , Annette Bruhn <sup>d,e</sup> , Jonne Kotta <sup>f</sup> , Bela H. Buck <sup>g,h</sup>, Jack R. Hall <sup>f</sup> , Georg Martin <sup>f</sup>, Antonio Agüera <sup>i</sup> , Marie Maar <sup>c</sup>, Manali Chakraborty <sup>a</sup>, Maxime Ekoule <sup>a</sup>, Ian Overton <sup>j</sup>, Mausam Budhathoki <sup>a</sup> 

<sup>a</sup> LCA and Sustainable Food Design, Department of Food Science, Faculty of Science, University of Copenhagen, Rolighedsvej 26, 1958 Frederiksberg C, Denmark

<sup>b</sup> Green Solution Center, University of Copenhagen, Bülowsvej 17, 1870 Frederiksberg C, Denmark

<sup>c</sup> Aarhus University, Department of Ecoscience, Frederiksborgvej 399, 4000 Roskilde, Denmark

<sup>d</sup> Aarhus University, Department of Ecoscience, C.F. Møllers Allé 3, 8000 Aarhus C, Denmark

<sup>e</sup> Center for Circular Bioeconomy, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark

<sup>f</sup> Estonian Marine Institute, University of Tartu, Mäealuse 14, Tallinn 12618, Estonia

<sup>g</sup> Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany

<sup>h</sup> Applied Marine Biology, University of Applied Sciences Bremerhaven, Bremerhaven, Germany

<sup>i</sup> Institute of Marine Research, Nordnesgaten 50, 5005 Bergen, Norway

<sup>j</sup> Global Climate Forum e.V., Neue Promenade 6, 10178 Berlin, Germany



## ARTICLE INFO

## Keywords:

Blue bioeconomy  
Marine spatial planning  
Environmental governance  
Ecosystem-based management  
Circular value chains  
Nature-based solutions  
Regulatory instruments

## ABSTRACT

Seaweed aquaculture is rapidly expanding in Europe and the Americas providing engineered ecosystem services (EES) such as nutrient removal, pH buffering, and carbon uptake. Used as a nature-based emission capture-and-utilisation technology, seaweed transforms emissions into revenue streams while delivering non-profit value, making seaweed aquaculture a promising eco-industrial system that fits well to the global agenda of green economic transitions and ecosystem health restoration. However, aquaculture activities may, in some cases, cause unwanted engineered ecosystem disservices (EED) which should be avoided.

We argue that an adaptive and cross-sectoral policy framework is imperative to guide the sustainable development of a blue circular bioeconomy, or phyconomy, from primary production to final products, involving actors across multiple governance levels and sectors. We identify likely EES/EED and their potential impacts on natural ecosystem services using the Common International Classification of Ecosystem Services (CICES), and we map stakeholder linkages and policy instruments through a snowball approach.

Finally, we adapt the Drivers-Pressures-State-Impact-Response (DPSIR) framework to seaweed aquaculture, redefining Pressure as Progress to recognise restorative outcomes. The resulting model connects EES/EED with relevant policies, supporting integrated and regenerative development of the seaweed sector.

## 1. Introduction

The human population is projected to grow from 8 to 9.7 billion in the period from 2022 to 2050 (United Nations Department of Economic and Social Affairs, 2022), leading to increasing demands for food, energy, and materials. Meanwhile, historic and ongoing anthropogenic disturbances to life-sustaining ecosystems cause declining levels of ecosystem resilience and integrity (Nabe-Nielsen et al., 2018; Steffen et al., 2015). These processes threaten the quantity and quality of Ecosystem Services (ES), i.e. benefits essential for human well-being

(Millennium Ecosystem Assessment MEA, 2005). A sustainable future therefore requires a transition towards a green economy based on eco-industrial regenerative and circular resource flows delivering engineered ecosystem services (EES) aimed at restoring natural ecosystem health. Seaweed aquaculture is a promising example of this approach.

Seaweed production requires no irrigation with fresh water, fertile land, or synthetic fertilisers and seaweed-based value chains can have a relatively lower environmental footprint compared to over-intensified fisheries (Kelly, 2025), fed aquaculture, and land-based production systems (Prabhu et al., 2019; Taelman et al., 2015). Moreover,

\* Corresponding author.

E-mail address: [mth@food.ku.dk](mailto:mth@food.ku.dk) (M. Thomsen).

<https://doi.org/10.1016/j.ecoser.2025.101800>

Received 2 April 2025; Received in revised form 17 November 2025; Accepted 30 November 2025

Available online 13 December 2025

2212-0416/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).



**Table 1**  
Licensing frameworks of emerging seaweed aquaculture in Europe, USA, and Australia.

COUNTRY	PERMITS	HIGHLIGHTS	PROCESS DURATION (Months)	VALIDITY (Years)	LEGAL COSTS	REGULATOR
Denmark	Seaweed aquaculture permit and environmental impact assessment	Investigation of the planned farm site (for seaweed) whether it interferes with other marine uses, any potential environmental impacts (related Natura 2000 sites), avoid sites containing <i>Zostera marina</i> , pre-engagement of stakeholders for potential public consultations, a framework to mitigate potential environmental effect, if there is any.	4 – 10	5–10	Free but a deposit is likely required	Danish Coastal Authority
England	Seaweed aquaculture licence	Consideration of Marine Information System for the selection of farm, focusing on environmental impact assessment (EIA), engagement with 'Local-level pre-engagement', monitoring fees for the farm (seaweed offshore farming fees are highly variable)	> 20	Licence specific	Highly Variable	Marine Management Organisation
Finland	Experimental permit	Reconciliation of good status in the aquatic environment with the growth of aquaculture, modelling and assessment methods for the environmental impact of aquaculture to improve the quality and predictability of the environmental permit process. Promote profitability, technical development, energy economy and reduction of the carbon footprint of RAS (Recirculating aquaculture systems) farms, as well as the development of water treatment methods. Exploration and implementation of measures for the development of organic aquaculture in Finland and the development of new low-trophic species such as seaweed farming.	6	2	–	(Finnish Railways Agency, Ministry of the Environment)
Estonia	Aquaculture permit	Restoration of marine ecosystem, development of multitrophic aquaculture system, including seaweed, shellfish, raising consumer awareness and increasing consumption, need of organic aquaculture in Estonia.	15–24	Licence specific	–	Environmental Board
	For infrastructure – building permit For aquaculture – water use permit		2 – 6	Variable	€2,800 base fee plus a per hectare annual charge	Building permit – Consumer Protection and Technical Regulatory Authority Water use permit – Estonian Environmental Board
Faroe Islands	Seaweed cultivation licence	Achieving sustainable growth in aquaculture besides minimizing environmental impacts through innovative approaches. Diversification of current culture systems to adapt to shifting environmental and biological factors, by shellfish farming, seaweed cultivation, and advancing offshore aquaculture techniques.	–	12	–	Application: Food and Veterinary Agency Granted: Ministry of Environment, Industry and Trade
France	Aquaculture permit	To define selected species for cultivation, farming technique, site and adjacent protected areas, if any. Need of sanitary approval, if produced seaweed, is for food consumption, involvement of other marine users (fisheries, shellfish farming, other commercial transport routes), Mandatory qualification/ experience in seaweed farming.	> 8	Variable	Variable	National authorities, interregional authorities, regional authorities & departmental authorities
Germany	Aquaculture permit	Environmental impact assessment (EIA) is needed, no EIA obligation up to 50 t/a; > 1000 t/a EIA obligation. Focus on Biotope protection, Species protection, Nature conservation measures, and Coastal aquaculture authorization procedure of a State (excluding the Exclusive Economic Zone – EEZ, which is regulated at the Federal level). Designation of a mussel and oyster production area, no	–	–	–	Federal Waterways and Shipping Agencies (WSDs, GDWS for the coastal sea up to 12 nautical miles (NM) off the coast) or state-level authorities (BSH for the sea beyond the 12 NM zone)

(continued on next page)

Table 1 (continued)

COUNTRY	PERMITS	HIGHLIGHTS	PROCESS DURATION (Months)	VALIDITY (Years)	LEGAL COSTS	REGULATOR
Ireland	Aquaculture permit	introduction and husbandry of alien and alien species. Detailed project location, target size, type of equipment and techniques to be used. Consideration of “folios” (i.e., existing harvest rights, even from adjacent landowners), and whether the chosen foreshore area is state-owned (that is not always the case). To work with an experienced and well-connected marine engineer. Ireland’s Seafood Development Agency (BIM) can support the process, e.g., by providing technical expertise or business support.	12—18	Licence specific	Hectare dependant	Department for Agriculture, Food and the Marine
Latvia	Aquaculture permit	Focus on suitability of environmental conditions and species for cultivation, off the coast of Latvia using innovative, environmentally friendly and acceptable cultivation technologies for the Baltic Sea ecosystem, promoting freshwater aquaculture without impact to the environment and sustainable. Involvement of research institutes in the development of applied research and innovation in the aquaculture sector, involving local and foreign experts, as well as the provision of advice and demonstration on the development of aquaculture entrepreneurship, involvement of Public awareness.	> 13	Up to 30	—	Ministry of Agriculture: National Board of Fisheries
Lithuania	No licence	—	—	—	—	—
Norway	Seaweed cultivation licence Environmental impact assessment (If size > 10 ha)	Understanding the current land use plan of the planned site for seaweed farming, impacts on the environment as well as natural resources and society point of view, plan to reach local interest groups (e.g. fisheries or other aquaculture activity), engage local authorities, detail assessment of environmental impact, look into permit regulation for aquaculture activity.	6 – 24	No limit	24,000 NOK + deposit	Directorate of Fisheries, Norwegian Coastal Administration, Food Safety Authority, Norwegian Water Resources and Energy Directorate, County Governor (Directorate of the Environment), Municipality and Public
Poland	Cultivation of living organisms permit Water and building permits	Boosting aquaculture production contributes to sustainable employment and environmental protection.	—	—	—	Ministry of Maritime Economy and Inland Navigation: Fisheries Department
Scotland	Farming licence	Assessment of potential impacts on the environment, other sea uses, cultural heritage sites, and biosecurity (i.e., impacts of invasive species) as well as visual impacts. Use of NMPi (Part of Scotland Government) for finding an appropriate location.	10	6	700 £	Marine Scotland
Sweden	Water permit (if size > 0,3 ha)	Impact on environment, natural resources, and society, farming technique and equipment types.	> 15	—	Variable. Depends on the cost of the water activity plus the deposit.	Land and Environmental Court County Administrative Board
Australia (New South Wales)	Aquaculture Lease Aquaculture Permit Landowner consent Development consent	Detailed Environmental Impact Statement, seaweed farming as an approach to protect local species diversity	—	Up to 15	—	Fisheries Department within the Department of Primary Industries
USA (Maine)	Limited-purpose aquaculture licence (If size < 122 m <sup>2</sup> ) Experimental lease (If size < 1,6 ha) Standard lease (If size < 40 ha)	State-level lease frameworks (limited-purpose, experimental, and standard) enable commercial kelp farming in Maine, Alaska, and California (Grebe et al., 2019; FAO, 2020).	—	1	—	Maine Department of Marine Resources
USA (California)	State water bottom lease Operation permit	—	18 24—120	15	—	Fish and Game Commission, Department of Fish and Wildlife

comprehensive stakeholder involvement, it can also lead to increased administrative complexity and potential delays, especially as regulatory frameworks continue to evolve (Havhøst, n.d.; Moylan et al., 2017).

The requirement for an Environmental Impact Assessment (EIA) varies between licensing frameworks. For example, California, USA, mandates an Environmental Impact Report (Greenwave, 2018), while Ireland requires an Environmental Impact Statement (Moylan et al., 2017). In contrast, Sweden and the Danish Environmental Protection Agency determine the need for an EIA based on case-specific conditions (Camarena-Gómez et al., 2022; Havhøst, n.d.).

Norway takes a different approach: rather than imposing penalties, its licensing process includes a mandatory deposit serving as a cleanup fund if a company abandons a site due to bankruptcy (Barbier et al., 2019; Parker et al., 2014). The absence of explicit penalties creates a business-friendly environment by prioritizing upfront accountability over enforcement measures. Meanwhile, Denmark allows operators to choose between a bank guarantee or insurance. If the goal is a streamlined, non-punitive system that relies on upfront financial safeguards rather than penalties, Norway's deposit model is a clear, low risk template.

Seaweed aquaculture regulations differ across countries, reflecting varied environmental priorities and governance structures. Permits and EIAs are central to most systems, ensuring aquaculture activities align with sustainability goals and other marine uses (Table 1). For example, the protection of Natura 2000 sites and stakeholder engagement have been emphasised in Denmark. Similarly, Norway mandates detailed EIA for farms larger than 10 ha, underscoring environmental safeguards. These requirements are tailored to each country's ecological and economic context, often prioritizing biodiversity conservation, sustainable resource use, and compliance with regulations.

Several countries incorporate specialized measures to promote sustainable aquaculture. Finland, for example, focuses on reconciling aquaculture growth with good aquatic environmental status by improving environmental modelling and supporting organic farming. Ecosystem restoration and multi-trophic aquaculture systems, including seaweed and bivalve farming are prioritized in Estonia. Such approaches aim to enhance environmental outcomes while supporting economic resilience. Overall, seaweed aquaculture regulation balances ecological protection, economic development, and social acceptance. By adapting legal frameworks to local conditions, these systems support sustainable growth while mitigating environmental footprint.

With this review study, we present an integrated analysis of the complexities within the existing policy regime surrounding seaweed aquaculture. By adopting an ecosystem-based approach (Zhang and Thomsen, 2019), we aim to develop instruments that enable a restorative eco-industrial seaweed aquaculture sector. This approach is grounded in a triple-helix partnership involving industry (seaweed cultivation and biorefinery companies), local authorities, and research institutions, which serves as an innovation hub. Through this partnership, stakeholders implement an adaptive water-quality monitoring program to balance marine ecological integrity with the sustainable use of ecosystem services.

Central to this analysis is the concept of EES and EED, capturing the range of human-induced ecosystem outcomes, both beneficial and detrimental. To provide a comprehensive understanding, we map the EES/EED-stakeholder network, focusing on responsibilities, benefits, and costs. Additionally, we analyse how governance instruments influence interactions between seaweed aquaculture and EES/EED outcomes.

Finally, we propose an adaptive DPSIR policy framework that redefines *Pressure* as *Progress*, reflecting a shift from challenges to positive contributions within the seaweed aquaculture sector. We further distinguish between policy 'Responses' aimed at reducing impacts and those that restore regulating and maintenance services (biodiversity and water-quality restoration) (Forbes et al., 2022; Seghetta et al., 2016). The *Restore* element introduces a focus on the regenerative and circular capacities of seaweed farming, aligning the framework with nature

positive sustainability goals (European Commission, 2020).

This updated framework highlights the dynamic interplay among Drivers, Progress, States, Impacts, and Restore, capturing the sector's potential for sustainable growth and innovation. Supported by practical tools and instruments, it offers a cohesive strategy to guide the expansion of seaweed aquaculture while balancing environmental stewardship, economic development, and social well-being.

## 2. Methods

This study is based on a qualitative, desk-based synthesis of existing scientific and policy literature, to examine the interactions between seaweed aquaculture, ecosystem processes, and governance frameworks. The research proceeded in three steps: (1) reviewing literature to identify ecological functions and human-ecosystem linkages associated with seaweed farming; (2) classifying these processes according to the Common International Classification of Ecosystem Services (CICES v5.1) to distinguish provisioning, regulating and maintenance, and cultural dimensions; and (3) applying a snowball approach to trace policy instruments and responsible institutions across international, EU, and Danish levels. Insights from these steps were integrated to develop the analytical framework presented in Section 3 (Results and Discussion).

### 2.1. The ecosystem approach and the concept of ecosystem services

The ecosystem approach, adopted by the EU, FAO, and other organizations (Grebe et al., 2019; FAO, 2010; Langton et al., 2019), places human society at the center of social-ecological systems. Unlike fragmented sectoral approaches, the ecosystem approach connects human activities with the carrying capacity and structural integrity of ecosystems. Its goal is to protect and maintain ecosystem functioning while allowing for the sustainable use and development of society (Atkins et al., 2011).

The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) introduced the concept of ecosystem services (ES), bridging ecosystem conservation and socio-economic goals. ES are defined as the ecological processes that directly or indirectly contribute to human well-being, i.e., "the benefits that people derive from functioning ecosystems" (Millennium Ecosystem Assessment, 2005). In contrast, ecosystem disservices (ED) are processes that harm humans or the environment (Bermejo et al., 2022; Bhuyan, 2023; Campbell et al., 2019; Costanza et al., 2017; Hasselström et al., 2018).

This framework categorizes ES into three main types: provisioning, regulating and maintenance, and cultural services. Provisioning and cultural services directly support human well-being, while regulating and maintenance services sustain ecosystem functions. Since the Millennium Assessment, numerous studies have refined ES definitions and classifications (Burdon et al., 2023; Costanza et al., 2017; Haines-Young and Potschin-Young, 2018). While the ES concept clarifies the value of ecosystems (Costanza et al., 2017; TEEB, 2010), it often overlooks human responsibility for biodiversity conservation (Filbee-Dexter and Wernberg, 2018), which underpins both ecosystems and human well-being (Beyersdorff and Lanthén, 2018; WBCSD, 2020).

The complexity of the ES concept also makes it difficult for industrial stakeholders to apply (McKinley et al., 2019). To bridge this gap, we introduce the concept of EES and EED for seaweed aquaculture. This framework identifies processes and functions that yield either beneficial or harmful outcomes, for both people and ecosystems, and maps affected stakeholders according to their roles and interests, linking them to policy instruments influencing EES/EED outcomes.

### 2.2. Snowball approach to mapping instruments and institutions

This study adopts the Common International Classification for Ecosystem Services (CICES) V5.1 (Haines-Young and Potschin-Young, 2018), which uses a five-level hierarchy, section, division, group,

class, and class type, to differentiate services. The three primary sections, provisioning, regulating, and cultural, form the basis for mapping EES/EED in seaweed aquaculture.

Case studies from the literature (Cabral et al., 2016; Campbell et al., 2019; Duarte and Krause-Jensen, 2018; Grebe et al., 2019; Hasselström et al., 2018), provide insights into positive and negative impacts in different geographic and disciplinary contexts. While this mapping outlines key patterns, the scale and intensity of impacts depend on local conditions, which are beyond the scope of this study.

### 2.2.1. Study area

The research focuses on regions with emerging seaweed aquaculture, particularly Denmark, which serves as the focal case for mapping policy instruments and institutional landscapes. Denmark's coastal and marine ecosystems (Fig. 2) provide numerous ecosystem services (Inácio et al., 2020; Turner et al., 2014). Seaweed aquaculture remains at an early stage compared to Asia (FAO, 2020), but cultivation of *Saccharina latissima* has reached up to 10 tonnes of wet biomass per hectare (Barbier et al., 2019), alongside technologies for *Palmaria palmata* (red dulse) and *Ulva* spp. (sea lettuce) (Schmedes and Nielsen, 2020; Steinhagen et al., 2021; Stévant et al., 2023).

Denmark currently hosts two *S. latissima* research sites (12 ha and 18.7 ha), two commercial producers (0.4 ha and 18.7 ha), and forty small marine gardens recently granted permits (Havhøst, n.a.).

**2.2.1.1. Mapping of instruments and institutions.** To map instruments and institutions related to Danish seaweed aquaculture, this study employs a snowball approach (Alexander et al., 2015), starting from scientific literature, industry reports, and legal databases such as EUR-Lex for EU laws, and resources from the Danish Maritime Authority and the Ministry of Environment for national environmental policies and regulations. Global sources, including FAOLEX and the European Maritime and Fisheries Fund (EMFF), provided insights into international and EU frameworks. Local databases and institutions such as the former National Environmental Research Institute (NERI) – now part of Aarhus University – provided relevant information on national research and environmental regulations.

Each identified policy instrument served as a reference point to locate additional ones, and institutions were mapped through literature review and targeted keyword searches (e.g. 'seaweed aquaculture Denmark,' 'marine policy Denmark,' 'aquaculture regulations Denmark,' and 'seaweed farming Denmark').

Following Vedung (1998), an instrument is defined as “a set of techniques by which governmental and non-governmental authorities exercise their power to secure support and influence (or prevent) societal change”. Instruments were categorised according to Bouwma et al. (2015), encompassing (1) legislative and regulatory instruments, (2) economic instruments, (3) agreement-based or cooperative instruments, (4) information and communication instruments, and (5) knowledge and innovation instruments. Information and communication instruments influence stakeholder behaviour by raising awareness and promoting transparency, for example through public campaigns or product labelling, whereas knowledge and innovation instruments foster learning and collaboration through workshops, networks and innovation partnerships.

## 3. Results and discussion

Fig. 3 provides an overview of the identified provisional (P), regulating and maintenance (R) and cultural (C) EES and EED associated with seaweed aquaculture. It also highlights the policy instruments addressing marine and coastal ecosystem health (e.g., farm location and its ecological context), maritime activities, and the stakeholders involved in the Danish seaweed value chain.

### 3.1. Mapping of engineered ecosystem services and disservices from seaweed aquaculture

Stakeholders involved in ecosystem management, maritime activities, and seaweed value chains are affected by EES and EED from seaweed aquaculture as shown in Fig. 3 (left). Examples of EES and EED experienced by different types of stakeholders are described in sections 3.1.1 to 3.1.3 and summarised in Tables 2 and 3.

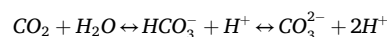
#### 3.1.1. Ecosystem — From farming sites to broader ecosystems

Most mapped regulating and maintenance EESs are relevant for stakeholders with environmental objectives. Their areas of influence range from on-farm processes to wider coastal and marine ecosystems, and, ultimately, to global atmospheric systems.

While all ESs are purposive (Haines-Young and Potschin-Young, 2018), regulating and maintenance ESs have less direct links to human beneficiaries (Sutherland et al., 2018). ESs such as food-web enhancement and eutrophication control are intermediate services that can deliver final benefits through cascading effects (Hasselström et al., 2018).

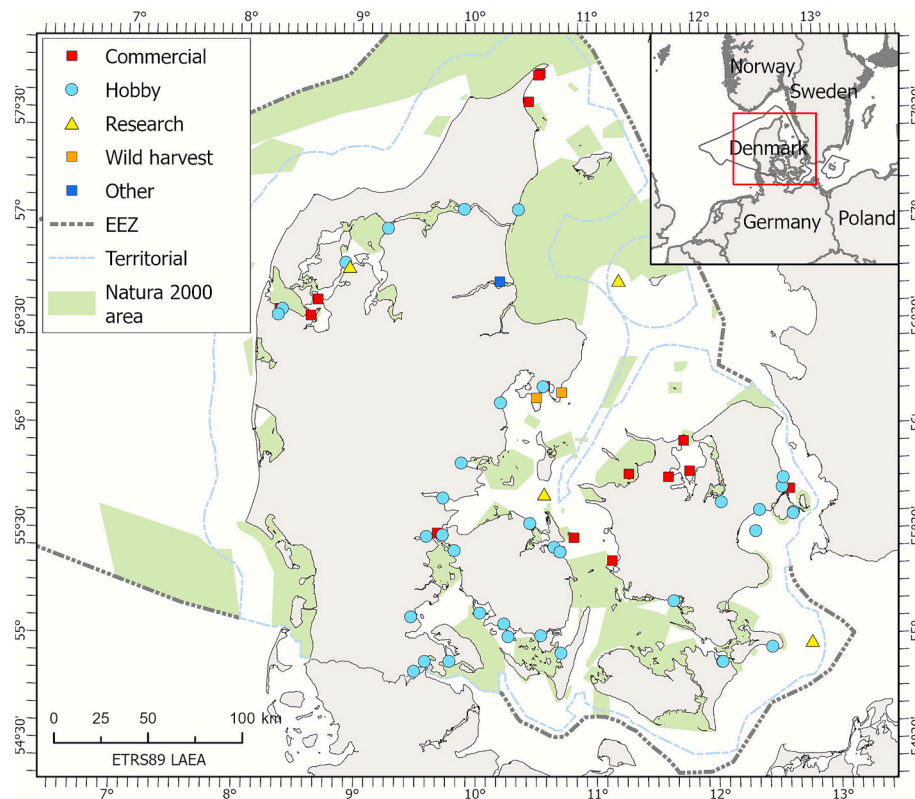
In aquatic systems, ES are hydrologically linked and interdependent (Sutherland et al., 2018). Seaweeds, as primary producers, enhance oxygenation and seawater pH (Gao and Beardall, 2022). Bottom-up effects may enrich biodiversity at farm or seascape levels, benefitting stakeholders such as fishers and divers, though such effects remain hypothetical (Forbes et al., 2022). Seaweed aquaculture thus complements natural provisioning and cultural services.

Seaweeds are autotrophs that form complex organic compounds from sunlight, water, carbon dioxide (CO<sub>2</sub>), and nutrients such as N and P. During photosynthesis, seaweeds rely on dissolved inorganic carbon, which exists predominantly as bicarbonate (HCO<sub>3</sub><sup>-</sup>) in seawater. Because Rubisco can only fix CO<sub>2</sub>, many species have evolved strategies to enhance CO<sub>2</sub> supply. Some utilise carbon concentrating mechanisms (CCMs) that actively transport HCO<sub>3</sub><sup>-</sup> and convert it to CO<sub>2</sub> within the cell (Giordano et al., 2005). Others modify the pH of their diffusive boundary layer using proton pumps that release H<sup>+</sup>, creating a locally acidic microenvironment that promotes HCO<sub>3</sub><sup>-</sup> conversion to CO<sub>2</sub>, thus making it available for photosynthesis (Xu et al., 2023). These processes collectively influence the surrounding seawater carbonate chemistry, governed by the following equilibrium:



Large-scale farming shifts this equilibrium by reducing dissolved CO<sub>2</sub> and HCO<sub>3</sub><sup>-</sup> concentrations, decreasing free hydrogen ions (H<sup>+</sup>) (Gao and Beardall, 2022; Xiao et al., 2021). This mitigates ocean acidification, benefiting calcifying organisms such as molluscs and crustaceans (Table 3; EES R3) (Jiang et al., 2022; Langton et al., 2019). Seaweed farms also assimilate N and P, delivering engineered regulating service of eutrophication mitigation (Table 3; EES R1), which improves water quality in nutrient-rich zones (García-Poza et al., 2022; Kotta et al., 2022; Zhang et al., 2022). Improved water quality can support wild fish populations and fisheries productivity; an EES valued by fishermen and consumers (Grebe et al., 2019).

The complex interrelationships between aquatic ESs, and the challenge of translating them into tangible benefits, make it difficult to value regulating and maintenance EES for stakeholders outside ecosystem management. Similarly, mismanagement or poor farm design (Table 3; Table 3; EEDs R6, R9, R14, R15, R19) can generate EED that threaten ecosystem health, including disease transmission, invasive species conveyance, altered community structure, and megafaunal mortality. Physical impacts include noise, shading, or nutrient depletion which may limit phytoplankton growth (Campbell et al., 2019; Grebe et al., 2019; Hasselström et al., 2018). However, concerns about nutrient depletion (Table 3; EED R2) remain largely hypothetical, as eutrophication stemming from excess nutrient loads is still widespread. Seaweed



**Fig. 2.** Distribution of Danish seaweed cultivation and harvesting sites overlaid with Natura 2000 areas within Denmark's Exclusive Economic Zone (EEZ). Site types include commercial, hobby (marine gardens), research, wild harvest, and other seaweed-related uses, based on data from the Danish Coastal Authority (<https://geodata-info.dk/srv/dan/catalog.search#/metadata/c9dfb6e3-c15e-4975-9094-bb27a985a0e2>) and Havhøst (havhost.dk), supplemented by expert input. Hobby sites are derived from Havhøst listings and may include mussel-only gardens. All other categories represent seaweed activities recorded in the Danish Coastal Authority's registry of marine structures. Green shaded areas indicate Natura 2000 sites (EU habitat and bird protection areas) (<https://geodata-info.dk/srv/dan/catalog.search#/metadata/a41eda70-0705-4641-8013-bb7348383eb7>). Borders to the EEZ and territorial waters are shown with dashed grey and blue lines, respectively (<https://geodata-info.dk/srv/dan/catalog.search#/metadata/08fc57cd-23fa-416f-8c46-61ab65e91379>). The inset shows Denmark's regional location in northern Europe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

farming therefore offers a nature-based solution to absorb excess nutrients (Andersen et al., 2019; Seghetta et al., 2016).

Although not directly related to seaweeds, modelling studies of bivalve-phytoplankton interactions (Gatti et al., 2023) show how nutrient competition can influence pelagic food webs.

The placement of farms is a key determinant of ecosystem effects (Table 3; R5–R10; Fig. 3, left panel) (Bruhn et al., 2016, Buck & Grote 2018). Impacts originate at the farm scale and propagate to surrounding ecosystems (Guerry et al., 2012; Visch et al., 2020). The alteration of local ecosystem processes is often most direct and immediate, and can be severe depending on the scale of operation. Kelly et al. (2020) reviewed carrageenophyte seaweed farming in 43 tropical and subtropical countries and reported overgrowth of corals by farmed seaweed species in eight cases, reduced productivity and shoot density of seagrass beds in five studies, and altered meiofaunal abundance and diversity in six studies. Similar negative effects may be anticipated in large-scale farms due to light limitation for understory seaweed forests. However, such impacts can be mitigated by using smaller farming units and locating farms in deeper waters (Table 3; R9, R17). In Denmark, this precautionary approach is already implemented in practice, as seaweed cultivation licences are generally granted only in water depth beyond the potential expansion zone of eelgrass.

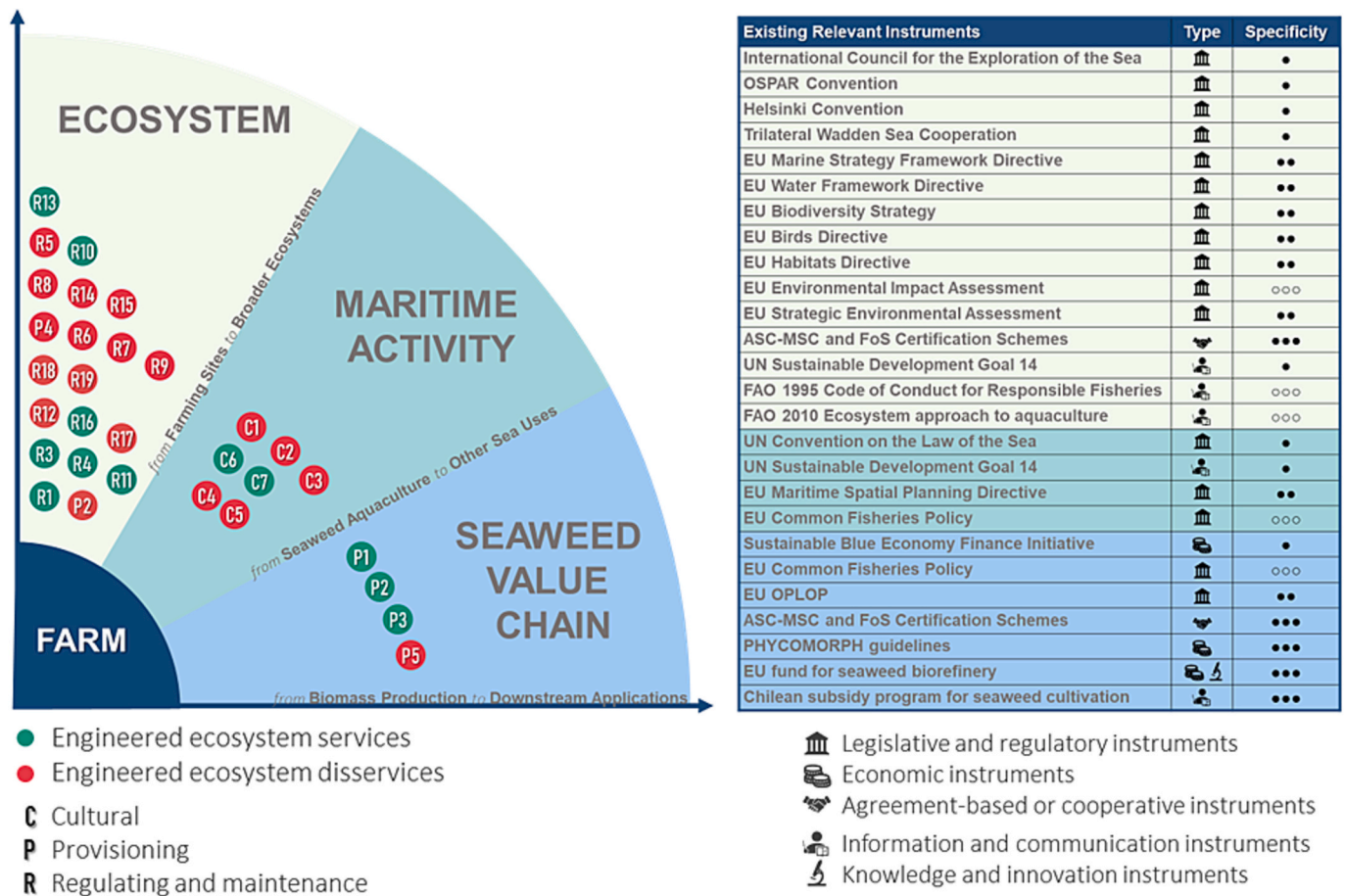
### 3.1.2. Marine activity — From seaweed aquaculture to other uses of marine space

Seaweed aquaculture is a relatively new component within the complex network of socio-economic and political interests that characterise marine stakeholder interactions. The grow-out phase requires at-

sea cultivation structures to support the growth substrate. These systems are positioned at the desired depth and location using buoys for buoyancy and anchors or weights for stability (Zhang et al., 2022). However, this occupation of marine space can conflict with other users' interests, particularly those dependent on natural and cultural ES. For example, seaweed farms may reduce the aesthetic value of seascapes and the perceived sense of wilderness, potentially diminishing spiritual or recreational experiences. In addition, these structures can impede navigation, diving, or other activities conducted in close proximity.

The engineered cultural disservices associated with seaweed farming (Table 2) stem from these potential conflicts with other marine activities. Such disservices can negatively influence stakeholders well-being by limiting their "freedom of choice and action", a key dimension of well-being identified in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005). The extent and severity of these impacts depend largely on stakeholder perceptions, which are shaped by their professional affiliations, institutional roles, and priorities in marine spatial planning and landscape management.

To mitigate conflicts and foster synergies, studies have suggested locating seaweed farms offshore and integrating them with other marine activities. Promising approaches include multi-use platforms (MUPs) with offshore wind farms and integrated multi-trophic aquaculture (IMTA) systems (Table 3; EES R10, R13; Fig. 3, right panel) that combine seaweed with fed species such as finfish and shrimp (Buck et al., 2018; Guyot-Téphany et al., 2024; Maar et al., 2023; Van den Burg et al., 2020a). These systems can reduce maintenance costs, enhance nutrient cycling between fed and extractive aquaculture, maximize spatial efficiency, and lower infrastructure demands. Empirical evidence indicates



**Fig. 3.** The left panel maps stakeholders affected by regulating and maintenance (R), provisioning (P), and cultural (C) engineered ecosystem services (green circles) and disservices (red circles) arising from seaweed aquaculture. The right panel illustrates policy instruments relevant to i) seaweed aquaculture stakeholders and the broader marine ecosystem (beige background), ii) seaweed cultivation and other marine space uses (light green background color) and iii) seaweed processing and downstream applications (blue background). Instruments are classified following Vedung (1998) and rated according to their specificity to seaweed aquaculture (the number of dots indicates the level of specificity, while hollow dots denote instruments that do not yet include seaweed aquaculture but could do so in future updates. Abbreviations: OSPAR Convention (The Convention for the Protection of the Marine Environment of the North-East Atlantic), EU (European Union), ASC-MSC (Aquaculture Stewardship Council and Marine Stewardship Council), FoS (Friend of the Sea), UN (United Nations), OPLP (Organic Production and Labelling of Organic Products). ES types and numbers are provided in Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both ecological and economic benefits, as well as favourable stakeholder attitudes (Budhathoki et al., 2024; Freitas et al., 2016). For instance, monitoring studies have reported a twofold increase in protein content in *S. latissima* biomass cultivated within IMTA systems, enhancing its commercial value for food and feed applications (Freitas et al., 2016).

### 3.1.3. Seaweed value chain — From biomass production to downstream applications

During growth, seaweed assimilate dissolved carbon and a range of macro- and micro-nutrients, converting them into carbohydrate-rich biomass. The biomass can be used directly for food and feed applications or processed into chemicals and biofuels (Table 2; EES P1–P3) (Buschmann et al., 2017). Downstream enterprises along the seaweed value chain benefit from the provisioning EES of seaweed production. In food applications (Table 2), these services further benefit consumers by enhancing food security and nutritional value (Bjerregaard et al., 2016; OECD, 2016).

However, elevated concentrations of heavy metals and iodine can limit the use of edible seaweeds (Table 2; EED P5; Table 3; EES R4) or necessitate additional processing to comply with food-safety regulations (Cherry et al., 2019; Hogstad et al., 2023). Consumer perceptions in European markets increasingly favour seaweed-based products for their health and sustainability attributes, although, concerns about metal or

iodine content may constrain acceptance in some regions (Tunca et al., 2024).

### 3.2. Mapping of policy instruments relevant to seaweed aquaculture

Management mechanisms of these policy instruments relevant to seaweed aquaculture are diverse, with legislative and regulatory instruments dominating at higher administrative levels. While Fig. 3 (right) presents an overview of the existing policy instruments, the following subsections describe key examples addressing ecosystem health, maritime activity, and seaweed value chains.

#### 3.2.1. Ecosystem — From farming sites to broader ecosystems

##### 3.2.1.1. Legislative and regulatory instruments.

Denmark is a member of the International Council for the Exploration of the Sea (ICES), an intergovernmental marine-science organisation. ICES developed a strategic plan (ICES, 2019) to guide science, data, and advisory priorities, and to strengthen capacity for understanding marine ecosystems and the benefits they provide (ICES, 2019).

The OSPAR commission produced a North-East Atlantic Environment Strategy 2010–2020 (OSPAR Commission, 2010) focusing on five themes, including biodiversity and ecosystem protection,

**Table 2**

Mapped provisioning and cultural engineered ecosystem services and disservices delivered by seaweed aquaculture to different stakeholders, based on literature sources. The classification follows CICES v5.1 (Haines-Young and Potschin-Young, 2018). The “+” symbols denote services (benefits to stakeholders), whereas the “-” symbols indicate disservices (negative impacts on stakeholder well-being). Determinants refer to factors influencing the scale and intensity of these services and disservices.

Classification Section	Division	From	Mapped EES and/or EEDs To	Type	Ref 1	No. <sup>2</sup>	Activities From	Stakeholders To	Determinants Influential factors
Provisioning	Nutrition	Macroalgae	Food or feed ingredient/supplement, proteins, dietary fibre, iodine, etc.	+	b, c, e	[P1]	Biomass production	Seaweed business & Consumers (basic material for good life)	Productivity Biomass quality (no fouling) Consumer preference
	Energy	Biorefinery feedstocks	Biofuels	+	b, e	[P2]	Biomass production	Seaweed business & Consumers (basic material for good life)	Productivity Consumer preference
	Materials	Biorefinery feedstocks	Chemicals or materials, e.g. phycocolloids, biostimulants, mannitol	+	b, e	[P3]	Biomass production	Seaweed business & Consumers (basic material for good life)	Productivity Consumer preference
		Littering	Cultivation infrastructural components	-	a	[P4]	Loss of cultivation infrastructural components	Marine and costal ecosystems	Materials of the components
	Toxicity	Macroalgae	Heavy metal	-	c	[P5]	Bioabsorption during biomass growth	Seaweed business & Consumers (health)	Product standards
Cultural	Symbolic	Aesthetic	Disturbed view of the landscape	-	b, d	[C1]	Cultivation structure	Sea users & Coastal communities (freedom of choice)	Marine spatial plans Public perception
		Cognitive	Sense of place Iconic wildlife and habitat Natural heritage	-	b, e	[C2]	Seaweed aquaculture	Sea users & Coastal communities (freedom of choice)	Marine spatial plans Public perception
		Spiritual	Sense of wilderness and naturalness	-	f	[C3]	Seaweed aquaculture	Sea users & Coastal communities (freedom of choice)	Marine spatial plans Public perception
	Experiential	Recreational	Access to water ways and water columns	-	b, d, e	[C4]	Sea occupation	Sea users, e.g. safari business divers (freedom of action)	Marine spatial plans Existing marine activities
		Commercial	Access to water ways and seabed	-	b	[C5]	Sea occupation	Sea users, e.g. shipping and aggregates extraction business (freedom of action)	Marine spatial plans Existing marine activities
	Intellectual	Educational & Inspirational	Genetic patterns	+	b, e	[C6]	Seaweed aquaculture	Biological researchers (human-nature relation)	Genetic diversity
Programs and books			+	b	[C7]	Seaweed aquaculture	Public (human-nature relation)	Public perception	

<sup>1</sup>Reference: a (Campbell et al., 2019); b (Hasselström et al., 2018); c (Langton et al., 2019); d (Cabral et al., 2016); e (Pereira et al., 2020); f this study.<sup>2</sup>P and C represents provisional and cultural ecosystem services.

eutrophication, hazardous substances, offshore industry, and radioactive substances. It promotes the ecosystem approach, and a joint assessment and monitoring programme (Inácio et al., 2020; Kotta et al., 2022). Denmark also participates in regional agreements including the Trilateral Wadden Sea Cooperation<sup>1</sup>(Germany, the Netherlands and Denmark) and the Helsinki Commission<sup>2</sup> (HELCOM) for the Baltic Sea (MST, 2020). Nationally, monitoring obligations are fulfilled through the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments (NOVANA)<sup>3,4</sup> which performs monitoring and

<sup>1</sup> The Trilateral Wadden Sea Cooperation. Link: <https://mst.dk/natur-vand/natur/international-naturbeskyttelse/det-trilaterale-vadehavssamarbejde/>.

<sup>2</sup> HELCOM. Link: <https://helcom.fi/>.

<sup>3</sup> NOVANA program description 2017–2021. Link: <https://mst.dk/media/141463/novana-2017-21-programbeskrivelse.pdf>.

<sup>4</sup> NOVANA national monitoring program in Denmark. Link: <https://mst.dk/natur-vand/overvaagning-af-vand-og-natur/>.

quality-assurance activities across eight sub-programs, including sea and fjords, lakes, streams, substance transport, point sources, groundwater, terrestrial habitats, and air.

The Marine Strategy Framework Directive (MSFD) 2008/56/EC<sup>5</sup> aims to protect marine ecosystems and resources. It required Member States to develop strategies for their marine waters and to apply the ecosystem-based approach to achieve Good Environmental Status (GES). Eleven descriptors characterise GES (Annex I of MSFD 2008/56/EC). Those relevant to seaweed aquaculture include D1 biological diversity, D2 non-indigenous species, D4 marine food webs, D5 eutrophication, D6 sea-floor integrity, D7 hydrographical conditions, D8 contaminant concentrations, D9 contaminants in seafood, D10 marine litter, and D11

<sup>5</sup> MSFD 2008/56/EC. Link: <https://data.europa.eu/eli/dir/2008/56/oj>.

**Table 3**

Mapped regulating and maintenance engineered ecosystem services and disservices delivered by seaweed aquaculture to different stakeholders, based on literature sources. The classification follows CICES v5.1 (Haines-Young and Potschin-Young, 2018). The + symbols denote services (benefits to stakeholders), whereas the – symbols indicate disservices (negative impacts on stakeholder well-being). Determinants refer to factors influencing the scale and intensity of these services and disservices.

Classification Section	Division	Group	EES (+) and EED (–) Class	Type	Ref <sub>1</sub>	No. <sup>1</sup>	Activities From	Stakeholders To	Determinants Influential factors
Regulating and Maintenance	Biophysical environment	Bioremediation	Eutrophication mitigation	+	<i>a, b</i>	[R1]	N and P assimilation during seaweed biomass growth	Marine ecosystem	N and P assimilation rates
			Lack of nutrients for phytoplankton	–	<i>a, e</i>	[R2]	N and P assimilation during seaweed biomass growth	Marine ecosystem	Background nutrient levels of the farm location
			Ocean acidification mitigation	+	<i>c</i>	[R3]	Carbon capture during photosynthesis	Marine ecosystem	Carbonate chemistry of marine waters Atmospheric concentration of CO <sub>2</sub> Heavy metal adsorption rate
			Heavy metal removal	+	<i>c</i>	[R4]	Bioabsorption during biomass growth	Marine ecosystem	
			Beach casting	–	<i>f</i>	[R5]	Biomass loss at sea	Coastal ecosystem	Engineering and farm design Harvest schedule
			Sedimentation and organic enrichment	–	<i>b, e</i>	[R6]	Loss of biomass or release of particulate organic matter	Marine ecosystem	Engineering and farm design Ecosystem community at the farm location
	Physio-chemical environment	Soil quality	Seabed cracking	–	<i>f</i>	[R7]	Installation of anchors on seabed	Marine ecosystem	Ecosystem community at the farm location
		Sound condition	Noise	–	<i>a</i>	[R8]	Installation of anchors and at-sea transportation	Marine ecosystem	Acoustical instrumentation to reduce noise from machinery and boat
		Light conditions	Shading for benthic community	–	<i>a, b</i>	[R9]	Absorption of light	Marine ecosystem	Spacing of the moored lines Benthic community at the farm location
	Flow regulation	Water flow	Coastal protection and prevention of coastal erosion	+	<i>a, b</i>	[R10]	Cultivation systems attenuate waves and dissipate energy	Coastal community (security)	Hydrodynamics Engineering and farm design
		Air flow	Microclimate regulation	+	<i>c</i>	[R11]	Oxygenation through photosynthesis	Marine ecosystem	Oxygen consumption and production rate
			Greenhouse gas regulation	–	<i>b</i>	[R12]	Emissions of halocarbons	Marine ecosystem	Emission rate of halocarbons
					+	<i>a, b, e</i>	[R13]	Carbon capture through photosynthesis	Global climate (health restoration)
	Biotic environment	Habitat and gene pool protection	Altered composition of local community and genetic composition of local seaweeds	–	<i>a</i>	[R14]	Release of reproductive materials of invasive species or robust breeds	Marine ecosystem	Choice of species Origins of seeding materials
			Mortality of megafauna	–	<i>a</i>	[R15]	Entanglement by cultivation lines	Marine ecosystem	Structure of growth substrate
			Creation of new habitats for epiphytes and non-indigenous species	+	<i>c</i>	[R16]	Cultivation systems provide habitat	Marine ecosystem	Harvest schedule
			Alternations between benthic and surface habitats	–	<i>c</i>	[R17]	The temporary existence of the floating cultivation system	Marine ecosystem	Ecosystem community and wild populations at the farm location
			Increased food dynamics via herbivores	+	<i>c</i>	[R18]	Biomass growth taking the role of primary production	Marine ecosystem	Harvest schedule Site selection
		Facilitation of algal diseases and parasites (e.g. bryozoan)	–	<i>a, c</i>	[R19]	Cultivation systems provide routes of transmission and habitat	Marine ecosystem	IMTA or monoculture Spacing of the moored lines	

<sup>1</sup>Reference: *a* (Campbell et al., 2019); *b* (Hasselström et al., 2018); *c* (Langton et al., 2019); *d* (Cabral et al., 2016); *e* (Pereira et al., 2020); *f* this study. <sup>2</sup>R represents regulating and maintenance ecosystem services.

underwater noise. According to the WISE<sup>6</sup> marine information system, Denmark did not achieve GES for D5 and D9 by 2020. By 2021, Denmark and other EU member states were required to revise action plans for 2021–2027 under MFSD.

The EU Water Framework Directive (WFD) 2000/60/EC<sup>7</sup> aims to achieve “good ecological status” for European surface waters (Capuzzo and McKie, 2016). Seaweed farms located within 1 NM of the coast and with potential to affect water quality should therefore be assessed under the WFD.

Marine-biodiversity protection is also ensured through the EU Biodiversity Strategy for 2030,<sup>8</sup> the Birds Directive 2009/147/EC,<sup>9</sup> and the Habitats Directive 92/43/EEC.<sup>10</sup> Over 8% of EU marine areas are designated Natura 2000 sites<sup>11</sup> (EEA, 2018), forming a network of protected areas covering Europe’s most valuable and threatened species and habitats.<sup>12</sup>

The Environmental Impact Assessment (EIA) Directive 2011/92/EU<sup>13</sup> requires mandatory EIA for Annex II projects potentially causing significant environmental effects; seaweed aquaculture may fall under Annex II project (Wood et al., 2017), with the need of an EIA determined by national authorities. The Strategic Environmental Assessment (SEA) Directive 2001/42/EC applies to public plans and programs, requiring SEA where activities overlap with the Habitats Directive or set a framework for Annex I EIA projects. Consultation and scoping of the SEA report are mandatory. In 2019, three seaweed-aquaculture permits were granted in Denmark without an EIA requirement owing to their small scale and location outside Natura 2000 sites (Kystdirektoratet, 2014; Kystdirektoratet, 2015; Anker et al., 2024). By contrast, California (USA) mandates an EIA for seaweed-cultivation licences, with high application costs and processing times (Greenwave, 2018).

**3.2.1.1.1. Agreement-based or cooperative instruments.** Voluntary third-party certification schemes are increasingly recognised as effective tools in global markets, including Europe and North America, enabling environmentally conscious consumers to choose sustainable aquaculture products (FAO, 2018).

Two certification schemes apply to seaweed aquaculture: the Aquaculture Stewardship Council and Marine Stewardship Council (ASC-MSC) Seaweed Standard (ASC-MSC, 2020) and Friend of the Sea Standard for Seaweeds and Algae Products (World Sustainability Organization, 2020). Both aim to conserve marine habitats by promoting certified products from responsible producers. The FoS Standard includes criteria for management systems, legal compliance, biomass and environmental impact assessments, water and air monitoring, waste management, and the use of chemicals and hazardous substances (World Sustainability Organization, 2020).

The ASC-MSC Standard applies a risk-based framework (ASC MSC, 2018) including productivity-susceptibility and consequence analyses across spatial scopes and scales. FoS requirement 3.2 mandates a positive EIA or equivalent assessment for producers harvesting 20 tonnes or more annually, supported by an independent regional or national assessment (World Sustainability Organization, 2020).

<sup>6</sup> WISE marine information system for europe. Link: <https://water.europa.eu/marine/countries-and-regional-seas/country-profiles/denmark>.

<sup>7</sup> WFD. Link: <http://data.europa.eu/eli/dir/2000/60/2014-11-20>.

<sup>8</sup> Biodiversity Strategy. Link: [https://ec.europa.eu/environment/nature/biodiversity/strategy/index\\_en.htm](https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm) Communication. Link: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0380&qid=1607357125048>.

<sup>9</sup> Birds Directive. Link: [https://ec.europa.eu/environment/nature/legislation/birdsdirective/index\\_en.htm](https://ec.europa.eu/environment/nature/legislation/birdsdirective/index_en.htm).

<sup>10</sup> Habitats Directive. Link: [https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index\\_en.htm](https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm).

<sup>11</sup> Natura 2000 Network (all sites map): <https://natura2000.eea.europa.eu/>.

<sup>12</sup> Natura 2000 Network <https://www.eea.europa.eu/themes/biodiversity/natura-2000>.

<sup>13</sup> EIA Directive. Link: <https://data.europa.eu/eli/dir/2011/92/oj>.

**3.2.1.1.2. Information and communication instruments.** UN Sustainable Development Goal 14 (Life Below Water)<sup>14</sup> sets targets to protect marine environments, including reducing nutrient and debris pollution (14.1), ecosystem-based management (14.2), mitigating ocean acidification (14.3), and integrating the United Nations Convention on the Law of the Sea (UNCLOS) into national legal frameworks to enhance conservation and sustainable use of oceans and their resources (14.c).

FAO technical guidelines promote responsible aquaculture practices that conserve aquatic resources and biodiversity. Key documents include the 1995 Code of Conduct for Responsible Fisheries<sup>15</sup> and the Ecosystem Approach to Aquaculture Strategy and Principles (FAO, 2010). Although not written for seaweed aquaculture, they are relevant due to the sector’s contribution to multiple UN SDGs (Bermejo et al., 2022; Duarte et al., 2021; Gao and Beardall, 2022; García-Poza et al., 2022; Spillias et al., 2022).

These frameworks have been applied to seaweed context, for example by Grebe et al. (2019) in Maine (USA) to map potential impacts and ensure long-term sustainability, and by Inácio et al. (2020) to assess and map marine ecosystem services in Denmark and the Baltic Sea.

### 3.2.2. Marine activity — From seaweed aquaculture to other uses of marine space

Managing engineered cultural ES and ED requires integrated marine spatial planning instruments that consider the diverse interests of coastal communities. In Denmark, governance of aquaculture and other marine activities is regulated by primary and secondary legislation at local, regional, and global scales. According to the UNCLOS, the Exclusive Economic Zone (EEZ) grants states special rights to explore and use marine resources, including energy production from water and wind (UN, 1982). The EEZ extends 12 to 200 NM from the coast, or to neighbouring EEZ boundaries. Denmark’s EEZ covers the North Sea, Skagerrak, Kattegat, Belt Sea, Sound, western Baltic Sea (the area around Bornholm), and sea areas of the constituent country of Greenland and the constituent country of the Faroe Islands (MST, 2020).

The EU Maritime Spatial Planning Directive (MSPD) 2014/89/EU<sup>16</sup> provides a framework for member states to develop maritime spatial plans that consider land-sea interactions, cross-border cooperation, and stakeholder involvement to promote the coexistence of activities. The MSPD was transposed into Danish laws (Act 615<sup>17</sup>) in 2016. Denmark’s first maritime spatial plan (MSP), prepared by the Danish Maritime Authority,<sup>18</sup> entered into force in March 2021 (an overview of the MSP of EU countries is available on the MSP platform<sup>19</sup>) and is subject to a SEA.<sup>20</sup>

In Europe, the Common Fisheries Policy (CFP) Regulation (EU) No 1380/2013<sup>21</sup> remains the only coherent regulation for aquaculture. It focuses on conserving marine biological resources and improving access to space and water. Although seaweed aquaculture is not yet covered by the CFP, its inclusion is possible as the sector matures.

### 3.2.3. Seaweed value chain — From biomass production to downstream applications

Global demand for contaminant-free, traceable edible seaweeds is

<sup>14</sup> UNSDG 14. Link: <https://sdgs.un.org/goals/goal14>.

<sup>15</sup> 1995 Code of Conduct for Responsible Fisheries. Link: <https://www.fao.org/fishery/code/en>.

<sup>16</sup> MSPD 2014/89/EU. Link: <https://data.europa.eu/eli/dir/2014/89/oj>.

<sup>17</sup> Act on MSP. Link: <https://www.dma.dk/Vaekst/Rammevilkaar/Legislation/Pages/Acts.aspx>.

<sup>18</sup> Danish Maritime Authority. Link: <https://www.dma.dk/Vaekst/Havplan/Pages/default.aspx>.

<sup>19</sup> European MSP platform. Link: <https://www.msp-platform.eu/>.

<sup>20</sup> Danish Maritime Authority. Link: <https://www.dma.dk/Vaekst/Havplan/Pages/default.aspx>.

<sup>21</sup> CFP. Link: <http://data.europa.eu/eli/reg/2013/1380/2019-08-14>.

increasing (CEVA, 2019; SAPEA, 2017), requiring management plans ensuring biomass quality and supply (Hogstad et al., 2023; Kulikowski et al., 2021). The CFP highlights the need for increasing competitiveness and exploiting competitive advantages due to high quality, health, and environmental standards.

Given its potential within the Blue Bioeconomy (European Commission, 2020), seaweed aquaculture attracts significant research and business investment. The PHYCOMORPH guidelines (Barbier et al., 2019) provide European stakeholders with science-based recommendations on seaweed cultivation, applications, and legislation.

Development is further supported by public and private funding, including EU projects on algae biorefineries (European Commission, 2016, 2020) and national subsidies such as the Restocking and Cultivation of Seaweeds in Chile (Henríquez-Antipa and Cárcamo, 2019). The Sustainable Blue Economy Finance Initiative<sup>22</sup> developed by the European Commission, WWF, the World Resources Institute and the European Investment Bank, guides financial institutions and organisations to align lending and insurance practices with ocean conservation and sustainable blue growth.

Concerning biomass quality, the Environmental Quality Standards (EQS) Directive 2008/105/EC<sup>23</sup> regulates chemical pollution in surface waters, while the Organic Production and Labelling of Organic Products (OPLP) Regulation 2018/848<sup>24</sup> governs the output quality of seaweed farms. In Denmark, production and marketing of organic food follow the OPLP regulation (MFF, 2020). Product-labelling systems should be developed to provide consumers clear guidance on treatment of the edible biomass (e.g. hot water rinsing) and recommended daily intake to avoid risks from high iodine levels, or arsenic accumulation (Bouga and Combet, 2015).

The mapping of engineered ecosystem services and disservices (EES/EED), together with the analysis of relevant policy instruments and institutional frameworks, reveals both the transformative potential and regulatory challenges of seaweed aquaculture. Current frameworks focus mainly on mitigating environmental pressures but often overlook the sector's restorative potential, such as nutrient cycling, habitat regeneration, and biodiversity enhancement. To develop a more regenerative and integrated seaweed sector, a balanced and forward-looking framework is required—one that explicitly captures both the beneficial and adverse effects of aquaculture practices across ecosystems, marine activities, and value chains.

In response, we propose an updated DPSIR framework tailored to seaweed aquaculture, redefining the traditional element of *Pressure* as *Progress* to better reflect the sector's contributions to ecosystem restoration and innovation.

### 3.3. Novel DPSIR: From Pressure to Progress

Building on the need for a balanced and integrative framework, this section presents a novel adaptation of the DPSIR model (Driver–Pressure–State–Impact–Response) (Smeets and Weterings, 1999), specifically designed for seaweed aquaculture. Our approach redefines *Pressure* as *Progress*, highlighting seaweed farming's potential not only to reduce environmental harm but also to restore ecosystem health. The updated model provides a transparent, adaptive management tool that captures both engineered ecosystem services (EES) and disservices (EED), guiding sustainable development across the emerging phyconomy.

To operationalise this framework, we apply an institutional landscape analysis using Denmark as a case study, linking policy instruments

<sup>22</sup> Sustainable Blue Economy Finance Initiative. Link: <https://www.unepfi.org/blue-finance/>.

<sup>23</sup> EU EQS. Link: <https://data.europa.eu/eli/dir/2008/105/oj>.

<sup>24</sup> EU Organic Production and Labelling of Organic Products (OPLP) Regulation 2018/848. Link: <https://data.europa.eu/eli/reg/2018/848/oj>.

to responsible institutions and exploring options for cross-sectoral coordination to enhance governance coherence.

The DPSIR framework is a well-established approach for analysing interactions between ecosystems and society (Smeets and Weterings, 1999). In this model, *Drivers* (societal demand) create *Pressures* on the environment, leading to *State changes* that cause impacts on society, which in turn calls for policy *Response*. DPSIR is widely used in policy-relevant research for its clarity in showing cause-effect relationships and its value in improving communications between policymakers, stakeholders, and scientists (Gari et al., 2015).

However, existing frameworks such as the MSFD and WFD focus mainly on negative impacts and pressures with little emphasis on positive effects. While these directives are vital for mitigating harm to the marine environment, they often overlook the potential benefits of aquaculture practices such as habitat restoration and enhancement of ecosystem services. As a result, they fail to reflect the full range of effects that seaweed aquaculture can have on the environment. Our proposed novel DPSIR framework addresses this gap.

The new approach recognises that environmental effects can be both positive and negative. While traditional frameworks associate pressures solely with negative impacts (EEDs), our model encompasses negative consequences (EEDs) and positive outcomes (EESs), such as habitat restoration and increased ecosystem resilience. By recognising these positive effects, the framework offers a more holistic view of seaweed aquaculture's environmental footprint.

For example, habitat restoration associated with seaweed cultivation can improve ecosystem health and enhance natural ES. These positive effects, often overlooked in current monitoring frameworks, are crucial to understanding seaweed aquaculture's full environmental scope. The monitoring gap is particularly important because positive effects may occur at different spatial and temporal scales than negative ones. A balanced approach is therefore required to account for both, especially under emerging policies such as the European Green Deal, 2019/640/EC.<sup>25</sup>

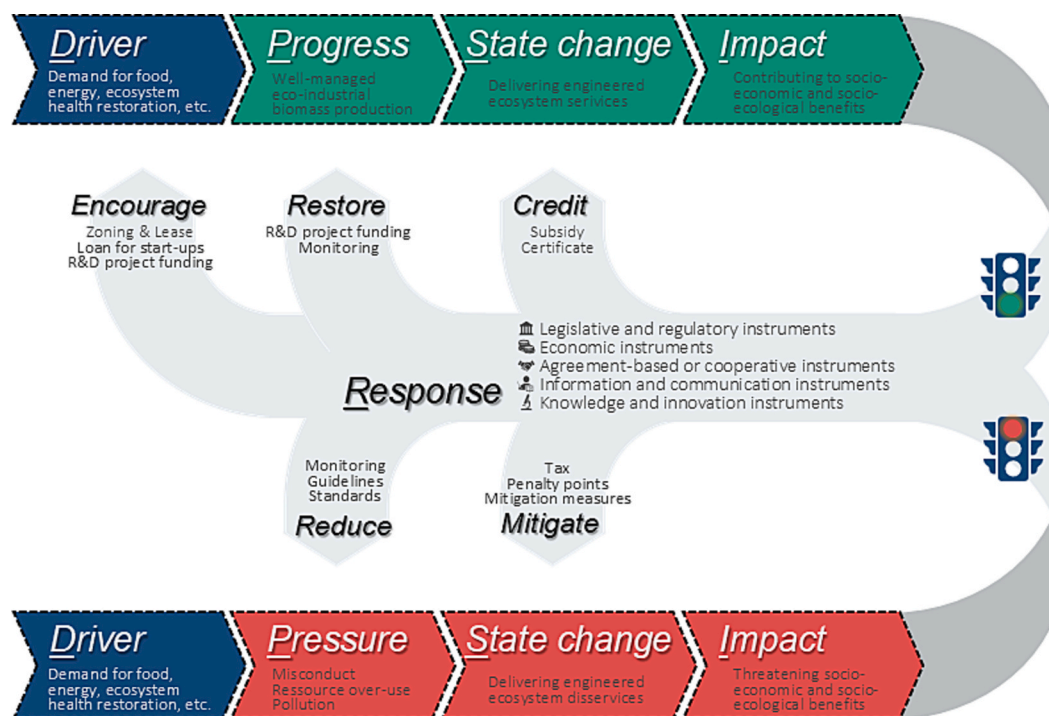
Negative impacts, or EEDs, can lead to a State changes that disrupts natural ES and reduce benefits to coastal communities, while positive effects (EESs) can enhance ecosystem resilience and integrity. By focusing on the restoration of natural ES and developing policy Responses that address both EEDs and EDSs, governance can better support the sustainable growth of the phyconomy.

In this framework, *Progress* refers to engineered ecosystem services that restore ecosystem health and strengthen natural ES. EEDs lead to State changes that inhibit ES, whereas EESs contribute to restoration and resilience. The framework advocates for a dual focus; minimising negative impacts while maximising synergies between engineered and natural ecosystem services. This can be achieved through biomimicry-based designs that optimise restorative EES, thereby transforming traditional *Pressures* into *Progress* and improving the health of coastal and marine ecosystems.

Engineered ecosystem services (EES) are designed interventions expected to generate long-term, nature-positive outcomes that reinforce underlying ecological processes. Functionally, they strengthen the foundation of natural ecosystem services, particularly those previously categorised as supporting services in the Millennium Ecosystem Assessment, 2005—now included within the regulation and maintenance group of CICES v5.1. Through mechanisms such as nutrient cycling, carbon regulation, and habitat provision, EES contribute to ecosystem recovery and stability, thereby sustaining the delivery of provisioning and cultural benefits over time.

This study therefore proposes a novel DPSIR framework (Fig. 4), evolving from the traditional goal of reducing *Pressure* to the new paradigm of achieving *Progress* (see also Fig. 3 for stakeholder and policy-instrument context) towards a restorative blue economy within a

<sup>25</sup> Green Deal EUR-Lex – 52019DC0640 – EN – EUR-Lex.



**Fig. 4.** Novel DPSIR framework integrating the Ecosystem Approach and the concept of engineered ecosystem services (EES) and engineered ecosystem disservices (EED).

safe operating space for humanity (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015). This framework integrates the ecosystem approach and the concept of engineered ecosystem services to overcome limitations of traditional DPSIR applications, such as their narrow focus on policymakers and lack of holistic, integrated perspectives on aquaculture impacts (Gari et al., 2015).

The integrated framework allows: (1) Inclusion of intermediate positive and negative effects on ecosystems, in addition to final societal outcomes, (2) Provide a system-wide mapping of all affected stakeholders, regardless of their power or influence in governance.

The upper pathway (*Progress*) represents positive, nature-positive effects where well-managed seaweed aquaculture delivers EES that reinforce ecological processes, restore natural ecosystem services, and contribute to societal well-being. The lower pathway (*Pressure*) depicts negative effects where poorly managed practices generate EED, leading to degradation of ecosystem structure and function. Policy and management responses shown in the central column illustrate legislative, economic, cooperative, informational, and innovation instruments that can encourage, restore, or credit positive outcomes while reducing or mitigating negative ones.

### 3.4. Perspectives on key instruments and institutions for Danish seaweed aquaculture

The sustainable development of Danish seaweed aquaculture relies on a well-structured institutional framework that integrates marine spatial planning, ocean zoning, and site monitoring as core components of effective governance. Together these tools act as both preventive and ongoing mechanisms to secure environmentally sustainable and economically viable operations. Spatial planning and zoning identify suitable cultivation areas while minimising conflicts with other marine uses, and continuous site monitoring ensures compliance with environmental standards and best practices.

#### 3.4.1. Stakeholder synergies and gaps

A key strategy to lower market-entry costs and operational risk for

small-scale farmers is to foster collaborative networks within the sector. By applying sharing-economy principles (Mi and Coffman, 2019), Danish seaweed farmers can share seedlings through a national seed bank (Cottier-Cook et al., 2016) and pool specialised equipment and infrastructure (Grebe et al., 2019). Training programs to disseminate technical knowledge and best-practice management (Henríquez-Antipa and Cárcamo, 2019) would further raise industry standards. Existing organisations, like the Danish Seaweed Organization (DSO, representing 16 SMEs),<sup>26</sup> Tang Netværket (a cross-sector stakeholder network),<sup>27</sup> and AlgeCenter Denmark (a science-industry network), provide a foundation for forming a national seaweed cooperative. Such a cooperative could reduce costs, improve access to resources, and enable a joint data collection on biomass production and sales.

Addressing data gaps is essential for evidence-based decision-making. The Scientific, Technical, and Economic Committee for Fisheries (STECF) of the European Commission have found discrepancies between EUROSTAT and FAO reporting for Danish algae-aquaculture production from 2008 to 2016 (STECF, 2018). Developing a robust, transparent database would allow consistent sectoral analysis and credible trend projections, supporting policy coherence and aligning with broader EU aquaculture strategies. By combining institutional support, stakeholder collaboration, and improved data infrastructure, Danish seaweed aquaculture can achieve sustainable growth while strengthening its contribution to the blue economy.

#### 3.4.2. Coordinated institutional efforts in developing and operationalising instruments

In Denmark, coordinated institutional collaboration has been central to advancing the seaweed-aquaculture sector. AlgeCenter Danmark is

<sup>26</sup> Danish Seaweed Organization (DSO) develops web portal for sharing information relevant for better marketing and sale, e.g. legislation, product quality standard, and certification schemes, and coordinates initiatives like participation in national and international tradeshows and exhibitions. Link: <https://www.danish-seaweed.org/> (last accessed 2021-01-25).

<sup>27</sup> Tang Netværket. Link: <https://tangnet.dk/>.

instrumental in this progress, organising the annual Nordic Seaweed Conference, facilitating knowledge exchange, and fostering stakeholder collaboration. It also disseminates scientific knowledge through social media, educational materials for schools, and public-engagement events such as the seaweed salad-making activity for schoolchildren during the national folk festival of Denmark in 2016 (Mouritsen, 2017). These initiatives help build public acceptance and stimulate domestic consumer markets. Nevertheless, the limited integration of seaweed into European food culture remains a challenge, emphasising the need for outreach to raise social-readiness levels for seaweed applications, including brand image campaigns and interactive workshops (Delaney et al., 2016; Jönsson et al., 2024; Van Den Burg et al., 2021). Recent behavioural research further indicates that targeted communication and product experience can effectively nudge consumer acceptance of seaweed-based innovations (Pandey et al., 2025).

Scientific research further supports Denmark's seaweed sector by providing practical resources, including cultivation manuals for *S. latissima* cultivation (Tørring and Oddershede-Nielsen, 2014), best practice guidelines for cultivation and analysis (Mooney-McAuley et al., 2016), and regulatory summaries for edible seaweeds (Ceva, 2019; Seaweed for Europe, n.d.). These tools enable producers to adopt sustainable practices and meet regulatory expectations, supporting sectoral growth. Exploring local markets for seaweed-based foods remains a strategic pathway for upgrading the European kelp industry (Van den Burg et al., 2020b).

Comparative experience abroad reinforced these lessons. In Chile, a governmental subsidy programme for seaweed cultivation revealed implementation gaps, including weak legislation, fragmented research with poor continuity, and bureaucratic inefficiencies (Henríquez-Antipa and Cárcamo, 2019). In the United States, ARPA-E launched the MARINER (Macroalgae Research Inspiring Novel Energy Resources) programme in 2016 to develop tools positioning the country as a leader in macroalgae production for human consumption and for feed and fertilisers, investing ~ US\$22 million in integrated cultivation and harvesting systems, advanced component technologies, computer-aided modeling, aquatic monitoring, and breeding tools (ARPA-E, 2017). These experiences underline the importance of long-term strategies, coherent governance, and sustained stakeholder engagement to ensure equitable benefit distribution and community sustainability. By addressing market, governance, and cultural barriers, Denmark and other European countries can draw on these global insights to develop cohesive strategies for sustainable expansion.

### 3.4.3. Zoning (ex-ante) and monitoring (throughout)

A joint-site monitoring programme as the core of a triple-helix management framework, linking academia, industry, and government, has been proposed for future growth of seaweed aquaculture (Zhang and Thomsen, 2019). This framework promotes cross-sectoral collaboration to build a shared understanding of ecological systems and seaweed biology, integrating scientific research with the practical and local knowledge of farmers. However, a critical gap persists: existing monitoring schemes rarely account for restorative actions such as habitat recovery, carbon capture sequestration, and nutrient removal (Duarte et al., 2021; Sondak et al., 2017). Without such metrics, positive environmental outcomes risk being under-reported or undervalued.

At present, the absence of a scientifically robust, standardised monitoring framework remains a bottleneck for sustainable sector development. Establishing clear indicators and methodologies, supported by long-term datasets and active stakeholder participation (Grebe et al., 2019; Henríquez-Antipa and Cárcamo, 2019), would strengthen assessments of ecological impacts and restorative contributions while ensuring regulatory compliance. Such a system would enable the sector to demonstrate measurable contributions to the blue economy, climate, and broader environmental restoration goals (Van den Burg et al., 2020b; van Duinen et al., 2023; Thomsen and Zhang, 2020).

Stakeholder perspectives also highlight the need for transparency

and trust-building. Interviews with community representatives in Scotland and France revealed limited trust in environmental-risk assessments and farming practices (Billing et al., 2020). To address this, a publicly accessible monitoring programme that regularly disseminates results would enhance transparency, document long-term environmental conditions, and improve understanding of farm-ecosystem interactions. Furthermore, introducing an ecosystem-service credit system, for carbon capture, nutrient removal, or habitat provision, could recognise and reward nature-positive outcomes, strengthening stakeholder confidence and reinforcing restorative EES principles.

Integration of seaweed monitoring into existing national frameworks such as Denmark's NOVANA programme<sup>28</sup> offers a practical pathway for implementation. NOVANA already covers chemical, physical and biological measurements (e.g. salinity, temperature, eelgrass depth limits, chlorophyll and phytoplankton productivity) as well as hazardous-pollutant monitoring. Expanding this infrastructure to include seaweed-specific indicators would enable streamlined, cost-effective data collection and alignment with broader marine-ecosystem assessments.

Globally, several approaches provide valuable methodological insights. In China, benthic impacts of shellfish and seaweed aquaculture were monitored using combined models and Environmental Quality Standards based on sediment chemistry and sensory parameters (Zhang et al., 2009). In the Netherlands, DNA metabarcoding evaluated biodiversity on settlement plates and explored environmental-DNA applications for mobile fauna (Bernard et al., 2019). Similarly, South Korea applied real-time carbonate monitoring to model carbon budgets in seaweed farms (Shim et al., 2012). These examples demonstrate that multi-parameter, technology-assisted monitoring can effectively capture both EES and EED effects.

Ocean zoning, which classifies marine space according to permitted uses (Agardy, 2010), remains a cornerstone in marine spatial planning (Douvere and Ehler, 2009). In Denmark, the Havplan<sup>29</sup> incorporates zoning; however, unlike shellfish and finfish aquaculture, seaweed cultivation is not restricted to specific zones, reflecting the industry's small scale. This flexible model contrasts with the zoned management of wild seaweed harvests in Norway, Chile, and South Africa, where concession areas and harvest rotations protect natural stocks while balancing multiple uses (Amosu et al., 2013; Norambuena, 1996; Vea and Ask, 2011).

As phyconomy-driven demand increases, so does the number and size of farm applications. Careful site selection becomes vital (Monagail and Morrison, 2020; Stévant et al., 2017). Yet under the current Danish licensing system (Table 1), expansion may be slowed by the administrative procedures and costly EIAs (Camarena-Gómez et al., 2022; Falconer et al., 2023; European Commission, 2016). Comparable challenges are observed elsewhere: coastal municipalities in Norway cite allocation delays (Gjertsen et al., 2020), and in California, filing an environmental-impact report for an ocean-farm licence costs approximately US\$ 3168 (Greenwave, 2018).

To streamline permitting while upholding environmental standards, authorities could adopt a proactive data-driven zoning approach, identifying and leasing pre-screened suitable areas rather than assessing each site individually (FAO, 2010). Operationalising such an approach requires advanced cumulative-impact assessment tools and open data systems. The increasing availability of environmental datasets and analytical techniques supports a shift from expert judgment to transparent, evidence-based evaluation. Emerging frameworks with

<sup>28</sup> Visualization of the monitoring data from the NOVANA program 2017–2021: <https://miljoegis.mim.dk/cbkort?profile=novana2017-21>; The description of the NOVANA program 2017–2021: <https://mst.dk/media/141463/novana-2017-21-programbeskrivelse.pdf#page=11> (marine and fjorden: pages 11–46).

<sup>29</sup> Denmark's marine plan. Link <https://havplan.dk/da/page/info>.

operationalisation plans (Kotta et al., 2020, 2022) could be adapted for seaweed-aquaculture zoning, enhancing consistency, transparency, and efficiency in permitting.

A streamlined, science-based licensing system would provide greater business certainty for applicants while enhancing public trust and stakeholder participation; key enablers of sustainable sector growth within the broader restorative-blue-economy transition.

#### 4. Conclusions and perspectives

The study proposes a novel DPSIR framework that shifts the focus from merely reducing environmental pressures to actively fostering progress towards a restorative circular blue economy. This framework integrates the ecosystem-services approach, providing a systemic understanding of both the positive and negative impacts on ecosystems and their societal implications.

Looking ahead, adaptive, cross-sectoral policy frameworks will be essential to sustain blue-growth pathways. Such frameworks must ensure coordinated governance of seaweed aquaculture, now a strategic component of the emerging phyconomy. By aligning with global sustainability transitions, these policies can ensure that seaweed aquaculture simultaneously supports economic growth, environmental restoration, and climate-mitigation goals (van Duinen et al., 2023; Thomsen & Zhang, 2020).

As offshore aquaculture expands, balancing growth and ecological limits becomes increasingly critical. Competition for ocean space, particularly with offshore-wind and other maritime industries, demands robust, data-driven spatial-planning tools to prevent exceedance of local carrying capacities for nutrients, light, and biodiversity (Depellegrin et al., 2021; Kotta et al., 2020; Villalba et al., 2022; Turschwell et al., 2022). Web-based cumulative-effects and ecosystems-threat assessment tools (Depellegrin et al., 2021; Menegon et al., 2018) further highlight the value of embedding ecosystem-service accounting into maritime spatial planning (Armoskaitė et al., 2023; Boussarie et al., 2023; Quinio et al., 2023; Sousa and Alves, 2020).

Multi-use platform concepts offer promising synergies, promoting industrial symbiosis between seaweed farms and offshore wind structures, where seaweed cultivation can help dampen wave energy and enhance ecosystem services (Schupp et al., 2019). Yet challenges remain, including biofouling, contamination risks, and regulatory complexity (Aryai et al., 2021; Depellegrin et al., 2019; Villalba et al., 2022).

The emerging carbon-credit market also presents opportunities and risks. As seaweed aquaculture becomes integrated into offset schemes, robust verification is required to avoid greenwashing and ensure credits reflect genuine climate- and ecosystem-restoration benefits.

Effective, harmonized policy and regulatory frameworks are crucial for balancing the pressures and progress associated with seaweed aquaculture. A unified legal approach, aligning local and regional regulations with broader EU directives, will underpin sustainable sector development (Paramana et al., 2023).

Finally, as awareness of ecosystem services and EES-linked co-benefits grows, discussions on economic incentives for seaweed aquaculture are expected to intensify. Well-designed incentives will encourage investment in sustainable practices, ensuring that seaweed aquaculture continues to strengthen ecological integrity, economic viability, and social well-being – the three pillars of the triple-layered business model canvas (TLBMC) (Joyce and Paquin, 2016; Van Den Burg et al., 2021).

In conclusion, navigating these governance and innovation challenges is essential to achieve a sustainable equilibrium between ecological, economic, and social objectives in the rapidly expanding global seaweed-aquaculture sector.

#### CRedit authorship contribution statement

**Marianne Thomsen:** Writing – review & editing, Writing – original

draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Annette Bruhn:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jonne Kotta:** Writing – review & editing, Investigation. **Bela H. Buck:** Writing – review & editing, Investigation. **Jack R. Hall:** Writing – review & editing. **Georg Martin:** Writing – review & editing. **Antonio Agüera:** Writing – review & editing. **Marie Maar:** Writing – review & editing. **Manali Chakraborty:** Writing – review & editing, Visualization, Investigation. **Maxime Ekoule:** Writing – review & editing, Investigation. **Ian Overton:** Writing – review & editing, Investigation. **Mausam Budhathoki:** Writing – review & editing, Investigation.

#### 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.

#### Acknowledgements

This research has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No. 101094065 (OLAMUR) and No. 101073471 (SEACHEM), and from the Danish VELUX FOUNDATION under the WIN@sea project (Grant # 37712).

The views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union, CINEA, nor the VELUX FOUNDATION Foundation can be held responsible for them.

#### Data availability

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

#### References

- Agardy, T. S. (2010). *Ocean zoning: Making marine management more effective* (1st ed.). Routledge. doi: 10.4324/9781849776462.
- Alexander, K.A., Potts, T.P., Freeman, S., Israel, D., Johansen, J., Kletou, D., Meland, M., Pecorino, D., Rebours, C., Shorten, M., Angel, D.L., 2015. The implications of aquaculture policy and regulation for the development of integrated multi-trophic aquaculture in Europe. *Aquaculture* 443, 16–23. <https://doi.org/10.1016/j.aquaculture.2015.03.005>.
- Amosu, A.O., Robertson-Andersson, D.V., Maneveldt, G.W., Anderson, R.J., Bolton, J.J., 2013. South african seaweed aquaculture: a sustainable development example for other african coastal countries. *Afr. J. Agric. Res.* 8, 5268–5279. <https://doi.org/10.5897/AJAR2013>.
- Andersen, M.S., Levin, G., Odgaard, M.V., 2019. Economic benefits of reducing agricultural N losses to coastal waters for seaside recreation and real estate value in Denmark. *Mar. Pollut. Bull.* 140, 146–156. <https://doi.org/10.1016/j.marpolbul.2019.01.010>.
- Anker, H.T., Baaner, L., Andersen, S.S., 2024. Retlige rammer for marine virkemidler og marin natur [Legal frameworks for marine measures and marine nature]. Institut for Fødevarer- og Ressourceøkonomi, Københavns Universitet. IFRO Rapport (Nr.), 307. [https://curis.ku.dk/ws/portalfiles/portal/385012034/IFRO\\_Rapport\\_307.pdf](https://curis.ku.dk/ws/portalfiles/portal/385012034/IFRO_Rapport_307.pdf).
- Armoskaitė, A., Aigars, J., Andersone, I., Bonnevie, I.M., Hansen, H.S., Stråke, S., von Thenen, M., Schröder, L., 2023. Setting the scene for a multi-map toolset supporting maritime spatial planning by mapping relative cumulative impacts on ecosystem service supply. *Front. Mar. Sci.* 10, 1213119. <https://doi.org/10.3389/fmars.2023.1213119>.
- ARPA-E. (2017). *Funding Opportunity No. DE-FOA-0001726: ARPA-E's MARINER (Macroalgae Research Inspiring Novel Energy Resources) program* (pp. 4–5). Advanced Research Projects Agency–Energy, U.S. Department of Energy. <https://arpa-e-foa.energy.gov>.
- Aryai, V., Abbassi, R., Abdussamie, N., Salehi, F., Garaniya, V., Asadnia, M., Baksh, A.-A., Penesis, I., Karampour, H., Draper, S., Magee, A., Keng, A.K., Shearer, C., Sivandran, S., Yew, L.K., Cook, D., Underwood, M., Martini, A., Heasman, K., Abrahams, J., Wang, C.-M., 2021. Reliability of multi-purpose offshore facilities: present status and future direction in Australia. *Process Saf. Environ. Prot.* 148, 437–461. <https://doi.org/10.1016/j.psep.2020.10.016>.
- ASC-MSC. (2018). *Seaweed (Algae) Risk-Based Framework*. <https://www.asc-aqua.org/wp-content/uploads/2017/11/ASC-MSC-Seaweed-Algae-Risk-Based-Framework-v1.0.pdf>.
- ASC-MSC. (2020). *Get certified: Farms*. <https://www.asc-aqua.org/what-you-can-do/get-certified/farms/>.

- Atkins, J.P., Burdon, D., Elliott, M., Gregory, A.J., 2011. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Mar. Pollut. Bull.* 62, 215–226. <https://doi.org/10.1016/j.marpolbul.2010.12.012>.
- Barbier, M., Charrier, B., Araujo, R., Holdt, S.L., Jacquemin, B., Rebours, C., 2019. *PEGASUS-PHYCOMORPH European guidelines for a sustainable aquaculture of seaweeds*. Roscoff, France. <https://doi.org/10.21411/2c3w-yc73>.
- Bermejo, R., Buschmann, A., Capuzzo, E., Cottier-Cook, E., Fricke, A., Hernández, I., Hofmann, L.C., Pereira, R., van den Burg, S., 2022. *State of knowledge regarding the potential of macroalgae cultivation in providing climate-related and other ecosystem services: a report of the Eklipse Expert Working Group*. Eklipse, Netherlands [https://eklipse.eu/wp-content/uploads/website\\_db/Request/Macro-Algae/EKLIPSE\\_DG-Mare-Report-PrintVersion\\_final.pdf](https://eklipse.eu/wp-content/uploads/website_db/Request/Macro-Algae/EKLIPSE_DG-Mare-Report-PrintVersion_final.pdf).
- Bernard, M.S., Tonk, L., de Groot, G.A., Glorius, S., Jansen, H.M., 2019. *Biodiversity monitoring in seaweed farms by DNA metabarcoding using settlement plates and water samples*. Wageningen. <https://doi.org/10.18174/496237>.
- Beyersdorff, S., Lanthén, E., 2018. *Baltic 2030 Bumps on the Road: how the Baltic Sea States are performing on the SDGs*. Nordic Council of Ministers. <https://doi.org/10.6027/ANP2018-783>.
- Bhuyan, M.S., 2023. Ecological risks associated with seaweed cultivation and identifying risk minimization approaches. *Algal Res.* 69, 102967. <https://doi.org/10.1016/j.algal.2022.102967>.
- Billing, S.L., Rostan, J., Tett, P., Macleod, A., 2020. Is social license to operate relevant for seaweed cultivation in Europe? *Aquaculture*. <https://doi.org/10.1016/j.scitotenv.2019.135577>.
- Bjerregaard, R., Valderrama, D., Sims, N., Radulovich, R., Diana, J., Capron, M., Forster, J., Goudey, C., Yarish, C., Hopkins, K., Rust, M., & McKinnie, C. A. (2016). *Seaweed aquaculture for food security, income generation, and environmental health in tropical developing countries*. doi: 10.1596/24919.
- Bouga, M., Combet, E., 2015. Emergence of seaweed and seaweed-containing foods in the UK: Focus on labeling, iodine content, toxicity, and nutrition. *Foods* 4, 240–253. <https://doi.org/10.3390/foods4020240>.
- Boussarie, G., Kopp, D., Lavialle, G., Mouchet, M., Morfin, M., 2023. Marine spatial planning to solve increasing conflicts at sea: A framework for prioritizing offshore windfarms and marine protected areas. *J. Environ. Manage.* 339, 117857. <https://doi.org/10.1016/j.jenvman.2023.117857>.
- Bouwma, I.M., Gerritsen, A.L., Kamphorst, D.A., Kistenkas, F.H., 2015. *Policy instruments and modes of governance in environmental policies of the European Union: past, present and future*. Wot-Technical Report. <https://edepot.wur.nl/373629>.
- Bruhn, A., Tørring, D., Thomsen, M., Canal-Vergés, P., Nielsen, M., Rasmussen, M., Eybye, K., Larsen, M., Balsby, T., Petersen, J., 2016. Impact of environmental conditions on biomass yield, quality, and bio-mitigation capacity of *Saccharina latissima*. *Aquac. Environ. Interact.* 8, 619–636. <https://doi.org/10.3354/aei00200>.
- Buck, B. H., & Grote, B. (2018). Seaweed in high energy environments: Protocol to move *Saccharina* cultivation offshore. In B. Charrier, T. Wichard, & C. R. K. Reddy (Eds.), *Protocols for Macroalgae Research* (pp. 1–25). CRC Press, Taylor & Francis Group. doi: 10.1201/b21460.
- Buck, B.H., Troell, M.F., Krause, G., Angel, D.L., Grote, B., Chopin, T., 2018. State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Front. Mar. Sci.* 5, 1–21. <https://doi.org/10.3389/fmars.2018.00165>.
- Budhathoki, M., Tunca, S., Martinez, R.L., Zhang, W., Li, S., Le Gallic, B., Brunson, K., Sharma, P., Eljasik, P., Gyalog, G., Panicz, R., Little, D., 2024. Societal perceptions of aquaculture: Combining scoping review and media analysis. *Rev. Aquac.* 12927. <https://doi.org/10.1111/raq.12927>.
- Burdon, D., Atkins, J.P., Potts, T., 2023. In: *Classification of Estuarine and Coastal Ecosystem Services*. Elsevier. <https://doi.org/10.1016/B978-0-323-90798-9.00078-0>.
- Buschmann, A.H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M.C., Pereda, S.V., Gomez-Pinchetti, J.L., Golberg, A., Tadmor-Shalev, N., Critchley, A.T., 2017. Seaweed production: Overview of the global state of exploitation, farming, and emerging research activity. *Eur. J. Phycol.* 52, 391–406. <https://doi.org/10.1080/09670262.2017.1365175>.
- Cabral, P., Levrel, H., Viard, F., Frangoudes, K., Girard, S., Scemama, P., 2016. Ecosystem services assessment and compensation costs for installing seaweed farms. *Mar. Policy* 71, 157–165. <https://doi.org/10.1016/j.marpol.2016.05.031>.
- Camarena-Gómez, M.T., Lähteenmäki-Uutela, A., Spilling, K., 2022. Macroalgae production in Northern Europe: Business and government perspectives on how to regulate a novel blue bioeconomy. *Aquaculture* 560, 738434. <https://doi.org/10.1016/j.aquaculture.2022.738434>.
- Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., Hughes, A.D., Stanley, M., 2019. The environmental risks associated with the development of seaweed farming in Europe—Prioritizing key knowledge gaps. *Front. Mar. Sci.* 6, 107. <https://doi.org/10.3389/fmars.2019.00107>.
- Capuzzo, E., McKie, T., 2016. *Seaweed in the UK and abroad—Status, products, limitations, gaps and Cefas role*. Cefas. <https://www.gov.uk/government/publications/the-sea-weed-industry-in-the-uk-and-abroad>.
- Ceva, 2019. *Edible seaweed and microalgae—Regulatory status in France and Europe*. Centre D'étude et De Valorisation Des Algues.
- Cherry, P., O'Hara, C., Magee, P.J., McSorley, E.M., Allsopp, P.J., 2019. Risks and benefits of consuming edible seaweeds. *Nutr. Rev.* 77, 307–329. <https://doi.org/10.1093/nutrit/nyy066>.
- Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? *Ecosyst. Serv.* 28, 1–16. <https://doi.org/10.1016/j.ecoser.2017.09.008>.
- Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M., Free, C.M., Froehlich, H.E., Golden, C.D., Ishimura, G., Maier, J., Macadam-Somer, I., Mangin, T., Melnychuk, M.C., Miyahara, M., de Moor, C.L., Naylor, R., Nøstbakken, L., Ojeda, E., O'Reilly, E., Parma, A.M., Lubchenco, J., 2019. *The future of food from the sea*. High Level Panel for a Sustainable Ocean Economy. <https://www.oceanpanel.org/future-food-sea>.
- Cottier-Cook, E. J., Nagabhatla, N., Campbell, M., Chopin, T., Hewitt, C., Hoon, G., Kema, G., Liu, F., Msuya, F. E., Rebours, C., Stentiford, G., Yarish, C., He, P., & Gachon, C. M. M. (2016, September 20–23). Safeguarding the future of the global seaweed aquaculture industry. *Aquaculture Europe 2016*, Edinburgh, Scotland. <https://aquaeas.org/MeetingAbstracts/PaperDetail/6827>.
- Delaney, A., Frangoudes, K., Li, S.A., 2016. In: *Society and Seaweed: Understanding the past and Present*. Elsevier, pp. 7–40. <https://doi.org/10.1016/B978-0-12-802772-1.00002-6>.
- Depellegri, D., Venier, C., Kyriazi, Z., Vassilopoulou, V., Castellani, C., Ramieri, E., Bocci, M., Fernandez, J., Barbanti, A., 2019. Exploring multi-use potentials in the Euro-Mediterranean sea space. *Sci. Total Environ.* 653, 612–629. <https://doi.org/10.1016/j.scitotenv.2018.10.308>.
- Depellegri, D., Hansen, H.S., Schröder, L., Bergström, L., Romagnoni, G., Steenbeek, J., Gonçalves, M., Carneiro, G., Hammar, L., Pålsson, J., Crona, J.S., Hume, D., Kotta, J., Fetisov, M., Miloš, A., Kaitaranta, J., Menegon, S., 2021. Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in European seas. *Ocean Coastal Manage.* 209, 105644. <https://doi.org/10.1016/j.ocecoaman.2021.105644>.
- Douvere, F., Ehler, C.N., 2009. New perspectives on sea use management: initial findings from European experience with marine spatial planning. *J. Environ. Manage.* 90, 77–88. <https://doi.org/10.1016/j.jenvman.2008.07.004>.
- Duarte, C.M., Krause-Jensen, D., 2018. Intervention options to accelerate ecosystem recovery from coastal eutrophication. *Front. Mar. Sci.* 5, 470. <https://doi.org/10.3389/fmars.2018.00470>.
- Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* 4. <https://doi.org/10.3389/fmars.2017.00100>.
- Duarte, C.M., Bruhn, A., Krause-Jensen, D., 2021. A seaweed aquaculture imperative to meet global sustainability targets. *Nat. Sustainability* 5, 185–193. <https://doi.org/10.1038/s41893-021-00773-9>.
- EMODnet. 2024. <https://emodnet.ec.europa.eu/en/map-week-algae-production-facilities-3>.
- European Commission. (2016). *Aquaculture in the EU—Tapping into blue growth*. [https://ec.europa.eu/fisheries/sites/fisheries/files/2016-aquaculture-in-the-eu\\_en.pdf](https://ec.europa.eu/fisheries/sites/fisheries/files/2016-aquaculture-in-the-eu_en.pdf).
- European Commission. (2020). *A farm to fork strategy for a fair, healthy and environmentally friendly food system*. Publications Office of the European Union. <https://op.europa.eu/en/publication-detail/-/publication/24b7d9d0-81e0-11ee-99ba-01aa75ed71a1/language-en>.
- European Commission, Directorate-General for Maritime Affairs, Fisheries, Joint Research, Centre., 2025. *The EU Blue Economy Report 2025*. Publications Office of the European Union. <https://op.europa.eu/webpub/mare/eu-blue-economy-report-2025/index.html>.
- European Environment Agency (EEA). (2018). *Marine protected areas*. Publications Office of the European Union. <https://www.eea.europa.eu/en/analysis/publications/marine-protected-areas>.
- Falconer, L., Cutajar, K., Krupandan, A., Capuzzo, E., Corner, R.A., Ellis, T., Jeffery, K., Mikkelsen, E., Moore, H., O'Beirn, F.X., O'Donohoe, P., Ruane, N.M., Shilland, R., Tett, P., Telfer, T.C., 2023. Planning and licensing for marine aquaculture. *Reviews in Aquaculture*. <https://doi.org/10.1111/raq.12783>.
- FAO. (2010). *Aquaculture development: Ecosystem approach to aquaculture*. FAO Technical Guidelines for Responsible Fisheries No. 5, Suppl. 4. <http://www.fao.org/3/i1750e/i1750e00.htm>.
- FAO. (2018). *FAO Fisheries and Aquaculture Circular No. 1157—Seafood certification and developing countries: Focus on Asia*. <https://openknowledge.fao.org/server/api/core/bitstreams/d7d341e3-b7b3-4b82-bf8d-6b7a620a544a/content>.
- FAO. (2020). *FAO Yearbook. Fishery and Aquaculture Statistics 2018/FAO Annuaire*. [http://www.fao.org/fishery/static/Yearbook/YB2018\\_USBcard/navigation/index\\_content\\_aquaculture\\_e.htm](http://www.fao.org/fishery/static/Yearbook/YB2018_USBcard/navigation/index_content_aquaculture_e.htm).
- Filbee-Dexter, K., Wernberg, T., 2018. Rise of turfs: A new battleground for globally declining kelp forests. *BioScience* 68 (2), 64–76. <https://doi.org/10.1093/biosci/bix147>.
- Filbee-Dexter, K., Wernberg, T., Barreiro, R., Coleman, M.A., de Bettignies, T., Feehan, C. J., Franco, J.N., Hasler, B., Louro, I., Norderhaug, K.M., Stehr, P.A.U., Tuya, F., Verbeek, J., 2022. Leveraging the blue economy to transform marine forest restoration. *J. Phycol.* <https://doi.org/10.1111/jpy.13239>.
- Forbes, H., Shelamoff, V., Visch, W., et al., 2022. Farms and forests: evaluating the biodiversity benefits of kelp aquaculture. *J. Appl. Phycol.* 34, 3059–3067. <https://doi.org/10.1007/s10811-022-02822-y>.
- Frank, 2020. K. Frank Seaweed Aquaculture. An assessment of the legal and management structure on seaweed farming in Iceland University Centre of the Westfjords. <https://samradapi.island.is/api/Documents/ea3c8e08-e7f8-ea11-9b99-005056bce7e>.
- Freitas, J.R.C., Salinas Morrono, J.M., Cremades Ugarte, J., 2016. *Saccharina latissima* (Laminariales, Ochrophyta) farming in an industrial IMTA system in Galicia (Spain). *J. Appl. Phycol.* 28, 377–385. <https://doi.org/10.1007/s10811-015-0526-4>.
- Froehlich, H.E., Afflerbach, J.C., Frazier, M., Halpern, B.S., 2019. Blue growth potential to mitigate climate change through seaweed offsetting. *Curr. Biol.* 29 (18), 3087–3093.e3. <https://doi.org/10.1016/j.cub.2019.07.041>.
- Gao, K., Beardall, J., 2022. Using macroalgae to address UN Sustainable Development goals through CO2 remediation and improvement of the aquaculture environment. *Appl. Phycol.* 3 (1), 360–367. <https://doi.org/10.1080/26388081.2022.2025617>.

- García-Poza, S., Pacheco, D., Cotas, J., Marques, J.C., Pereira, L., Gonçalves, A.M.M., 2022. Marine macroalgae as a feasible and complete resource to address and promote sustainable development goals (SDGs). *Integr. Environ. Assess. Manag.* 18, 1148–1161. <https://doi.org/10.1002/ieam.4598>.
- Gari, S.R., Newton, A., Icely, J.D., 2015. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. *Ocean and Coast. Manag.* 103, 63–77. <https://doi.org/10.1016/j.ocecoaman.2014.11.013>.
- Gatti, P., Agüera, A., Gao, S., Strand, Ø., Strohmeyer, T., Skogen, M., 2023. Mussel farming production capacity and food web interactions in a mesotrophic environment. *Aquac. Environ. Interact.* 15, 1–18. <https://doi.org/10.3354/aei00448>.
- Giordano, M., Beardall, J., Raven, J.A., 2005. CO<sub>2</sub> concentrating mechanisms in algae: Mechanisms, environmental modulation, and evolution. *Annu. Rev. Plant Biol.* 56, 99–131. <https://doi.org/10.1146/annurev.arplant.56.032604.144052>.
- Gjertsen, A., Bay-Larsen, I., Bjørkhaug, H., Vangelsten, B.V., 2020. Access to areas for algae cultivation in Norway. *Mar. Policy* 115, 103853. <https://doi.org/10.1016/j.marpol.2020.103853>.
- Grebe, G.S., Byron, C.J., Gelais, A.S., Kotowicz, D.M., Olson, T.K., 2019. An ecosystem approach to help aquaculture in the Americas and Europe. *Aquacult. Rep.* 15, 100215. <https://doi.org/10.1016/j.aqrep.2019.100215>.
- Greenwave. (2018). *Guide to navigating lease & permit approvals for ocean farming in California*. <https://static1.squarespace.com/static/58d2a2d36b8f5bd9d98ba51/t/5b7ac0c040ec9a9bc8996dd/1534771392649/GreenWave+Guide+to+Lease+%26+Permit+Approvals+for+Ocean+Farming+in+California+8.19.2018.docx.pdf>.
- Guerry, A.D., Ruckelshaus, M.H., Arkema, K.K., Bernhardt, J.R., Guannel, G., Kim, C.-K., Marsik, M., Papenfus, M., Toft, J.E., Verutes, G., Wood, S.A., Beck, M., Chan, F., Chan, K.M.A., Gelfenbaum, G., Gold, B.D., Halpern, B.S., Labiosa, W.B., Lester, S.E., Tallis, H., 2012. Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. *International Journal of Biodiversity Science, Ecosystem Services & Management* 8, 107–121. <https://doi.org/10.1080/21513732.2011.647835>.
- Guyot-Téphany, J., Trouillet, B., Diederichsen, S., Juell-Skielse, E., Thomas, J.-B.-E., McCann, J., Rebours, C., Scherer, M., Freeman, P., Gröndahl, F., Walsh, J.P., Lukic, I., 2024. Two decades of research on ocean multi-use: Achievements, challenges and the need for transdisciplinarity. *NPJ Ocean Sustainability* 3, 8. <https://doi.org/10.1038/s44183-024-00043-z>.
- Haines-Young, R., Potschin-Young, M.B., 2018. Revision of the common international classification for ecosystem services (CICES V5.1): a policy brief. *One Ecosyst.* 3, e27108. <https://doi.org/10.3897/oneco.3.e27108>.
- Hasselström, L., Visch, W., Gröndahl, F., Nylund, G.M., Pavia, H., 2018. The impact of seaweed cultivation on ecosystem services—A case study from the west coast of Sweden. *Mar. Pollut. Bull.* 133, 53–64. <https://doi.org/10.1016/j.marpolbul.2018.05.005>.
- Havhost, n.a. De maritime nyttehaver (marine community gardens). <https://xn-havst-ey.dk/de-maritime-nyttehaver/>.
- Havhost, n.d. Ansøgning til Kystdirektoratet for lineanlæg (Application to the Danish Coastal Authority for longline installation). <https://xn-havst-ey.dk/kopi-af-4-3-2-ansoegning-til-kystdirektoratet-for-lineanlaeg>.
- Henríquez-Antipa, L.A., Cárcamo, F., 2019. Stakeholder's multidimensional perceptions on policy implementation gaps regarding the current status of Chilean small-scale seaweed aquaculture. *Mar. Policy* 103, 138–147. <https://doi.org/10.1016/j.marpol.2019.02.042>.
- Hurtado, A.Q., Neish, I.C., Critchley, A.T., 2019. Phytonomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. *Phycologia* 58, 472–483. <https://doi.org/10.1080/00318884.2019.1625632>.
- ICES. (2019). *ICES strategic plan*. doi: 10.17895/ices.pub.5470.
- Inácio, M., Karnauskaitė, D., Baltranaite, E., Kalinauskas, M., Bogdzewicz, K., Gomes, E., Pereira, P., 2020. Ecosystem services of the Baltic Sea: an assessment and mapping perspective. *Geogr. Sustainability* 1, 256–265. <https://doi.org/10.1016/j.geosus.2020.11.001>.
- Jiang, Z., Jiang, W., Rastrick, S.P.S., Wang, X., Fang, J., Du, M., Gao, Y., Mao, Y., Strand, Ø., Fang, J., 2022. The potential of kelp *Saccharina japonica* in shielding Pacific oyster *Crassostrea gigas* from elevated seawater pCO<sub>2</sub> stress. *Front. Mar. Sci.* 9, 862172. <https://doi.org/10.3389/fmars.2022.862172>.
- Jönsson, M., Maubert, E., Merkel, A., Fredriksson, C., Karlsson, E.N., Wendin, K., 2024. A sense of seaweed: Consumer liking of bread and spreads with the addition of four different species of northern European seaweeds—A pilot study among Swedish consumers. *Future Foods* 9, 100292. <https://doi.org/10.1016/j.fufo.2023.100292>.
- Joyce, A., Paquin, R.L., 2016. The triple layered business model canvas: A tool to design more sustainable business models. *J. Cleaner Prod.* 135, 1474–1486. <https://doi.org/10.1016/j.jclepro.2016.06.067>.
- Kelly, J., 2025. Insights for the emerging seaweed industry in Australia. Nuffield Australia. <https://www.nuffield scholar.org/sites/default/files/2025-05/Kelly%20J%20FINAL.pdf>.
- Kelly, J., Cannon, A.L., Smith, J.E., 2020. Environmental impacts and implications of tropical carrageenophyte seaweed farming. *Conserv. Biol.* 34 (2), 326–337. <https://doi.org/10.1111/cobi.13462>.
- Kim, J.K., Stekoll, M., Yarish, C., 2019. Opportunities, challenges, and future directions of open-water seaweed aquaculture in the United States. *Phycologia* 58, 446–461. <https://doi.org/10.1080/00318884.2019.1625611>.
- Kotta, J., Fetisov, M., Szava-Kovats, R., Aps, R., Martin, G., 2020. Online tool to integrate evidence-based knowledge into cumulative effects assessments: linking human pressures to multiple nature assets. *Environ. Adv.* 2, 100026. <https://doi.org/10.1016/j.envadv.2020.100026>.
- Kotta, J., Raudsepp, U., Szava-Kovats, R., Aps, R., Armoskaite, A., Barda, I., Bergström, P., Futter, M., Gröndahl, F., Hargrave, M., Jakubowska, M., Jänes, H., Kaasik, A., Kraufvelin, P., Kovaltchouk, N., Krost, P., Kulikowski, T., Kõivupuu, A., Kotta, I., Barboza, F.R., 2022. Assessing the potential for sea-based macroalgae cultivation and its application for nutrient removal in the Baltic Sea. *Sci. Total Environ.* 839, 156230. <https://doi.org/10.1016/j.scitotenv.2022.156230>.
- Kulikowski, T., Kachel-Jakubowska, M., Krupska, J., & Psuty, I. (Eds.). (2021). *Guide to macroalgae cultivation and use in the Baltic Sea region*. National Marine Fisheries Research Institute. [https://submariner-network.eu/wp-content/uploads/2024/01/INTERNET\\_MIR-monografia.pdf](https://submariner-network.eu/wp-content/uploads/2024/01/INTERNET_MIR-monografia.pdf).
- Kystdirektoratet, 2014. Tilladelse til tanganlægget Havhaven Ebeltoft Vig (Permit for the Havhaven aquaculture facility in Ebeltoft Vig). <https://www.xn-havst-ey.dk/wp-content/uploads/2021/03/Tilladelse-Ebeltoft-Havmark-2014.pdf>.
- Kystdirektoratet, 2015. Kystdirektoratets administrationsgrundlag for søterritoriet: Oceaner af værdier – et hav af muligheder (The Coastal Authority's administrative framework for the territorial sea: Oceans of values – a sea of opportunities). <https://kyst.dk/media/pl5nlz1e/administrationsgrundlagforsoeterritoriet.pdf>.
- Langton, R., Augyte, S., Price, N., Forster, J., Noji, T., Grebe, G., Gelais, A. S., & Byron, C. J. (2019). *An ecosystem approach to the culture of seaweed*. NOAA Technical Memorandum NMFS-F/SPO-195. <https://spo.nmfs.noaa.gov/sites/default/files/TMSPO195.pdf>.
- Maar, M., Holbach, A., Boderskov, T., Thomsen, M., Buck, B.H., Kotta, J., Bruhn, A., 2023. Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. *Commun. Earth Environ.* 4, 447. <https://doi.org/10.1038/s43247-023-01116-6>.
- McKinley, E., Pagés, J.F., Wyles, K.J., Beaumont, N., 2019. Ecosystem services: a bridge or barrier for UK marine stakeholders? *Ecosyst. Serv.* 37, 100922. <https://doi.org/10.1016/j.ecoser.2019.100922>.
- Menegon, S., Depellegrin, D., Farella, G., Saretta, A., Venier, C., Barbanti, A., 2018. Addressing cumulative effects, maritime conflicts and ecosystem services threats through MSP-oriented geospatial webtools. *Ocean Coastal Manag.* 163, 417–436. <https://doi.org/10.1016/j.ocecoaman.2018.07.009>.
- MFF. (2020). *Organic aquaculture*. <https://www.foedevarestyrelsen.dk/Leksikon/Sider/Økologisk-akvakultur.aspx>.
- Mi, Z., Coffman, D.M., 2019. The sharing economy promotes sustainable societies. *Nat. Commun.* 10, 5–7. <https://doi.org/10.1038/s41467-019-09260-4>.
- Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Island Press. <https://www.millenniumassessment.org/en/Synthesis.html>.
- Monagail, M.M., Morrison, L., 2020. The seaweed resources of Ireland: a twenty-first-century perspective. *J. Appl. Phycol.* 32, 1287–1300. <https://doi.org/10.1007/s10811-020-02067-7>.
- Mooney-McAuley, K. M., Edwards, M. D., Champenois, J., & Gorman, E. (2016). *EnAlgae Project Report WPIA5.01 - Best practice guidelines for seaweed cultivation and analysis*. Mouritsen, O.G., 2017. Those tasty weeds. *J. Appl. Phycol.* 29, 2159–2164. <https://doi.org/10.1007/s10811-016-0986-1>.
- Moylan, M., Cinnéide, L. O., & Whelan, K. (2017). *Review of the aquaculture licensing process: Report of the Independent Aquaculture Licensing Review Group*. <https://www.agriculture.gov.ie/media/migration/seafood/aquacultureforeshoremanagement/aquaculturelicensing/aquaculturelicensingreview/ReviewoftheAquacultureLicensingProcess210617.pdf>.
- MST. (2020). *Danmarks Havstrategi II Anden del Overvågningsprogram*. <https://www2.mst.dk/Udgiv/publikationer/2020/07/978-87-7038-209-0.pdf>.
- Nabe-Nielsen, J., Van Beest, F.M., Grimm, V., Sibly, R.M., Teilmann, J., Thompson, P.M., 2018. Predicting the impacts of anthropogenic disturbances on marine populations. *Conserv. Lett.* 11, e12563. <https://doi.org/10.1111/conl.12563>.
- Neveux, N., Bolton, J. J., Bruhn, A., Roberts, D. A., & Ras, M. (2018). The bioremediation potential of seaweeds: Recycling nitrogen, phosphorus, and other waste products. In *Blue biotechnology: Production and use of marine molecules, Volume 1* (pp. 217–239). doi: 10.1002/9783527801718.ch7.
- Norambuena, R. (1996). Recent trends of seaweed production in Chile. In *Fifteenth International Seaweed Symposium* (pp. 371–379). Springer Netherlands. doi: 10.1007/978-94-009-1659-3\_54.
- OECD. (2016). *The ocean economy in 2030*. doi: 10.2166/978178048927-9.
- OSPAR Commission. (2010). *The North-East Atlantic Environment Strategy*. [https://www.ospar.org/site/assets/files/1200/ospar\\_strategy.pdf](https://www.ospar.org/site/assets/files/1200/ospar_strategy.pdf).
- Pandey, S., Budhathoki, M., Thomsen, M., 2025. Consumer intentions and willingness to pay for seaweed-fed cow's milk: the impact of attitude, knowledge, taste, and price. *Future Foods* 11, 100539. <https://doi.org/10.1016/j.fufo.2025.100539>.
- Paramana, T., Dassenakis, M., Bassan, N., Dallangelo, C., Campostrini, P., Raicevich, S., Ronchi, F., Giorgi, G., Murillas-Maza, A., Uyarra, M.C., Papadopoulou, N., Smith, C., Jami, K., Koren Bačovnik, Š., Klančnik, K., Pavičić, M., Skejić, S., Vidjak, O., Cadiou, J.F., López-López, L., Alvarez, I., Giannoudi, L., Strefataris, N., Pagkou, P., 2023. Achieving coherence between the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive. *Marine Policy* 155, 105733. <https://doi.org/10.1016/j.marpol.2023.105733>.
- Parker, B., Benson, D., Hasenauer, C., Malin, G., & Schlarb-Ridley, B. (2014). Regulations and permitting concerning algal cultivation in North West Europe. Public Output report WP2A10.01 of the EnAlgae project, Swansea, September 2014, 88pp. <http://www.enalgae.eu/public-deliverables.htm>.
- Pereira, S.A., Kimpara, J.M., Valenti, W.C., 2020. Sustainability of the seaweed *Hypnea pseudomonociformis* farming in the tropical Southwestern Atlantic. *Ecol. Ind.* <https://doi.org/10.1016/j.ecolind.2020.107101>.
- Pessarrodona, A., Howard, J., Pidgeon, E., Wernberg, T., Filbee-Dexter, K., 2024. Carbon removal and climate change mitigation by seaweed farming: a state of knowledge review. *Sci. Total Environ.* 918, 170525. <https://doi.org/10.1016/j.scitotenv.2024.170525>.

- Peteiro, C., Sánchez, N., Martínez, B., 2016. Mariculture of the asian kelp *Undaria pinnatifida* and the native kelp *Saccharina latissima* along the Atlantic coast of Southern Europe: an overview. *Algal Res.* <https://doi.org/10.1016/j.algal.2016.01.012>.
- Prabhu, M., Chemodanov, A., Gottlieb, R., Kazir, M., Nahor, O., Gozin, M., Israel, A., Livney, Y.D., Golberg, A., 2019. Starch from the sea: the green macroalga *Ulva ohnoi* as a potential source for sustainable starch production in the marine biorefinery. *Algal Res.* 37, 215–227. <https://doi.org/10.1016/j.algal.2018.11.007>.
- Quinio, L., Ripken, M., Klenke, T., Trouillet, B., Hansen, H.S., Schröder, L., 2023. Exploring ecosystem-based approaches in MSP through actor-driven perceptual mapping. *Marine* 152, 105604. <https://doi.org/10.1016/j.marpol.2023.105604>.
- Richardson, J., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Fetzer, I., et al., 2023. Earth beyond six of nine planetary boundaries. *Sci. Adv.* 9 (37), eadh2458. <https://doi.org/10.1126/sciadv.adh2458>.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., De Wit, C.A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Foley, J.A., 2009. A safe operating space for humanity. *Nature* 461, 472–475. <https://doi.org/10.1038/461472a>.
- Sæther, M., Diehl, N., Monteiro, C. Li, H., Niedzwiedz, S., Burgunter-Delamare, B., Scheschonk, L., Bischof, K., Forbord, S., 2024. The sugar kelp *Saccharina latissima* II: recent advances in farming and applications. *J. Appl. Phycol.* <https://doi.org/10.1007/s10811-024-03213-1>.
- SAPEA. (2017). *Evidence Review Report No. 1/2017: Food from the oceans - How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?* <https://www.sapea.info/wp-content/uploads/GFOFINALREPORT.pdf>.
- Schmedes, P.S., Nielsen, M.M., 2020. New hatchery methods for efficient spore use and seedling production of *Palmaria palmata* (dulse). *J. Appl. Phycol.* 32, 2183–2193. <https://doi.org/10.1007/s10811-019-01998-0>.
- Schupp, M.F., Bocci, M., Depellegrin, D., Kafas, A., Kyriazi, Z., Lukic, I., Schultz-Zehden, A., Krause, G., Onyango, V., Buck, B.H., 2019. Toward a Common Understanding of Ocean Multi-Use [Hypothesis and Theory]. *Front. Mar. Sci.* 6. <https://doi.org/10.3389/fmars.2019.00165>.
- Seaweed for Europe. (n.d.). *Licensing Toolkit*. Seaweed for Europe. <https://www.seaweedeurope.com/toolkit/>.
- Seghetta, M., Tørring, D., Bruhn, A., Thomsen, M., 2016. Bioextraction potential of seaweed in Denmark - an instrument for circular nutrient management. *Sci. Total Environ.* 563–564, 513–529. <https://doi.org/10.1016/j.scitotenv.2016.04.010>.
- Shim, JeongHee, Kang, Dong-Jin, Han, In-Seong, KWON, Jung-No, & Lee, Yong-Hwa. (2012). Real-time Monitoring of Environmental Properties at Seaweed Farm and a Simple Model for CO2 Budget. *The Sea: JOURNAL OF THE KOREAN SOCIETY OF OCEANOGRAPHY*, 17(4), 243–251. <https://doi.org/10.7850/JKSO.2012.17.4.243>.
- Smeets, E., & Weterings, R. (1999). *Environmental indicators: Typology and overview*. <https://www.eea.europa.eu/en/analysis/publications/tec25>.
- Sondak, C.F., Ang, P.O., Beardall, J., Bellgrove, A., Boo, S.M., Gerung, G.S., Hepburn, C. D., Hong, D.D., Hu, Z., Kawai, H., 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *J. Appl. Phycol.* 29, 2363–2373.
- Sousa, L.P., Alves, F.L., 2020. A model to integrate ecosystem services into spatial planning: Ria de Aveiro coastal lagoon study. *Ocean Coastal Manage.* 195, 105280. <https://doi.org/10.1016/j.ocecoaman.2020.105280>.
- Spillias, S., Cottrell, R.S., Kelly, R., O'Brien, K.R., Adams, J., Bellgrove, A., Kelly, B., Kilpatrick, C., Layton, C., Macleod, C., Roberts, S., Stringer, D., McDonald-Madden, E., 2022. Expert perceptions of seaweed farming for sustainable development. *J. Clean. Prod.* 368, 133052. <https://doi.org/10.1016/j.jclepro.2022.133052>.
- Stecf, 2018. *Scientific, Technical and Economic Committee for Fisheries (STECF) – Economic report of the EU aquaculture sector (STECF-18-19)*. Publications Office of the European Union. <https://doi.org/10.2760/45076>.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347. <https://doi.org/10.1126/science.1259855>.
- Steinhagen, S., Enge, S., Larsson, K., Olsson, J., Nylund, G.M., Albers, E., Pavia, H., Undeland, I., Toth, G.B., 2021. Sustainable Large-Scale Aquaculture of the Northern Hemisphere Sea Lettuce, *Ulva fenestrata*, in an Off-Shore Seafarm. *J. Mar. Sci. Eng.* 9 (6), 615. <https://doi.org/10.3390/jmse9060615>.
- Stévant, P., Rebours, C., Chapman, A., 2017. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquac. Int.* 25, 1373–1390. <https://doi.org/10.1007/s10499-017-0120-7>.
- Stévant, P., Schmedes, P.S., Le Gall, L., Wegeberg, S., Dumay, J., Rebours, C., 2023. Concise review of the red macroalga dulse, *Palmaria palmata* (L.) Weber & Mohr. *J. Appl. Phycol.* 35, 523–550. <https://doi.org/10.1007/s10811-022-02899-5>.
- Sutherland, I.J., Villamagna, A.M., Dallaire, C.O., Bennett, E.M., Chin, A.T.M., Yeung, A. C.Y., Lamothe, K.A., Tomscha, S.A., Cormier, R., 2018. Undervalued and under pressure: a plea for greater attention toward regulating ecosystem services. *Ecol. Ind.* 94, 23–32. <https://doi.org/10.1016/j.ecolind.2017.06.047>.
- Taelman, S.E., Champenois, J., Edwards, M.D., De Meester, S., Dewulf, J., 2015. Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation. *Algal Res.* 11, 173–183. <https://doi.org/10.1016/j.algal.2015.06.018>.
- Teeb, 2010. *The economics of ecosystems and biodiversity: Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB*. UNEP.
- Thomsen, M., & Zhang, X. (2020). Life cycle assessment of macroalgal ecoindustrial systems. In *Sustainable seaweed technologies* (pp. 663–707). Elsevier. doi: 10.1016/b978-0-12-817943-7.00023-8.
- Tunca, S., Budhathoki, M., Brunso, K., 2024. European consumers' intention to buy sustainable aquaculture products: an exploratory study. *Sustainable Prod. Consumption* 50, 20–34. <https://doi.org/10.1016/j.spc.2024.07.021>.
- Turner, K.G., Odgaard, M.V., Bøcher, P.K., Dalgaard, T., Svenning, J.C., 2014. Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landsc. Urban Plan.* 125, 89–104. <https://doi.org/10.1016/j.landurbplan.2014.02.007>.
- Turschwell, M.P., Hayes, M.A., Lacharité, M., Abundo, M., Adams, M., Blanchard, J., Brain, E., Buelow, C.A., Bulman, C., Condie, S.A., Connolly, R.M., Dutton, I., Fulton, E.A., Gallagher, S., Maynard, D., Pethybridge, H., Plagányi, E., Porobic, J., Taelman, S.E., Trebilco, R., Woods, G., Brown, C.J., 2022. A review of support tools to assess multi-sector interactions in the emerging offshore Blue Economy. *Environ. Sci. Policy* 133, 203–214. <https://doi.org/10.1016/j.envsci.2022.03.016>.
- Tørring, D., & Oddershede-Nielsen, K. (2014). *Manual til dyrkning af sukkertang (Saccharina latissima) i Limfjorden, Danmark*.
- UN. (1982). *Part V – Exclusive Economic Zone, Article 56*. [https://www.un.org/Depts/los/convention\\_agreements/texts/unclos/part5.htm](https://www.un.org/Depts/los/convention_agreements/texts/unclos/part5.htm).
- United Nations Department of Economic and Social Affairs, Population Division (UN DESA). (2022). *World population prospects 2022: Summary of results (UN DESA/POP/2022/TR/NO.3)*. United Nations.
- Van den Burg, S.W., Röckmann, C., Banach, J.L., Van Hoof, L., 2020a. Governing risks of multi-use: Seaweed aquaculture at offshore wind farms. *Front. Mar. Sci.* 7, 60.
- Van den Burg, S., Selnes, T., Alves, L., Giesbers, E., Daniel, A., 2020b. Prospects for upgrading by the European kelp sector. *J. Appl. Phycol.* <https://doi.org/10.1007/s10811-020-02320-z>.
- Van Den Burg, S.W.K., Dagevos, H., Helmes, R.J.K., 2021. Towards sustainable European seaweed value chains: a triple P perspective. *ICES J. Mar. Sci.* 78, 443–450. <https://doi.org/10.1093/icesjms/fsz183>.
- van Duinen, R., Rivière, C., Strosser, P., Dijkstra, J.W., Rios, S., Luzzi, S., Bruhn, A., Nielsen, M.O., Göke, C., Samarasinghe, M.B., Chassé, E., Nielsen, C.H., Thomsen, M., 2023. *Algae and climate: Final Report*. Publication Office of the European Union. <https://doi.org/10.2926/208135>.
- Vea, J., Ask, E., 2011. Creating a sustainable commercial harvest of *Laminaria hyperborea* in Norway. *J. Appl. Phycol.* 489–494. <https://doi.org/10.1007/s10811-010-9610-y>.
- Vedung, E., 1998. *Carrots, sticks, and sermons: Policy instruments and their evaluation*. J. Transp. Geogr.
- Villalba, J., Abdussamie, N., Aryai, V., Nikolova, N., Tenekedjiev, K., Wang, C.-M., Penesis, I., 2022. Assessment of uncertain alternatives for co-located aquaculture and offshore wind farm in Tasmania. *Ocean Eng.* 259, 110949. <https://doi.org/10.1016/j.oceaneng.2022.110949>.
- Visch, W., Bergström, P., Nylund, G.M., Peterson, M., Pavia, H., Lindegarth, M., 2020. Spatial differences in growth rate and nutrient mitigation of two co-cultivated extractive species: the blue mussel (*Mytilus edulis*) and the kelp (*Saccharina latissima*). *Estuar. Coast. Shelf Sci.* 246, 107019. <https://doi.org/10.1016/j.ecss.2020.107019>.
- WBCSD. (2020). *Modernizing governance: ESG challenges and recommendations for corporate directors*. <https://docs.wbcsd.org/2020/01/WBCSD-Modernizing-governance-key-recommendations-for-boards-to-ensure-business-resilience.pdf>.
- Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., Kerrison, P., 2017. UK macroalgae aquaculture: what are the key environmental and licensing considerations? *Mar. Policy* 83, 29–39. <https://doi.org/10.1016/j.marpol.2017.05.021>.
- World Sustainability Organization. (2020). Friend of the Sea seaweeds and algae product standard (Rev. 3, 27 October 2020). <https://friendofthesea.org/wp-content/uploads/FoS-Seaweed-and-algae-v3-27102020.pdf>.
- Xiao, X., Agustí, S., Yu, Y., Huang, Y., Chen, W., Hu, J., Duarte, C.M., 2021. Seaweed farms provide refugia from ocean acidification. *Sci. Total Environ.* 776, 145192. <https://doi.org/10.1016/j.scitotenv.2021.145192>.
- Xu, J., Liu, Y., Cui, Y., Yao, Q., Gao, X., Zhou, G., 2023. Diversity of CO<sub>2</sub> concentrating mechanisms in macroalgae photosynthesis: a case study of *Ulva* sp. *J. Mar. Sci. Eng.* 11 (10), 1911. <https://doi.org/10.3390/jmse11101911>.
- Zhang, X., Thomsen, M., 2019. Biomolecular composition and revenue explained by interactions between extrinsic factors and endogenous rhythms of *Saccharina latissima*. *Mar. Drugs*. <https://doi.org/10.3390/md17020107>.
- Zhang, J., Hansen, P.K., Fang, J., Wang, W., Jiang, Z., 2009. Assessment of the local environmental impact of intensive marine shellfish and seaweed farming—Application of the MOM system in the Sungo Bay, China. *Aquaculture* 287, 304–310. <https://doi.org/10.1016/j.aquaculture.2008.10.008>.
- Zhang, X., Boderskov, T., Bruhn, A., Thomsen, M., 2022. Blue growth and bioextraction potentials of danish *Saccharina latissima* aquaculture—A model of eco-industrial production systems mitigating marine eutrophication and climate change. *Algal Res.* 64, 102686. <https://doi.org/10.1016/j.algal.2022.102686>.