

A baseline studies programme for
**sustainable and resilient
seaweed cultivation in
Faroese fjords**



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Summary

The overall aim of this report is to provide an overview of the most relevant environmental effects and potential impacts on the marine environment related to seaweed cultivation in the Faroe Islands. The report is based on standard Environmental Impact Assessment (EIA) principles and the identified environmental impacts were evaluated for their relevance and significance for cultivation in the Faroe Islands. The work is based on actual and ongoing cultivation activities characterised as small to medium sized farms (20–150 ha), and a compilation of previous results and experiences from the Nordic countries including the Norwegian KELPPRO project and available reports and scientific literature.

The report includes a number of potential effects and impacts that have been identified and addressed according to their expected significance. These include potential changes in light conditions, oxygen concentrations, nutrient and carbon dioxide availability, potential changes in hydrography, as well as effects from cultivation on natural seaweed communities. Further, the report addresses potential disturbance from noise on wildlife, effects on natural seabed communities, potential pollution from emissions, and discharges, as well as release of organic material from the farming activities.

From this scoping of potential environmental impacts from seaweed cultivation in the Faroe Islands, a baseline programme is suggested. The suggested baseline programme aligns with the recommendations from the KELPPRO project but includes amendments according to the newest information and is weighted towards Faroe Islands conditions and natural parameters.

Such a baseline programme, and a consecutive monitoring program, is needed to safeguard a future sustainable and resilient seaweed cultivation in Faroese fjords. The suggested baseline programme is a first step in this direction, and may contribute to development of a management strategy and monitoring of seaweed cultivation activities in the Faroe Islands.

This report presents an implementation plan for a baseline studies program. The plan involves identifying existing relevant data for the Faroe Islands and suggesting studies that could fill the knowledge gaps related to the environmental baseline, specifically focusing on the (genetic) biodiversity of and within the natural seaweed stock. This includes: (1) Mapping the biodiversity of the natural seaweed stock, (2) Population genetics of seaweed species most suitable for farming, (3) Biodiversity of associated fauna in the natural seaweed beds. Our assessment suggests that these studies address the deficiency of information regarding environmental elements susceptible to irreversible impacts from seaweed cultivation activities. Therefore, prioritizing efforts to address these aspects is recommended.

1. Introduction

Seaweed cultivation is a developing aquaculture in Europe, and is expected to grow considerably by 2030 (e.g., Vance *et al.* (2023).

Seaweed aquaculture has been suggested to facilitate a number of ecosystem services such as nutrient and carbon dioxide uptake, oxygen production, and stimulation of biodiversity (Duarte *et al.*, 2017) and is in addition projected to advance across a range of the United Nations Sustainable Development Goals (Duarte, Bruhn and Krause-Jensen, 2022). To safeguard and guide the development of the seaweed aquaculture towards sustainable development some studies have been conducted on potential risks and negative effects of seaweed aquaculture (e.g., (Campbell *et al.*, 2019; Hancke *et al.*, 2021). With significant upscaling of seaweed aquaculture, small effects, both positive and negative, could have important implications. The United Nations Environment Programme (UNEP) acknowledges the potential of seaweed cultivation and has recently published a report that critically examines the potential to sustainably expand seaweed aquaculture with minimal environmental and social risks (United Nations Environment Programme, 2023).

The overall aim of this report is to provide an overview of the most relevant environmental effects and potential impacts related to seaweed cultivation and its activities in the Faroe Islands (Chapter 1.2). The current seaweed cultivation activities in the Faroe Islands are described (Chapter 1.1) for assessing the potential impacts on the marine environment (Chapter 3). Assessment of the environmental impacts related to seaweed aquaculture in the Faroe Islands, will be based on standard Environmental Impact Assessment (EIA) principles.

1.1 Seaweed cultivation practices in the Faroe Islands

In the Faroe Islands, there is currently an area of 2.3 km² (230 ha), that is licenced to seaweed aquaculture. The cultivation areas are located in Kaldbaksfjørður, Funningsfjørður and Gøtuvík (á Norði *et al.*, 2023) and are in sizes from 27 to 153 ha. There are licenses to produce three brown algal species; *Alaria esculenta*, *Laminaria digitata* and *Saccharina latissima*, and two red algal species; *Palmaria palmata* and *Porphyra umbilicalis*.

As in Europe, the seaweed aquaculture in the Faroe Islands has the potential to expand and the area demand for seaweed cultivation in the Faroe Islands thus will increase correspondingly.

Production practices are important for the potential environmental impact. At this early stage in the development of the Faroe Island seaweed aquaculture there are no proven methods (best practices) and the authorities have not yet specified methodical requirements.

Most commonly, the production cycle starts with fertile sporophytes also called mother plants (see Table 1). The fertile sporophytes can be picked from natural populations or from a sea farm production. Most producers harvest their farm's biomass before the produced sporophytes become fertile, but the immature sporophytes of some of the species can be harvested and sporogenesis can be induced in the hatchery by a method where the transport of sporulation inhibitors is blocked (Pang and Lüning, 2004). The sporogenesis method has occasionally been used in the Faroese seaweed aquaculture.

Depending on the seeding method, the need for mother plants varies. Seeding with spores requires a higher number of mother plants than seeding with sporophyte culture. When seeding spores from *A. esculenta* or *S. latissima* onto twine or rope, the farmer would need approximately 5 to 10 kg fresh weight of mother plants to produce spores enough to seed 1000 m of rope. Only a few mother plant individuals would be enough when seeding with sporophyte cultures because the density of the dormant or hibernating cultures can be increased.

To minimise the potential genetic impact from the sea farm to the natural seaweed population in the area surrounding the sea farm, it is important to collect mother plants from local populations to produce spores for farming. This precaution is generally demanded by Norwegian authorities for cultivation in Norway (Fredriksen and Sjøtun, 2015; Hancke *et al.*, 2021). Another important factor is to harvest the biomass on the sea farm before the seaweed individuals become fertile.

Seeding with spores on twine or rope and providing the seeded material a hatchery period of ca. 6 weeks before deployment on the sea farm was found to give the best biomass yield and frond length results in *S. latissima* (Forbord *et al.*, 2020). The poorest results were observed when the ropes were seeded directly with sporophyte culture and deployed without a hatchery period after seeding (Forbord *et al.*, 2020). Direct seeding with deployment right after seeding can increase the genetic impact on the surrounding natural seaweed populations because the seeded sporophytes are not well attached to the rope and are easily washed off. Developing the seeded twine or rope in the hatchery demands space and a pumping and cleaning system of seawater and a water treatment before discharge. Hatchery facilities are expensive to obtain and the hatchery is also energy demanding to run, however, a well-functioning hatchery is probably a good investment in the long run.

Biofouling, especially of fast-growing diatoms can be very difficult to avoid. Some level of biofouling is acceptable in the tanks with developing sporophytes on twine

or rope but in free floating gametophyte and sporophyte cultures, diatoms can be controlled at a low level with adding germanium dioxide (GeO_2) to the culture solution. Addition of nutrients is often required when developing a healthy sporophyte culture. In a hatchery with a flow through system of seawater and sporophytes developing on twine or ropes in tanks, additional nutrients are not required.

The deployment period of seeded ropes in the Faroe Islands is usually from October to January, and harvest of food grade biomass is from May to June. In late June and through the summer, there is a significant increase in biofouling on the seaweed biomass (Koester, 2022) and therefore a decrease in quality. It is, however, possible to use an alternative harvesting method called partial harvest or multiple partial harvest (Bak, Mols-Mortensen and Gregersen, 2018). The method makes it possible to seed a rope once and harvest two or multiple times. The method has been found to work well for *S. latissima* in the Faroe Island, however, leading to different quality grades of biomass. Koester (2022) found that the re-growth in *A. esculenta*, cultivated in the Faroe Islands, was limited after the first partial harvest in June and that the quality of the crop was compromised by biofouling before the second harvest in August.

As such, the potential environmental impact from a sea-based seaweed farm depends on the farming practices. A farm that is deployed in October and harvested in June will likely have a different environmental impact compared to a farm that carries biomass year-round.

1.2 Principles of an Environmental Impact Assessment (EIA)

To improve environmental management and minimise the impact from cultivation of seaweeds and its related activities, an Environmental Impact Assessment (EIA) must be performed.

EIA principles are generally described as being a process to avoid, prevent or reduce adverse environmental consequences of human activities, in this case, seaweed cultivation and its associated activities. If adverse environmental impacts cannot be fully avoided, measures should be considered to reduce and control such impacts within established limits or criteria.

An EIA describes all activities with expected significant impacts, in this case, the seeding activities and on-grow in sea. Further, the EIA includes potential impacts and how they can be mitigated. In EIAs, this is typically followed up by a monitoring programme for assessing the efficiency of mitigation measures and being able to identify potential (unexpected) effects or changes to natural conditions and ecosystems, and adjust activities and mitigation measures accordingly (feedback

monitoring). To be able to detect potential changes and impact on the environment, the natural status and background information of the environment must be measured and mapped. As such, sufficient knowledge about the environmental baseline (i.e., the biochemical and ecological status as well as ecosystem functioning prior to seaweed cultivation) needs to be established and presented in the EIA.

1.2.1 Baseline

An initial site survey to establish an environmental baseline is needed to identify environmental impacts from an activity or construction (including buildings and other infrastructure). Site surveys should include data on biotic and abiotic conditions, i.e., biological, environmental, physical, and ambient conditions; and thus information, which are relevant to all types of impact from seaweed cultivation operations.

Hence, through a site survey, a baseline is established based on compiled information such as:

- Hydrography
- Oxygen, nutrient and light conditions in seawater and seabed
- (Natural) background concentrations of contaminants (e.g., heavy metals, plastics)
- Biotopes and habitats (including biodiversity of pelagic and seabed communities)
- Particular sensitive species and/or areas (marine mammals, bird colonies, moulting areas, red listed species, etc.)
- Special considerations in relation to the local community.

From baseline information, as mentioned above, collected through fieldwork and designed sampling, impacts from activities or infrastructure can be assessed and modelled, e.g., by measuring and modelling nutrient cycling from coastal hydrography, changes in oxygen levels and light attenuation, mapping of seabed communities and presence of sensitive species, their breeding and moulting seasons. In addition, focus on assessment of unintended dispersal of harmful diseases and gene pools is relevant.

1.2.2 Environmental impacts

The potential environmental impacts relevant to cultivation of seaweed species in the Faroe Island are listed in Table 1, based on the actual described cultivation activities (Chapter 1.1), compilation of the KELPPRO project's results (Chapter 2) as well as potential impacts treated in the literature (Hancke *et al.*, 2018; Campbell *et al.*, 2019; Visch *et al.*, 2020; Armoskaite *et al.*, 2021; Norderhaug *et al.*, 2021).

Please note, that due to presently relatively small-scale activities, and no factories as such are (yet) established, the EIA components only include cultivation activities, that is from hatchery seeding activities to harvest including potential loss of biomass during harvest, but do not include downstream activity components. This means that in the present EIA scoping, no downstream activities such as, e.g., emissions and discharges from factories (e.g., drying and packing processes), and waste management (e.g., lines and waste biomass on lines are included). Further, no visual or social impacts are included in the present scope of EIA.

Table 1. Overview of potential environmental impacts from cultivation of seaweed and related activities, as described in Chapter 1.2.1, and references. The list is developed with Campbell *et al.*, (2019, fig. 2) as basis, and amended according to KELPPRO (Chapter 2), relevant literature, and input from the project workshop (á Norði *et al.*, 2023). As an addition, the list includes emission and discharges.

Drivers/ disturbance	Environm. compartment	Impact	Reference
Light	Pelagic Seabed	Shading from cultivation system	(Hancke <i>et al.</i> , 2018; Campbell <i>et al.</i> , 2019; Visch <i>et al.</i> , 2020; Armoskaite <i>et al.</i> , 2021; Norderhaug <i>et al.</i> , 2021)
Nutrient uptake	Pelagic Seabed	Removal of nutrients leaving less nutrients for phytoplankton and seaweed	(Hancke <i>et al.</i> , 2018, 2021; Campbell <i>et al.</i> , 2019; Visch <i>et al.</i> , 2020; Armoskaite <i>et al.</i> , 2021; Norderhaug <i>et al.</i> , 2021)
Carbon dioxide uptake	Pelagic	Removal of carbon by harvest of cultivated seaweed biomass	(Duarte <i>et al.</i> , 2017, 2023; Campbell <i>et al.</i> , 2019; Duarte, Bruhn and Krause-Jensen, 2022; O'Dell <i>et al.</i> , 2023)
Change in hydrography	Pelagic	Change in current and wave speed and pattern with following change or reduction in nutrient availability	(Campbell <i>et al.</i> , 2019; Armoskaite <i>et al.</i> , 2021)
Harvest of mother plants for seeding	Seabed	Change in natural populations and ecosystem biodiversity	(Greenhill, Sundnes and Karlsson, 2021)
Noise	Air Pelagic	From vessel and working equipment Noise above water may disturb breeding/feeding birds and underwater noise may disturb marine mammals	(Campbell <i>et al.</i> , 2019; Armoskaite <i>et al.</i> , 2021)

Emissions	Air	Energy production, i.e., CO ₂ , black carbon, SO ₄ from laboratory / hatcheries / processing facilities and vessel traffic	
Discharges	Seabed	Potential gene and / or pathogene pollution from hatcheries	(Hancke <i>et al.</i> , 2018, 2021; Evankow <i>et al.</i> , 2019)
	Pelagic	Vessels	
Contaminants	Pelagic	GeO ₂ from seeding phase	(Campbell <i>et al.</i> , 2019; Norderhaug <i>et al.</i> , 2021)
	Seabed	Plastic from seeding lines and system ropes	
DOM / POM* release	Pelagic Seabed	Contribution of organic material for feed and decomposition (oxygen consumption) resulting in change in seabed communities	(Campbell <i>et al.</i> , 2019; Armoskaite <i>et al.</i> , 2021; Hancke <i>et al.</i> , 2021; Norderhaug <i>et al.</i> , 2021; Broch, Hancke and Ellingsen, 2022)
Change in oxygen levels	Pelagic Seabed	Increased oxygen production in the pelagic Oxygen depletion due to degradation of surplus of DOM and POM	(Duarte <i>et al.</i> , 2017; Campbell <i>et al.</i> , 2019; Visch <i>et al.</i> , 2020; Boldreel <i>et al.</i> , 2023)
Habitat creation	Pelagic Seabed	Attraction and establishment of native and non-native (potentially invasive) species due to available substratum from floating cultivation system and anchors, attraction or blooms of native species due to structures and seaweed community Biofouling	(Campbell <i>et al.</i> , 2019; Hancke <i>et al.</i> , 2021; Norderhaug <i>et al.</i> , 2021; Bekkby <i>et al.</i> , 2023; GESAMP, 2024)
Transfer and dispersal of pathogens	Pelagic Seabed	Unintended spreading of harmful diseases	(Campbell <i>et al.</i> , 2019; Armoskaite <i>et al.</i> , 2021; Norderhaug <i>et al.</i> , 2021; Strittmatter <i>et al.</i> , 2022)
Transfer and dispersal of seaweed genetic material	Seabed	Changes of genetic composition in natural seaweed populations	(Loureiro, Gachon and Rebours, 2015; Campbell <i>et al.</i> , 2019; Evankow <i>et al.</i> , 2019; Hancke <i>et al.</i> , 2021)
Disturbance from mooring	Seabed	Disturbance of seabed communities	(Armoskaite <i>et al.</i> , 2021)
Disturbance from floating cultivation system	Sea surface	Entanglement of birds and marine mammals Barriers for migration routes	(Campbell <i>et al.</i> , 2019; Armoskaite <i>et al.</i> , 2021)

*DOM = Dissolved Organic Matter, POM = Particulate Organic Matter.

The potential impacts listed and described in Table 1 will be assessed in detail for relevance and significance for seaweed cultivation in the Faroe Islands for scoping the EIA in Chapter 3. From this basis a baseline programme (Chapter 1) and a proposed implementation plan (Chapter 1) is outlined. A monitoring plan is only touched upon and is expected to be developed as a phase 2 of the present project (Chapter 1).

1.2.3 Mitigation

Mitigation measures are initiatives that seek to reduce the environmental impacts of an activity, e.g., mooring methodology, timing of on-grow in sea, seawater management, etc. Mitigation measures should be identified for all significant impacts of seaweed cultivation flow scheme, and should be included in the EIA. Thus, mitigation measures can be behavioural adjustments (timing, speed), technical solutions (biodegradable mooring devices), design solutions (cultivation line spacing) or resource management (e.g., energy, water). To assess the applicability and efficiency of potential mitigation measures, knowledge about new environmentally friendly technologies, available standards and best practices must be continuously updated to have state-of-the-art mitigating measures in place. In general, the best available techniques (BAT) and best environmental practice, e.g., according to OSPAR ([OSlo-PARis Conventions](#)), should be followed and applied.

1.2.4 Monitoring

As part of the EIA and identified mitigation measures, a plan for monitoring impacts is developed to assess that the activities do not have any unexpected effects as well as to evaluate if the mitigation measures have the desired effect and environmental aims and targets are being met. Hence, an environmental impact monitoring plan describes which parameters are to be monitored and how, in accordance with the established baseline. This can include monitoring of, e.g., period of time for activities at sea, use of seawater, seawater nutrient levels, and loss of seaweed material to the seabed.

1.3 National and relevant regulation frameworks

The current legislative framework on aquaculture for the Faroe Islands was adopted in 2003 and has been focused on salmon aquaculture with the objective to promote a profitability and competitiveness in aquaculture within a sustainable framework. The Aquaculture act (2009) is the general and coordinating law and stipulates the concept of one farming licence per management area, typically on the scale of fjords. This concept was changed to allow farming licences issued for low trophic species assuming that low trophic aquaculture pose no risk to the fish farming activity in the management area. This was done in the Aquaculture Licensing Regulation (2019) which allowed for multiple species in six management

areas (Kaldbaksfjørð, Eystan fyri Nólsoynna, Gøtuvík, Skálafjørð, Funningsfjørð, and Fámjin) (ICES, 2023; á Norði *et al.*, 2023). As mentioned in Chapter 1.1 the first seaweed cultivation licences were issued in 2020. Even though the Aquaculture Act refers to the Environmental Protection Act (1988), based on which an environmental permit is required (issued by the Faroese Environment Agency, FAE) to have a farming licence issued (by the Faroese Food and Veterinary Agency, FFVA), the newly issued seaweed cultivation licences do not have an environmental permit. This is due to the fact that currently there is no specific regulatory regime comprising seaweed cultivation with regards to environmental management and thus it is regulated by general rules in the Aquaculture Act (2009) and the Marine Environmental Protection Act (2005) including requirements of EIAs (á Norði *et al.*, 2023).

In May of this year the new Nature Protection Act (2024) was passed and will be enacted on January 1st 2024. The objective with the act is to protect biodiversity and the ecological processes in nature, both for nature itself and for nature as the foundation for sustainable activities, resources, culture, health, and well-being of the Faroese people now and in the future. The Nature Protection Act is a framework law and still has to be implemented through regulations, and as such will take some time to be realised.

Present work thus comes at an opportune time, while still at the beginning phases of a seaweed cultivation industry in the Faroe Islands, to both guide necessary changes in the current Environmental Protection Act and to prioritise development of necessary regulation in the new Nature Protection Act to accommodate a sustainable seaweed cultivation industry.

2. KELPPRO, Norway

The following chapter is a short summary of the main results from the Norwegian project “Kelp industrial production: Potential impacts on coastal ecosystems” (KELPPRO, 2017–2020) that was carried out in Norway, funded by the Research Council of Norway. The project aimed to establish a knowledge base for sustainable management of large-scale kelp cultivation, and the following chapter is based on the concluding project report “Environmental impacts of kelp cultivation and recommendations for a management strategy” from 2021 (Hancke *et al.*, 2021).

The background for the project was a numerical modelling study that demonstrated a large potential for kelp cultivation along the Norwegian coast and offshore, with harvesting potentials ranging from 70 to 200 tonnes per hectare (Broch *et al.*, 2019). The study concluded that Norway’s long coastline with clean and nutrient-rich water provides ideal conditions for cultivation of kelp, although conditions vary at scale and with distance to the coast. Areas with stable and good nutrient supply, often at a good distance to the coast, stood out as particularly suitable and productive locations.

To ensure a long-term and profitable industry, kelp cultivation must be developed in a sustainable way with an understanding of potential impacts on the marine environment. Thus, KELPPRO investigated how cultivation of kelp possibly could impact the environmental conditions and marine life on the seafloor and in the pelagic, and it assessed whether kelp farms play a role in spreading alien or endangered species.

Detailed studies of Norwegian kelp farms showed that under normal operational conditions there was a loss of biomass from cultivation farm to the environment, in the scale of 8 to 13% of the actually harvested biomass per year. If the harvest is delayed until late summer, the loss of biomass from the farm to the ocean interior could be >50% of the harvested biomass (Fieler *et al.*, 2021). This biomass originated from kelp eroded from the cultivation farm and is subsequently transported with the water currents while sinking towards the bottom. A case study using numerical modelling (which was informed from laboratory experiments) showed that >90% of the released kelp biomass ended up at the seafloor within 4 km of the kelp farm (Broch, Hancke and Ellingsen, 2022).

At scales of current Norwegian kelp farms (< 100 ha), the effects on the seafloor of released kelp biomass were minimal, and no significant effects on biodiversity or ecological function were documented during normal operations. In contrast, field experiments with deposition of a large amount of kelp (>8 kg fresh kelp per square metre), corresponding to “worst-case” scenarios such as loss of kelp lines, showed a

significant worsening of bottom oxygen conditions, reduction in animal diversity, and increased production of toxic sulphide (Hancke *et al.*, 2021). Degradation of deposited kelp was fast, and about 50% of the biomass had disappeared after 3 weeks, and more than 90% after 3 months, indicating reversible impacts on seafloor ecosystems. Laboratory studies showed that the decomposition time was dependent on temperature and bottom oxygen and was longer for winged kelp (*Alaria esculenta*) than for sugar kelp (*Saccharina latissima*) (Boldreel *et al.*, 2023). The amount of kelp that constitutes the 'tipping point' from a bioresource for the food web to an ecosystem threat was not possible to quantify in this project.

In open water habitats, the impact of kelp cultivation is closely linked to the competition for nutrients. Field measurements showed that nutrient concentrations in the water around kelp farms, as well as the nutrient status of the phytoplankton, were unaffected by the cultivated kelp. Calculations showed that this applies regardless of the size of the kelp farm. A short-term reduction in light availability under kelp farms (as when phytoplankton is drifting through) will not influence phytoplankton growth. The net discharge of nutrients from kelp plants is negative (kelps take up nutrients during growth), and kelp cultivation might contribute positively to nutrient reduction where concentrations are too high (eutrophic conditions).

Biodiversity studies demonstrated that kelp farms can function as artificial habitats and establish ecosystems but with fewer species and individuals than natural kelp forests (Bekkby *et al.*, 2023). The location of farms will likely play a role in the spread of species and in the impacts on biodiversity. The established principle of not moving kelp plants between ecoregions was supported since different population genetic structures for sugar kelp were identified across ecoregions.

Although, with the above findings, the KELPPRO project found that there are still significant knowledge gaps on the environmental effects of kelp cultivation, including the significance of season, latitude, and location. If kelp cultivation develops into a large-scale industry, the KELPPRO project recommends that further studies of environmental effects on the seafloor, spread of species and of genetic material are performed to ensure a sustainable industry. The project's recommendations for baseline studies and monitoring according to scale of kelp production in Norway are summarised in Table 2.

Table 2. Summary of the findings and recommendations to regulatory authorities of environmental parameters to include in 1) standard baseline studies, 2) for monitoring programs, and 3) for case-specific monitoring in case of significant loss of seaweed biomass from farms. The recommendations are based on evaluation of Norwegian conditions and needs by the KELPPRO project. Modified from Hancke et al., (2021).

Facility	Small	Medium	Large
Production scale, tonnes per year	30–300	1000–3000	10000–30000
Baseline:			
Currents	+	+	+
Natural seaweed stock	+	+	+
Other habitats affected by reduced light conditions		+	+
Seafloor types and conditions (soft/hard, erosion/deposition)		+	+
Register of alien species in adjacent seaweed communities		+	+
Monitoring:			
Register of alien species			
• in the kelp farm after each production cycle	+	+	+
• in the kelp farm during operation		+	+
• in adjacent seaweed communities		+	+
Potential monitoring of seafloor and seawater			+
Monitoring in case of significant loss of seaweed biomass from farm			
Monitoring of seafloor impact in areas of seaweed biomass accumulation	+	+	+

3. Potential environmental impacts and mitigation

In the following, the environmental impacts, which were identified in Table 1, are assessed for their relevance and significance for seaweed cultivation in the Faroe Islands and potential mitigation measures are suggested. Present assessments are based on small to medium sized (20–150 ha) cultivation farms, and an upscaling will call for a large-scale specific assessment including cascading, and potential compensating, effects as well as cumulative impacts.

3.1 Light attenuation

The on-grow of seaweed species in the cultivation farm at sea, requires that the seaweeds are positioned in the top metres of the water column where light conditions are optimal. However, this may result in light attenuation (shading of light) below the farm towards the seafloor. At shallow water sites it may reduce the light available for benthic autotrophic organisms adapted to the natural conditions (Hancke *et al.*, 2018; Campbell *et al.*, 2019; Visch *et al.*, 2020; Armoskaite *et al.*, 2021; Norderhaug *et al.*, 2021). Visch *et al.* (2020) found from in situ light logger measurements underneath a *Saccharina latissima* cultivation site and at a control site, that the irradiance was significantly reduced up to 40% beneath the cultivated kelp biomass a week before harvest. No effects from shading from a medium sized kelp farm (18 ha) was reported on an eelgrass meadow beneath the farm (Walls *et al.*, 2017), even though impacts from reduction in light may be expected on light sensitive species such as eelgrass (Nielsen *et al.*, 2002). Visch *et al.* (2020) suggest that it may be due to a relative short time period of light reduction, only when the kelp biomass is peaking before harvest.

The impact from reduction in light conditions on the seafloor communities may also depend on if, e.g., the seafloor substratum is suitable for autotrophic organisms at all or is situated at a depth outside the photic zone, as well as if the light attenuation rate is naturally high. However, to apply the precautionary principle as a mitigation measure, it is in general recommended to avoid placing the cultivation farm above other light dependent benthic communities (Armoskaite *et al.*, 2021).

The Faroese shore is quite steep and the maximal depth for growth of the naturally occurring kelp species is reached at 20–30 m (Bruntse, Lein and Nielsen, 1999). In general, as the straits and fjords are characterised by these steep slopes, reaching maximum depths of 40–100 m, but with a flat muddy base as well as the more offshore seafloor substratum (central shelf) consists of a < 1 mm grain size

sediment, and depths ≥ 100 m (Erenbjerg *et al.*, 2020; ICES, 2023), a large area is thus not suitable for benthic autotrophs. As such, the total area of natural kelp forests is restricted by substrate availability and estimated to 275 km² in the Faroe Islands (Kvile *et al.*, 2022). Thus, to minimise the risk for light reduction impacts in the Faroe Islands from seaweed cultivation, cultivation areas close to shore and depths < (20) 30 m for medium sized farms should be avoided. According to Chapter 1.1, and the description of present size of seaweed farming in the Faroe Islands, the sea surface areas used are around or below medium size (150 ha). Monitoring of light conditions beneath Faroese seaweed cultivation farms as well as establishing baseline data on the local depth distribution of seaweed may give information causing the need to change or adjust the mitigation recommendations (see Chapter 1).

3.2 Uptake of nutrients and carbon

For growth of autotrophic organisms, besides light, sufficient concentrations of nutrients and inorganic carbon is necessary. Thus, introducing a growing kelp biomass to a natural habitat that take up nutrients may impact the natural competition of autotrophic organisms (phytoplankton) in the water phase (Hancke *et al.*, 2018; Campbell *et al.*, 2019; Visch *et al.*, 2020; Armoskaite *et al.*, 2021; Norderhaug *et al.*, 2021; ICES, 2023).

However, it has been found that the concentration of dissolved inorganic nutrients is not negatively affected by seaweed cultivation farms (Visch *et al.* (2020), and references herein), as such, if the background concentration of nutrients is large, the amount taken up by cultivated kelp may be neglectable. However, if ambient nutrient concentrations are low (which they often are in coastal regions in summer) and nutrients is a limiting source, farmed kelp might take up significant amounts of nutrients, but Hancke *et al.* (2021) found that phytoplankton outcompete seaweed in the efficiency for nutrient uptake and thus it is unlikely that seaweed will pose a threat for phytoplankton nutrient uptake even when concentrations are low and availability is limited. In general, at small to medium scale cultivation activities, negative environmental effects from nitrogen depletion are not expected (Campbell *et al.*, 2019).

For the Faroe Islands, the coastal areas can roughly be divided in two, when it comes to the ecological state of nutrients; the mixed shelf water and the stratified fjords with estuarine circulation. In the mixed shelf water, the tidal currents are strong and the water masses are vertically mixed from surface to bottom. This implies that there is seldom nitrogen depletion and that effluents from anthropogenic activity are quickly dispersed over wide areas. In the fjords, nitrate depletion is regularly occurring in the upper water masses during the growth season, but the stratification is so weak that there is frequent upwelling of nutrients. Thus, the annual microalgae production in Faroese fjords is 2–3 times

higher than in neighbouring regions due to the frequent nutrient upwelling (ICES, 2023). Therefore, considering that phytoplankton may be the strongest competitor for nutrients (Hancke *et al.*, 2021), it is not expected that the installation of small to medium sized seaweed cultivation farms in the Faroe Islands will cause nutrient depletion that may impact phytoplankton production negatively. As a potential mitigation measure, areas with periodically establishment of a stratified water column, limiting nutrients in the upper water masses, may be avoided, also due to potential limiting seaweed biomass growth and yield. However, establishment of a local baseline for nutrient fluctuations may give information for adjusting the placement of the cultivation farms in space and depth.

Regarding uptake of CO₂, it is not expected to have any detrimental effects in and around the cultivation sites (Campbell *et al.*, 2019). However, in the Arctic where long summer photoperiods create optimal conditions for marine vegetated habitats' photosynthesis, a sustained up-regulation of pH can be observed (Krause-Jensen *et al.*, 2016). This effect is not considered to be of potential negative impact; however, the findings may suggest potential CO₂ limitation of photosynthesis in such dense communities during summer (Krause-Jensen *et al.*, 2016). In the Faroe Islands (see Chapter 1.1), it may have no implications for the cultivated seaweed biomass yield, which is harvested before summer due to avoidance of biofouling. However, for biomass harvested during the period from April to October, data on pH in and outside the cultivated seaweed biomass may give information on potential CO₂ limitation for biomass growth and yield, and, as such, may lead to adjustments in harvest timing.

3.3 Hydrography changes

In-sea cultivation systems may influence the water velocity, the tidal drag and turbulence within and around (beneath) the seaweed cultivation farm, and thus affect the pelagic and benthic organisms and communities by, e.g., oxygen conditions as well as nutrients and food supply (Campbell *et al.*, 2019; Armoskaite *et al.*, 2021). If these parameters are critical, careful considerations must be applied when selecting the cultivation site. However, in the Faroe Islands, the effect from the cultivation farm on hydrography is overall assessed as insignificant on the pelagic ecosystem, although local effects may be observed. In the Faroe Islands there are strong tidal currents in most straits, which, to a lesser degree though, also influence the water exchange in the fjords, as well as many areas are exposed to ocean swells (ICES, 2023). As such, data for water velocities inside and outside the farm, effects on sediment transportation, i.e., sedimentation rates within and outside the farm (up- and downstream) as well as data on potential changes in sediment deposition locations is recommended (Armoskaite *et al.*, 2021).

3.4 Mother plant harvest

To follow established protocols and practices using spores for seeding lines for cultivation of kelp species (and also other species), mother plants must be collected from nature in vicinity to the farm site. The plants may be harvested from kelp forests, which otherwise are creating habitats and sustaining communities of flora and fauna (e.g., (Norderhaug *et al.*, 2021; Bekkby *et al.*, 2023)). The number of specimens needed for spore production may be relatively low, though, depending on the scale of activities, as 5–10 kg mother plant can produce spores for 1000 m of seeding lines (See Chapter 1.1). However, the need for mother plants from nature can be reduced by establishing hibernating gametophytes, which can be sprayed onto the seeding lines (Kraan and Guiry, 2000; Mols-Mortensen *et al.*, 2007). In addition, sporogenesis in cultivated plants can be induced by blocking the transport of sporulation inhibitors in the lamina of the kelp species (Pang and Lüning, 2004) (see also Chapter 1.1).

There is little local knowledge on the importance of seaweed as nursing areas for commercial fish stocks in the Faroe Islands (á Norði *et al.*, 2023), although there is an ongoing study on Faroese kelp forest as nursery ground for cod and pollock in Kaldbaksfjørð^[1], which may serve as an indicator of the importance of kelp forest and provide an understanding for the baseline.

3.5 Noise

Boat transport and activity due to initiation of on-grow, maintenance and harvest of the seaweed cultivation farm, may increase disturbance and underwater noise (Campbell *et al.*, 2019; Armoskaite *et al.*, 2021).

Disturbance from activities may have an above-water impact on especially breeding birds and haul-out areas of, e.g., seals, whereas underwater noise may scare off marine mammals from their migration routes and feeding grounds or mask their communication (Christensen *et al.*, 2015; Campbell *et al.*, 2019).

The impact from small boats and vessels are likely small in connection with small and medium scale cultivation farms, and thus it is unlikely to cause significant impact on birds and marine mammals, as long the presence and migration is taken into account (Campbell *et al.*, 2019). Thus, baseline information on presence, seasonality and migration of relevant species should be collected, to avoid sites of or adjust activity timing with important breeding, feeding and migratory activities. In case of large-scale seaweed cultivation activities, cumulative impacts with other industrial activities must be considered.

1. <https://fiskaaling.fo/en/departments/biotech/current-research-projects/kelp-forest-monitoring-pilot-study/>

There is relatively good information on the presence of breeding seabirds and marine mammals in the Faroe Islands (ICES, 2023). Mitigating measures are avoiding activities in seasons when especially very site-specific breeding birds are present as well as avoiding activities close to haul-out areas, migration routes and feeding grounds. Local baseline information on breeding seabirds and marine mammals should be collected and taken into account when selecting areas for seaweed cultivation farms. A noise level and impact assessment should be performed for larger projects (Armoskaite *et al.*, 2021).

3.6 Emissions

From energy consumption using fossil fuels, emission of greenhouse gases (carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O)), other air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs) and benzene (C₆H₆) are emitted into the environment and impacting air quality. Further, sulphur compounds (SO_x) can be emitted, depending on the sulphur content of the fuels used.

It is not expected that the emissions from seaweed cultivation activities will have a significant impact on the Faroe Islands total emission of, e.g., CO₂, which is relatively high due to a large fishing fleet with a high dependence on fuel oils. The Faroese fishing fleet accounts for around half (48% and 42% in 2021 and 2022 respectively) of the Faroe Islands' CO₂ emissions (Hansen, 2023; Nielsen *et al.*, 2023).

However, in general, emissions from burning of fuel for power can be reduced by the use of electricity from renewable sources, such as hydro, wind or solar power, e.g., for laboratory activities, which may be established locally (see Chapter 1.1).

To reduce, e.g., emission of sulphur from shipping, the maximal sulphur content of ships' fuel oil allowed was reduced to 0.5% in the IMO 2020 regulation prescribed in the MARPOL Convention^[2]. This is a global requirement and relevant for the Faroe Islands, since the limit of 0.1 % in the Sulphur Emission Control Areas (SECAs) from 2015 was only partially incorporated in the Faroe Islands in 2018^[3]. However, smaller boats are not included in the IMO regulation, but they usually use marine gas oil (MGO), which is a compliant fuel.

3.7 Discharges and pollution

Discharges may be wastewater from hatchery, process water from seeding in hatchery or discharges from boats in operation.

2. <https://www.imo.org/en/MediaCentre/PressBriefings/pages/02-IMO-2020.aspx>
3. <https://www.us.fo/strangari-reglur-fyri-brenniojju-til-skip/>

In general, it is assessed that normal wastewater from toilets and washing (black and grey) is treated as part of the municipality wastewater treatment or handling, and is not considered of particular concern within the environmental assessment of seaweed cultivation activities in the Faroe Islands.

Further, process water from the seeding and sporeling development tanks is as such not considered of concern if discharged to sea. The process water will be of salinities within the natural range and although, if nutrients are added to the sporeling development tanks, and may have a higher content of nutrients than ambient waters, the expected limited amounts of discharged water can be diluted considering the water exchange in the Faroe Islands' waters and natural nutrient levels (see Chapter 3.2). However, in large-scale amounts of process water discharge, the salinity and nutrient concentrations in the process water for discharge should be measured and assessed if concentrations may impact the recipient water body, and thus if mitigation measures will be necessary, e.g., water treatment before discharge. Where national regulation is in place, this should be followed. In small scale production, and if a continuous seawater flow system is used (see Chapter 1.1), the impact is assessed as insignificant.

However, in sporeling development tanks without a continuous seawater flow system, and where nutrients are added, germanium dioxide (GeO_2) may be added to prevent growth of diatoms competing for light and nutrients (see Chapter 1.1). GeO_2 is toxic to diatoms because it disrupts silica deposition, but has also been shown to inhibit kelp growth in higher concentrations in one study (1 millilitre of the stock solution (4.47 mg ml^{-1}) per litre corresponding to $4470 \mu\text{g l}^{-1}$) (Shea and Chopin, 2007). Addition of low concentrations of GeO_2 (0.02 ml of the stock solution (4.47 mg ml^{-1}) per litre corresponding to $89.4 \mu\text{g l}^{-1}$) was shown to block diatom growth. There is no regulation or established threshold concentrations of GeO_2 within the EU water frame directive (WFD, Directive 2000/60/EC), and according to the toxicity test presented in the safety data sheet of GeO_2 (as Germanium (IV) oxide)^[4], the acute toxicity concentration for aquatic environment given for ErC50 (50 % reduction in growth rate) for algae is $206.7 \mu\text{g l}^{-1}$, which is twice as high as the concentration recommended to prevent diatom growth in kelp cultivation systems (Shea and Chopin, 2007). However, discharging process water containing GeO_2 may be of concern regarding impacts on the natural primary production by diatoms in the recipient water body if on a larger scale. Thus, in such a case, the amount of GeO_2 discharged needs to be monitored or calculated with models for water exchange, and thus the dilution effect, in the recipient water body for assessing a potential environmental impact. However, the use of GeO_2 in cultivation systems in the Faroe Islands is not common due to the use of continuous

4. <https://www.carlroth.com/medias/SDB-1L52-MT-EN.pdf?context=bWFzdGVyfHNIY3VyaXR5RGFOYXNoZWV0c3wyMzU1OTd8YXBwbGJjYXRpb24vcGRmfHNIY3VyaXR5RGFOYXNoZWV0cy9oMGYvaGMjLzkwMzgxMzQ4MDQ1MTAucGRmfDBiMDI5ODA5Zjk3ZWixYTU3ZDRkZTFkYjh mMTMxNWZhYmRlZDFjNzFmNjA3NDkN2ZlMDgwZGE3MjlkY2Y3N2M>

seawater flow systems. Such systems also prevent competing growth of diatoms due to constant natural nutrient levels (see Chapter 1.1).

As Campbell et al. (2019) state, debris and discarded or lost components may contribute to existing environmental pollution such as plastics. Especially, in case of large-scale cultivation, proper maintenance and responsible management must ensure that loss of deployed cultivation gear to the environment is avoided.

A study, also mentioned by Norderhaug et al. (2021), showed that a large-scale cultivation system for *Pyropia yezoensis* in China, was a source for a relatively high amount of microplastics in the environment (Feng *et al.*, 2020). There are rising concerns for microplastics in the environment of the Faroe Islands (Bråte *et al.*, 2020; Collard *et al.*, 2022), and Norderhaug et al. (2021) recommend for Norway that technical solutions and monitoring are considered to mitigate addition of more microplastics to the environment as more knowledge may be obtained on seaweed cultivation systems as source for microplastics.

Pollution by heavy metal is not expected as such toxic materials are not used in seaweed cultivation in the Faroe Islands (see Chapter 1.1). However, within the finfish aquaculture in the Faroe Islands, background as well as threshold values are established (ICES, 2023).

3.8 DOM / POM contribution to the ecosystem and potential changes in seabed oxygen concentrations

From the farmed seaweed there may be a loss of organic material (Dissolved Organic Material, DOM, and Particulate Organic Material, POM) during the on-growth period as well as during harvest (Fieler *et al.*, 2021; Hancke *et al.*, 2021). Contribution of organic material for feed and decomposition may affect the benthic fauna communities and oxygen concentration in the seabed. As such, the contribution of POM may have a positive impact increasing the feed, on the other hand higher oxygen demand may lead to hypoxia and stress on infauna at the seafloor.

It has been shown for kelp farms in Norway that the loss of organic material from kelp farms is about 5% of the harvested biomass during the first months of the growth season and increases to 8–13% of the harvested biomass before harvest during summer (Fieler *et al.*, 2021). If the biomass is not harvested the loss increases to more than 50% in late summer (August). The distance within which the POM may settle depends highly on the degree of exposure driven by currents and/or wind, and thus it is shown that 90% is settled within 4 to 28 km to the kelp farm anticipated to produce a kelp biomass of 100 t ha⁻¹, the 4 km being at a relatively sheltered location (Hancke *et al.*, 2021; Broch, Hancke and Ellingsen, 2022).

Investigations, studying potential change in benthos communities due to an increased POM load, have not observed a decrease in benthos as a result of seaweed cultivation in the smaller scale, which is practised in Norway and Sweden at present (Visch *et al.*, 2020; Hancke *et al.*, 2021). In the study in Sweden, a positive impact was observed on the benthic infauna increasing the abundance of a number of different species (Visch *et al.*, 2020).

Regarding the potential increase in oxygen consumption due to degradation of a surplus of POM from the seaweed cultivation farm, the same studies did not find any impact on oxygen uptake by the seaweed farm (Visch *et al.*, 2020; Hancke *et al.*, 2021). However, in case of accidental loss of biomass, e.g., due to storms etc., a large amount of seaweed biomass is placed on the seabed, Hancke *et al.* (2021) found that there was a decrease in benthos biodiversity but an increase in abundance of those species that are hypoxia tolerant, though the effects were reversible.

At present, only a rough modelling study estimates the extent of kelp forests in the Faroe Islands (Kvile *et al.*, 2022), and kelp forest biomass, and thus the natural loss and contribution of POM to the ecosystem, is not yet quantified. An earlier study on the marine benthic algae and invertebrate communities from the shallow waters of the Faroe Islands (Bruntse, Lein and Nielsen, 1999) was restricted to the tidal zone. An ongoing study on mapping kelp forests, with the aim of estimating the blue carbon contribution to shelf areas in the Faroe Islands and Greenland ([BlueCea](#)), may provide data to assess the significance of the contribution of POM from the loss of cultivated seaweed biomass compared to the natural standing stock, and if any mitigation is needed. However, in any case, timing of harvesting is a measure to mitigate the losses (Hancke *et al.*, 2021).

The benthic macrofauna diversity in the Faroe Islands is well investigated in connection to fish farm monitoring and a classification system for evaluation of environmental state is established (Mortensen *et al.*, 2021). However, for identifying potential changes in the benthos communities due to changes in POM contribution and seabed oxygen concentrations, local baselines for content of organic material, benthos communities and natural oxygen conditions in the seabed need to be established (see Chapter 1).

3.9 Habitat creation, biofouling and invasive species

Introducing anthropogenic structures such as a floating cultivation system with and without seaweed, as well as anchoring systems may serve as substratum and habitat, attracting benthic and pelagic organisms to settle or to live in for shelter and feed (Campbell *et al.*, 2019; Bekkby *et al.*, 2023). Thus, these cultivation systems may lead to the establishment of native and non-indigenous (potentially invasive) species or potential settlement and blooms of native species in unwanted amounts inhibiting growth of the cultivated species (biofouling).

3.9.1 Habitat creation

Introducing a floating cultivation system with growing seaweed will offer a new opportunity for benthic and pelagic organisms to settle and live in (e.g., (ICES, 2023)). In connection with the project KELPPRO (see Chapter 2), the effect as habitat was studied, and how and which ecosystem may have developed in the "hanging forest" (Bekkby *et al.*, 2023). It was shown that a kelp farm of *Saccharina latissima* and *Alaria esculenta*, had a lower taxa number and abundance of associated fauna compared to natural (wild) kelp forests of the same species but including *Laminaria hyperborea*. The farmed kelp forests exhibited the natural fauna communities, but dominated by the isopod *Idotea pelagica* and the amphipod species of *Caprella*, depending on the age of the cultivated kelp (Bekkby *et al.*, 2023). In connection with the KELPPRO studies it was also found that recruitment from natural habitats is determined by distance, and was more important than the type of the seaweed community type (Hancke *et al.*, 2021).

3.9.2 Biofouling

Offering substratum in the water column usually without substratum for benthic organisms may also lead to biofouling, which is unwanted organisms settling on the cultivation systems and on the cultivated seaweed. The biofouling species reflect the species in the natural area, such as hydroids, bryozoans and sea squirts (Wegeberg, 2010; Matsson *et al.* 2021; Norderhaug *et al.*, 2021; Wegeberg, Geertz-Hansen and Mols-Mortensen, 2021; GESAMP, 2024). Koester (2022), when testing the partial harvesting method on *Alaria esculenta* with first harvest in June and the second harvest in August, found a limited re-growth of *A. esculenta* after the first harvest, and biofouling increased significantly between the harvests. Biofouling is generally best practised by timing deployment and harvest time according to season so it fits into the local environment for avoiding on-grow of unwanted organisms (GESAMP, 2024).

3.9.3 Invasive species

There have been concerns regarding the cultivation systems providing vectors for spreading of non-indigenous species (NIS). NIS may become invasive if they cause ecological or economic damage (Campbell *et al.*, 2019; Gustavson *et al.*, 2020). According to Campbell *et al.* (2019) seaweed species have been introduced throughout the world with aquaculture as a vector, besides the introduction of fauna species (GESAMP, 2024).

NIS, with the potential to become invasive, which have been observed in connection with aquaculture farms, e.g., in Norway, are the amphipod *Caprella mutica* and the bryozoan *Styela clava* (Hancke *et al.*, 2021; Norderhaug *et al.*, 2021).

Only native species of seaweed are cultivated in the Faroe Islands, and as such does not represent a risk of introducing potential invasive seaweed species.

With respect to invasive fauna species in the Faroe Islands, grazers such as the native snail *Lacuna vincta* can appear on the seaweed crop in very high and unnatural densities and the NIS, *Caprella mutica*, also observed in connection with kelp cultivation systems in Norway, has been found on the seaweed crop, when the crop was harvested in August (Schlund, 2022; GESAMP, 2024).

There is definitely a need for monitoring of invasive species, native and non-indigenous, as well as an assessment of which species may be potentially introduced and become invasive as well as identifying pathways for the spreading (Gustavson *et al.*, 2020). Although boat and vessel traffic in connection with seaweed cultivation farm activities is considered to be only domestic, the seaweed cultivation systems (floating and mooring structures) may act as stepping stones for NIS, and as such, mitigation in relation to aquaculture must be considered. In addition, using second hand gear from other nations with risk of introducing species able to establish in the Faroe Islands, should be carefully considered.

3.10 Pathogens, transfer and dispersal

Overcrowding and monocultures within the seaweed industry have led to diseases and pests is an area of significant concern. Diseases in seaweed cultivation may impact the economy by decreasing yield and quality of the seaweed biomass, but may also be of ecological significance, and yet be another stressor, which also is considered emphasised by climate change (Campbell *et al.*, 2019; Armoskaite *et al.*, 2021; Strittmatter *et al.*, 2022).

Diseases on seaweeds may be caused by a great diversity of microorganisms, including pathogens such as fungi, oomycetes, phytomyxids, and other algae as well as bacteria and virus (Strittmatter *et al.*, 2022).

Norderhaug *et al.* (2021) state that the impact from pathogens and its transfer and dispersal is one of the biggest knowledge gaps within seaweed cultivation. They assess that pathogens known from the Asian species *Saccharina japonica* could be of risk for its close relative, *S. latissima*, which is widely cultivated in the Nordic countries, including Denmark, the Faroe Islands, Greenland, Norway, and Sweden (Broch *et al.*, 2019; Visch *et al.*, 2020; Wegeberg and Geertz-Hansen, 2021; Wegeberg, Geertz-Hansen and Mols-Mortensen, 2021; Boderskov, Rasmussen and Bruhn, 2023; ICES, 2023).

Thus, as mitigating measures, it is important to use local mother plants, also due to conservation of the local population genetic structure (see Chapter 3.11), and clean (new) gear for all cultivation processes (see also Chapter 3.9).

For a sustainable development of the seaweed cultivation sector in the Faroe

Islands, it is important to consider mitigation, and, in due time, regulate the seaweed industry in order to avoid introduction and dispersal of seaweed diseases, as well as to follow the development of practical tools for diagnostics.

3.11 Transfer and dispersal of seaweed genetic material

From the KELPPRO project it was shown that populations of the kelp species, *Laminaria hyperborea* and *Saccharina latissima*, along the Norwegian coast, clustered into four and three distinct genetic groups corresponding to distinct geographical ecoregions, respectively (Evankow *et al.*, 2019). From their findings, they recommend that plants are not moved too far from their natural growth area, i.e., that mother plants are not used from one ecoregion for seeding and on-growth at sea in another ecoregion. The transfer of plant material may increase the risk of impacting the local natural population genetics by release of reproductive material through a crop-to wild gene flow (Loureiro, Gachon and Rebours, 2015; Campbell *et al.*, 2019). Thus, although breeding for optimal commercial properties, the evolutionary ability to adapt to a changing environment should be maintained in order to minimise genetic impacts on the natural populations (Campbell *et al.*, 2019).

Thus, establishing genetic baselines may be of importance to regulate that the cultivated seaweed does not diverge from the local populations in a way that puts future health of the natural stocks at risk.

3.12 Disturbance from mooring

The floating seaweed cultivation structures are most often moored by anchors, which may disturb the natural benthic communities or provide substratum for other benthic organisms (see Chapter 3.9).

At small to medium scale seaweed cultivation farms, the footprints of the anchoring are considered so small that the disturbance is assessed as insignificant (Armoskaite *et al.*, 2021). However, as a mitigation measure, the location of the cultivation system may be considered with respect to the vulnerability of the benthic communities, including potential shading of natural marine vegetation (see Chapter 3.1). Further, the mooring system may be left at the seabed when the seaweed cultivation farm is abandoned, and, as such, biodegradable and natural materials may be considered, e.g., hemp bags filled with sand/gravel as have been suggested for mooring of, e.g., passive acoustic monitoring (PAM) systems.

3.13 Disturbance from floating cultivation system

The floating seaweed cultivation structures, including ropes and lines, may provide a risk of seabirds and marine mammals to get entangled if attracted by the floating "habitat" (Campbell *et al.*, 2019; Armoskaite *et al.*, 2021). In addition, the presence of the system may reduce or alter habitat for feeding or displacement from feeding grounds or disrupt migration routes.

The adverse effects at present scale are not considered significant, and only reports in the Faroe Islands regarding entanglements in seaweed farms are of drifting litter and waste. However, grey seals are known to interact with salmon farms as they feed in the vicinity of the farms, and accidental mortalities due to entanglement, also for birds, do occur (ICES, 2023).

Therefore, to be able to evaluate potential changes in presence and numbers of seabird breeding colonies and presence of marine mammals in the area of the seaweed cultivation farm, a baseline of such species abundance needs to be established, also for considering selecting a site avoiding seabirds' critical breeding and foraging habitats as well as known marine mammals' migration routes. To reduce potential entanglement of attracted species, though, mitigation measures may be to scare off seabirds and marine mammals by scarecrow and underwater ping sounds.

Reporting of incidents is important to initiate further actions if needed.

4. Baseline programme outline

From the environmental impact assessment of seaweed cultivation in the Faroe Islands, and where the impacts are scaled according to their assessed significance, the following baseline programme is suggested. The aim of the programme is to establish data for the natural conditions before any seaweed cultivation activities commence to be able to assess if the level of impacts is in accordance with the expected and that mitigation measures are efficient. Also from the baseline, unexpected impacts can be identified so that activities, mitigation measures, and regulation can be adjusted accordingly.

The baseline programme aligns with the recommendations from the KELPPRO project (Table 3) and in addition includes amendments according to the newest information and weighted towards Faroe Island conditions and natural parameters.

Table 3 compiles the environmental components and parameters to be measured in order to establish a baseline before any activities are initiated, and refers back to the chapter, where the potential impacts are described.

Table 3. Compiled list of environmental components to be measured when establishing a baseline for seaweed cultivation activities in the Faroe Islands to be able to detect potential environmental impacts, mitigate these, and regulate the activities accordingly.

	Potential impacts	Attributes
<i>Physical environment</i>		
Light Chapter 3.1	Measure for potential shading of phototrophic benthic and pelagic organisms	Irradiance at different depths from surface to seabed
Nutrients and carbon Chapter 3.2	Changes in concentrations may lead to nutrient depletion and inhibition of growth of natural populations of phytoplankton and seaweed	Seawater concentrations of N, P and C
Hydrography Chapter 3.3	Changes in water exchange due to seaweed cultivation farm acting as a barrier for water flow and exposure	Current velocity and direction Wind direction and degree of exposure
Contaminants Chapter 3.7	Pollution by microplastics in different environmental compartments; seabed, invertebrates, fish, seabirds and marine mammals	If relevant, microplastics abundance (AMAP, 2021)
Organic matter Chapter 3.8	Driver for changes in benthos community by increased feed and or increased oxygen consumption	Organic matter in seabed

Oxygen conditions Chapter 3.8	Changes in oxygen conditions from degradation of potential enhanced contribution of POM to pelagic and seafloor habitats	Oxygen concentration and consumption in bottom water and seafloor
<i>Living environment</i>		
Phytoplankton Chapter 3.1,3.2	Changes in primary production and biomass of lowest trophic level as a result of shading and/or nutrient depletion	Chlorophyll a fluorescence
Benthos Chapter 3.8, 3.9, 3.12	Changes in benthic communities due to changes in POM contribution, habitat creation and/or disturbance from mooring	Diversity, distribution, composition, abundance
Marine vegetation communities Chapter 3.1, 3.4, 3.9	Changes in natural seagrass and seaweed communities caused by shading, introduction of NIS, sampling of mother plants	Diversity, distribution, composition, coverage, density
Fish Chapter 3.9	Changes in local fish population due to attraction by introduction of habitat creation and/ or NIS	Diversity abundance (?)
Seabirds Chapter 3.5, 3.13	Disturbance from breeding and feeding habitats, mortality from entanglement	Diversity breeding colonies' abundance
Marine mammals Chapter 3.5, 3.13	Disturbance from breeding and feeding habitats, mortality from entanglement	Diversity abundance
Pathogens Chapter 3.10	Diseases due to crowding and monoculture. Risk for transfer to natural populations	If relevant, due to knowledge deficiency, eDNA mapping
Seaweed population genetics Chapter 3.11	Genetic divergence from the local populations which by genetic transfer may put future health of the natural stocks at risk.	Species population DNA mapping

5. Monitoring programme

The monitoring plan will be developed together with an environmental impact assessment of a specific seaweed cultivation activity, when the implementation plan is developed, and may be considered as part of a phase 2 of the present project.

However, a monitoring plan should include:

- Description of the potential environmental impacts to be monitored
- Baseline information
- Current level of impacts (cumulative impacts)
- Environmental aims/targets
- Variable(s) to be monitored
- Methodologies (adaptive monitoring method, frequency)
- Possible analysis and feedback to potential need for monitoring plan adjustment.

For best practice, some standards regarding, e.g., seabed sediment monitoring exists, and is already implemented in the Faroe Islands regarding aquaculture. Thus, the Faroese "Alivegleiðing" is in some respects based on the Norwegian Standard NS9410:2016 (2016) concerning soft bottom sediment monitoring (Umhvørvisstovan, 2018, 2023). As stated in Hancke et al. (2021), existing methods for monitoring the enrichment of seabed by organic material can be adjusted for monitoring below and around a seaweed cultivation system if assessed necessary.

Hence, in general, it is recommended that a monitoring programme is targeted and adjusted to the impacts and their levels, which also may depend on the size of the cultivation systems (Campbell *et al.*, 2019; Norderhaug *et al.*, 2021). A monitoring programme will therefore be based on the environmental baseline, the EIA and implemented mitigating measures.

6. Implementation plan for the baseline programme

Here follows a suggestion for an implementation plan for the baseline studies programme described in Chapter 4 for a seaweed cultivation farm site in the Faroese coastal area. The implementation plan seeks to identify existing relevant data for the Faroe Islands and point out the baseline studies that are still needed to facilitate an environmental impact assessment for sustainable seaweed cultivation in Faroese fjords.

Generally, establishment of an environmental baseline is more easily prepared in countries or regions where environmental databases are readily available, e.g., results from monitoring programmes and research. As environmental monitoring data are limited for the Faroe Islands, because neither an environmental database nor strong monitoring programmes in the coastal area are available, a comprehensive, though not exhausting, list of relevant existing data is presented herein.

It should be noted that the implementation and prioritisation of national monitoring programmes for the Faroese coastal area is beyond the scope of this report. The importance of well-established national monitoring programmes should, however, be emphasised, as potential changes in drivers due to other stressors e.g., climate change or eutrophication from anthropogenic sources along the coast, have to be addressed in parallel in order to assess the potential impact from the seaweed cultivation activities.

The data available on the Faroese coastal area with relevance for each of the environmental components proposed measured in Table 3 for establishing an environmental baseline have been compiled in Table 4, with a short description of the larger datasets or monitoring programmes given below:

- Database with sediment sample data from the environmental assessments of salmon aquaculture (EASA) including, but not limited to, benthic macrofaunal taxonomy, redox, pH, loss on ignition (LOI), copper (Cu), and Zinc (Zn). The Faroese Environment Agency (FEA) hosts and curates the database, permission from the relevant fish farming company is needed to access the database.
- The Faroe Marine Research Institute (FAMRI) has performed a yearly fjord survey in and around Skálafjørð starting in 1985, consisting of sediment samples and CTD measurements (parameters measured depends on additional setup through the years). Data format and availability is not known.

- Historical data from the BIOFAR I and BIOFAR II stations. The focus of the initial study was to compile a taxonomic overview of benthic fauna in Faroese waters at depths > 100 m. The subsequent investigation focused on the coastline and shallow waters at depths < 100 m and included both fauna and seaweed samples (Nørrevang *et al.*, 1994; Bruntse, Lein and Nielsen, 1999; Sørensen *et al.*, 2001; Tendal *et al.*, 2005). Some of this data from > 1400 samples have been organised in databases or more or less complete datasets; however, the level of data curation is not known and the organised data is not publicly accessible.
- A number of research projects (concluded and on-going) have produced data relevant to establishing a baseline. These consist of single sporadic measurement to longer surveys. They are not long-term monitoring time series, but can, however, give a good indication of the physical and living environment functions and potential ecological statuses at certain points in time. Data format and availability varies from project to project.
- Some environmental data from the Faroese area is available at [ENVOFAR](#) (Environmental data on terrestrial and marine ecosystems in the Faroe Islands). ENVOFAR is a collaboration between Fiskaaling (Aquaculture Research Station of the Faroes), FEA, and FAMRI.

Table 4. Summary of existing data sources most relevant to establishing a baseline programme in the Faroe Islands as outlined in Chapter 1.

Parameter	Collection effort/ project/ institution/ reference	Sampling years	Data format	Availability
Physical environment				
Light	Copious amounts of unprocessed PAR (photosynthetic active radiation) sensor data from CTD measurements by Fiskaaling and Havstovan	unknown	various	various
	Kalbaksfjørður (Gaard, Northi and Simonsen, 2011)	2006–2007	scientific paper	public
Nutrients and carbon	Fiskirannsóknir nr. 6 (Hansen, Kristiansen and Reinert, 1990)	1984–1990	book	public
	Effects of fish farming in Kalbaksfjørð (Gaard, Northi and Simonsen, 2011; á Norði <i>et al.</i> , 2011; á Norði and Patursson, 2012)	2006–2007	scientific papers	public
	Fjarðarannsókn: Kaldbaksfjørður (Østerø <i>et al.</i> , 2022)	2021–2022	report	public
	Potential sites for seaweed cultivation in the Faroes by modelling		report	closed
Bathymetry	Faroese Environment Agency		database	various
	Landsverk		database	various
Sediment type	Biofar (I and II), visual estimate	1988–	database and datasets	permission required
	EASA, visual estimate	1998–	database	permission required
	(á Norði <i>et al.</i> , 2011; á Norði and Patursson, 2012; á Norði, Debes and Christensen, 2013), grainsize	2006–2007	scientific paper	public
Hydrography	Fiskirannsóknir nr. 6 (Hansen, Kristiansen and Reinert, 1990)	1985–1990	book	public
	Fjarðakanningar	1985–	unknown	unknown
	Kalbaksfjørður (Gaard, Northi and Simonsen, 2011; Østerø <i>et al.</i> , 2022)	2021–2022	report	public

Ocean models	FMHAT ^[5] , FarCoast 10 year hindcast library	2012–2022	NetCDFs	public at end of project
	FarCoast (Erenbjerg <i>et al.</i> , 2020), 3D ROMS based model	2013	NetCDFs	on request for non-commercial use
	Potential sites for seaweed cultivation in the Faroes by modelling (Kristmundsson and á Norði, 2020)		report	closed
Current measurements	Streymur og alda í umhvørvisfyrirsitning av firðunum (Larsen <i>et al.</i> , 2020), metadata list of available measurements around the Faroe Islands	1976–2019	Processed datasets	various
Contaminants	Chemical sediment variables from the Faroe area (Sørensen <i>et al.</i> , 2009)	1985–2008	scientific paper	public
	(Hoydal and Dam, 2004), different contaminants in sediment	1992–2003	book	public
	EASA, sediment Cu and Zn	1998–	database	permission required
Organic matter	(Sørensen <i>et al.</i> , 2009), sediment	1985–2008	scientific paper	public
	EASA, sediment LOI	1998–	database	permission required
	(á Norði <i>et al.</i> , 2011, 2018; á Norði and Patursson, 2012), sediment and sediment traps	2006, 2007, 2009	scientific paper	public
	ADepoPlan ^[6] , sediment, particle tracking and deposition models forced by FarCoast	2024–2025	dataset + modelling scripts	public at end of project
Oxygen conditions	Fiskirannsóknir nr. 6 (Hansen, Kristiansen and Reinert, 1990)	1984–1990	book	public
	Fjarðakanningar	1985–	unknown	unknown
	Fjarðarannsókn: Kaldbaksfjørður (Østerø <i>et al.</i> , 2022)	2021–2022	report	public

5. <https://fiskaaling.fo/fiskaaling/deildir/fjar%C3%B0aelvi/granskingarverkaetlanir/fmhat/>

6. <https://pure.fo/en/projects/accessible-deposition-modelling-tools-for-improved-environmental->

	FjordProcess ^[7] , Kaldbaksfjørður	2022– 2023	dataset	public at end of project
Living environment				
Phyto-plankton	Phytoplankton production in Kaldbaksfjørður (á Norði <i>et al.</i> , 2011)	2006– 2007	scientific paper	public
	Phytoplankton on Faroese fjords in 2020 (Jacobsen, Jacobsen and Dam, 2020)	2020	report	closed
	Integrated approaches for phytoplankton dynamics ^[8] , phytoplankton dynamics using microscopy, flowcam and eDNA analysis	2021–2022	Not known	Public at end of project
Benthos	Biofar (I and II), benthic fauna and algae	1988–1999	database and datasets	permission required
	EASA, Benthic macrofauna	1998–	database	permission required
	BlueCea ^[9] , Sediment eDNA and seaweed stock survey	2023– 2025	Not known	Public at end of project
	Modelled and predicted distribution of kelp forest in the Nordic region (Kvile <i>et al.</i> , 2022). Based partly on Biofar data from the Faroese region	1988–1999	scientific paper dataset	public upon request
Marine vegetation communities	Kelp forest monitoring study ^[10] , Kelp Forest biodiversity	2022– 2023	Not known	Public at end of project
Fish, sea-bird, and marine mammals	A summary is given in the Faroese Ecoregion Aquaculture overview (ICES, 2023)		report	public
Pathogens				
Seaweed population genetics	Alaria esculenta (Bringloe <i>et al.</i> , 2022; Inaba <i>et al.</i> , 2022) Foliose Bangiales species (Mols-Mortensen <i>et al.</i> , 2012)		scientific papers	public

7. <https://pure.fo/en/projects/key-processes-governing-pelagic-productivity-in-sub-arctic-north->
8. <https://fiskaaling.fo/en/departments/biotech/current-research-projects/integrated-approaches-for-phytoplankton-dynamics/>
9. <https://www.gransking.fo/en/resources/news/two-marine-research-projects-awarded-funding>
10. <https://fiskaaling.fo/en/departments/biotech/current-research-projects/kelp-forest-monitoring-pilot-study/>

The existing data for each of the environmental components to be measured for establishing a baseline (Table 3,4), should be reviewed to evaluate if the data are sufficiently site specific and updated, and data/ knowledge gaps and limitations must be identified.

Site surveys or planned sampling are then conducted to collect environmental data where no data exist, data are not available or sufficient, or are in need of an update. Further, simple ambient environmental parameters (such as temperature, light, salinity, etc.) should routinely be logged on the cultivation site.

However, although some studies are on-going there is a lack of knowledge for an environmental baseline with respect to the (genetic) biodiversity of and within the natural seaweed stock, which may be addressed by the following studies: (1) Mapping the biodiversity of the natural seaweed stock to be able to detect potential changes as impact from, e.g., the cultivation farm and mother plant harvest (see for instance Bekkby et al. (2023)). From such studies an accessible curated database with occurrence/abundance maps including existing BIOFAR II seaweed data along with newer data from BlueCea and the Kelp Forest monitoring study can be initiated and established. (2) Population genetics of seaweed species most potentially farmed for detection and prevention of genetic changes and contamination. (3) Biodiversity of associated fauna in the natural seaweed beds for detection of potential changes.

7. Conclusions

From the described activities of seaweed cultivation in the Faroe Islands, a number of potential impacts have been identified and addressed according to their expected significance. The impacts treated are from potential changes in the natural conditions of light, oxygen concentrations, nutrient and carbon dioxide availability, potential changes in hydrography as well as in the natural seaweed communities. Further, potential disturbance from noise and on seabed communities, potential pollution from emissions, discharges as well as release of organic material have been addressed.

As the suggested baseline programme developed for the Faroe Islands aligns with the recommendations from the KELPPRO project (Hancke *et al.*, 2021), and which has been supported by the review by Norderhaug *et al.* (2021), the significance of the potential impacts rely on the size of the seaweed cultivation activities. As such, the overall conclusion in Norway was that with farms increasing in numbers or considerably in size there would be an increasing need to include studies and monitoring of environmental effects on the seafloor, potential spread of species and of genetic material, and screening for kelp disease, to ensure a sustainable growth of a kelp cultivation industry.

In addition, and as mentioned by Hancke *et al.* (2021), the environmental components impacted from seaweed cultivation that are estimated to have long term, irreversible and regional effects should be prioritised over those seen to have short term, reversible and local effects in monitoring programs.

Therefore, it is recommended that efforts in the Faroe Islands should be made towards mapping the biodiversity of the natural seaweed communities and in understanding the population genetics of the seaweed species most suitable for farming, to be able to detect potential changes to natural communities over time. This is an important step towards safeguarding the natural genetic pool and diversity of Faroe Island habitats and for ensuring long-term ecosystem resilience. Given the irreversible risk posed by the possible introduction of alien species and the potential for genetic contaminations, establishing a baseline is crucial for long-term sustainable seaweed cultivation. It is essential to implement such a program before embarking on large-scale seaweed cultivation to prevent potential alteration of the natural biodiversity.

Following these recommendations will contribute to ensure a sustainable and resilient development of seaweed cultivation for the Faroe Islands.

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