



Ecological impacts of algae cultivation - a learning guide

Dag Gjetø, Alexander Jüterbock, David Aldridge, Magnus Johansson, Henning Reiss



Authors:

Dag Gjetø, Alexander Jüterbock, Henning Reiss – Faculty of Biosciences and Aquaculture, Nord University, Universitetsalléen 11, 8026 Bodø, Norway

David Aldridge - Seaweed Solutions AS, Bynesveien 50 C, 7018 Trondheim, Norway

Magnus Johansson – Bromangymnasiet, Gymnasievägen 4, 824 34 Hudiksvall, Sweden

How are macroalgae used and produced today?

Macroalgae are getting increasing attention in the field of aquaculture in Europe in recent years. The most obvious reason is that the aquaculture industry can see a potential for production and sale, but also for their ecosystem services, such as the ability to reduce the greenhouse gas CO₂ from the atmosphere via photosynthesis, and the ability for bioremediation (see glossary), as well as in hybrid aquaculture concepts such as *Integrated Multi-trophic Aquaculture* (IMTA).



Figure 1. Cultivated Saccharina latissima (© Photo: David Aldridge)

It is important to understand that when we start growing a species in an ecosystem, we change the balance of the ecosystem already in place. To what extent? And if the goal is to produce more algae, how does the impact compare to trawling, the traditional method for getting macroalgae? In Norway, a system has been developed where areas with macroalgae are divided into sectors and harvested over a 5-year period, where each field within a sector is harvested once, then allowed to regrow for 5 years before it is harvested again (Vea & Ask, 2011). This is possible because beneath the larger algae, grow smaller ones called *recruits*. A possible problem with this harvesting scheme, however, is that the recruits might gradually deplete with each round of harvesting –

bad news for the macroalgae, but also communities depending on them. On the macroalgae themselves, *epiphytes*, and sessile organisms grow, and they are also homes for invertebrates such as snails, and serve as habitats and nurseries for fish. These organisms make up much of the biodiversity in macroalgae forests, and are important parts of the communities living there. Although harvested algae may regrow, the organisms living with them do not recover to the same extent (Christie et al. 1998; Steen et al. 2016). If the associated organisms do not get the time to recover, the ecosystem will lose much of its biodiversity, and would then be directly threatened. All of these factors together make harvesting a large-scale disturbance for biodiversity. This stands in stark contrast to cultivation, where the organisms harvested were put there for the express purpose of harvesting, rather than removing already existing, and fully functioning ecosystems.

1. Species and cultivation

In Norway, the macroalgae primarily harvested are *Laminaria hyperborea* (forest kelp/northern kelp) and *Ascophyllum nodosum* (knotted wrack, 154 000 t fresh weight in 2014). In terms of cultivation, efforts are mostly focused on kelps, with *Saccharina latissima* being the most popular (followed by *Alaria esculenta*) due to biomass and nutritional content (Stevant et al., 2017). Other species of interest are *Palmaria palmata*, *Asparagopsis* spp. and *Ulva* spp., but current production occurs on smaller scales.

1.1. Cultivation species and period

Saccharina latissima is usually fertile during late autumn/early winter when the days are short, and temperatures are low (Parke, 1948). Outside of this period fertility can be induced artificially by removing the meristem and controlling light conditions (Lüning, 1988). This enables spores to be reliably obtained throughout the year for seeding or setting up vegetative gametophyte cultures (for upscaling and seeding at a later point in time). For cultivation at sea, deployment of seeded lines has to occur in the autumn/winter to maximise growth during the spring when nutrients and light are nonlimiting. Nutrient limitation, following rapid uptake during the spring phytoplankton bloom, is thought to be the main limiting factor for growth in most Norwegian fjords during summer (e.g. Paasche & Erga, 1988, Forbord et al., 2012). One problem with *S*. latissima cultivation is the growth of epiphytic invertebrates (especially bryozoans) on the blades during summer months (reviewed by Stévant et al., 2017). This reduces the seaweed quality, and ultimately the marketable biomass. For this reason, harvesting of the crop must be timed carefully and is a compromise between maximising biomass while minimising biofouling. The exact timing varies based on latitude, and is frequently between April (southern Norway) and August (Northern Norway). From the point of view of IMTA, the requirement to harvest kelp before the onset of biofouling creates a suboptimal mismatch between the kelp growing season and the period of highest nutrient discharge from salmon farms (Fossberg et al., 2018).

Palmaria palmata (also known as Dulse) is a red seaweed that is commonly found on rocky shores in the Northern Hemisphere. It has been eaten for many centuries all over the world. Recently, it has become very popular due to its high nutritional value (including high protein content) in addition to its favourable flavour; It is sometimes even marketed as "vegan bacon". There are several companies producing this species using tank cultivation, where biomass growths vegetatively when supplied with nutrients and sunlight (Pang & Lüning, 2004). However, this method requires land area and is also labour intensive, as well as requiring a large intake of seawater, high construction costs and high power inputs. All of these factors reduce the economic feasibility. Cultivation at sea has the potential to produce high biomass volumes more economically, but the methods for developing large-scale hatchery protocols are still in their infancy (Schmedes et al. 2021).

Asparagopsis is a genus of red algae that is widely distributed in temperate, subtropical and tropical oceans. There is currently interest in cultivation of *Asparagopsis* due to its potential to reduce methane emissions in ruminants by up to 98% when included as part of their diet (Zhu et al. 2021). Attempts to cultivate *Asparagopsis* date back to the 80s, with methods developed in France and Ireland in the 90s culminating in 14km of cultivation ropes being tested in Brittany (France) in 2004. However, truly large-scale cultivation is currently held back by an inability of researchers to gain full control over the environmental conditions required to close the life-cycle from the tetrasporophyte to gametophyte phase (Zhu et al. 2021).

The green seaweed *Ulva*, commonly known as sea lettuce, has favourable traits for cultivation: widely distributed, environmental tolerance, high growth rates, combined with favourable nutritional characteristics that make it desirable not just in food and feed, but also for cosmetics, nutraceuticals and pharmaceuticals. *Ulva*, like *Palmaria*, has been successfully cultivated in Europe using tank cultivation, and also in near shore environments on nets and in cages. Competing with terrestrial crops, however, requires the cost savings that are made possible by large-scale cultivation at sea. Recent research in Sweden has demonstrated hatchery methods for seeding of twine for sea cultivation of *Ulva fenestrata*, concluding that it "is a suitable crop for large-scale off-shore cultivation in the northern European hemisphere and that it copes well with the prevailing, often harsh (storms, heavy precipitation, strong wave action) winter conditions." (Steinhagen et al. 2021). Successful sea cultivation was subsequently carried out in 2022 (Nordic Seafarm).

1.2. Associated fauna

Compared to natural kelp forests (Christie et al. 2003; Fig. 2), kelp farms are short-lived habitats that do not exist in the environment longer than one year due to annual harvests of biomass. They are also habitats that grow suspended in the water column, whereas natural kelp forests grow on the seabed. For these reasons there can be some doubts about how comparable "artificial kelp forests" are with their natural counterparts. Thus, it is not surprising that one study in Norway has shown that kelp farms support fewer species, and, in consequence, host lower species biodiversity (Torstensen, 2020). However, the same study did show similarities between artificial and natural forests, with amphipods and snails being the dominant organisms in common across both locations. Other invertebrates that were common only at the kelp farm were decapods, polychaetes and bivalves.



Figure 2. Kelp (*Laminaria hyperborea*) in Saltstraumen (Bodø, Norway) with associated benthic fauna i.a. sea anemonies (*Metridium senile* and *Urticina eques*) and Ascidians (*Halocynthia pyriformis*) (© Photo: Vebjørn Karlsen)

2. Cultivation sites

In comparison to Asia, the seaweed cultivation industry in Europe is very much in its infancy, although it is growing rapidly. In Norway the cultivation of macroalgae, which mostly focuses on *Saccharina latissima* and *Alaria esculenta*, was initiated over 10 years ago with small-scale experiments. Cultivation is still in an early phase in Norway, but there is strong commercial interest: there were 475 permits for macroalgal cultivation distributed over 97 locations and 16 companies in 2020 (Directorate of Fisheries 2020). Production in Norway is also growing rapidly. In 2015, total production (cultivation) of macroalgae (*S. latissima* and *A. esculenta*) was 51 t, increasing to over 300 t in 2020 (Directorate of Fisheries 2020); in 2022 it is estimated that production will exceed 500 t (Norwegian Seaweed Association, *Personal communication*).

Both *S. latissima* and *A. esculenta* are widespread in Europe, preferring cold water below 20°C (Druehl 1967, Munda and Lüning 1977). Approximately half of the natural kelp beds of *S. latissima* are found along the coast of Norway (Moy et al. 2006), demonstrating the suitability of Norway for kelp cultivation. Theoretically the whole of the Norwegian coastline can be used for kelp cultivation, with a 2-month lag in the growing season when comparing northern to southern latitudes (Forbord et al., 2021). Currently, cultivation is focused in areas that are sheltered and semi-sheltered, as this reduces logistical and engineering problems and costs that would be associated with offshore production. As production scales, however, offshore locations are likely to become more common and are likely to offer a number of benefits, including reduced biofouling, increased nutrient concentrations and longer growing season.



Figure 3. Algae farm site cultivating *Saccharina latissima* (© Photo: David Aldridge).

3. Environmental impacts of macroalgae cultivation

The human introduction and cultivation of any organism in an ecosystem may shift the existing balance of the system, and even more so in cases where the cultivation is large-scale. Exactly what effect this has on the ecosystem can vary, and be either beneficial or detrimental to the surrounding ecosystem. The overarching question is therefore whether expanding the macroalgae cultivation industry is harmful, benign or beneficial. The following consequences are presented in this learning guide, while more detailed background information can be found in the associated review.

3.1 Carbon sequestration and release

Sequestration of carbon, or the capture and storage of carbon, happens when macroalgae take up carbon as part of photosynthesis, converting it to biomass. The ultimate fate of the carbon will differ, parts will be recycled when consumed by other organisms, and other parts will be stored long-term in the deep sea (Renaud et al., 2015). This happens when macroalgae biomass breaks off in the form of *detritus*, or as whole plants gets swept away, the biomass in either case drifting to be stored beneath sediment deep in the sea, where it will not be consumed and recycled. As the kelp grows and the season progresses, more particles are released. The exact mechanics of long-term (that is, in the deep sea) storage of biomass is, however, not well understood, and we need more knowledge about how the volume of algae becomes deposited, the distribution of the biomass, and the physical and biological requirements for the algae to be successfully stored, rather than recirculated.

In nature, as well as from kelp cultivation sites, macroalgae release carbon in the form of detritus, and the volumes of *particulate organic matter* (POM) released from cultivation sites as well as its dispersion is a source of concern. The concern is namely that large volumes of algae will be deposited on the sea floor, where it may become a danger to benthic life forms by increased microbial activity, creating an *anoxic* environment (Kutti et al., 2007), or through the production of sulfides, that may occur as the material is broken down.

Kelp serves as an important form of connectivity between shallow, productive areas and deeper areas, affecting regional productivity and spatial organization of marine ecosystems. Kelp detritus can provide an important addition of resources and enhance *secondary production* in downstream communities ranging from tens of meters to hundreds of kilometers (Krumhansl & Scheibling, 2012).

Through the first months of growth, less than 5% of biomass is lost, steadily increasing to about 8-13% by the time of harvesting (typically April-June, depending on latitude). If

the kelp is left unharvested, as much as 50% may be lost to the environment in the late summer, until eventually, everything will have eroded away.

However, exported kelp detritus does not tend to accumulate to any great degree. Research on kelp detritus found that kelp detritus tends to spread thinly over large areas, depending on conditions around the cultivation site, such as topography, currents, and sediment type (Hancke et al., 2021). At one site it was found that under normal operating conditions, the detritus was deposited from right below the cultivation site to several kilometers out, with 90% being deposited within 4 km. The density of deposited carbon was found to be 25g C/m² directly below the cultivation site, to 1g C/m² a few kilometers out; the pattern of dispersion was found to be independent of production volume – but this will vary with local conditions such as topography and currents.

Results from "worst-case-scenario"-simulations where fresh biomass of kelp was purposefully deposited in a 10cm thick layer directly on the sea floor (>8kg/m²), simulating a situation that could arise in case of total collapse of the site, showed that the biodiversity fell drastically due to the affected area growing anoxic and toxic, with only a few tolerant species surviving and thriving (Hancke et al., 2021). This was a short-lived consequence, though, as after only two weeks 50% of the deposited biomass was gone, and after 3 months more than 90% had disappeared and conditions normalized, although this process is slowed in colder waters. There was also a notable difference in the species deposited, with *S. latissima* having a shorter degradation period than other species such as *Alaria esculenta*.

Organic material that is not broken down, eroded or consumed will contribute to longterm storage and sequestering of carbon, meaning a net reduction of carbon in the water column. Macroalgae in the wild do not typically grow in habitats where large amounts of it may accumulate for storage (which would happen in deeper waters, and they grow close to shore), but the presence of algal detritus in deep waters has been reported, suggesting it may be transported and stored there (Krause-Jensen & Duarte, 2016). It has to be noted though that the purpose of algae cultivation is not the sequestration of carbon through deposition of the e.g. kelp, but the harvest and consumption of the kelp and consequently the release of carbon back in the atmosphere.

Learning module 3.1

Global sequestration

Use Table 1 and 2 in McLeod et al. (2011) to create a bar chart that compares the carbon sequestration potential (in Tg C yr⁻¹) of terrestrial and marine habitats. Add the value estimated for kelp forests from Krause-Jensen & Duarte (2016). Thus, what percentage of the global carbon emission (about 43 billion tons of CO₂ a year) is sequestered annually by kelp?

Norwegian kelp sequestration - Along the Norwegian coast an area of 8000 km2 is covered with kelp forests. Assuming a production of 300 g C m-2 yr-1, what percentage of the annual Norwegian carbon emissions (53 mill. ton yr-1) is sequestered by the growth of natural kelp forests? This can be calculated based on the figure below.

Ecosystem	Carbon burial rate (g C m ⁻² yr ⁻¹) mean ± SE	Global area (km²)	Global carbon burial [*] (Tg C yr ⁻¹) mean ± SE	Sources	
				Global area	Carbon burial
Salt marshes	218 ± 24 (range = 18-1713) n = 96 sites	22 000"- 400 000	4.8 ± 0.5 87.2 ± 9.6	Chmura et al. (2003); Duarte et al. (2005a)	Chmura et al. (2003); Duarte et al. (2005a)
Mangroves	226 ± 39 (range = 20-949) n = 34 sites	137 760- 152 361	31.1 ± 5.4 34.4 ± 5.9	Giri et al. (2010); Spalding et al. (2010)	Chmura et al. (2003); Bird et al. (2004); Lovelock et al. (2010); Sanders et al. (2010)
Seagrasses	138 ± 38 (range = 45-190) n = 123 sites	177 000 600 000	48-112	Charpy-Roubaud and Sournia (1990); Green and Short (2003); Duarte et al. (2005b)	Duarte et al. (2005a); Duarte et al. (2010); Kennedy et al. (2010); Duarte (unpublished data

Notes: ¹We calculated global carbon burial values using the mean carbon burial rate and the minimum and maximum global area values for salt marshes and mangroves. Global carbon burial values for seagrasses are from Kennedy et al. (2010). "No global inventory of salt marshes has been published, so Chmura et al. (2003) estimated 22000 km² of salt marshes based on inventories for Canada, Europe, the US and South Africa. SE = standard error.

Table 2. Carbon burial and global area of terrestrial forest ecosystems								
Forest type	Carbon burial (g C m ⁻² yr ⁻¹) mean ± SE	Global area (km²)	Global carbon burial (Tg C yr ⁻¹)	Sources				
				Global area	Carbon burial			
Temperate	5.1 ± 1.0 (range = 0.7–13.1) n = 18	10 400 000	53.0	Schlesinger (1997)	Schlesinger (1997); Zehetner (2010)			
Tropical	4.0 ± 0.5 (range = 1.4-7.6) n = 15	19622846	78.5	Schlesinger (1997); Asner et al. (2009)	Schlesinger (1997); Zehetner (2010)			
Boreal	4.6 ± 2.1 (range = 0.8–11.7) n = 5	13 700 000	49.3	Schlesinger (1997)	Schlesinger (1997); Zehetner (2010)			



Figure 4. Tables from McLeod et al. (2011; on top) and carbon sequestration estimates provided in Fig. 3 in Krause-Jensen & Duarte (2016) with all values in TgC yr^{-1}

3.2 Light limitation

Cultivated macroalgae grow close to the sea surface, down to about 30m depth, and will therefore absorb most of the sunlight, which means they may possibly shade the waters below. For this reason, a concern is that the shading might reduce the ability of phytoplankton in the area to perform photosynthesis, reducing primary production. This in turn would be negative for zooplankton, larvae and other organisms dependent on primary producers, and in this way shading can therefore undermine the basis for local food webs.



Figure 5. Cultivated Saccharina latissima (© Photo: David Aldridge)

In addition to this, the structures and biomass of the cultivation site could dampen the wave action and in- and outflow of water to the area, reducing nutrient availability and the transport of planktonic organisms. However, phytoplankton will likely not remain below the cultivation site, and the bigger threat is therefore to sedentary marine plants and -algae growing below a cultivation site.

The consequences of shading is still not clear: results from Zanzibar suggest that the wild seagrass populations there were negatively affected by macroalgae cultivation, but this occurred in very shallow waters were workers would walk directly on the seagrass, so the seagrass was damaged as a result of trampling, making it difficult to determine the impact of only the shading (Moreira-Saporiti et al., 2021). Field experiments performed in Ireland, although not specifically focused on the effects on shading, suggested that effects of macroalgae cultivation in shallow (6-20m) waters had little to no impact on the benthic community, including seagrass *Zostera marina* (Walls et al., 2017).

Our knowledge about the effects of shading is limited, although one can to some degree extrapolate from research dedicated to other effects of macroalgae cultivation on the surrounding ecosystem. It can, however, be counted as logical that the effects of shading on life below the cultivation site will decrease the deeper the location is. Although our knowledge is limited, certain assumptions can be made for wild populations of microalgae, based on research on the antagonistic relationship between microalgae blooms and intertidal kelp, showing that shading has a negative effect on benthic primary producers in the intertidal. At present, it seems effects of shading is limited in terms of negative impacts, and is worse in very shallow waters. It is also logical that the problems of shading will scale as European kelp farms increase in size and coverage.

Learning module 3.2

Algae growth under different light conditions

The green algae of the genus *Ulva* can be found at many European coasts. *Ulva lactuca* is one common species, but species identification is difficult – therefore we use her its common name: sea lettuce (including other species of *Ulva*). Sea lettuce is fast growing and can be used in short experiments to assess growth just by using a ruler.

If you have access to sea water and sea lettuce, a simple experiment can be designed to simulate the shading effect by cultivated algae on green algae on the sea floor. You need three small tanks, sea water, collected sea lettuce blades, an aquarium pump.

From the sea lettuce blades you stamp or cut out equally sized circles (e.g. \emptyset =5 cm, see Fig. 6) – five circles for each tank. Put them in the tanks and manipulate the light exposure for each tank (e.g. one in the sunlight, one covered with semi-transparent fabric, one covered with less transparent fabric). After one or two weeks measure the disc sizes in each aquarium by unfolding the discs on a laminated millimetre paper. If possible, you can also use a fine- scale to measure the biomass increase.

How has light intensity affected the growth of sea lettuce? Can you transfer that to natural habitats? Can you find other changes except growth e.g. changed colour? Could you also find ways to measure these effects (determine the colour of the discs on digital photos)?

This experiment can be done with different species (e.g. *Porphyra* as a red algae with different light requirements, Fig. 6) or other set-ups. For example, growth at different light conditions could be simulated in dark rooms with light cycles on different timers or with light bulbs of different wavelengths.

If you have easy access to natural habitats, you could also sample algae from different depth (with an algae-scrape) and compare e.g. size, coloration, branching (if applicable).



Figure 6. Discs for growth experiments of *Ulva* (left) and *Porphyra* (right) ideally placed on laminated millimeter paper (© Photos: Michael Streicher).

3.3 Nutrients and pollution

In addition to taking up CO₂, macroalgae absorb nutrients from the waters around them, assimilating dissolved inorganic nitrogen and phosphorous. This gives us something to consider: On the one hand, it is believed macroalgae may help reduce *eutrophication* which happens when nutrients are put into the ecosystem, often by runoffs from agriculture next to the aquatic system, or released directly into the water from fish farms. However, another thing to consider is that macroalgae may absorb too many nutrients in "healthy" waters, depleting them so that the natural populations of macro-and microalgae may be negatively impacted, which in turn has consequences cascading up the food web (Hancke et al., 2018).

Microalgae have a more effective uptake of nutrients than macroalgae, being able to absorb nitrate at very low concentrations, which macroalgae cannot (Eppley et al., 1969). While nutrients are so low that macroalgae may only grow at 1-2% of their maximum growth rate, microalgae can be thriving and grow at close to maximum growth rate (Hancke et al., 2021), meaning that in terms of nutrient availability, macroalgae are unlikely to negatively impact microalgae via direct competition, a conclusion which is independent of production volume.

However, as cultivated algae and the wild microalgae absorb nutrients from the water, this may reduce the availability of nutrients and thus impact the wild macroalgae growing in the area, not able to take up nutrients as efficiently as microalgae. This same process can also occur within kelp farms, reducing growth internally. This competitive situation may negatively affect wild macroalgae populations, which in turn might have negative consequences on the food web (Hancke et al., 2018).

The uptake of nutrients is not necessarily negative, as it may have a positive effect in reducing eutrophication resulting from runoffs from agriculture, rivers, and fish farms. The higher level of nutrients in the water is then readily available to all primary producers, limiting growth only when the system is no longer eutrophic. In this way, cultivated kelp may positively impact the surrounding ecosystems and help towards restoring and bringing balance to ecosystems surrounding the cultivation site (Hancke et al., 2018).

The "nutrient-negative" footprint of algae cultivation sites is often believed to be synonymous with pollution-free, or put differently, a site which removes excess nutrients from the environment, is by definition part of the cleanup rather than a source of pollution; however, the framework needed to be able to grow the algae may be a source of microplastics or other pollutants.

Learning module 3.3

Bioremediation potential of cultivated algae

The potential for removing nutrients from the water through primary producers is called bioremediation and algae cultivation might therefore compensate for eutrophication effects of fish farming that are releasing nutrients. But how much algae are needed to remove the nutrients from an entire fish farm?

Based on the calculation of Sanderson et al. (2012), we can calculate and visualise the amount of algae needed to remove the dissolved nitrogen released from an average salmon farm (approximately 3.600 t) or a farm in your vicinity. According to Sanderson et al one hectare of *Saccharina latissima* culture might remove the equivalent of 5.3% of the Dissolved Inorganic Nitrogen (DIN) from a 500t salmon production over 2 growth seasons. Assumptions are: 'The range of values for wet weight of seaweed cultured per metre of longline was for *S. latissima*: 22–330 kg m–1. Percent nitrogen dry weight for harvested seaweed was for *S. latissima*: 1–3% nitrogen dry weight. The analysis assumes there are 40 longlines, each 100 m in length, per hectare (approximately 2.5 m between each). Wet to dry weight ratios used are 7:1 9:1 for *S. latissima*' (Sanderson et al. 2012).

How many hectare do we need for 100% nutrient compensation of your selected fish farm? You could visualise the effect for your coast by either plot the size around a farm you have in your vicinity or create one at your coast? Or a small scaled model could be crafted with a match-box sized farm as a basis.

For Norway, you can use directory of fisheries web resources to find out about existing farms and their production size (<u>https://portal.fiskeridir.no/portal/home/</u>) and you may use Kartverkets mapping tool to map the dimensions of the algae farm you calculated (<u>https://norgeskart.no</u>; drawing tool).

Nutrient experiment

You can also expand or modify the sea lettuce experiment (learning module 3.2) by experimenting with fertilizer to simulate nutrient effects on algae growth.

3.4 Macroalgae as artificial habitats

Natural kelp forests are key ecosystems, providing habitats and nurseries for a wide range of organisms (Christie et al. 2003). A macroalgae cultivation site will therefore also create temporary habitats for both invertebrates and fishes, and the moorings could possibly functioning as artificial reefs, and contributing to ecological interactions within nearby ecosystems. Their role as habitats has not yet been systematically investigated to a great degree, but they have been shown to function as habitats like their wild counterparts (Stevant et al., 2017). These artificial habitats differ from natural kelp forests in that they are exclusively *monocultural*, as well as growing close to the surface on artificial structures or ropes, all of which are removed upon harvesting. These features lead to concerns, among which are the possibility of artificially sustaining an unnaturally large population which will be taxing on the surrounding ecosystem upon harvesting of the cultivated macroalgae, or allowing non-native species to establish a foothold they would not otherwise have been able to gain.

Macroalgae serve as both a food source as well as a habitat, and importantly act as nurseries. The removal of such habitat-forming species could lead to a collapse of the ecosystem; however, in naturally occurring vegetation beds, both overgrazing and overgrowth is uncommon, suggesting that self-regulation is the rule in healthy systems. Kelp forests are vulnerable to a range of factors such as large grazing events by sea urchins, overfishing of predators, trawling and other extraordinary events.



Figure 7. Kelp (*Laminaria hyperborean*) attracting saithe (*Pollachius virens*)) in Saltstraumen (Bodø, Norway) (© Photo: Vebjørn Karlsen)

In the context of cultivation, it has been found that cultivation sites provide habitats with a species composition mimicking that of natural kelp forests in the immediate vicinity (Hancke et al., 2021), establishing an ecosystem in connection with the cultivation site, which would not otherwise have existed. Unlike natural kelp forests, these artificial forests will be removed upon harvesting. The most pressing concern then is whether this will result in an overload of, and subsequent collapses in surrounding ecosystems, or simply be part of a natural flux in increase and reduction in associated populations, or even a beneficial addition leading to a healthier ecosystem in general. The answer to these questions is still unknown.

In addition to this, any human-caused disturbance to an ecosystem, such as the creation of cultivation sites with supporting structures, may allow foreign species to invade and establish themselves in the ecosystem. This has been observed to happen in empty kelp cultivation sites, where great abundances of the invasive species Japanese skeleton shrimp, *Caprella mutica*, which is designated as a "(especially) high risk" on the Norwegian black list of invasive species, were recorded (Hancke et al., 2021).

The skeleton shrimp was however only present when the cultivation site was empty, but it had also spread to other structures such as buoys, ropes, floating docks and other artificial structures in the area; but when the macroalgae were growing again, only native species of skeleton shrimp were observed. The problem also seems to be contained to artificial structures, as there were no observations of the invasive skeleton shrimp in surrounding kelp forests at any point. It is important to note, though, that the findings are limited to a time frame of less than a year, and only in one locality; the effects of multiple, large-scale cultivation sites operating simultaneously is unknown. It has often been found that non-native species are more abundant on artificial structures than natural habitats (Airoldi et al., 2015).

Learning module 3.4

Diversity survey

Macroalgae can provide habitat for many species and not only the large sublittoral kelp harbour a vast amount of different species. To get a better understanding of this variety, a diversity survey could be carried out in an intertidal macroalgae habitat. Brown algae such as Fucus or Ascophyllum species are easily accessible during low tide. Many mobile animals living in between and under the algae. These habitats can be easily sampled with a squared frame, some jars for mobile animals, tweezers and plastic bags.

A wooden or metal square can be self-made and could have an area of e.g. 0.25 m^2 or smaller (use whatever is at your hand – most important is that the size is always the same; Fig. 8). Find a suitable area with macroalgae cover and use the frame to delineate the area you take the sample from. You can either harvest the macroalgae from the frame and store it in a bag (careful not to loose all the mobile animals before) or you shake the algae over a large sieve to retrieve the mobile animals (try to use the same

procedure throughout e.g. duration and handling). The under storage of the macroalgae habitat can be assessed too by identifying all attached animals or algae under the algae macroalgae canopy. Collect all animals in the frame and either identify on the spot and release or store them in a jar for later inspection at school. Count the number of individuals of the species you find. Repeat that several times for the same algae habitat (different frames).

Identifying benthic animals can be difficult and stereo microscopes would be needed, although for some it is still too difficult. Online resources to identify macroinvertebrates are the Marine Species Identification Portal (<u>http://species-identification.org/identify species.php</u>) and for some more species information and taxonomy in the World Register of Marine Species (<u>https://www.marinespecies.org/</u>).

How many different species do you find? Are there differences in diversity among different algae habitats? If you have access to a fish or algae farm site, you could compare the algae associated fauna between a location close to the farm and in further distance.



Figure 8. Diversity assessment: (on the left) self-made sampling frame with an inner edge length 22.6 cm ($\sim 0.051 \text{ m}^2$), for larger macroalgae a larger size is recommended; the inner ropes divide the area into four equal parts to count highly abundant small species. (On the right) students sampling rocky shore habitats in Northern Norway (© Photos: Henning Reiss).

3.5 Genetic interchange

To avoid ecological disaster, it is vital to remember a core principle, and it is that one should never import non-native species into an aquatic environment, as it may have catastrophic effects on the existing ecosystems. This has been observed time and time again in our world's oceans, examples being the green algae *Caulerpa taxifolia* (nicknamed the "killer algae") in the Mediterranean, the brown algae *Undaria pinnatifada* and *Sargassum muticum* in Western Europe (Fredriksen & Sjøtun, 2015; Stevant et al., 2017), and is one of the major threats to biodiversity (Schaffelke et al., 2006). The non-native species have evolved in another ecosystem, and may thrive especially well in new biomes where the local species is not used to the competition from a particular introduced organism, and may therefore be completely replaced, with unknown and possibly cascading consequences for the other organisms in the ecosystem. Keeping in mind that non-native species should not be introduced into a naïve ecosystem, interactions between local species can be addressed.

Gene flow between cultivated and wild populations is generally limited by distance and current strength, and high levels of genetic isolation between populations has been found from 0-50km. Spores of most kelp possess flagella, and are thus capable of some autonomous movement, but this is very limited (Fredriksen & Sjøtun, 2015). Research on the spore dispersal of *L. hyperborea* indicates that it ranges is around 200m at a minimum, depending on current and depth, but that the spore dispersal varies extremely from species to species with examples such as *Alaria esculenta* being limited to dispersal within 10m of adult colony (Fredriksen et al., 1995).

It has been found that genetic exchange between wild and cultivated populations of macroalgae seemingly do not result in much of a negative consequence for the ecosystem (Guillemin et al., 2008). Rather, it seems that the real danger comes from introducing *generalist* species able to thrive better than native species, which could then outcompete the native species and drastically change the ecosystem (Schaffelke et al., 2006).

Beyond this, it has also been found that there are local genetic adaptions within the same species, which varies with latitude (Hancke et al., 2021). These differences, albeit minor ones, *may* be important, but a case can equally be made that areas laid barren due to overgrazing by sea urchins could benefit from a reintroduction of species that were once established in the area, and which may gradually regrow through natural migration from adjacent areas in any case.

The effects of large-scale cultivation with regards to both gene flow and disease spread is not well known, although there is concern around the introduction of non-native species and risks associated with genetic interchange between wild and farmed populations of the same species based on experience from animal aquaculture as well as agriculture, where crop-to-wild gene flow has been shown to result in the impoverishment of genetic resources available for selection (Loureiro et al., 2015).

Learning module 3.5

Bowls with smarties

The loss of genetic variation through interbreeding of wild with farmed kelp can be demonstrated with bowls filled with objects of different colour (e.g. smarties). Each colour represents a specific genetic variant. Some of the variants can be adaptive to pathogens, heat, etc. (see Fig. 9).

A group of 2-3 students has a set of bowls as presented below: Wild, Farmed, and Interbreeding. The farmed bowl has only one genotype (extreme case). Then, the next generation is produced by selecting 6 smarties randomly from the bowl and adding the same colour of smarties (shown in transparent colour below) for each of the selected ones (shown in 100% opacity below), so that the total number of individuals stays at 12. That repeats for 4 generations. For the Interbreeding bowl, 3 of the selected individuals that start the new generation, originate from the farm, so have that genotype/colour.

In the 4th generation, some adverse effects can happen, e.g. a spread of a disease. The different groups evaluate then which of their populations (wild, farmed, or interbred) has the potential to survive this impact. We expect that several groups report back that the wild population survives while the farmed and interbred ones don't.

Based on this experiment, the student should be able to formulate the value of genetic variation versus the threat that lies in genetic impoverishment and they should be able to explain why cultivated kelp should not be transferred from distant locations.



Figure 9. Schematic overview of the smarties bowl experiment.

3.6 Algae as vectors of diseases

Infamous examples of disease spread as a result of human cultivation of aquatic species include the crayfish plague, where a pathogen was carried by American crayfish into Europe, or cultivated salmon acting as reservoirs for the indigenous sea lice (Costello, 2009), a copepod parasite, spreading to wild populations and enhancing mortality.

Although research on the topic is lacking, examples from Asia shed some light on disease in cultivated algae crops: The red algae *Porphyra yezoensis* is an important commercial food crop which has seen an explosive increase in cultivation in recent decades, is under attack by the parasitic oomycetes *Pythium porphyrae* and *Olpidiopsis sp*, responsible for "red rot", and cythrid blight, respectively (Ding & Ma, 2005). The disease causes cell death and biomass loss, and as a result farmers routinely see losses of 10% of yield on average, even as high as 30% localized. The diseases were found to occur more frequently when grown in higher densities and more intensively (Gachon et al, 2010). Treatment effectivity is lacking, and severe methods such as the complete removal of seedlings, or the acid washing with resulting discoloration of the product is often necessary to get rid of the disease.

Knowledge about algal disease spread is not extensive, and models of algal parasite effect on the food web are imprecise due to a lack of basic understanding of algal pathogen biology (Loureiro et al., 2015).

Summarising learning activity

Debate about algae cultivation

Based on the theoretical basis, the learning activities, and the further reading provided in this learning guide, a debate might be a good conclusion. An organised debate can be carried out in many ways and we just provide her one possible format.

The class should be divided into two groups well in advance, because the groups should prepare for the debate. One team will represent the viewpoint of the farmers and algae cultivation enthusiast and the other team will represent the viewpoint of the conservationists and cultivation sceptics.

Both teams should prepare for this debate in group discussion (1-2 hours) maybe compiling a digital presentation.

The debate in class:

1. Each side will get a strict seven minutes to present their view, flip a coin to identify the starting group. In those first seven minutes the team should present their viewpoint *without* reference to the other team's presentation.

2. Short discussion round within each team, then each side has one person who has three minutes to talk during which they should oppose specific points in the opposing team's presentation (that person should be a different person to the original presenter/s). Do not use this time to expand on your own presentation.

3. Again short discussion and each side then has a different person who has three minutes to refute the arguments made in round 2.

4. Both teams must then answer questions from the audience/teachers who might act as neutral observers.

5. Finally, each team will switch sies and has five minutes to construct and propose a compromise solution which takes into account the presentation of the opposing team.

Presentations should be about the scientific basis for the viewpoint of each team. Use the terminology and concepts that were introduced in this learning guide.

Glossary

Bioremediation - Bioremediation is the process of using living organisms to remove environmental pollutants and/or nutrients. In marine ecosystems, high concentrations of nitrogen and phosphorous, often as a result of human activity such as fish farming, can have detrimental effects on water quality. For instance, excess concentrations of these nutrients can for instance lead to blooms of microalgae which reduce the oxygen in the water, which in the worst case can lead to mass death of fish and other animals. Macroalgae, which utilize nitrogen and phosphorous to grow, have been suggested as a way to reduce excess nutrients in problematic areas

IMTA / Integrated Multitrophic Aquaculture - is a concept for food production where species from different trophic levels – occupying different levels in the food web – are farmed in the same location to maximize the utilization of energy put in to the system, by using the byproducts of one species as feed for another, thereby creating more biomass without increasing energy input. A common example of IMTA is the culture of a fed finfish species such as salmon, together with macroalgae such as kelp that extract inorganic nutrients, and with blue mussels that extract organic nutrients.

Sequestration – (of carbon) the capture and long-term storage of atmospheric carbon through photosynthesis.

Epiphyte - Non-parasitic plant or algae growing on another plant or algae.

Detritus – Dead particles or fragments, in the context of macroalgae, fragments released from the algae

Particulate organic matter (POM) – Particles of organic matter that can be suspended in the water column or settle to the seafloor and accumulates there.

Anoxic- waters or sediment depleted of oxygen, uninhabitable for most marine life except bacteria.

Secondary production – The consumption of organic material for energy, as opposed to primary production, which is the creation of organic matter mostly by means of photosynthesis.

Eutrophication – The enrichment of a body of water by nutrients and its effects in the environment

Monoculture - The farming of only one species of organism

Generalist – A generalist species is a species with a broad ecological niche, i.e. which can thrive in various environmental conditions or is able to utilize several sources of energy

References

- Airoldi L., Turon X., Perkol-Finkel S. & Rius M. (2015). Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. *Diversity and Distributions 21*(7), 755–768. <u>https://doi.org/10.1111/DDI.12301</u>
- Christie H., Fredriksen S. & Rinde E. (1998). Regrowth of kelp and colonization of epiphyte and fauna community after kelp trawling at the coast of Norway. *Hydrobiologia* 375/376, 49–58. <u>https://doi.org/10.1023/A:1017021325189</u>
- Christie H., Jørgensen N. M., Norderhaug K. M. & Waage-Nielsen E. (2003). Species distribution and habitat exploitation of fauna associated with kelp (*Laminaria hyperborea*) along the Norwegian coast. *Journal of the Marine Biological Association of the United Kingdom* 83(4), 687-699.
- Costello M. J. (2009). How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proceedings of the Royal Society B: Biological Sciences*, 276(1672), 3385–3394. https://doi.org/10.1098/RSPB.2009.0771
- Ding, H. & Ma, J. (2005). Simultaneous infection by red rot and chytrid diseases in Porphyra yezoensis Ueda. *Journal of Applied Phycology*, *17*(1), 51–56. <u>https://doi.org/10.1007/S10811-005-5523-6</u>
- Directorate of Fisheries (2020) Akvakulturstatistikk (tidsserier)-Alger (*in Norwegian*). <u>http://www.fiskeridir.no/Akvakultur/Statistikk-akvakultur/Akvakulturstatistikk tidsserier/Alger (accessed 30.10.2020).</u>
- Druehl, L.D. (1967) Distribution of two species of *Laminaria* as related to some environmental factors. *Journal of Phycology* 3 (2):103-108
- Eppley R.W., Rogers J.N. & McCarthy J.J. (1969) Half-saturation constants for uptake of nitrate and ammonium by marine phytoplankton. *Limnology and Oceanography* 14, 912-920.
- Forbord S., Etter S.A., Broch O., Dahlen V.R. & Olsen Y. (2021) Initial short-term nitrate uptake in juvenile cultivated Saccharina latissima (Phaeophyceae) of variable nutritional state. *Aquatic Botany* 168: 103306
- Forbord S., Skjermo J., Arff J., Handå A., Reitan K. I., Bjerregaard R., & Lüning K. (2012). Development of Saccharina latissima (Phaeophyceae) kelp hatcheries with yearround production of zoospores and juvenile sporophytes on culture ropes for kelp aquaculture. *Journal of Applied Phycology*, 24(3), 393–399. <u>https://doi.org/10.1007/s10811-011-9784-y</u>
- Fossberg, J., Forbord, S., Broch, O. J., Malzahn, A. M., Jansen, H., Handå, A., et al. (2018). The potential for upscaling kelp (*Saccharina latissima*) cultivation in salmon-driven integrated multi-trophic aquaculture (IMTA). *Frontiers in Marine Science*. 5:418. <u>https://doi.org/10.3389/fmars.2018.00418</u>

- Fredriksen S., Sjøtun K., Lein T. E., & Rueness J. (1995). Spore dispersal in laminaria hyperborea (laminariales, phaeophyceae). *Sarsia*, *80*(1), 47–54. https://doi.org/10.1080/00364827.1995.10413579
- Fredriksen S. & Sjøtun K. (2015). Risikovurdering ved utsetting av ikke-stedegen tare. Report from Norwegian Environment Agency, M-299 (in Norwegian).
- Gachon C. M. M., Sime-Ngando T., Strittmatter M., Chambouvet A., & Kim G. H. (2010). Algal diseases: spotlight on a black box. *Trends in Plant Science*, *15*(11), 633–640. <u>https://doi.org/10.1016/J.TPLANTS.2010.08.005</u>
- Hancke K., Bekkby T., Gilstad M., Chapman A., Christie H. (2018). Taredyrking mulige miljøeffekter, synergier og konflikter med andre interesser i kystsonen. NIVA-rapport 7265-2018, ISBN 978-82-577-7000-6
- Hancke K., Broch O.J., Olsen Y., Bekkby T., Hansen P.K., Fieler R., Attard K., Borgersen G. & Christie H. (2021). Miljøpåvirkninger av taredyrking og forslag til utvikling av overvåkningsprogram. NIVA rapport ISSN 1894-7948, ISBN 978-82-577-7325-0
- Krause-Jensen D & Duarte CM (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* 9: 737-42.
- Krumhansl K. A. & Scheibling R. E. (2012). Production and fate of kelp detritus. *Marine Ecology Progress Series*, 467, 281–302. <u>https://doi.org/10.3354/MEPS09940</u>
- Kutti T., Hansen P. K., Ervik A., Høisæter T. & Johannessen P. (2007). Effects of organic effluents from a salmon farm on a fjord system. II. Temporal and spatial patterns in infauna community composition. *Aquaculture*, 2–4(262), 355–366. <u>https://doi.org/10.1016/J.AQUACULTURE.2006.10.008</u>
- Loureiro R., Gachon C. M. M. & Rebours, C. (2015). Seaweed cultivation: potential and challenges of crop domestication at an unprecedented pace. *New Phytologist 206* (2), 489–492. <u>https://doi.org/10.1111/NPH.13278</u>
- McLeod E., Chmura G. L., Bouillon S., Salm, R., Björk M., Duarte C. M., et al. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment 9, 552–560.*
- Moy F., Alve E., Bogen, J., Christie, H., Green, N., Helland, A., Steen, H., Skarbøvik, E. & Stålnacke, P. (2006). Sugar Kelp Project: Status Report No. 1. Norsk Institutt for Vannforskning –NIVA, Oslo, Norway.
- Lüning K. (1988). Photoperiodic control of sorus formation in the brown alga Laminaria saccharina. *Marine Ecology Progress Series* 45:137–144.
- Moreira-Saporiti A., Hoeijmakers D., Msuya F. E., Reuter H. & Teichberg M. (2021). Seaweed farming pressure affects seagrass and benthic macroalgae dynamics in

Chwaka Bay (Zanzibar, Tanzania). *Regional Environmental Change* 21 (1), 1–12. https://doi.org/10.1007/S10113-020-01742-2/TABLES/2

- Munda I. M. &, Luning K. (1977). Growth Performance of Alana esculents off Helgoland. Helgolander wissenschaftliche Meeresuntersungen 29, 311-314
- Paasche E. & Erga S.R. (1988). Phosphorus and nitrogen limitation of phytoplankton in the inner Oslofjord (Norway). *Sarsia* 73:229–243.
- Pang S. & Lüning K. (2004). Tank cultivation of the red alga Palmaria palmata: effects of intermittent light on growth rate, yield and growth kinetics. *Journal of Applied Phycology* 16, 93-99.
- Parke M. (1948) Studies on the British Laminariaceae. I. Growth in *Laminaria saccharina* (L.) Lamour. *Journal of the Marine Biological Association of the United Kingdom* 27, 651–709.
- Renaud P. E., Løkken T. S., Jørgensen L. L., Berge J. & Johnson B. J. (2015). Macroalgal detritus and food-web subsidies along an Arctic fjord depth-gradient. *Frontiers in Marine Science* 2, 31. https://doi.org/10.3389/FMARS.2015.00031
- Sanderson J. C., Dring M. J., Davidson, K. & Kelly M. S. (2012). Culture, yield and bioremediation potential of *Palmaria palmata* (Linnaeus) Weber & Mohr and *Saccharina latissima* (Linnaeus) CE Lane, C. Mayes, Druehl & GW Saunders adjacent to fish farm cages in northwest Scotland. *Aquaculture*, 354, 128-135.
- Schaffelke B., Smith J. E. & Hewitt C. L. (2006). Introduced Macroalgae a Growing Concern. Journal of Applied Phycology 2006 18:3, 18(3), 529–541. https://doi.org/10.1007/S10811-006-9074-2
- Schmedes P. S., Nielsen M. M., Reitan K. I., Andersen K. L. & Petersen J. K. (2021). Updated hatchery and cultivation methods for the Atlantic rhodophyte Palmaria palmata. Abstract from 7th Conference of the International Society for Applied Phycology, Tsukuba, Ibaraki, Japan.
- Steen H., Moy F. E., Bodvin T. & Husa, V. (2016). Regrowth after kelp harvesting in Nord-Trøndelag, Norway. *ICES Journal of Marine Science* 73(10), 2708–2720. https://doi.org/10.1093/ICESJMS/FSW130
- 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 sea farm. *Journal of Marine Science and Engineering* 9, 615. <u>https://doi.org/10.3390/jmse9060615</u>
- Stévant P., Rebours C. & Chapman, A. (2017). Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquaculture International* 25(4), 1373–1390. <u>https://doi.org/10.1007/S10499-017-0120-7</u>

- Torstensen R.R.G. (2020). Miljøeffekter ved dyrking av sukkertare *(Saccharina latissima)* Et taredyrkingsanleggs rolle som kunstig habitat. Master thesis, University of Oslo, Norway; 97 pp.
- Vea J. & Ask E. (2011). Creating a sustainable commercial harvest of *Laminaria hyperborea*, in Norway. *Journal of Applied Phycology 23*(3), 489–494. <u>https://doi.org/10.1007/S10811-010-9610-Y</u>
- Walls A. M., Kennedy R., Edwards M. D. & Johnson, M. P. (2017). Impact of kelp cultivation on the Ecological Status of benthic habitats and Zostera marina seagrass biomass. *Marine Pollution Bulletin*, 123(1–2), 19–27. <u>https://doi.org/10.1016/J.MARPOLBUL.2017.07.048</u>
- Zhu P., Li D., Yang Q., Su, P., Wang H., Heimann K. & Zhang W. (2021). Commercial cultivation, industrial application, and potential halocarbon biosynthesis pathway of *Asparagopsis* sp. *Algal Research* 56, 102319. https://doi.org/10.1016/j.algal.2021.102319