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Deliverable 4.1: Salmon-seaweed co-culture: Beyond farm-level integrated multi-trophic aquaculture (IMTA)

Authors:	Shirra Freeman (lead), Asael Greenfeld, Dror Angel
WP/WP-leader:	WP 4/ Wout Abbink, Stichting Wageningen Research
Task/Task leader:	Task 4.1/Dror Angel, University of Haifa
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Table of Contents

Executive summary

In recent years, seaweed aquaculture in northern Europe has been growing. Historically, seaweed production in this region was dominated by collection of wild plants, cultivation was relatively rare. Nevertheless, for many years, seaweed was considered an excellent component of sustainable aquaculture because of the plants' capacity to extract dissolved nutrients and sequester carbon from aquatic environments. For example, a number of large EU projects and Canada's a research program, CIMTAN investigated the production, environmental, and economic performance of integrated multi-trophic aquaculture (IMTA), a production system that cultures two or more different trophic level species. Many of these studies demonstrated the efficiency with which seaweed removes nutrients in effluent from cages growing fed finfish such as salmon. IMTA studies and others also demonstrate optimal growth conditions (e.g., light, baseline nutrients, nutrient flux) for kelp varieties and other species found in northern Europe. Despite the advances in farming methods and demonstrable benefits for the environment, the culture of seaweed lagged behind traditional collection activities and production in Asian countries. In large part this was the result of underdeveloped markets for seaweed produced in Europe. The direct consumption of aquatic plants is not part of most European cuisine, seaweed imported from Asia easily outcompetes the price of European products, and the potential environmental benefits were not embedded in European regulatory systems.

The potential benefits of seaweed as part of a healthy diet, as a component of food supplements, or as an ingredient in animal feed and fertilizer has greatly expanded markets for seaweed and sparked interest in increasing European production. Because expanding production based on wild stocks carries with it the risk of over-exploitation and the loss of ecosystem services from resources such as kelp forests, regulators have tightened restrictions on collection activities. As a result, farming seaweed is attracting more and more attention. Norway has been an early European leader with a collaboration of researchers, producers and regulators leading to an intensive expansion of production. The growing economic interest in seaweed aquaculture has also sparked interest in ways of harnessing its environmental advantages. This is especially relevant for areas where intensive farming of fed finfish is prevalent, including Norway that has one of the world's largest salmon farming sectors.

The purpose of this report is to shed light on ways of combining salmon and seaweed culture that are environmentally sustainable, profitable and attractive to growers. Past studies focusing on salmon-seaweed co-culture in a single farm unit found that in generally, salmon farmers were wary of undertaking IMTA and preferred to specialise on one highly profitable crop. The reasons for this reluctance are discussed in the report and has led to an exploration of integration at a larger spatial scope such as a bay or fjord. We draw on approximately 15 years of research on IMTA that includes numerous European and Canadian studies, many of which have involved the authors.

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Introduction

Sustainable aquaculture is one of the cornerstones of the EU's Blue Bioeconomy and a contributor to major policy initiatives such as the Green Deal [1]. The cultivation of macro-algae is part of this movement because seaweed provides numerous ecosystem services including the extraction of dissolved nutrients, the provision of habitat, carbon sequestration, and coastal protection [1–3]. The extractive capacity of seaweed can contribute to preventing eutrophication in water bodies. Since some of the nutrients used by seaweeds are also discharged by fish farms, integrating seaweed with finfish culture is regarded as one way of making aquaculture more sustainable [2].

Other reasons for developing seaweed aquaculture include its market potential and the preservation of wild seaweed stocks. Global markets for products derived from macro-algae are large and growing. Although the EU contributes less than 5% of global seaweed production, there have been long-standing sectors that collect (manually and mechanically) and dry wild plants in countries bordering the Atlantic Ocean. Over exploitation of wild stocks, particularly kelp forests would lead to loss of habitat, biodiversity and other important ecosystem services and thus, seaweed aquaculture is seen as a sustainable alternate source of macroalgae and an important opportunity for European producers [4].

In the past ten years, European researchers and industry have been taking an active role in exploring the potential for cultivating seaweed and expanding domestic markets for products ranging from food to fertilizer. Norway has been particularly active in promoting seaweed aquaculture and is now the largest producer in Europe [2]. Ways of harnessing seaweed's carbon sequestration potential are being actively explored worldwide, and a lot of this activity occurs in EU countries [5]. The potential for seaweed aquaculture to remediate nutrient loads emanating from fish farms has led to several research initiatives involving integrated multi-trophic aquaculture (IMTA) (e.g., ECASA, AquaVitae, IDREEM, Mermaid, IMPAQT, CIMTAN).

This report addresses the dual objectives of increasing the sustainability of aquaculture in the EU and promoting seaweed production as a component of the blue bioeconomy. The focus is on options for integrating salmon and seaweeds that are suitable for culture in northern Europe. The reasons for this are:

1. Seaweed aquaculture is more advanced in northern Europe, especially Norway than in many other parts of Europe [5] (Nordic Blue Carbon, 2020). For example, although it has abundant sunlight, the Mediterranean Sea is considerably more oligotrophic and therefore less suited to cultivation of commercial macro-algae species.
2. The environmental impacts of salmon monoculture have been extensively studied and although they are not fully understood, with respect to nutrient discharges, there is a solid knowledge base from which to move forward.
3. The strengths, weaknesses and potential of IMTA involving salmon and seaweeds have been addressed by multiple studies in Europe and Canada. The findings provide background on gaps and priorities for researchers, industry and policy-makers for considering alternative configurations for co-culture that meet the sustainability criteria for environmental and economic performance [1, 6–12].

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METHODS

This is a desktop study that incorporates peer-reviewed literature and grey literature, including multiple EU and national policy-related documents on seaweed production, mariculture and in particular IMTA. In addition, several interviews were conducted with experts in both seaweed production and IMTA.

Literature was identified using a systematic scan of EBSCO Host data bases, Google Scholar, EU and selected national websites. Keywords searched included combinations of the following terms: seaweed, macro-algae, aquaculture, mariculture, sustainable, integrated multi-trophic aquaculture, IMTA, salmon, finfish, nutrient, eutrophication, France, Norway, Sweden, England, Scotland, Ireland, Spain. The search returned over 1,000 titles. The literature selection was a tiered process involving three researchers. The first tier, a title search reduced the total by half. The second tier, an abstract scan identified 200 documents which were read and summarized and used in the preparation of this report.

Experts were identified via networks of the authors of this report, each of whom has extensive experience in marine ecology and mariculture, in particular IMTA, and the BioMarine Digital networking event on blue biopackaging and biomaterials (Nov 17-18, 2021). Interviews were conducted during November and December 2021 [13].

The report was compiled as a narrative review with particular attention paid to the gaps and challenges for IMTA and seaweed cultivation.

SEAWEED

Seaweeds or macroalgae are aquatic flora that grow naturally on hard substrates (excluding *Sargassum* spp), usually in coastal areas. There are three main groups: brown algae or kelp (phylum Ochrophyta, class Phaeophyceae), red algae (phylum Rhodophyta) and green algae (phylum Chlorophyta, classes Bryopsidophyceae, Chlorophyceae, Dasycladophyceae, Prasinophyceae, and Ulvophyceae). All three are found in marine waters and green seaweeds also grow in freshwater ecosystems [14]. Algal biomass is seen as an important resource for multiple commercial applications and algal communities are recognized as important for their biodiversity and ecosystem functions, in particular their capacity to remove excess nutrients from coastal waters.

Global production overview

Globally, China and Indonesia account for 92% of annual global seaweed production with 13.6 and 10.1 mm MT respectively. Production in Asia is dominated by aquaculture. It is noteworthy that seaweeds, mainly carrageenan species and kelps, are also harvested in North and South America but this production will not be included in this review. In contrast, EU production has traditionally been based on the collection of wild varieties in Spain, France, Ireland, Iceland and Norway. European production is dwarfed by its Asian counterpart. The most recent statistics place European production just under 1% of the world total. Until recently France and Ireland dominated European production, but there is evidence that this is changing as Norway has made large strides in the development of domestic aquaculture [15,16]. According to the FAO, in 2015, Norway, Ireland, France, and Iceland were in third, sixth, seventh, and ninth place for collection of wild seaweed (0.15, 0.03, 0.019, and 0.017 MT each)

[16]. In 2019, Norway remained in third place with 163,080 MT (15.5% of global catches), France rose to fifth place at 51,300 MT, Ireland fell to eighth place (29,500 MT), and Iceland was in tenth place at 17,533 MT [16]. (See Table 1). Some caution needs to be exercised with regard to seaweed statistics. Both the literature and experts agree that totals may be under-reported because national statistics often overlook artisanal activities which can make up a large proportion of production. Also, different reporting methods may make it difficult to compare reports across countries [10, 11]

Table 1 European seaweed production

Country/Region	Total production (farmed & wild) (tonnes)	Share of global total (%)	Aquaculture share of total production (%)
Europe	287 033	0.80	3.88
Norway	163 197	0.46	0.07
France	51 476	0.14	0.34
Ireland	29 542	0.08	0.14
Russian Federation	19 544	0.05	54.10
Iceland	17 533	0.05	0.00

Source: [15]

European production – Collection of wild stocks

Ireland, France, Spain and parts of Scandinavia have communities with longstanding traditions of harvesting wild seaweed. The most commonly collected species are *Laminaria hyperborea*, *Laminaria digitata*, and *Ascophyllum nodosum*, and other kelp forest varieties. Much of the collection is artisanal, though in many places, hand-collection has been replaced by mechanical processes. For example, in France (mainly Brittany) and Norway (Rogaland to Sør-Trøndelag)), substantial quantities of L. digitata, *L. hyperborea* and *A. nodosum* are collected mechanically by fishing vessels and specialized seaweed harvesting boats [3, 19]. Most of the seaweed harvested has been used for human consumption, animal feed and fertilizer.

There is growing concern over the integrity of wild seaweed resources, in particular kelp forests that provide important ecological functions and ecosystem services. The issue is particularly relevant for mechanical harvests because they remove large quantities of plants and this can disrupt the functioning of the kelp forest ecosystem and its ability to regenerate. These concerns have driven much of European regulation pertaining to the collection of wild seaweed. Regulation of harvests varies from region to region and includes licenses and harvesting authorisations, quotas by zone, operator or boat, rotation. For example, the implementation of a Natura 2000 marine area in the Spanish Basque country curtailed harvests entirely. Preventing the over-exploitation of natural seaweed resources has also been put forward as a rationale for the development of seaweed farming [18].

European production – Aquaculture

Historically, aquaculture of seaweeds has been a very small part of European production. With the exception of Norway, France and the Faroe Islands rapid development of its seaweed aquaculture sector, most European production is still based on the collection of wild stocks. There are many reasons for developing cultivation capacity. In addition to the concerns for the depletion of wildstocks, there is a strong business case for seaweed farming. It offers a more stable revenue flow, larger volumes and flexibility to adjust species and quantities in response to market demands, compared to collection [2, 13].

Most cultivation uses rafts, ropes or other artificial substrates in open waters. A smaller amount is grown on land in ponds, tanks and raceways. Seed may be obtained from wild or cultivated plants. There are many considerations involved in the choice of the seaweed species to grow, the optimal farm site, the cultivation methodology and infrastructure. Seaweeds have a few basic needs, and if these are supplied, growth is generally guaranteed. Macroalgae need adequate sunlight, but not too much. They require an ample supply of carbon dioxide and nutrients and in northern waters, these are generally not growth-limiting factors. Seaweeds are sensitive to water temperature, salinity and turbulence, but the sensitivity is species specific, so sites with variable conditions are by necessity more suitable to resilient species [14, 15]. Biotic interactions are equally important and there is also variability in terms of seaweed sensitivity to pathogens, grazers and biofouling biota. All of these variables need to be considered when debating over the suitability of species and farm sites for growing these [23].

Brown kelp species are the main seaweeds cultivated in northern Europe. Production takes place in several stages beginning in the autumn and ending with a harvest in late spring or summer. Farming consists of the following stages

1. Preparation of broodstock either from cultivated or collected wild seaweed
2. Collection of zoospores from the brood stock
3. Hatchery/growing chamber rearing of gametophytes and young seedlings
4. Transplantation of young sporophytes to rafts or longlines
5. Grow-out
6. Harvesting

[23]

Farming seaweeds involves the use of propagules. In some environments, wild propagules may be collected at sea directly on substrates such as ropes or nets, thereby saving added costs and efforts. In most cases, it is necessary to produce the propagules in hatcheries by promoting sexual or asexual reproduction and these are then induced to adhere to the substrates that they will grow on at sea. The hatchery stage is generally costly and labour intensive, but provides the option to ensure that the crop is clonal, pathogen free and also affords the possibility for genetic selection and improvement. Another option, in some species, is to leave part of the seaweed attached to the substrate, in the field, after harvest, and to allow it to regenerate and grow out vegetatively (ORF, Faroe Islands).

The timing of deployment of the propagules is often a function of marine conditions and on the projected arrival of epiphytes and epizoa which dictate when seaweeds will need to be harvested. During the grow-out phase, maintenance of the crop may involve thinning to optimize growth conditions, raising or lowering of the lines and removal of biofouling biota, but generally not more than that.

Species overview: Candidate species for cultivation in Europe

This section summarises details of the main relevant species for seaweed aquaculture in northern Europe. It is largely narrative because of the scarcity of accurate, comprehensive data on production (collection and cultivation) and sales. Studies of macroalgae vary in their objectives and methods and can be difficult to compare. As the European seaweed market has expanded, the monitoring of production and sales has improved, but is still far from complete [24]. Nevertheless, the review below provides a summary of the state of the science as well as considerations for expansion of seaweed cultivation.

Table 2 provides an overview of yields for the different species described below.

Saccharina latissima

Saccharina latissima is a perennial species and is one of the more commonly grown kelps in the North Atlantic and has been widely studied in European aquaculture. As with most kelp, it is widely distributed in cold and temperate waters. It grows particularly well in cold, high-nutrient environments. Kerrison et al. (2015) concluded optimal growth is obtained at 5°-15° C as long as summer temperatures do no exceed 18°-20° C [20–22, 25].

Cultivation in sheltered waters is easier from the standpoint of farming infrastructures than farms in exposed waters that require more substantial gear that can withstand higher wind and wave activity. In-shore cultivation tends to have poorer light exposure and flushing and greater susceptibility to biofouling. Studies vary in how these advantages and disadvantages translate into productivity. For example, average yields reported from offshore sites in Atlantic Spain were 16 kg wet biomass per m rope compared to 12 kg in sheltered sites [19], though there is concern that these reported yields are incorrect. In contrast sheltered and moderately-exposed sites in Sweden were up to 40% more productive than more exposed sites despite having triple the biofouling cover [27].

Cultivation and harvesting techniques are also an important determinant of yields, though evidence on the timing and size of harvests is rather varied. *Saccharina latissima* requires reseeding which can be accomplished either by self-reseeding from existing crops or from seed gathered at remote sites (wild or farmed) but productivity associated with self-seeding is not guaranteed. In the Shetland Islands, attempts were made to develop self-seeding techniques by partially harvesting mature crops of *S. latissima* and *L. digitata*. The result was increased costs associated with biofouling on the unharvested portion and no increase in biomass yield [28]. In contrast, two staggered harvests per season in the Faroe Islands reduced costs without compromising yields [29]. Seeding and incubation onshore prior to planting is another alternative which is more expensive but produced higher yields in an Atlantic Spain study [26].

Undaria pinnatifida

Commercial cultivation of *Unidaria pinnatifida* began in China during WWII and spread to Japan and Korea [30] . *Unidaria pinnatifida* was first introduced into Brittany in 1983 and is now present in several northern European countries [31]. Native to the Pacific, it is an important food crop, more commonly known as Wakame, and is similar to the European native kelp, *Alaria esculenta*. *Unidaria pinnatifida* is temperature sensitive, growing best between 10-15°C, but robust to wave exposure. It is an efficient self-seeder. Although invasive in Europe, it does not appear to have outcompeted native species. Nevertheless, cultivation in Europe is tightly controlled. For example in France, licenses are granted in areas where *Unidaria pinnatifida* has been grown for a long time.

Macrocystis pyrifera

Macrocystis pyrifera is a large and fast growing kelp that grows optimally around latitudes of 33° in Pacific North America, yielding 0.537 of Carbon per m2 / year. Yields were most affected by light availability and harvest timing. In Chile, a grow-out period of 45 days was achieved. This is shorter than the 50-60 day period observed for other brown kelps. Seventy percent of the crop was food quality and

30% was destined for the feed and fertilizer industry. Pharmaceutical applications have also been explored [32].

Laminaria (digitata and hyperborea)

Both Laminaria species are native to Europe and used for hydrocolloid extraction and fertilizers. *Laminaria digitata* has also attracted interest as a source of bioethanol [32]. Both are managed similarly. Collection of wild plants are subject to quotas on the numbers of vessels used and harvest days per week. *Laminaria hyperborea* harvest areas are also managed on three year rotations. L. digitata is harvested between May and September and *L. hyperborea* has two harvests, one in September and one in May. Denmark was an early cultivator of Laminaria spp [32]. Reproduction has been extensively studied in several projects and seeding is from wild stock [33]. Both species are temperature sensitive and require moderate levels of wave action to thrive. *Laminaria digitata* is prone to biofouling in inshore sites, therefore harvesting of coastal crops by the end of May appears to be important to maintaining usable yields [28] . Offshore cultivation is a lot more promising as the biofouling issue is considerably reduced.

Palmaria palmata

Palmaria palmata, also known as dulse is a red seaweed that historically, has been hand-picked in the wild for niche markets such as high-end restaurants, but increased interest has led to cultivation [34]. There is also interest in its production for food supplements, animal feeds and biofuel [35]. Currently, *Palmaria palmata*, must be grown on shore before deployment at sea but work continues on the optimal in-tank growth period. One study in North Ireland showed that longer on-land growth with more nutrients and irradiances were found to produce stronger seedlings with higher survival rates, but those that survived did not produce higher yields at maturity than seedlings with less intensive incubation[36].

Other seaweed species

Other species currently hand-picked include *Ulva* spp and *Porphyra* spp, mainly for food. Other types of algae were studied in warmer climates such as *Gracilariopsis persica* that is used for agar production.

Table 2 Yields for selected algae species with relevance to production in northern Europe

Species	Location	Conditions	Annual wet yield per 1m of rope (kg)	Annual wet yield per 1m2 of cultivation area (kg)	Reference	Comments
Saccharina latissima	Atlantic Spain	Exposed	16		Peterio and Freire 2013	Differences in yields between exposed and sheltered sites could not be explained by site attributes. In both sites, the main determinants of yield were water velocity and light.
	Atlantic Spain	Sheltered	12		Peterio and Freire 2013	
	Atlantic Spain	low density of frons (25-30 per m rope)	7.8	4.56	Peteiro et al. 2013	
	Faroe Islands	Double harvest	3*	0.71*	Bak et al. 2018	Area reported included handling area
	Shetland Islands	Single and double harvest	9-11.6		Rolin et al. 2017	Combined harvest with *L. digitata*
	Scotland	IMTA (Salmon farm)		22	Sanderson et al. 2012	
	Scotland	Without IMTA		8.58*	Sanderson et al. 2012	
Macrocystis pyrifera	Pacific N. America (lat.33°N)	3 m plant spacing, water absorbance of 0.115 m-1 and 12 m depth		537g of Carbon	Jackson 1987	
	southern Chile		14.4		Gutierrez et al 2006	
Laminaria digitata	Shetland Islands	Single and double harvest	9-11.6		Rolin et al 2017	Combined harvest with *S. latissima*
	China	"Rongfu" heat tolerant variant		840g-1020g of Carbon	Zhang et al 2011	
	China	Commercial Laminaria		625g of Carbon*	Zhang et al 2011	
Palmaria palmata	Scotland	IMTA (Salmon farm)		18	Sanderson et al. 2012	

	Scotland	Without IMTA		9.36*	Sanderson et al. 2012	

* adjusted calculation based on reported results

Development of seaweed aquaculture - Case study for Norway

There are various estimates of the biomass of wild seaweeds growing along the coasts of northern Europe, and particularly Scandinavia [5]. These estimates range in the millions of tons, indicating that this environment is highly suitable for seaweed growth. There are currently several operations harvesting wild seaweeds in various Scandinavian countries, and while the potential harvest is huge, the amounts taken are mainly limited by demand and the limited capacity of industry to process and sell the seaweed. Although wild harvest is financially attractive (there are several Scandinavian seaweed companies that specialize in this, selling niche products profitably), it is regulated and may, ultimately be more costly to harvest sustainably than to grow it. With this and other rationales in mind, various seaweed aquaculture operations are gearing up to produce macroalgae in large volumes once the market demand develops further.

Norway has the largest number of seaweed aquaculture companies in Europe [37]. A concerted effort by the government to promote research and implementation of bioeconomy enterprises together with a long coastline that can accommodate seaweed cultivation has led to this growth [2,24] . After the first farm licenses were granted in 2014, the sea surface area grew to 834 ha by 2019 with potential to produce 48,000 tonnes (wet weight). In practice, this potential was not realized and only 336 tonnes were harvested in 2020. Currently, *S. latissima* is the only seaweed grown commercially in Norway, although, licences have been granted for *P. palmata, Ulva spp, L. digitata* and *Porphyra sp*p [24]. Modellers at SINTEF estimate aquaculture production in the range of 70 – 140 tons/hectare wet weight in coastal areas with optimal growth conditions and year-round cultivation. Estimates are that Norway could produce 20 million tonnes wet (2 million tonnes dry) weight if 4,000 sq km sea space were utilised. This compares to approximately 2 tonnes of cereal crops produced on 4,000 sq km of land [38].

The achievements to date in expanding Norwegian seaweed aquaculture are due to a combination of collaboration (e.g., MACROSEA project) among industry, research institutions, and government agencies in developing and applying know-how, especially in the area of industrial infrastructure [37]. Although initial aquaculture production estimates focused on the coastal zone, the potential production would be much greater if operations went offshore as well. In order to realize the full potential of seaweed aquaculture, both nearshore and offshore, there's need for considerable investment in infrastructure and in new technologies. A review of Norwegian seaweed projects reveals that many of these focus on research as well as R & D to address the current gaps to move the sector forward [37]. In the spirit of sustainable development, there is a strong emphasis on sustainable seaweed cultivation. [39]

One of the areas propelling Norwegian seaweed aquaculture development is the race to sequester carbon in the effort to reduce atmospheric CO_2. There are numerous efforts worldwide to grow seaweeds at large scale, thereby capturing C in this biomass, and then sinking this to the seafloor as a Carbon sequestration exercise.

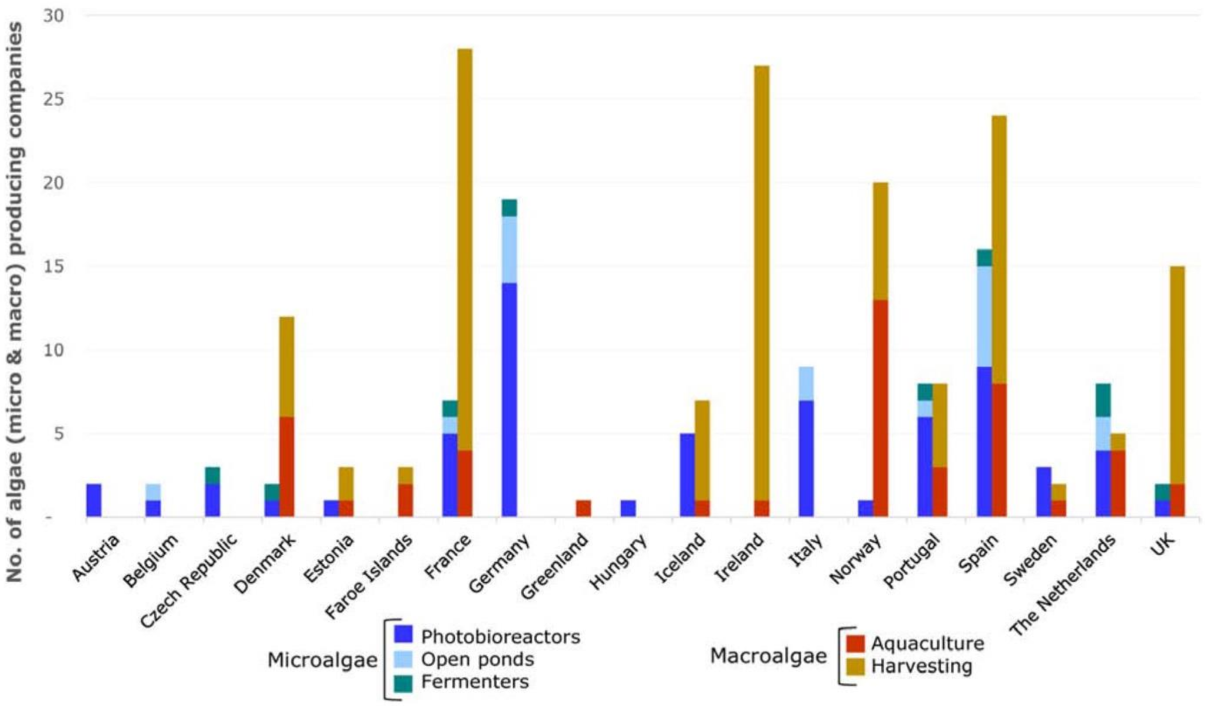

Figure 1 Algae production in Europe (source: [2]

Market Outlook

Users of seaweed products in Europe

Some seaweeds may be used directly or with minor processing such as drying, and consumed by humans or animals or added to fertilizer, whereas others require more intensive processing before they can be consumed or marketed. Much of the drying takes place in the harvesting areas because transportation of wet biomass is costly and harvesting is cyclical. It is therefore easier to rationalize local rather than distal infrastructure [19]. More complex industrial processing is used to extract hydrocolloids such as alginate, agar agar, carrageenan, and a variety of bioactive molecules. These extracts are used by the pharmaceutical, cosmetic (and personal care), food supplement, nutraceutical, functional food, and food processing industries. Other industrial applications include bioplastics and biorefineries (energy production); areas of rapid development and interest [3].

Transportation costs of raw algae are substantial and most processing plants are located in the harvesting areas, as mentioned above with respect to drying. Main constraints in Northern Europe have been harvests which are cyclical and the high cost of European labour. When local supplies are insufficient (due to low yields or seasonality) dried seaweed is imported.

The European market for edible seaweed (including food supplements and nutraceuticals) has been growing steadily and intra-Europe trade accounts for a sizeable portion of the market[40,41]. Despite considerable efforts, exact data on purchases of raw seaweed in Europe could not be obtained. According to Eurostat, between 2015 and 2019, the UK, France, Germany, Austria, Italy, and Belgium were the largest importers of edible seaweed and other algae products in Europe. Exporters include Spain, Chile, Ireland, the Netherlands, China, Germany, Italy, and France. Trends driving the increase include rising demand for plant-based diets and rising demand for nutritional supplements [38]. For example, in the UK, rising veganism appears to be an important source of demand while in Austria, concerns about chronic disease and the use of supplements may be a more important source [40]. The number of products containing seaweeds has been rising

When eaten as a vegetable, the entire plant is generally used. Products are sold fresh, dried, frozen, canned, and salted. They may also be added to prepared foods. Table 3 provides a list of the main macroalage species that are consumed in these ways.

Table 3 Edible macroalgae

Seaweed species
BROWN ALGAE • *Ascophyllum nodosum* • *Fucus vesiculosus* • *Himanthalia elongate* • *Undaria pinnatifida* • *Laminaria digitata* • *Laminaria saccharina* • *Laminaria japonica*
RED ALGAE • *Palmaria palmata* • *Porphyra spp. (7 species)* • *Chondrus crispus* • *Gracilaria verrucose* • *Lithothamium calareum*
GREEN ALGAE • *Ulva lactuca* • *Enteromorpha* spp

Source: [41,42]

A survey of 20 European companies found that the average retail price for dried seaweed was 107 Euros per kg. *Porphyra* spp. (nori) sheets were the most expensive at 383 Euros per kg and *Fucus* spp were the least expensive at 25 Euros per kg [2]. Estimates of comparable producer prices could not be found at the time of writing this report.

The three most common seaweed derivatives produced in Europe are alginates, agar-agar, and carrageenans. Alginates are produced from several brown seaweed varieties and are the source of stabilisers for colouring agents and are especially important for reconstituted food products (e.g., frozen fish and chicken fingers). Outside the food industry, alginates are used to enhance thickening, gelling, absorption, varnishing, agglutinating, and waterproofing. Agar-agar, obtained from red algae species such as *Gracillaria* spp. and *Porphyra* spp. is a versatile gelling agent and has the attribute of being thermoreversible (i.e., it regels when cooled after heating). The microbiology industry is heavily dependent on agar as a substrate for cultures. In the food-processing industry, it is used as a thickener and stabiliser for prepared foods such as custards, puddings, and ice creams and is a vegetarian substitute for gelatine. Agar-agar is calorie free but filling and is in high demand as a weight-loss aid. The dairy industry is one of the major users of carageenans where it is used for thickening, stabilising and gelling. Most of the red algae used to produce carrageenans are native to Asia rather than Europe;

however, as interest in seaweed production has grown in Europe, the uses of native sources of carrageenans is being explored [41]

Seaweeds used in the cosmetics and pharmaceutical industries may be used directly in their dried form or in more extensively processed forms such as the hydrocolloids described above. Frequently, particular molecules of interest are extracted from the plants (e.g., vitamins, beta-glucans, polyphenols, antioxidants, amino acids, minerals, and polyunsaturated fatty acids) [38]. Most of the seaweeds used in the food industry are also used in the manufacture of cosmetics and pharmaceuticals [41].

New niches that are garnering interested but that have yet to be operationalised at industrial scales include biorefinery and bioplastics, carbon capture, and organic production. A 2020 workshop conducted within the EU Knowledge4Policy programme provided an overview of stakeholders' views of the potential for European seaweed markets. Appendix III provides a list of the major challenges, actions needed to meet these challenges, and perspectives on future potential [4].

SEAWEEDS AS PART OF INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA) SYSTEMS

IMTA

Concept

IMTA is the practice of combining the cultivation of fed aquaculture species (e.g., carnivorous finfish, shrimp) with species that feed on organic and inorganic waste (e.g., filter feeders such as bivalves, bottom feeders such as mullets, plants such as macroalgae)[43]. The combination mimics the functioning of natural ecosystems and is more sustainable than monoculture for a number of reasons [44]:

1. Environmental advantages: The waste from uneaten feed, and metabolic processes produced by intensively cultivated fed species is consumed by the lower trophic species [43].
2. Economic benefits: Co-cultivation can provide farmers with marketable products in addition to their primary crop [8, 45].
3. Risk reduction: Adding crops increases diversification and reduces the farmer's reliance on a single crop [44].
4. Regulatory compliance: The environmental advantages of IMTA may increase farmer's abilities to manage farm waste, reduce pollution and cost-effectively comply with effluent and water quality regulation [8, 44].
5. Social acceptability: For fish consumers and other stakeholders concerned with the environmental sustainability of farmed fish, the environmental benefits may be appealing. This may translate into greater willingness to purchase products from IMTA and tolerance for the process [46–51]

The concept of IMTA draws on the idea that the natural food chain depicted in Figure 2 can be reproduced by combining species occupying different feeding niches so that wastes from higher trophic species are used as inputs to support the growth of lower trophic species.

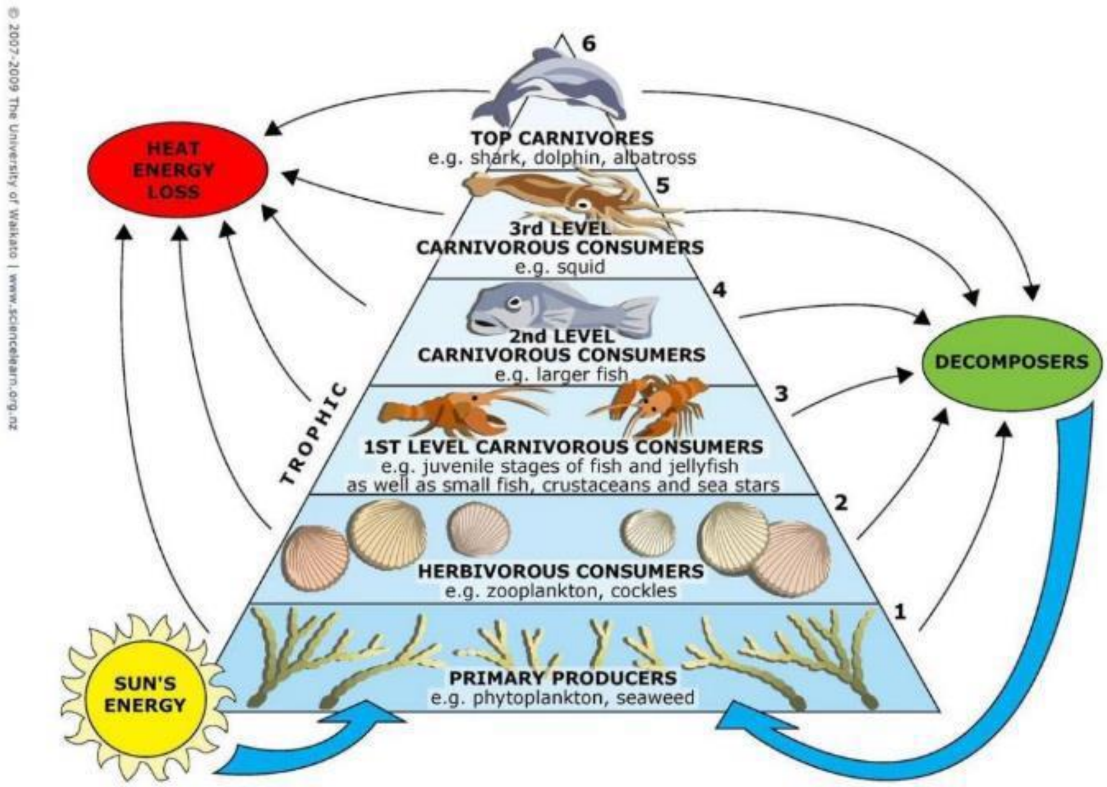

Figure 2 Food Chain

Source: New Zealand Science Learning Hub; www.sciencelearn.org.nz

In an aquaculture ecosystem, at least two organisms of different trophic levels are needed to produce some nutrient recycling. As more species are added, the potential for replicating the nutrient recycling functioning of natural ecosystems grows. Figure 3 depicts a range of possible combinations that include fed finfish with organic deposit feeders such as sea cucumbers and sea urchins, organic filter feeders such as mussels and scallops, and inorganic nutrient feeders that include kelp and a range of other macroalgae species.

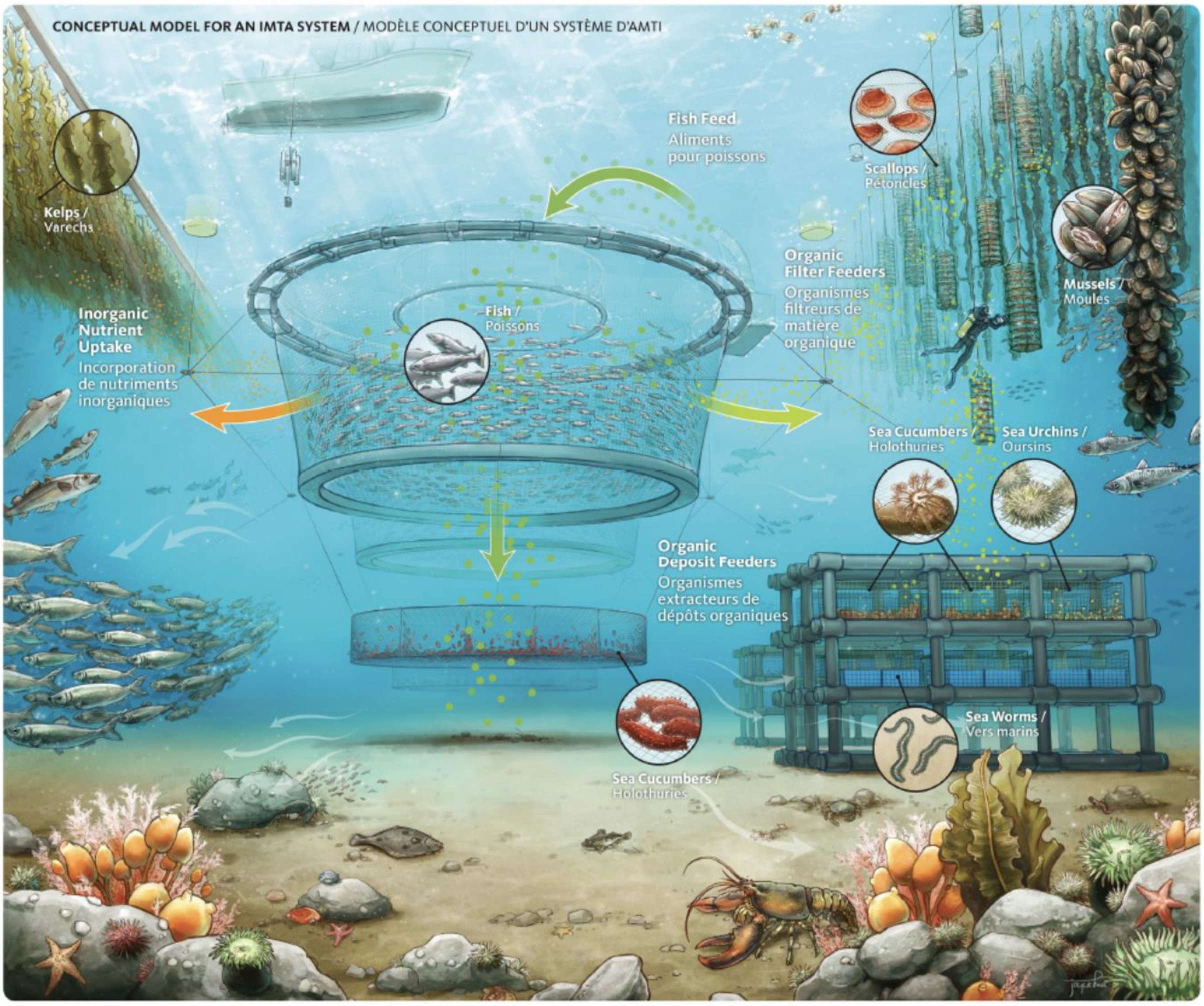

Figure 3 IMTA System Conceptual Model

Source: Fisheries and Oceans Canada, Integrated Multi-Trophic Aquaculture (2019) https://www.dfo-mpo.gc.ca/aquaculture/sci-res/imta-amti/index-eng.htm

History

Since the 1980's marine aquaculture (mariculture) has become a major supplier of fish and seafood. Most mariculture still occurs in coastal areas where it competes with many other users of the seascape. Monoculture, the farming of a single species, usually high value finfish such as Atlantic salmon and sea bream and sea bass dominates production. The potential negative environmental impacts of monoculture became apparent in the 1990s and includes nutrient loading of water bodies from uneaten feed and other fish farm waste, over-fishing to supply ever-increasing demands for fish feed, and stakeholder conflicts in the coastal zone [43]. This led to research into alternative fish farming frameworks (e.g., Munday et al., 1994[52]; Pillay 2004 [53]; Pusceddu et al. 2007 [54]; Holmer et al. 2008 [55]) and coining of the term "Ecosystem Approach to Aquaculture" [43]. In Europe, advancing mariculture that is environmentally, economically and socially sustainable has become an important aspect of Blue Bioeconomy, Marine Strategy Framework Directive, the Green Deal, and other recent initiatives.

IMTA is part of these efforts and much of the research and model systems have been oriented towards addressing the economic and environmental considerations of finfish farms [1, 9, 56].

Studies of IMTA involving salmon and seaweed found that the fish farm environment was well suited to kelp growth and that depending on the variety and placement relative to fish cages, co-culture could result in a 30% to 100% reduction in dissolved nitrogen [20, 50, 57–59]. Between 2004-2016, IMTA in northern European countries was studied in several EU funded projects (e.g., POLYCULT 2004–2006, INTEGRATE 2006–2011, MACROBIOMASS 2010–2012 and MAXIMTA, EXPLOIT and IDREEM). The positive contribution of nutrient availability to the extractive seaweeds and shellfish has been demonstrated in numerous IMTA studies [60]. In Northwest Scotland, the *Saccharina latissima* lines within IMTA farms produced 63% more biomass per season than control sites reaching yields of 20.3kg wet mass per metre rope annually [61]. Uptake of salmon-derived nitrogen declined with distance from the cages and nitrogen content was lowest in kelp 1,000 m away from the cages. Similarly, the farm's influence on seaweed growth rates was negligible at stations >200 m from the cages. Kelp growth rates from Feb-June were highest at the station closes to the salmon net pens (100 m). Simulations predict a 100 tons difference between the 1,000m station (30 tonnes seaweed, wet weight (WW) produced) and the 100 m station (130 tons WW produced) [62]. In Canada, there have been several commercial IMTA initiatives involving salmon, bivalves and kelp [44]. Since 2010, discussions of broader ecosystem functions provided by IMTA were added to the narrower focus of farm-centred benefits [8]. Nutrient and carbon accounting are two additional benefits discussed that are particularly well-s suited to seaweed.

Notwithstanding encouraging results with respect to the environmental and production benefits of co-cultivating salmon and seaweed, sustained uptake within the European aquaculture industry has been limited [7].This is not unique to salmon-seaweed co-culture, but to IMTA as a whole. During the late 2000's, this was attributed to a general lack of familiarity on the part of industry, regulators and other stakeholders and the concomitant need to:

- Demonstrate the economic benefits of IMTA for farmers [50]
- Verify that species fulfil required ecosystem functions [50, 63]
- Conduct more industry-oriented, production focused research including demonstration sites to confirm the feasibility of different co-culture techniques [50]
- Resolve certain regulatory barriers to co-culture [63, 64]

In a 2014 survey of producers as part of the IDREEM project, producers highlighted the following barriers to adoption [65]:

- Reluctance on the part of finfish producers to diversify production to the detriment of the primary highly profitable species (Salmon and Sea bream) especially given the non-existent markets for seaweed co-products at the time
- Concerns about biosecurity
- Concerns about regulatory barriers to IMTA in particular but also to aquaculture in general
- Scepticism as to the potential for "more sustainably" farmed finfish to attract higher prices

Concerns about the profitability of salmon-seaweed co-culture were confirmed in an IDREEM financial analysis of a Norwegian pilot involving *S. latissima* grown adjacent to salmon pens. Adding kelp, at best increased profitability by a small amount, but much less than expanding the salmon production. The study concluded that higher prices for the seaweed co-product and/or the salmon would be needed for farmers to rationalize the cost of investing in seaweed infrastructure and operations [66].

At the time of the IDREEM study (2013-2016), the market for seaweed produced in Europe was relatively undeveloped and producers had limited capacity to develop the marketing expertise needed to navigate this new niche. There was also some scepticism regarding the potential for attracting higher prices for Salmon that was recognized as sustainably produced [65]. This attitude was supported by several consumer surveys that confirmed that while fish consumers would be willing to pay a premium for sustainably farmed finfish, a significant number still had a strong preference for wild-caught fish. In addition, several surveys of fish consumers showed that respondents were willing to pay a higher premium for domestically produced fish than for sustainably produced imported fish. [46–49, 51]. An additional barrier to premium pricing for sustainable products is the supply chain in Europe because power tends to be skewed towards large retailers who directly control retail price points [1].

Another Norwegian initiative, Ocean Forest by Lerøy Seafood Group and the Bellona Foundation was designed to exploit the capacity of seaweed to absorb dissolved nutrients and CO2 through co-culture of *S. latissima* with Atlantic Salmon [67]. One of the project's most important results was that optimal seaweed growth was achieved with co-location of salmon and seaweed within a distance of 50 metres and that there was little benefit for seaweed when it was placed at more than 100 metres from the cages. Ultimately, the project was abandoned because it was impossible to cost-effectively arrange co-location in a manner that permitted access for maintenance vehicles and equipment for the cages when the seaweed was growing out [1]. However, an equally important finding was that seaweed grew well as long as there were sufficient nutrients in the water body and that direct uptake of nutrients from fish cages was not necessary for good growth. Lerøy Seafood Group continues to grow seaweed but at separate sites from its salmon cages under conditions that have been assessed as providing optimal growth conditions (e.g., temperature, light, ambient concentrations and fluxes of N, P, and C).

Current trends and challenges

Many of the issues facing IMTA of seaweed and salmon have been resolved. The market for the algae co-products has developed rapidly and industry and regulators have actively pursued programs to promote seaweed farming, processing and marketing. For example, in addition to Norway's programme, Ireland has aggressively pursued the development of organic macro-algae. Through projects such as AquaVitae (AquaVitae.eu), IMPAQT (impaqt.eu), and SeafoodTomorrow (seafoodtomorrow.eu) more is known about the nutrient output from fish cages and the uptake and growth of macro-algae.

Several important issues remain and persist and may present barriers to industrial scale implementation of single farm IMTA. First, as shown in IDREEM, when IMTA is undertaken as a supplement to salmon farming, if salmon farmers are not convinced of the potential profitability of co-culture projects, they will be unlikely to adopt this practice.

Ocean Forest demonstrated that operationally, salmon-seaweed co-cultivation is challenging. Convincing farmers is a complex process and will require addressing issues such as the social and consumer acceptability of IMTA and its products and a range of risks related to policy and regulation. In addition, the trade-offs between salmon and algae may make salmon farmers resistant to devoting sea space to algae. Salmon output exceeds seaweed output by orders of magnitude and attracts a price that is 90% higher [12].

Environmental performance remains one of the most important considerations for adopting IMTA. Kletou et al. (2018) found that 56% of 34 aquaculture stakeholders interviewed considered mitigation and nitrogen removal as a motivating factor to adopt IMTA and 24% considered it integral to research and development of sustainable mariculture. This compares with 47% who were willing to consider

IMTA if it enhanced production and 18% who were motivated to determine its production suitability [7]. This study suggests that environmental performance remains an important driver of interest in IMTA, but the challenges of implementation at the farm level are likely to remain a major barrier. There may also be limitations to the environmental performance of IMTA systems. For seaweed, the timing of harvests is usually determined by the appearance of nuisance and fouling epi-biota. As a result, seaweeds may need to be harvested before other species in an IMTA system with the result that nutrients may be released unabated between the fish and seaweed harvests. In Denmark, an interesting trade-off was found between extraction of nutrients and the risk of biofouling. When harvested in August or September, seaweed's total biofiltration was highest, but biofouling was also high with resulting yield reductions and harvest cost increases. Harvesting in May produced the highest yield of un-fouled seaweed but far less biofiltration benefits [68].

Moving Forward with Salmon-Seaweed co-culture: Combining different trophic culture at large spatial scales (basin-level IMTA)

The concept of IMTA emerged to address the prevention of nutrient loading of waters by farms raising fed finfish. The focus of IMTA research on the farm as a single unit may be an artifact of this origin and regulators focus on farms as potential polluters. However, IMTA has failed to achieve the economic sustainability that farmers require. Nevertheless, the ecosystem interactions that underlie the IMTA concept are sound, and this has led a number of researchers to consider integrating different species fulfilling different trophic niches at broader spatial scales.

The spatial decoupling of culturing different trophic species goes under several names, basin-level, spatial, regional or ecological IMTA. This larger scale IMTA concept was elaborated in the ECASA project [69]. Sanz-Lazaro & Sanchez-Jerez (2020) advocated using basin scale nutrient budgets to guide licenses for monoculture operations of finfish and a variety of extractive species. They noted the potential for overcoming limited implementation of IMTA and stressed the need to engage multiple stakeholders, in particular regulators and planners in zoning of the basins [6]. The Research Council of Norway has funded several initiatives on monoculture or seaweeds in areas near fish farms but not as part of a single farm unit [70].

The concept is not without its detractors, in part because the environmental benefits of IMTA have been contextualised within regulatory frameworks focused on mitigating wastes generated by farm units. The idea of co-regulating the licensing and operation of multiple farms in a water body has been greeted with suspicion by some who fear that it may allow finfish farms to pollute more [71]. For regulators, basin level IMTA requires a greater level of coordination than currently exists in order to account for the different types of aquacultures as well as other sources of nutrient loads [51, 70]. One example of planning and regulation from Australia is the Tassal Group which considers kelp cultivation as a means of complying with a nitrogen cap in the D'Entrecasteaux Channel. By reforesting areas that were once abundant with kelp, the company hopes to increase its salmon production. The seaweed would be used for human consumption and alginates. Other regulatory provisions have been advocated, but not yet enacted. These include nutrient trading credits for nitrogen, phosphorous, and carbon [39, 71].

While many point sources and near-farm impacts of aquaculture effluents on sediments and water columns have been identified, data on the more distant impacts are still largely unavailable. A study by Sara et al. (2011) detected large spatial scale and long-term variations in nutrients from mariculture in surface waters of the Castellammare Gulf. The authors noted that at greater distances from fish cages, the confounding effects of other pollution sources are significant and that better biomonitoring protocols designed to identify finfish aquaculture impacts at larger spatial and longer temporal scales were needed [74]. Although it is difficult to identify the level of remediation needed at the basin level, spatially decoupling seaweed and finfish aquaculture could improve environmental quality of basins with multiple sources of dissolved nutrients. Flexibility as to the siting of algae farms could also take advantages of other ecosystem services, including habitat structuring and coastal defense [2].

From the standpoint of policy and regulation, IMTA, seaweed culture and sustainable aquaculture in general feature prominently in EU legislation, directives and regulations. In 2018, the European Parliament adopted a resolution (P8_TA(2018)0248) in which IMTA is mentioned as one of the aquaculture systems requiring further research, studies and pilot projects and calls for "further development of the emergent seaweed aquaculture sector." [75]. This resolution broadly reflects the aims of the EU's Bioeconomy Strategy (2012) and the EU Blue Growth Strategy (2012) that encourage advancing sustainable food systems and job creation in regions that rely on the coasts. [2] Within the context of the EC's Green Deal (2020) expanding seaweed production is consistent with targets such as becoming climate neutral by 2050, biodiversity protection, sustainable food, and advancing the circular economy. The growing political interest and markets for macroalgae may also improve the lack of clarity around licenses for seaweed cultivation that exists in many countries[2, 3]. Norway has been a leader in promoting its domestic industry, but many other countries lack the regulatory infrastructure that is needed to bolster seaweed aquaculture [2, 3, 24].

In order to move forward with further explorations of basin-level IMTA, new collaborations among industry, scientists and regulators will be needed to understand optimal growth conditions for seaweed, environmental benefits and risks associated with expanded seaweed production and to meet the concerns of regulators and develop planning management frameworks capable of accommodating aquaculture in the context of integrated frameworks such as ICZM and MSP. In addition, opportunities in the rapidly developing seaweed value chain need to be understood by current and prospective producers.

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APPENDICES

Appendix I Functionalities of hydrocolloids sourced from different types of macro-algae

Table 4 Functionalities of macroalgae-based hydrocolloids

Hydrocolloid type	Source	Uses and attributes
Alginic acid (alginate)	Brown algae	Food, pharmaceutical, paper, and textile production; Gelling, thickening, bioactive properties
Agar agar	Red algae	Various food processing; gelling, culture substrate, impression materials in dentistry
Carrageenan	Red algae	Dairy products, meat and fish reconstruction; thickening, gelling, stabilizing

Source: [41]

Appendix II – Seaweed yield measures and conversions

Table 5 summarises different approaches to reporting yields in different publications.

Table 5 Seaweed yield measures and conversions

Production method	Unit	Wet (W)/Dry (D)	Comparator
Rope	Mass (kg biomass)	W/D	Metre rope
Raft and wild collection	Mass (kg biomass)	W/D	Hectare, m^2
Various	cm^2	W	Blade area
Various	Mass (kg carbon)	W/D	Hectare, m^2

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Appendix III EU-JRC Workshop on algae production in Europe

Challenges for upscaling and exploiting potential markets

- Need for professional education in food biotechnology related to macroalgae
- Need for certification of products of European origin
- Need for strategic view that includes market potential coupled with environmental and bioremediation advantages
- Low iodine thresholds in EU MSs make it difficult for industry to comply
- No differentiation between organic (dangerous) and inorganic (more abundant & less toxic)
- Biorefinery approach in processing needs to move from lab to industry
- Import control/inspection
- The production in Europe is too marginal to match the demand;
- Difficult to prove health claims of algae raw biomass or products;
- Price of protein of land based products not comparable to algae;
- Novel food: costly, time consuming and risky procedures to submit an application;
- No harmonisation between non-European and European guidelines which leads to a decrease in market alignment and fairness;
- Organic certification: lack of harmonisation of criteria for organic certification at EU and non- EU (mainly Asia) level and stricter requirements at EU level; need of EU organic labelling to increase competitiveness of the sector.
- Stimulation of consumer interest (currently lacking)
- Aquaculture: issues with social acceptability, uncertainty of ecological impacts and problems with disease control;
- No agreement on definition of Integrated Multi- Trophic Aquaculture (IMTA);
- Limitations related to iodine content threshold and inorganic versus organic arsenic;
- Mismatch between market needs and length of the administrative procedures;
- Removal of carbon might be overrated and/or difficult to promote since it involves disposal of commercially viable product

Actions needed to meet challenges

- Better support for the applications under the novel food regulation;
- Higher education programmes on food and biotechnology focused on algae;
- More transparency in identification of the product origin;
- Better support for product development (claims, regulation, harmonisation);
- Deeper harmonisation of parameters across MS and in relation to imported products (due to the lower thresholds in European MSs than in Asia), which would require a regulatory action;
- Enforcement of control of imported products to assess compliance with European rules (random analysis required to assure safety);
- Marketing support and education of consumers to increase consumer awareness;
- Scientific evidence to support market claims.

Requirements for future products and market expansion

- Need to promote the EU high-quality biomass (in comparison to algae biomass from Asia);
- Need to expand the market out of European borders;
- Promote consumers' awareness;
- Development of the biorefinery approach;
- Scientific evidence to support claims related to algae biomass;
- Harmonization of requirements for European and imported products;
- Need to change the organic regulation (see Topic 2);

- Development and harmonisation of guidelines: translation of international guidelines to the European context (for example to consider establishing an equivalent to the US process) ;
- Stability in the pool of experts advising about the algae sector at the EU level;
- Need to solve the problems related to the novel food regulation that is preventing the development of new products;
- Streamline the mismatch between national and European regulatory frameworks and facilitate the implementation of EU directives at national level;
- Increase control at the borders for imported products.
- Research developments on quantification of removal capacity (nutrients, etc.) by seaweed biomass;
- Transfer the good standards already available for other food sources to seaweeds;
- Harmonise the safety requirements with other food ingredients (food safety should not be stricter for seaweeds);
- Valorise the ecosystem services provided by the cultivated seaweed biomass: assigning costs to pollution and payments for cleaning.