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Report

Seaweed Carbon Solutions

Carbon Dioxide Removal (CDR) through industrialised ocean seaweed (kelp) farming

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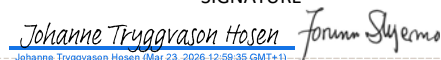
SUMMARY

Since its inception in April 2022, the Seaweed Carbon Solutions joint industry project has gained valuable knowledge and experience in open ocean seaweed cultivation, identifying critical areas for optimisation and improvement towards a negative-emission industrial offshore seaweed value chain. Both active CDR (biochar from cultivated seaweed) and passive CDR (organic carbon losses from seaweed farming) have been investigated, whereof biochar for use as a soil amendment represents the most mature carbon pathway. However, the project emissions are currently estimated to be higher than the carbon removal potential of the biochar. Further research and technology development is needed to mature the seaweed CDR value chain, including monitoring, registration and verification (MRV) for passive removals. Continued efforts can enable long-term carbon storage through seaweed biomass, and verification of such, hence the possibility for certified CO₂ removals through both seaweed cultivation and biomass conversion in the future.

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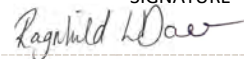
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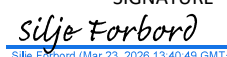
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Abbreviations, acronyms, and explanations	
AIS	Automatic identification system, for tracking of vessels and sea infrastructure
BiCRS	Biomass Carbon Removal and Storage. BiCRS is an umbrella term for hybrid CDR solutions which combine photosynthesis with technology specifically to achieve carbon removal
CAPEX	Capital expenditure
1 carbon credit	= 1 metric tonne (t) of CO ₂ equivalent (CO ₂ e).
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CORC200+	CO ₂ removal certificate for 200+ years (Puro.earth)
CRCF	Carbon Removals and Carbon Farming Regulation (EU action)
DOC	Dissolved organic carbon
EU ETS	EU Emission Trading System
GHG	Greenhouse gases
ICROA	International Carbon Reduction and Offset Alliance
IPCC	Intergovernmental Panel on Climate Change
JIP	Joint Industry Project
Kelp, seaweed, macroalgae	are used interchangeably throughout the report
LCA	Life cycle assessment
Long term	refers to the mid- to far-future period, often focusing on 2050 and beyond
mCDR	Marine Carbon Dioxide Removal (also referred to passive CDR in this context)
Mitigation	In the context of climate change, mitigation relates to a human intervention to reduce the sources or enhance the sinks of GHGs. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to solar energy or wind power, improving the insulation of buildings, and expanding forests and other “sinks” to remove greater amounts of CO ₂ from the atmosphere.
MRV	Monitoring, Reporting, Verification
NBS	Nature-Based Solutions
Permanence	In the voluntary carbon markets permanence refers to the long-term durability of carbon offset projects, ensuring that the sequestered carbon remains stored and does not re-enter the atmosphere.
POC	Particulate organic carbon
RDOC	Refractory dissolved organic carbon (carbon pool from seaweed farming) highly resistant to microbial decomposition, chemically stable, persists for centuries to millennia, does not rapidly return to CO ₂
SCS	Seaweed Carbon Solutions
Short term	refers to the immediate to near-future period, typically covering the next 0–10 years.
SSRs	Sinks, Storage and Reservoir’s
VCM	Voluntary Carbon Market
VERs	Verified Emission Removals

1 The Seaweed Carbon Solutions project

Novel, cost-efficient Carbon Dioxide Removal (CDR) methods are urgently needed. Aligned with Oxford Principal 2¹, the aim of the Seaweed Carbon Solutions Joint Industry Project (SCS JIP) has been to develop scalable technological solutions for industrialised open ocean kelp farming and conversion of kelp biomass to biochar, and to achieve negative emissions and outline possibilities to qualify “seaweed CDR” as a CO₂ offset mechanism and potential business case. In this value chain (Fig.1), the total amount of biosphere CO₂ removed and permanently stored must be significantly higher than the total amount of CO₂-equivalents emitted to the atmosphere during the production process to qualify as carbon removal. By investigating CDR technologies for ocean- and seaweed-based CO₂-removal, including both passive marine CDR and BiCRS, and conducting carbon accounting throughout the value chain, the SCS JIP has gained a deeper understanding of the status quo, possibilities, and challenges of seaweed CDR.

The R&D&I project has been closely aligned with the European Green Deal and the European Blue Growth Strategy² and was organised as a joint industry project between SINTEF Ocean, DNV, Equinor, AkerBP, Wintershall and Ocean Rainforest, with SINTEF AS, SINTEF Energi AS, NIVA and South Pole as R&D providers, Seaweed Solutions and Hortimare as service suppliers, and UN Global Compact and REV Ocean as advisors.

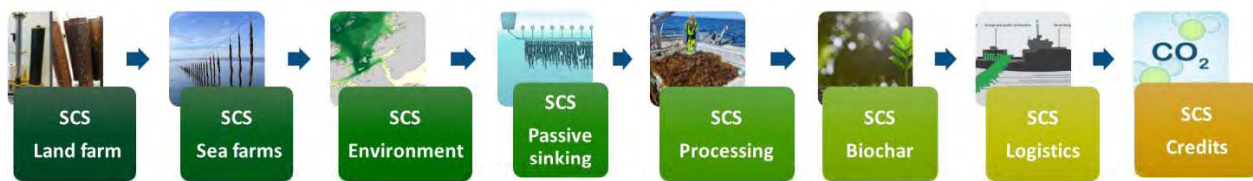


Figure 1 The Seaweed Carbon Solutions Joint Industry Project (SCS JIP; 2022-2026) encompasses multidisciplinary scientific work areas along the entire value chain, from land-based kelp seedlings production via biomass growth in the ocean sea farm to CO₂ credits. A life cycle assessment has been performed for the biomass to biochar CDR pathway.

1.1 Project scope

A range of experiments were carried out during 2023-2025 to build new knowledge and a better understanding of the CDR potential of this concept, starting with the installation of the “Storflua” seaweed farm with a theoretical production capacity of 500 tonnes sugar kelp (wet weight) in Frohavet in Trøndelag in 2023, followed by two cultivation seasons.

Two pathways for CDR were followed: Active CDR, which involves harvesting and pyrolysis of seaweed biomass to produce biochar (BiCRS), and passive, marine CDR (mCDR) which involves sinking and sedimentation of particulate (POC) and dissolved (DOC) seaweed organic carbon in marine sediments and the deep-sea during farming (Fig. 2).

The quantification of the different carbon pools derived from the seaweed farm and thus the passive, marine CDR potential was investigated in laboratory experiments and *in situ*. An environmental baseline was

¹ Revised Oxford principles for net zero aligned carbon offsetting

² The EU’s strategy for sustainable marine and maritime growth: Blue Growth | EUR-Lex

established, the farm’s environmental impact was monitored during and after the cultivation trials, concluding that the Storflua kelp farm poses no environmental risk, but also no clear ecological benefit.

Long-term storage of the kelp biomass is a prerequisite to enable an all-year supply from a seasonal crop and facilitating continuous biochar production at an industrial scale, monitoring of the carbon content in acid-preserved biomass was thus conducted. The produced seaweed biochar was tested for soil applications to investigate its effects on soil and plant health, in both large-scale and small-scale plant trials, and has through these preliminary experiments achieved a no harm status after adding a washing step of the biochar to remove problematic components (salt and boron). These experiments are to our knowledge the first of its kind, and seaweed biochar is not yet a commercial product. Still, the importance of finding good substitutes for conventional raw materials for an increasing demand for biochar is critical, and this research indicates that seaweed biochar should be further investigated, for several applications and end use.

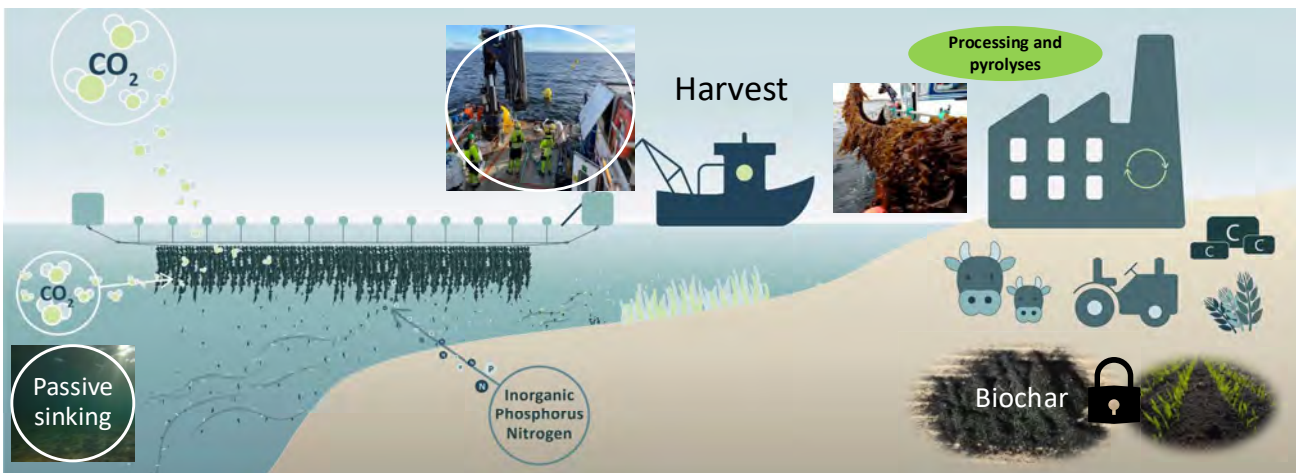


Figure 2 The SCS JIP concept and value chain with the two identified certification pathways, differing in maturity and market readiness: Passive sinking (mCDR) and biomass conversion to seaweed biochar (BiCRS).

To identify the most critical emission hotspots in the value chain DNV has provided a life cycle assessment (LCA). The LCA also includes a comparison of emissions from near-shore and offshore cultivation, as well as an examination of material use in sea farm design (to understand the CDR potential), followed by a proposal for optimisation scenarios for future development and scaling aligned with net zero requirements.

1.2 Main findings

The SCS JIP concept has two identified and viable certification pathways, differing in maturity and market readiness: mCDR and BiCRS. Biochar's ability to convert biogenic carbon into a chemically stable form allows the sequestered carbon to remain locked away for decades, centuries, or even millennia, depending on the properties of the biochar and its application³ (Fig. 2). Biochar is considered one of the more mature solutions for carbon capture and storage currently on the market. Biochar is approved as a CDR mechanism under several established frameworks.

³ Synthesis Report — IPCC

1.2.1 Feasibility assessments of multiple carbon certification pathways for seaweed farming

To better understand the current SCS JIP project design opportunities and risks, DNV initiated SouthPole⁴ to conduct two carbon pathways assessments. One investigating the feasibility of multiple carbon certification pathways for seaweed farming, the other one deep dived into the feasibility of seaweed farming methodology development. Regarding the latter, passive sinking for oceanic storage pathways, these methodologies have not yet been developed due to the immaturity of the topic and existing knowledge gaps. These gaps make monitoring the fate of the carbon, and thus carbon accounting, challenging. However, there has been significant recent attention on blue carbon and the ocean's role in carbon storage and there are multiple new methodologies for monitoring, registration and verification (MRV) under development for blue carbon projects, including for seaweed farming through, e.g. by Verra.

Cultivated seaweed is increasingly being recognised as a marine CDR method, independent of the target use of the biomass, but it is not yet an acknowledged CDR method due to early-stage development of related MRV and therefore not mature nor verified with developed high-integrity carbon-credit standards. Still, we know that the passive marine CDR contribution during the growth phase is of significance, and refractory carbon (RDOC) will accumulate annually. More research is needed to enable and establish marine CDR from seaweed cultivation.

Puro.earth, one of the leading certification standards for engineered carbon removals, was identified as applicable for seaweed CDR. Based on the SouthPole assessments, it was found that The Puro.earth⁵ carbon removal standard does allow for *purpose grown* aquatic biomass sourcing into biochar production, which is critical for cultivated seaweed for CDR purposes. Applying this biochar methodology, **today, the SCS JIP carbon emissions are estimated to be higher than the carbon removal potential for biochar, meaning negative emissions are not achieved at this stage.** Accounting for all project emissions, the current project design results in emissions 2-3 times higher than the removals through biochar in the 500 tonnes wet weight scenario. In this calculation the passive marine CDR is not included due to beforementioned lack of standards to perform MRV.

1.2.2 Biomass and biochar yields

The seaweed cultivation trials at the Storflua location showed high productivity in both cultivation seasons, with 10 kg biomass per m of cultivation rope. This corresponds to about twice the yield obtained at a sheltered farm used as a reference in the first cultivation trial and supports the location choice modelled for optimal yields. In a 500 tonnes of seaweed harvest per year scenario, a wet-to-dry ratio for seaweed of 10%, and a yield of 33% of biochar from dry seaweed, 340 tonnes of biochar can be produced yearly. Assuming a carbon content of 33% of the biochar and that 100% of the biochar can be reported, around **19 tonnes CO₂eq can be stored in biochar produced from 500 tonnes wet weight seaweed**⁶. In other words, to sequester 1 tonne CO₂ in biochar, 30 tonnes of kelp is needed (Fig. 3)

⁴ SouthPole Norway

⁵ World's leading crediting platform for engineered carbon removal; Issues CO₂ Removal Certificates (CORCs) for biochar projects; requires third-party verification via a "Production Facility Audit," lifecycle assessments (LCA), sustainable feedstock sourcing, proof of permanence, environmental & social safeguards

⁶ The mean soil temperature in Norway is used to define permanence over 100years.

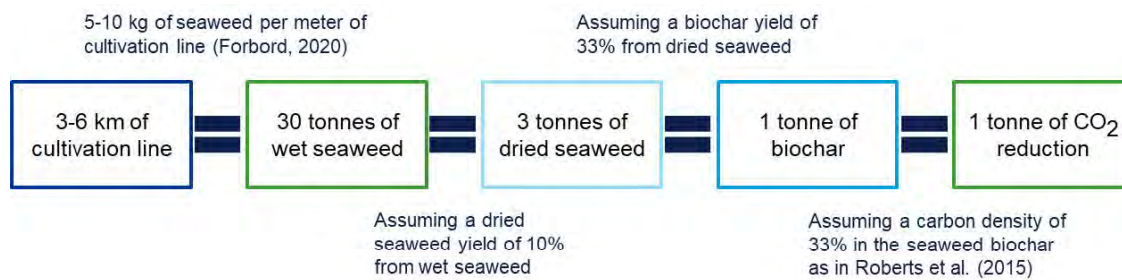


Figure 3 Approximate volume of seaweed needed to achieve 1 tonne of CO₂ stored in biochar. The calculation does not account for emissions that occur within the value chain and production process.

1.2.3 CO₂ emission hotspots in the value chain

A complete LCA is a criterion for qualifying and registering a project under the Puro.earth Framework, and the LCA carried out by DNV has identified the emission hotspots and make recommendations towards net zero. The farm-to-gate system boundaries applied encompass the installation of the seaweed farm, the deployment and harvesting of seaweed, pre-processing to stabilize the fresh biomass, the drying of seaweed, and pyrolysis to produce biochar⁷. Seedlings production is excluded from this analysis due to its assumed low impact compared to other parts of seaweed farming, as indicated by findings from existing LCA studies on seaweed farming⁸. The final application of the biochar as an end-product is also excluded. The assumed production volume in the calculation is 500 tonne wet weight (WW) yearly, corresponding to a yield of 10 kg WW per metre growth line.

The identified CO₂ emission hotspots in the seaweed CDR value chain are

- Material use in infrastructure associated with the seaweed farm.
- Diesel consumption of vessels for deploying and harvesting the seaweed.
- Energy consumption needed for drying the seaweed.

The GHG emissions related to the farm infrastructure were high mainly due to the materials used, specifically steel, and inclusion of seabed and mooring considerations into location choice is suggested to enable more innovative low-emission sea farm designs and alternative anchoring options. Scaling offshore should emphasise repurposing and integration with O&G assets and co-location with offshore wind to create innovative farm designs with lower emissions in material usage.

High GHG emissions related to vessel operations were adopted from the aquaculture service sector due to the current status of not having sector-specific vessels for seaweed cultivation. The vessel energy usage also increased due to challenging operations in this open ocean area in Frohavet, with strong currents and wave exposure, taxing larger vessels and more working hours. On site solutions and low-emission vessels will be even more crucial in an offshore scenario.

Fig.4 compares emissions at a near-shore cultivation site with the exposed in an optimised biochar scenario. Increased biomass yields are not considered here, but it is clearly one way to improve the CDR. A simplified energy balance indicates that the pyrolysis of seaweed can theoretically be self-sustaining if the moisture content is sufficiently reduced before entering the reactor. However, real-world inefficiencies, including energy losses during drying and pyrolysis, must be accounted for, also if considering residuals as zero

⁷ Life cycle environmental impacts of kelp aquaculture through harmonized recalculation of inventory data - ScienceDirect

⁸ A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing - ScienceDirect

emission input towards biochar production. Seaweed’s high initial water content and low energy density emphasise the importance of efficient drying and heat recovery if the process is to be viable at scale.

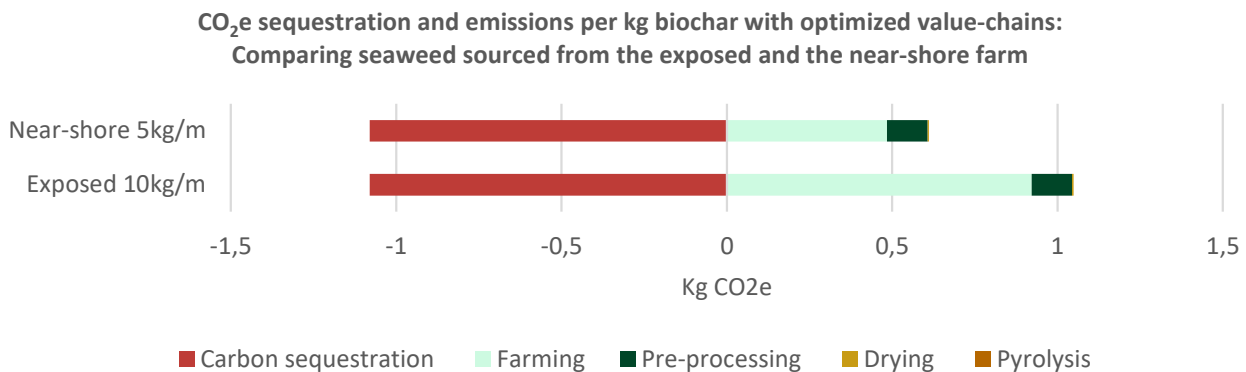


Figure 4 CO₂e sequestration and emissions per kg of biochar produced after optimisation of the emission hotspots in the seaweed biochar value chain. Near shore/lower yield can become climate neutral in the short term with high production due to less emissions related to operations and logistics. GHG burdens and benefits from the pyrolysis process are assumed to be net zero.

It is possible to generate negative emissions also at the exposed site *if* a range of optimisation strategies are implemented:

- All operations with work vessels and boats are electric.
- Assuming 100% renewable power has been sourced for all electric processes.
- The seaweed is dried using excess heat from other industries, assuming no additional energy input is needed for drying, but includes a transport stage by an electric boat.

The current SCS project design reflects the most cost-efficient and readily available equipment and services at present, with few sector-specific and low-emission technologies, low production volumes and a fragmented value chain, and the current project design and activities are expected to result in net negative emissions. From a LCA and value chain perspective, to be able to achieve carbon negativity, which is a requirement under the Puro.earth methodology, industrial scale regional low emission value chain components like drying facilities (preferably excess heating) and a pyrolysis plant must also be in place. Before registering the project under the Puro.earth biochar methodology, the SCS JIP needs to meet several project design criteria and demonstrate compliance. Therefore, there is a strong need for establishing regional infrastructure and optimisation throughout the value chain to design for minimised CO₂ emissions, thereby improving the potential for negative emissions, to qualify for CDR. This will take time and requires significant investment in technology development, including processing capacity, that will enable scaling and facilitate greater yields, that furthermore contributes to reduce overall production costs.

1.2.4 Passive CDR at large-scale and long-term

Macroalgae farming can contribute to natural carbon sequestration processes during the grow-out phase at sea through the erosional production of particulate (POC) and dissolved organic carbon (DOC). New data is provided for carbon release from cultivated sugar kelp⁹. In Table 1 these results are used to calculate the CDR potentials in a 1 million tonnes wet weight seaweed production scenario, showing that 46 000 tonnes

⁹ Neves et al., 2025. Particulate and dissolved organic carbon losses in high-latitude seaweed farms. *Science of the Total Environment* Vol.982

CO₂e is passively lost to the ocean every year. Especially the recalcitrant fraction (RDOC) of these carbon compounds contributes to CDR through long-term storage in sediments and in the deep-sea. These findings encourage further investigation into the dynamics and characterization of POC and DOC in marine environments to assess their contribution to marine biogeochemical cycles and long-term impacts on carbon sequestration and possibly towards blue carbon credits (mCDR). There are uncertainties regarding the quantities and long-term storage of RDOC in the ocean and methods for monitoring, registration and verification (MRV) of marine CDR is crucial. Methodologies are being developed for marine sediment storage to quantify the natural flux of seaweed debris to the seafloor that is contributing to long-term geological carbon storage. Tracking the long-term fate of carbon and ensuring accuracy in ocean environments, will require sophisticated, often automated, monitoring technologies. Until we have these technologies, models can be used to calculate the passive contribution.

Table 1 Annual production of 1 million tonnes (t) wet weight (WW) for active and passive CDR purposes. The RDOC fraction of the total “passives” and thus potentially sequestered CO₂ is not calculated.

Wet weight biomass cultivation potential (harvested/harvestable)	1,000,000 t WW
Dry weight biomass (assuming 10 % dry matter content)	100,000 t DW
Carbon in biomass at harvest (assuming 30 % C in dry matter)	30,000 t C
CO₂ equivalents in biomass at harvest	110,000 t CO₂
Particulate Organic Carbon (POC) released to the ocean during cultivation “passives”*	7,800 t C
Dissolved Organic Carbon (DOC) released to the ocean during cultivation, “passives”*	5,000 t C
Total carbon released to the ocean during cultivation	12,800 t C
Total CO₂ equivalents released to the ocean during cultivation, potentially sequestered	46,000 t CO₂

*The calculations for “passives” release of C to the ocean are based on Neves et al (2025).

1.2.5 Environmental interactions

The project focused on three main environmental interactions: the release of particulate organic matter (POM), nutrient uptake by cultivated kelp, and the role of the kelp farm as a temporary habitat. The monitoring program included ROV surveys of the seafloor, sediment, and benthic fauna sampling, eDNA analysis from water and lumpfish stomach contents, and traditional fish and invertebrate sampling:

- Sediment and benthic fauna sampling showed high species diversity and very good ecological status both before and after kelp cultivation. After two cultivation trials, the benthic fauna remained stable.
- Fish diversity and abundance were lower at the kelp farm compared to natural kelp forests, with lumpfish being the only species consistently observed. eDNA results are pending but are expected to show limited biodiversity differences based on experience from other kelp farms. Invertebrate richness was higher on long-term structures such as buoys and ropes than on cultivated kelp, suggesting that early harvesting limits habitat complexity.
- The presence of the alien amphipod species *Caprella mutica* was noted, highlighting the potential for artificial structures to facilitate the spread of non-native species.
- Nutrient uptake by cultivated kelp was assessed through literature review and concluded that nutrient uptake will most likely not affect the local phytoplankton negatively.

- Based on the two cultivation trials, with low volumes, it is not possible to determine how larger-scale, longer-term production at Storflua would have affected the surrounding environment, nor how long traces of the activity might remain visible after the farm is eventually shut down.
- Environmental impact of kelp cultivation is site-specific and depends on scale, hydrodynamics, and local conditions. The indication of limited negative impacts from kelp cultivation aligns with sustainability goals and support development of low-impact aquaculture.

The results call for further research and policy development to enhance the environmental contributions of industrial scale kelp farming, particularly in relation to biodiversity, nutrient cycling, and alien species management.

1.3 Maturity of Seaweed CDR pathways

Based on the project results, continuing to work towards establishing seaweed CDR in the short term by developing and optimising the biomass-to-biochar value chain is the most mature CDR pathway due to existing methodologies and an established CDR market. The seaweed biomass waste-to-biochar pathway presents another opportunity, for a zero-emission starting point for biochar production, eliminating emissions from cultivation activities and infrastructure, thereby an opportunity in qualifying the BiCRS removals for certification in the short term.

Developing a passive/mCDR methodology, i.e. the loss of dissolved and particulate organic carbon from the seaweed farm, requires a thorough and well-documented quantification of carbon removals from key pools and the associated carbon fluxes from seaweed cultivation, particularly focusing on refractory dissolved organic carbon (RDOC) and carbon storage in ocean floor sediments. Although the literature has reached a consensus that seaweed farming has potential for climate change mitigation through passive carbon pathways, for it to be recognised as a viable carbon project type that properly values these passive sequestration pathways there are still some gaps to address. However, significant progress has been made through SCS JIP research by Neves et al. (2025). Feill Bokmerke er ikke definert.

A continued focus on providing critical research and data on monitoring, reporting and verification (MRV) towards a longer-term possibility of implementing the passive marine CDR as a blue carbon credit certification pathway could benefit the CDR business case - and development of such, due to an add-on to the total carbon removal budget for seaweed biomass cultivation activities. The passive carbon sinks are well-identified, but uncertainties remain regarding carbon pool amounts, fractions of recalcitrant carbon, degradation rates, and long-term storage, particularly in the context of location-dependent environmental conditions and variability in species and farming practices.

In the short term, carbon avoidance opportunities are a perspective worth exploring for seaweed biomass and its derived components. While maturing and developing low-emission offshore cultivation and passive CDR technologies, applying cascading principles in processing can facilitate the full utilisation of biomass, also for new products and markets. These new products could be used as inputs in other value chains, providing carbon avoidance opportunities from the replacement effect of fossil inputs. This will potentially have a greater overall climate impact, and new product development will also enable a return on investment from the first harvest by serving already existing biobased markets. The residuals from processing these products should then be converted to biochar for carbon sequestration purposes.

1.4 Recommendations for further developing Seaweed Carbon Solutions

Based on the findings in this 3-year R&D project it is recommended to focus further work on the following topics:

- To optimise value chain emissions to qualify for biochar carbon credit methodologies (e.g., Puro.earth).
- To enhance kelp biomass and biochar production to eventually demonstrate negative emissions at the industrial level.
- To advance R&D into MRV (Monitoring, Reporting, Verification) needed to verify mCDR.
- To explore cascading biomass processing for improved business cases.
- To explore synergies, *i.e.*, multi-use and co-existence, with offshore industries¹⁰, for improved business cases.
- To establish an economic model to explore how key low emission value chain components can generate regional value creation.
- To engage with regional and national authorities and decision makers to maintain the momentum and remain focused on local value creation and improved social impact related to developing new sustainable value chains “at home”.
- To engage with certification bodies to tailor frameworks for marine biomass cultivation and biochar production.
- To investigate other complementing crediting opportunities, e.g. EU nature credits

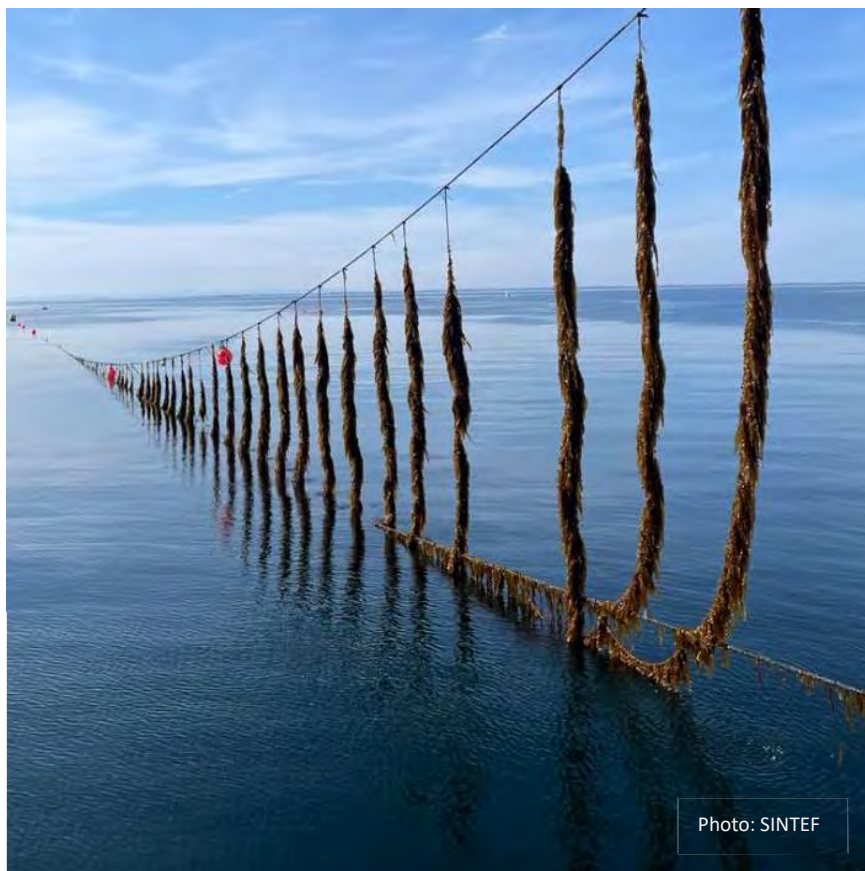


Photo: SINTEF

¹⁰ WEF_Nature_Positive_Role_of_the_Offshore_Wind_Sector.pdf

2 Highlighted CDR results from the Seaweed Carbon Solutions project

In chapter 2 the highlighted CDR results are presented, followed by a more in-depth presentation of the overall project results, looking at the value chain and outlook for seaweed CDR, in chapter 3. The referred to results in chapter 2 and 3 are extracted and sourced from the technical work package reports.

2.1 Quantification of the passive CDR potential from kelp cultivation

Cultivating kelp in a farm that is dimensioned for harvesting of 500 tonnes biomass per year, like the Storflua farm, correspond to a total capture of 57-77 tonnes CO₂ capture per year, depending on the timing of the harvest (Figure 5).

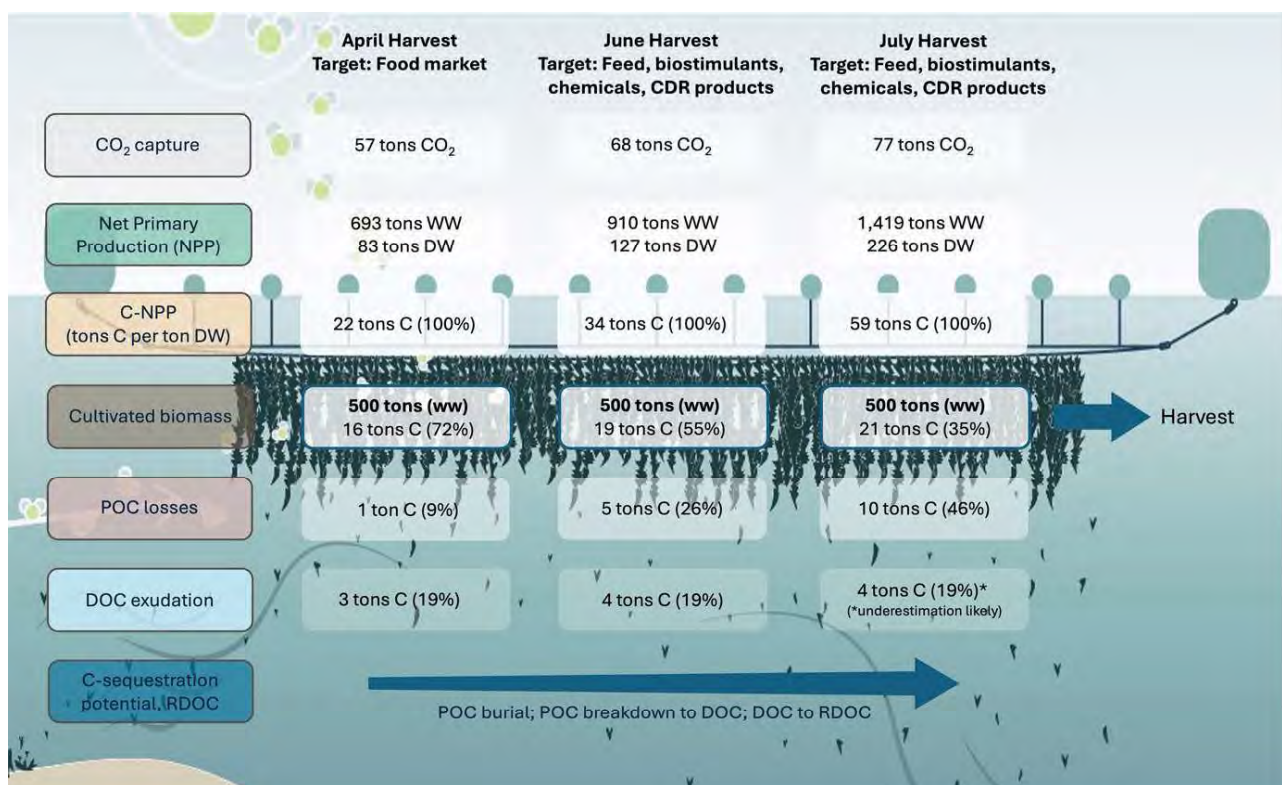


Figure 5 Particulate and dissolved organic carbon losses in a high-latitude (63°N) seaweed farm with a harvestable yield capacity of 500 tonne per year. Values represent averages for two cultivation cycles in 2022 and 2023, relative to C-NPP (%) and biomass volumes at different harvest times, targeting various markets. X tonnes C in cultivated biomass is the carbon remaining in kelp tissue after losses are accounted for in one cultivation cycle (Illustration from Neves et al. 2025).

In general, young kelp has a lower carbon content than more mature ones. The later the biomass is harvested the larger is the loss of carbon to the surrounding water masses and eventually sea floor sediments due to increasing leakage of exudates and increasing biofouling and breakage of tissue fragments as the kelp grow older during the summer. Sugar kelp, the species cultivated in this project, is normally harvested in April-May at these latitudes (63°N) to ensure high food quality, but to reach larger biomass and thus target the carbon capture potential better the biomass should be kept in the farm until June-July. For industrial purposes a combination could be envisaged. Figure 5 indicates the CO₂-capture potentials for different target applications.

The 57-77 tonnes of captured CO₂ corresponds to 16-21 tonnes of carbon in the harvested kelp biomass. *In addition*, 4-14 tonnes of carbon are passively lost to the environment as POC and DOC. Depending on seedlings deployment and biomass harvest times this loss correspond to 28-65% of the carbon that has been captured during the cultivation phase. As DOC eventually is microbially degraded to RDOC with a strong potential for long-term storage in marine sediments and deep ocean, the dynamics and characterisation of POC, DOC and RDOC in marine environments is under investigation to assess their contribution to marine biogeochemical cycles and long-term impacts on carbon sequestration.

2.1.1 Long term and large-scale calculus

The long-term net carbon storage of a 500 tonnes capacity kelp cultivation module was calculated using a simple model (Figure 6). Both the total bound (passive and active) and released carbon (all project emissions) is accounted for. The passive carbon storage includes annual releases of DOC and POC, transport to sediments (permanent) and breakdown of DOC and RDOC over time - in addition to the assumed permanent. The emissions of CO₂ through offshore cultivation (following the LCA and Puro.earth methodology) have been taken into account.

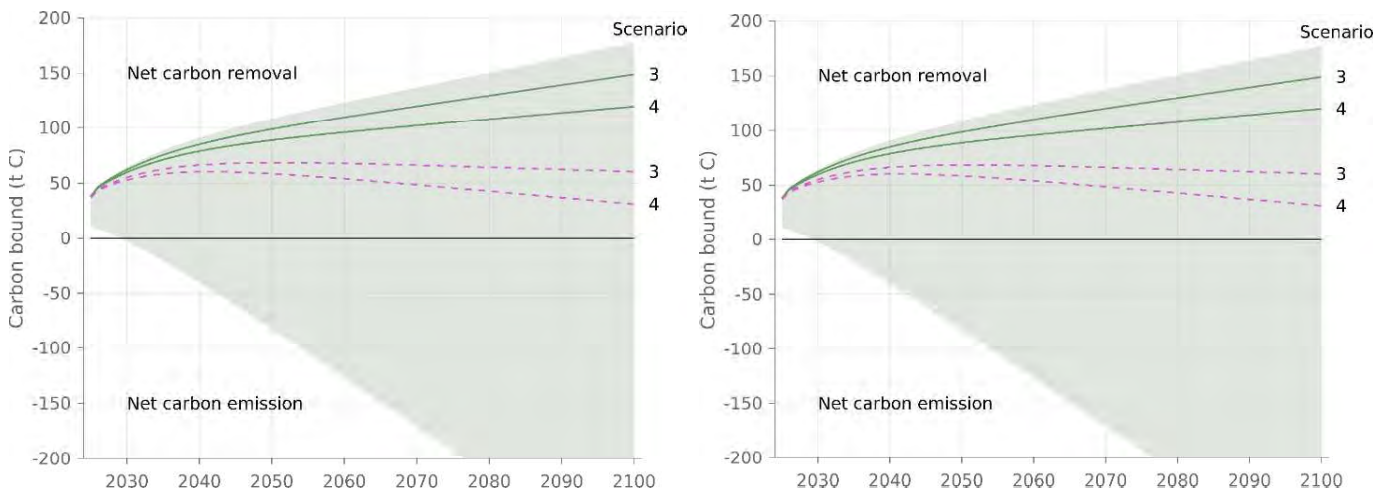


Figure 6 Carbon calculus scaling the current research farm with a 500 tonnes capacity in a longer-term perspective, the total bound (passive and active) and released carbon (all project emissions) is accounted. Any position above the time-axis indicates a net removal of CO₂ up to that point, while any point below indicates a net release of CO₂. The shaded regions indicate the total range of results from varying cultivation site (near/offshore), harvest time, yield per unit cultivation substrate, present and future technologies etc. The solid green lines indicate scenarios 1 to 4 described in the text. The pink dashed lines indicate the same scenarios without stabilization (biochar production) of the harvested biomass. Cases are for the current and early stages of farm development (left) and for optimised scenarios (right).

We have considered four scenarios as seen in Figure 6:

Scenario 1 - Near-shore cultivation with low yields (5 kg biomass per m rope substrate) and high GHG emissions (present technology).

Scenario 2 - Offshore cultivation with high yields (10 kg biomass per m rope substrate) and high GHG emissions.

Scenario 3 - Near-shore cultivation with high yields and low GHG emissions (improved technology).

Scenario 4 - Offshore cultivation with high yields and low GHG emissions. Optimisation has thus been assumed in scenarios 3 and 4.

The «stable» situation arises because some of the passive carbon (three C pools) breaks down continuously. Thus, a balance/steady state is achieved at the assumed stable annual production of 500 tonnes.

Scenarios 1 and 2 are based on the knowledge and experimental data from the SCS JIP project, hence reflecting the current and early stages of development (Fig. 6, left). Emissions through the current project design, value chain and operations at sea, are expected to be optimised and minimised as the seaweed industry develops alongside the overall energy transition in the marine sector. Optimisation includes low emission sea farm design and vessels, with a focus on increasing yields and optimising capacity on land and at sea. Such considerations are taken into account in scenarios 3 and 4 (Fig. 6, right), with a 50 % reduction in emissions during biomass production, deployment and harvest, and a 70 % reduction in emissions during farm design and deployment. **Considering the farm area use of 7.5 ha per 500 tonnes module, the green scenario 3 in Fig. 6 leads to a sequestration of more than 1.8 kg C⁻² over 75 years, or on average a removal of more than 24 g C m⁻² year⁻¹. This is significant compared to the average global annual net primary production of the oceans at ca 110 g C m⁻² year⁻¹ ¹¹.**

2.1.2 Blue carbon credits status

Blue carbon credits are highly sought after and constitute a growing market segment (VCM). Although the uncertainties still related to MRV, Japan has certified mCDR from wild and farmed seaweed as part of the so-called J-Blue Credits, Japan's official certification system for *blue carbon projects*, from January 2025. Seaweed Cultivation included. Blue carbon has the largest annual issuance (conventional methods) with above average prices. There are several initiatives to develop carbon credits from seaweed farming and other related activities, however, there are no existing methodologies yet due to knowledge gaps. According to the Southpole assessment¹², globally, blue carbon credits sell for €15-40 per tonne. Other European nature-based solutions projects have been shown to have a premium compared to other regions, selling for as high as €30-70 per tonne.

2.2 The Puro.earth Standard Biochar Methodology

Puro.earth, one of the leading certification standards for engineered carbon removals, has developed a methodology specifically for biochar. It sets strict quantification, permanence, and additionality requirements and mandates third-party verification to ensure environmental integrity. Puro.earth's approach is focused exclusively on net-negative emissions (not avoidance, nor reductions) and is designed to foster transparency and trust in carbon credit issuance. This methodology has been applied to calculate the SCS JIP net removal potential for biochar.

2.2.1 Net removal potential of the SCS JIP biochar

In order to yield a net removal, the SCS project emissions plus leakage need to be lower than the carbon that can be stored within the biochar. As around 38 kg of CO₂eq can be stored per tonne of fresh seaweed, the maximum project emissions plus leakage should not exceed this number. With the current value chain, technologies, and emission factors for seaweed production, harvesting and drying, the project emissions are currently estimated to be between twice and three times higher than carbon storage in biochar. Hence, the project activity would result in net carbon emissions with the current project design.

¹¹ Woodward FI (2007) Global primary production. *Current Biology* 17:R269-R273. <https://doi.org/10.1016/j.cub.2007.01.054>

¹² Southpole Feasibility assessment of multiple carbon certification pathways for seaweed farming

2.2.2 Seaweed biochar for soil applications

SCS JIP provides an assessment of seaweed biochar production, properties, and potential for soil-based applications. The results highlight that while untreated seaweed biochar presents significant challenges for soil use due to phytotoxicity, it also offers clear opportunities for carbon removal and other material-based applications, especially if production and post-treatment steps are carefully managed.

The biochar produced from seaweed in this study may be considered chemically stable, based on its low H/C and O/C molar ratios, qualifying it as a durable carbon sink under leading CDR certification frameworks. However, its low carbon content and very high ash, chlorine, and bromine levels pose constraints for soil application and raise environmental concerns. Phytotoxic effects observed in greenhouse trials could be mitigated after washing the biochar post-pyrolysis. After adequate pretreatment, seaweed biochar could be added to soil and performed well in comparison to woody biochar.

From an energy perspective, seaweed pyrolysis could be self-sustaining if feedstock moisture is reduced to an acceptable value, but this requires efficient drying systems and ideally integration with waste heat sources. Seaweed's high initial water content and low energy density emphasise the importance of efficient drying and heat recovery if the process is to be viable at scale for biochar production.

The Puro.earth Biochar methodology¹³ also establishes that the point of creation of the CO₂ removal certificate is the production process of biochar. Therefore, the producer of the biochar is also the supplier of CO₂ removal (see also the Puro.earth [General Rules Cover](#)¹⁴).

Biochar is increasingly recognised as an effective carbon dioxide removal (CDR) strategy with significant mitigation potential¹⁵. The IPCC's 2019 Special Report also estimates that, under conservative assumptions, biochar could facilitate the removal of up to 1 gigatonne of CO₂ per year by 2050. The Puro.earth price index shows that biochar carbon credits registered with the standard have been sold at prices between €100-180 over the past two years.



¹³ Biochar Report - Final.pdf

¹⁴ General Rules Cover

¹⁵ AR6 Synthesis Report: Climate Change 2023 — IPCC

3 Research and technological development

Seaweed cultivation offers significant potential for scalable renewable biomass production and ocean-based carbon removal (CDR), capturing CO₂ from the atmosphere and oceans. By rapidly scaling these solutions, these technologies could possibly remove 1 million tonnes of CO₂ by 2050.

The Intergovernmental Panel on Climate Change (IPCC), again, highlighted the planetary crisis in their 2023 Climate Change Synthesis report: “Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater, cryosphere and coastal and open ocean ecosystems (high confidence). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (high confidence)”¹⁶. In this context, due to the transboundary nature of many climate change risks, SINTEF, DNV, Equinor and Aker BP initiated and funded the Seaweed Carbon Solutions joint industry project (JIP) to address the urgent need for climate action. After its start Ocean Rainforest and Wintershall joined the project as adequate partners. The main goal of the project was to pilot a scalable technology for open-ocean seaweed CDR, with a focus on the seaweed-to-biochar for soil amendment, which supports carbon removal and storage (BiCRS) credits in the short term, and passive marine CDR through loss of organic carbon from the seaweed farm during the cultivation phase.

3.1 Approach

To adequately address the challenges and research tasks at hand, including value chain complexity, towards establishing Seaweed CDR as a climate mitigation method, a multidisciplinary approach was applied (Table 2). Although the overall focus in this project is on CDR outcomes, the SCS concept and dedicated work areas are interconnected and will be assessed holistically hereafter, maintaining the focus on establishing the seaweed cultivation value chain as a sustainable new low-emission industry in Norway with several potential future applications for the biomass, thereby generating new business opportunities and greater social impact while contributing to the green shift.

Table 2 Overview of the research activities in the SCS JIP project.

Work Package	Activity	Responsible partner
0	Establish JIP: Partners, work plan, contracts	SINTEF Ocean and DNV
1	Scaling, site selection and licensing	SINTEF Ocean and DNV
2	Offshore pilot farm design and construction, installation and operations	SINTEF Ocean
3	Start offshore pilot farming: Seeding, deployment, harvest, field surveys	SINTEF Ocean
4	Monitoring – environmental data, growth and biofouling, carbon capture	SINTEF Ocean
5	Environmental impact and biodiversity monitoring	NIVA
6	Deep sea deposition of seaweed (passive and active), lab and field trials	SINTEF Ocean
7	Pre-processing and long-term storage of seaweed	SINTEF Industry
8	CDR products – biochar. Processing and quality assessment	SINTEF Energy
9	Biochar for soil improvement - testing	SINTEF Energy
10	Verification of effect, LCA and certification of Seaweed CDR	DNV
11	Mid-way evaluation	SINTEF Ocean and DNV
12	Project management and communication	SINTEF Ocean and DNV

¹⁶ IPCC_AR6_SYR_SPM.pdf

3.1.1 Sinking trial called off

In 2023, the project decided not to conduct a biomass sinking trial due to insufficient scientific data on the effects of depositing larger volumes of biomass at depth as a CDR method, as initially planned in the original project scope (Table 2). As this CDR mechanism was not performed nor investigated in the SCS project, it significantly reduced the planned production volumes and potential CDR from this method. Hence, the SCS had the two identified CDR pathways to further research and develop.

3.2 Site selection, licensing process and sea farm design

The SCS project commenced with site selection for a highly productive location in offshore conditions, taking into account the CO₂ uptake potential and the availability of nutrients to support the kelp, which is crucial for CDR purposes. Simultaneously, the ocean cultivation rig concept was selected from an external supplier, a feasibility study was conducted, concluding that the cultivation rig design (also referred to as the sea farm) was feasible for the selected site.

Today, commercial sea farms for large-scale industrial seaweed cultivation in offshore conditions do not exist in Norway. Cultivation in open sea areas requires the development and testing of new, robust, and cost-effective seaweed farm concepts, both in terms of the structural integrity of the facilities and in performing cost-efficient operations under demanding weather conditions. The exposed farm at Storflua provides a state of the art infrastructure, for testing and improving the technology, with production and survivability demonstrated in Norway, the Faroe Islands and California.

The aquaculture license process to obtain permission to install the sea farm and initiate kelp cultivation was not without complications. A change of location from Grip in Møre og Romsdal to Storflua in Trøndelag was made early on, followed by a year of approval process and stakeholder management, including negotiations with local fisheries that ended in a 50% reduction of planned farm size, a compromise for co-existence, reflecting the competition for space and many interests in the Norwegian coastal areas. Because of non-existing standards for offshore seaweed farm design, the overall approach considered several technical and HSE requirements for local adaptation, including the mooring system, positioning of the farm, line load (hydrodynamic) and capacity calculations (and adjustments), and vessel requirements for all operations. During the prolonged licensing process, several changes were made to the sea farm design to accommodate the changing and in the end reduced location requirements, customising the sea farm to fit the actual area, which incurred additional costs in reengineering the infrastructure. Affecting both the CAPEX, LCA, cost of operations and overall productivity.

3.2.1 Mooring analyses report

The initial mooring analyses report resulted in extremely large mooring line components. In addition, it was necessary to investigate ways to reduce the loading, to achieve dimensioning anchor line loads that resulted in anchor, chain, and rope sizes that were manageable with a typical aquaculture service vessel.

Several iterations of the mooring analyses were conducted to achieve acceptable loads and compliance with nationally recognised design standards and industry practice. There is no specific standard that sets requirements for the design of seaweed farms. In the absence of a specific standard for seaweed farms, the common practice in Norway is to adopt relevant requirements from the governing standard for fish farms, NS9415:2021, "Floating aquaculture farms - Site survey, design, execution and use" (NS9415:2021)".

The following adaptations were used as the basis for the revised mooring analyses:

- Maximum allowable anchor load limited to 30 tonnes – to ensure reasonable size of anchors and to allow for proof load testing of anchors according to NS9415 standard (50% of design load).
- Increased size of corner buoys (equipped with AIS) to ensure positive freeboard in storm conditions. Seasonal growth data combined with seasonal wave statistics are implemented to reduce design loads

3.2.2 Storflua Capacity - adjusted based on operational experience

The maximum cultivation capacity of the OCU was reduced from 55 km of seeded lines to 30 km of seeded lines to reduce the hydrodynamic loads on the OCU and the corresponding mooring line loads. I.e. spacing between each vertical cultivation rope increased from 1m to 1.8m.

Furthermore, during deployment, harvesting and maintenance operations the vessels need to operate between the lines, so based on experience, for the 2024/2025 cultivation season we decided to remove every second support line, meaning that the separation between the lines is currently 30m, to operate vessels more safely, especially in challenging weather. With five of the eleven mainlines removed from the cultivation unit, the cultivation capacity is correspondingly reduced.

Due to the increase in capital costs related to the sea farm redesign and reengineering, it was decided that the SCS project should limit its ownership in the sea farm to renting these facilities from SINTEF Ocean through the national research infrastructure [RI Seaweed - SINTEF](#)

When the aquaculture license was approved, an environmental baseline survey was conducted to assess the site's existing biodiversity and environmental state before the commencement of any project activities.

3.3 Cultivation Trials

Two cultivation seasons have been conducted at Storflua, accompanied by related value chain activities, including land-based upscaling of cultures and seeding of cultivation ropes for deployment at sea. Logistics and transport of biological material from labs were coordinated with other suppliers to execute both deployments and harvests. During the growth phase, biomass monitoring and data on environmental parameters have been collected as part of a yield-optimising strategy for increased CDR.

3.3.1 Seeding and Deployment

Coordinated with the installation of the sea farm, the first batch of cultures and seedlings was produced on land in hatcheries, from wild “motherplants” from local kelp populations to safeguard biological requirements, and the first deployment of seeded lines was executed in December 2023 and then in February 2024. For the second cultivation season (2024/2025) the seedlings were deployed in October 2024 and February 2025. The different deployment methods (twine and direct seeding) and deployment times are designed to learn more about the new site and its growth potential. During the growth phase, monitoring and testing of various remote monitoring technologies were conducted to investigate and help develop new methods that will reduce the need for physical inspections and labour, thereby also reducing logistics emissions, and implement more automated processes for large-scale farming.

A critical trade-off exists between high-yield, reliable twine seeding and the “newer”, more cost-effective, scalable direct seeding method. Twine seeding and high-density direct seeding delivered the best results, however, direct seeding's success is more variable and requires further optimization. The SCS JIP project highlighted significant logistical challenges related to deployment in exposed offshore conditions. If adverse weather conditions delay deployment, then the optimal deployment time will be missed, and yields will be

reduced. Using local seedling suppliers is recommended to simplify logistics and better align with narrow weather windows. Further improvements for deploying in adverse weather conditions are required.

3.3.2 Recommendations for Improvement

The current method of deploying a large number of individual 10-meter vertically positioned ropes (sea farm design) is a major bottleneck as it restricts attempts to implement continuous operations and reuse rope. It is recommended to shift to a continuous line system (e.g., in a zig-zag pattern) to improve operational speed, reduce vessel dependency, and facilitate the reuse of materials, thereby lowering costs and environmental impact.

3.3.3 Harvesting and Season Extension

A full harvesting and processing pipeline was successfully tested, although the processing operations (acid preservation) was identified as the primary bottleneck. A custom-developed rope cutter allowed harvesting to proceed without a large crane vessel. With a larger boat and optimized processing (e.g., larger mixers), harvest rates could be significantly increased.

The offshore farm site showed less severe biofouling, suggesting a potentially longer harvest season compared to inshore locations, likely due to higher nitrate concentrations and lower temperatures. However, attempts to achieve a second-year crop (cropping) failed due to the seaweed dying off during the end of summer, suggesting nutrient-limitation in these months. One way around this would be to explore possibility of submerging the farm into deeper, colder water during summer to mitigate environmental (high light, low nutrient) stress and potentially enable a second-year crop. Despite being unable to obtain a second-year crop under current practice, the cropping test showed extremely fast recovery in biomass growth, meaning there is a possibility to obtain 2-3 crops per year, for different target markets if needed/wished, knowing that the biomass recovers fully in 3-4 weeks after cropping. It is necessary to leave behind ca. 20 cm of the meristem for re-growth to occur. A scientific paper on this work is being prepared for publication.

3.3.4 Monitoring

Environmental: While satellite data is useful for observing broad seasonal trends, *in-situ* monitoring is essential to capture critical differences between farm sites. *In-situ* data revealed that the offshore site likely benefits from higher stability, with warmer seawater during winter, colder temperatures in summer, and increased nutrient entrainment into surface waters¹⁷, likely contributing to the higher yields.

Biomass: The use of an Unmanned Surface Vehicle (USV) for remote monitoring was successfully demonstrated, proving its capability to navigate the farm and generate qualitative biomass maps from underwater imagery.

3.3.5 Biomass yields

The offshore Storflua site consistently produced significantly higher biomass yields than the inshore Skarvøya site across both seasons (23/24 and 24/25). This advantage is attributed to factors like higher seaweed density in the first season and a greater abundance of large seaweeds in the second, likely driven by superior environmental conditions such as improved light distribution and nutrient availability resulting from a more dynamic offshore location.

3.4 Biomass pre-processing and storage trials

¹⁷ Phytoplankton community succession and dynamics using optical approaches - ScienceDirect

Seaweed biomass is commonly preserved by lowering the pH with the addition of acids, which is the established methodology for preserving seaweed for applications in the food industry or as a raw material for biorefining. The project has examined chemical (adding acids) and biological (adding microbes) preservation methods for cultivated sugar kelp to extend the processing window and maintain carbon content for downstream use. Key tasks include pre-treatment and stabilisation of seaweed biomass for transportation and storage, long-term storage (weeks to months) to extend the processing window, and recovery of valuable side streams from dripping losses. A long-term storage and carbon content preservation was conducted using sulphuric, formic, and acetic acid. They all effectively prevented microbial degradation over nine months, with sulphuric acid at pH 2.9 giving the best results. This treatment reduced ash content and increased theoretical carbon availability by up to 10% per tonne of wet biomass as compared with other types of acid. Biological preservation using the organic acid-producing inoculum achieved stable storage under mild, non-sterile conditions. Effective acidification occurred only when mannitol was added, indicating that fermentation depended on available carbon substrates. Carbon retention remained high but was slightly lower than in chemically preserved samples. Together, the results show that both preservation methods can stabilise seaweed biomass, with chemical acidification offering higher efficiency and biological fermentation representing a sustainable alternative.

3.4.1 Pre-processing for biochar production

Acid preservation reliably inhibits microbial growth, which is the primary source of quality loss, but will affect many of the quality parameters of the biomass. Targeting biochar production rather than food application changes the desired quality parameters. This means that optimum storage conditions for biomass intended for biochar production can't be inferred from existing literature, and new experiments had to be designed and performed. In preparation of biomass for biochar production, the main quality parameter desired is the dry matter content of the biomass, as well as carbon and ash contents of the solid fraction. Preservation in SCS JIP is therefore an adaptation of established method to a new application. In this project, we tested a three acid types and pH levels commonly applied to preserving the seaweed as means to stabilize and improve the qualities of seaweed as a raw material for biochar production.

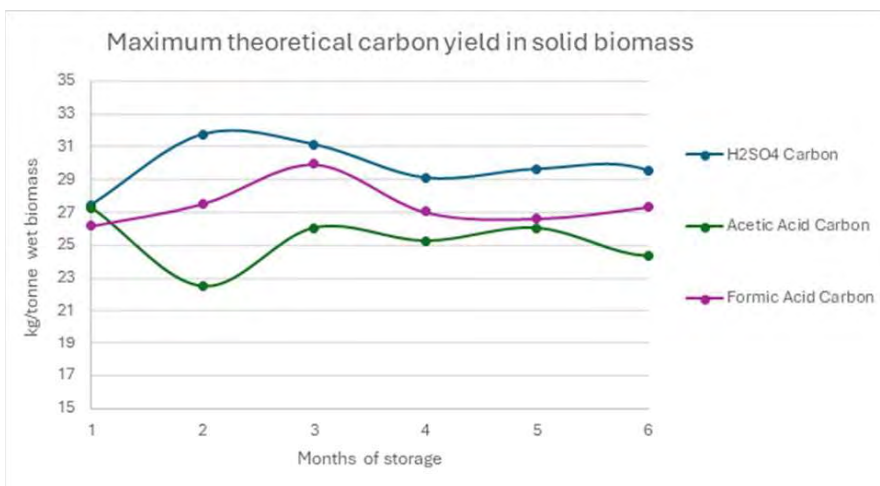


Figure 7 Carbon content of stored biomass as kg of elemental carbon per tonne of wet weight of starting biomass. Sulfuric, formic and acetic acid were selected as preservatives.

Of the three preservation conditions, the lowest pH (2.9) preservation with sulfuric acid appeared to be the most promising. The drop in ash content was the fastest and most pronounced for storage in sulfuric acid, resulting in biomass with a higher theoretical maximum of available carbon per tonne. Sulfuric acid treatment, especially in the 1–3-month window, is the best treatment, as it's the cheapest, increases the

relative carbon content, reduces the ash content, and results in a biomass with up to 10% more carbon content per tonne wet weight. In conclusion, acid preservation was shown to be a reliable method for extending the processing window for cultivated seaweed biomass at the bench scale. All three acids showed good antimicrobial effects and protected the biomass from undesired fermentation.

3.4.2 Recovery of side streams

Recovery of compounds such as laminarin, fucoidan, polyphenols, and mannitol could improve overall process economics and generate valuable products from what is considered a waste stream. To obtain an estimate of the potential content of key value streams (proteins, laminarin, fucoidan, and polyphenols) the liquid fractions from samples stored for six months under each acid treatment were fractionated by ultrafiltration. Bench scale experiments on recovery of side streams have shown that the exudate carries significant amounts of valuable biochemical components. The study was very preliminary and warrants extensive further research on method development and quality of recovered protein and polysaccharides. The calculated potential yields indicate that recovery of polysaccharides and protein from exudate can be a factor in determining the process economics.

3.4.3 Bench scale microbial preservation of seaweed

The microbial preservation tests using PIG 400 showed that microbial acidification is highly dependent on upstream processes and the available fermentable carbon sources. Biomass was stored in conditions that left too little mannitol to sustain efficient acid production, resulting in only minor pH reduction. When mannitol was added, rapid acidification to pH 3.8 was achieved and maintained, demonstrating that the bacteria in the inoculum were active and capable of driving fermentation under mild, non-sterile conditions.

Overall, carbon preservation in the biologically acidified biomass remained good, but slightly lower than in the acid-preserved treatments, likely due to partial transfer of soluble carbon compounds to the liquid phase. Based on the samples of biomass treated with the ensilaging agent in the presence of additional mannitol, the microbial preservation route holds promise as the microbial activity dropped the pH to relevant levels and within a relatively short time. Unfortunately, due to the low mannitol content we were not able to obtain data on the carbon balance associated with microbial metabolism and its impact on the biomass.

3.5 Biochar made from seaweed biomass

Biochar is an efficient and comparably cheap option for carbon storage, which has gained increasing popularity in recent years due to the possibility of carbon sink certification. The classic feedstock for biochar production is wood, which yields beneficial properties such as a high carbon content and a high surface area. However, a fast-developing biochar market and large-scale consumers of woody biochar (metal industry) necessitate alternative feedstocks in biochar production. Aquatic feedstocks, such as seaweed, have a high potential, as they, to a much lesser extent, compete with food and feed production as well as with alternative area use. On the European Biochar Certificate (EBC) positive list of permissible biomasses for the production of biochar¹⁸, feedstock from vegetal marine biomass is listed (ID: W-02 Aquatic plants and algae), meaning that it is eligible for a variety of applications.

¹⁸ positivlist_en_2022_1_V10_1

3.5.1 Seaweed biochar - composition

Due to the high ash content of the feedstock, an increase in production temperature does not lead to a relative increase in carbon content, as is the case for woody feedstocks. Hence, a lower pyrolysis temperature was selected as it is more economical. Its high moisture and ash content result in lower biochar yields and higher energy demands for drying and handling.

The main characteristics of seaweed biochar are:

- Seaweed biochar has a comparably high mass yield, which is due to the high ash content.
- The carbon content and fixed carbon are considerably lower than in woody biochar, reflecting the mineral-rich nature of the feedstock.
- Nonetheless, the low H/C and O/C molar ratios indicate high chemical stability, which meets the threshold for carbon dioxide removal (CDR) certification.
- Elemental analysis revealed a very high content of Cl and elevated Br, which are typical of marine biomass but may limit the biochar's suitability for soil applications due to potential phytotoxicity or salinity issues.

3.5.2 Seaweed biochar tested for soil application

To create carbon sinks from seaweed biochar, a permanent storage option is desired. There are several approved biochar carbon sinks, such as soil amendment or concrete. Whereas adding biochar to concrete only serves the purpose of carbon sequestration (without expected improvement of concrete properties), adding biochar (or biochar-based substrates) to the soil may have other benefits, such as improved soil fertility and plant growth. However, these effects have been shown for woody biochar with its large surface area and high carbon content. There is little experience using seaweed biochar in planting experiments.

Two sets of planting trials were executed as part of this project: a large-scale greenhouse trial at Mære landbruksskole and a smaller climate chamber trial at SINTEF Energy, comparing plant growth and crop yield to a reference. The climate chamber trial was conducted to investigate further the reasons for the poor plant performance observed in the greenhouse tests, with a particular focus on the role of salinity.

The following conclusions are drawn from these tests:

- The addition of unwashed seaweed biochar had a strong phytotoxic effect on radish, with severely reduced leaf biomass and nearly complete inhibition of root development.
- Artificial salt addition (at levels corresponding to estimated salt content in biochar) reduced plant growth only moderately and did not reproduce the strong negative effect of seaweed biochar.
- Woody biochar (EBC-certified), with and without added salt, did not significantly impact plant growth compared to the control.
- Washing the seaweed biochar after pyrolysis fully mitigated the phytotoxic effect and resulted in the highest radish yield across all treatments.
- The results indicate that the negative impact of seaweed biochar cannot be explained by salinity alone. Other factors, such as organic residues or unknown inhibitory compounds in the unwashed material, may contribute to phytotoxicity.
- The root biomass was generally low compared to the leaf biomass in all treatments, likely due to the high plant density per pot. This does not affect the relative comparison of treatments, which was the primary objective of the trial.

Based on these results, post-treatment of seaweed biochar (e.g. washing) is essential to reduce phytotoxic effects and unlock its potential for soil application. Further research is needed to identify the exact causes of growth inhibition and optimise biochar treatment protocols.

Recommendations for further research and development into seaweed biochar and potential applications:

- Explore non-agronomic applications for seaweed biochar: Due to its chemical stability and mineral-rich profile, use in concrete, asphalt, or bricks may be more viable than soil application. These applications unlock carbon credit potential while avoiding phytotoxicity issues. To work with partners in the construction and materials sector to assess performance and acceptance criteria for biochar integration is thus recommended.
- Utilise residues instead of fresh seaweed for biochar production: To improve environmental performance and reduce emissions associated with harvest, logistics, and drying, it is recommended to source seaweed side streams such as processing residues from other seaweed products. This supports cascading use principles and improves allocation of environmental impacts across product systems.
- Implement efficient drying strategies: Drying is a major energy bottleneck in seaweed biochar production. Future systems should prioritise low temperature drying using waste heat and integration with industrial processes that produce surplus thermal energy.
- Investigate targeted washing or purification methods: Simple rinsing before pyrolysis is insufficient. Post-pyrolysis washing shows clear benefits and should be developed into a scalable, resource-efficient treatment step.
- Conduct techno-economic and lifecycle assessments: To support decision-making and commercialisation, detailed LCA and TEA models should be developed, reflecting realistic processing steps, transport logistics, and multiple use cases (e.g., soil vs. materials).

3.6 Environmental Impact and Biodiversity Monitoring

Seaweed farms placed in the open sea will interact with the environment, and it is essential to monitor both the positive and potential negative impacts. The Aquaculture Act regulates macroalgae cultivation in Norway (Akvakulturloven), which mandates “environmentally sound practices.” In the aquaculture licensing process, the Storflua kelp farm was granted “Permit for activities under the Pollution Control Act” by the County Governor of Trøndelag in 2023.

Table 3 Overview of potential environmental impacts (both positive and negative) of macroalgae cultivation.

	Positive effects	Negative effects	Severity of negative effects
Nutrient uptake	Macroalgae absorbs nutrients from surrounding seawater, potentially reducing nutrient load in eutrophic coastal areas and mitigating eutrophication effects	Competition for nutrients may lead to reduced phytoplankton growth	Local and reversible effects
Release of POC/DOC	Kelp cultivation acts as a carbon sink, taking up carbon dioxide from the	The release of particulate organic matter may lead to organic overload on sea	Local and reversible effects

	water and permanently removing some carbon from the cycle by natural processes	bottom, affecting benthic fauna and sediment chemistry	
Artificial habitat	Cultivated kelp can serve as artificial habitats, increasing local biodiversity, aiding species dispersal, and contributing to habitat restoration for species that have lost their natural habitats.	Artificial structure may facilitate the spread of alien species, spread of disease/parasites, causing potentially large-scale impacts on marine ecosystems	Regional and irreversible effects
Spread of genetic material		Negative effects on local macroalgae	Regional and irreversible effects
pH increase	Kelp photosynthesis increases seawater pH, potentially reducing local ocean acidification.		Local and reversible effects
Shading effect		Reduced primary production (phytoplankton, eelgrass beds)	Local and reversible effects

SCS JIP has investigated effects associated with the release of particulate organic matter, nutrient uptake and a limited study on the role of the Storflua cultivation rig as a temporary habitat. The focus has been on local effects associated to above mentioned.

3.6.1 Baseline Study

A baseline study was conducted September 2023 before installing the sea farm and initiating seaweed cultivation to document the biodiversity and overall environmental status before intervention. Results from the baseline study of benthic fauna gave ‘very good’ quality status according to the WFD classification system¹⁹, and the benthic biodiversity was very high at all test sites.

These results were as expected, since Storflua is in a region of Norway with high species diversity for benthic infauna. The coarse sediment type, mainly consisting of sand and shell fragments, also supports species-rich benthic communities. The high permeability of larger sediment grains and coarse shell sand can enhance water flow and oxygen penetration, which benefits most benthic species.

3.6.2 Monitoring

The monitoring program used at Storflua is summarised in Table 4. The environmental impact of kelp cultivation depends on farm size and production volumes; however, Norway has no standardised monitoring program for macroalgae cultivation.

¹⁹ The WFD classification system refers to the Water Framework Directive (WFD) of the European Union, which establishes a framework for the assessment and classification of surface and groundwater bodies in terms of their ecological and chemical status. It is a core part of environmental monitoring and water management across Europe.

Table 4 Monitoring program at Storflua Kelp Farm, designed by NIVA and SINTEF Ocean. The baseline study (benthic fauna and sediment, and water samples for eDNA) was conducted in September 2023, and the follow-up survey in May and June 2025.

Habitat	Survey type	Prior to deployment	After deployment	
			Before harvest	After harvest
Seafloor	ROV survey of the seafloor	Around anchor point (Åkerblå 2023) Below the kelp farm (NIVA, Sept. 2023)		
	Benthic survey	Sampling for sediment and benthic fauna near kelp farm	Sampling for sediment and benthic fauna near kelp farm	
Kelp farm as temporary habitat	Biodiversity study	eDNA sampling (water) near kelp farm and near natural kelp forest	eDNA sampling (water) near kelp farm and near natural kelp forest Netting or trapping of fish, underwater cameras, netting of epifauna	eDNA sampling (water) near kelp farm and near natural kelp forest Netting or trapping of fish, underwater cameras, netting of epifauna
Water masses	Desk top study: Effect of nutrient uptake			

Please note that the monitoring scheme initially designed for scaling Storflua assuming the sea farm would produce biomass on a much larger scale, categorizing it as a ‘large’ kelp farm (10,000 to 30,000t/year). Due to reasons explained in this report, volumes were not scaled, and the biomass production for R&D purposes was in the range of 15 – 30t in 2024, therefor the Storflua kelp farm is in the category of a ‘small’ kelp farm (30 – 300t/year).

If the farm eventually increases production and moves into the category of ‘medium’ or ‘large,’ the results from the second benthic survey would be very interesting for comparing the ecological status of benthic fauna at a reference point (baseline), at small-scale production, and at large-scale production.

3.6.3 Environmental interactions

Nutrient uptake

At present, the Storflua kelp farm covers about 20 hectares and has a permit for growing 800t kelp (wet weight) per year (40t per hectare), corresponding to 80-20t dry weight (4-6t per hectare) assuming that dry weight is approximately 10-15 % of wet weight²⁰. Assuming that macroalgae tissue typically contains 1-4 %

²⁰ Modelling seasonal growth and composition of the kelp *Saccharina latissima* | Journal of Applied Phycology

N and 0.2-0.6 % P of dry weight²¹, every 1t of dry weight seaweed harvested will remove about 20-40 kg of N and 2-6 kg of P permanently from the water column. Harvesting 800t of kelp wet weight at Storflua would consequently theoretically remove 1600-4800 kg nitrogen and 160-720 kg phosphorus (per hectare: 80-240 kg N, 8-36 kg P).

Regarding competition with microalgae the overall conclusion from NIVAs desktop study was that kelp farming does not negatively affect phytoplankton because kelp is outcompeted for nutrients, regardless of farm sizes. The conclusion applied to sugar kelp, and likely also to other large brown algae, but the authors emphasize that further studies are needed for other algal groups. In a risk assessment of macroalgae cultivation and environmental impact, Norderhaug et al. concluded that the risk associated with uptake of nutrients (competition with microalgae), shading effect and effect of particulate organic matter on the seafloor was small, because the potential effect is both local and reversible²²

3.6.4 Kelp farm as temporary habitat

Through traditional sampling, NIVA find that fish species diversity and abundance is lower at kelp farm sites compared to natural kelp forest control sites, instead it is more similar to pelagic control sites. The lumpfish was the only fish species present at the Storflua kelp farm. Previous studies and current studies show that this may be the only relevant fish species present in Norwegian kelp farms from a nature-positive perspective. This aligns with previous findings that kelp farms may not replicate the ecological complexity of natural blue forest habitats^{23 24}

It should be recognized that the Storflua site was very limited in extent, biomass of kelp and that its cultivation set up is vertical (compared to previous studies on near coastal horizontal sea farms) which may have contributed to poor shelter for fishes and insufficient prey. In addition, its exposed location far from coast probably hinders the migration of many benthic fish species. Moreover, caution should be taken in the interpretation of the results due to them only representing a pre-harvest time without representing a late-summer or post-harvest period.

The presence of alien species requires action to define guidelines (like Wilding et al., 2021²⁵) that identify their impacts to limit their colonisation and spread. Regular cleaning of structures may be effective in controlling marine alien species at kelp farms, although this was not tested herein. Actions such as these could be deemed as a nature positive action that if applied broadly enough to multiple industries and species, might aid the achievement of international biodiversity targets under the Kunming–Montreal Global Biodiversity Framework or national ones e.g. Norway’s ‘Ocean Management Plan’²⁶.

3.6.4.1 Environmental impacts – main conclusions

The Storflua kelp farm was found to pose no environmental risk, but also no clear ecological benefit, for the ecosystems investigated. It is not likely that the nutrient uptake from kelp cultivation at Storflua will outcompete the local phytoplankton. The benthic fauna remained stable and habitat provisioning was limited; however, the presence of a marine alien species can be considered a serious concern and future monitoring and research at Storflua is recommended to focus on the knowledge gap related to the spread of species, including alien species, microorganisms and diseases, and genes. These findings also underscore

²¹ The nitrogen bioextraction potential of nearshore *Saccharina latissima* cultivation and harvest in the Western Gulf of Maine | Journal of Applied Phycology

²² Miljøpåvirkning fra dyrking av makroalger | Institute of Marine Research

²³ Environmental impact of kelp (*Saccharina latissima*) aquaculture - ScienceDirect

²⁴ 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 | Cambridge Core

²⁵ Wilding_et_al_2021_-NE_Seaweed-aquaculture-and-mechanical-harvesting.pdf

²⁶ Meld. St. 21 (2023–2024) - regjeringen.no

the importance of site-specific assessments and the need for continued monitoring and research to guide sustainable macroalgae cultivation in Norway.

3.6.5 Ecosystem services – SINMOD

Monitoring $p\text{CO}_2$ in the oceans helps scientists understand how much CO_2 is being absorbed from the atmosphere, contributing to climate change models. When cultivating in the ocean, conditions shift very quickly, like currents, light, temperature, and phytoplankton blooms that absorb all the nutrients. It is impossible to measure all these variables, but we need to quantify these data to assess CO_2 removal. We thus use a dynamic ocean model, the SINMOD framework, that can inform us about the amount of CO_2 removed, biomass produced, the increase in pH, and environmental interactions, among other factors.

Furthermore, the complete carbon uptake and sequestration, as well as the large-scale environmental interactions, of the farm can only be quantified appropriately by upscaling calculations. SINMOD couples the most important processes shown in the in addition to the physical environment (currents, S, T); nutrients, light and ecosystem interactions through a basic food web model; kelp growth, composition, and biomass through a kelp growth model; the ocean carbon and oxygen system through a carbon module, including ocean-atmosphere CO_2 exchange.

In the context of the oceans, $p\text{CO}_2$ is used to measure the amount of CO_2 dissolved in seawater. It is a crucial factor in studying ocean acidification because CO_2 reacts with water to form carbonic acid, which lowers the pH of the water.

When seaweed grows through photosynthesis, removing CO_2 , it leads to an increased pH, thus having a positive impact on ocean acidification. However, this effect seems to be mainly local (Fig. 8, image to the left) for a farm the size of the one at Storflua, though local depends on one's point of view: each pixel in Fig. 8 left represents an area of 160×160 m. Moreover, pH increases with production volumes (Fig. 8, to the right). These changes in alkalinity are counteracting "ocean acidification". Larger scale simulations have been made, indicating that production of a 1 million t per year magnitude might have regional impacts.

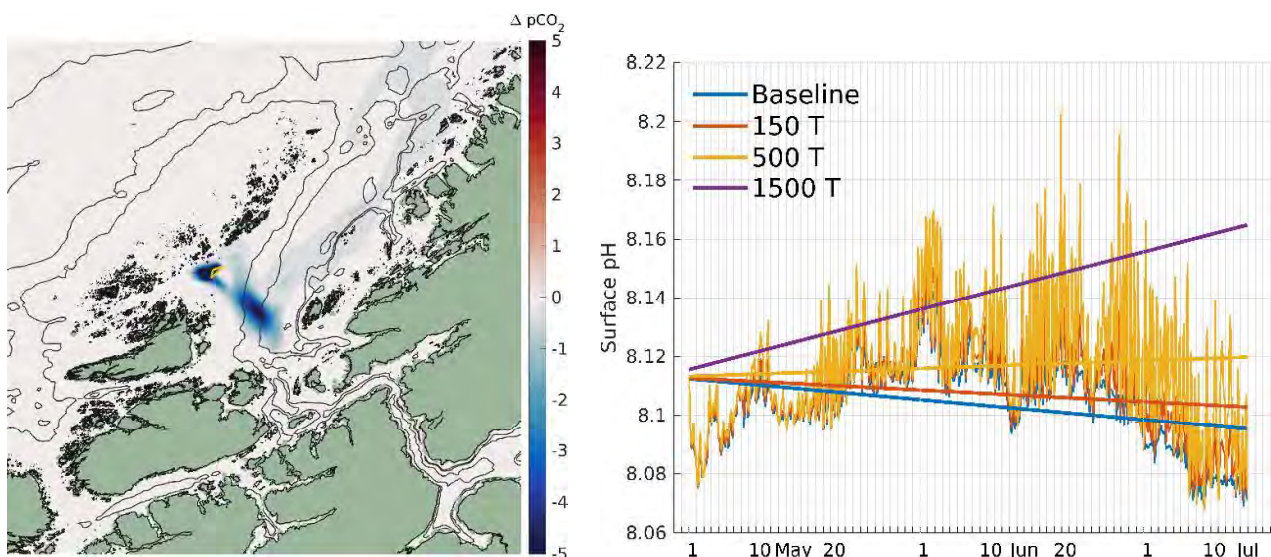


Figure 8 Effects of seaweed cultivation on the $p\text{CO}_2$ in and around the farm at Storflua (left) and on the pH in three different biomass production scenarios of 150, 500 and 1,500 tonnes biomass per year (right).

Simultaneously, field and laboratory trials have been conducted as part of a PhD on the quantification of marine CDR from cultivation. A possible low-cost, low-emission solution to store the seaweed carbon is to deposit freshly harvested, fully grown seaweed in deep-sea trenches outside the continental shelf. Initially, the project was planned to study the technological challenges associated with sinking as a solution, including the technologies that needed to be developed and tested *in situ*, as well as measures to mitigate possible risks of harmful effects on the ecosystem. Due to the highly unknown effects on deep-sea ecosystems, the active sinking of kelp biomass was precluded from the project, and the focus shifted to quantifying only the passive CDR. The project thus includes the evaluation of the fate of seaweed released and deposited naturally during farming (DOC, POC, DIC and RDOC).

3.7 Passive CDR during cultivation

The role of macroalgae as natural sinks for carbon dioxide (CO_2) has long been recognised, and interest in climate-mitigating solutions from seaweed cultivation is quickly rising. Kelp forests, seaweed, seagrass meadows, and tidal marshes and swamps are marine ecosystems in Norway that absorb and store carbon. The sediments on the seafloor represent the largest marine reservoir of organic carbon. The Norwegian Institute for Water Research (NIVA) estimates that coastal areas within 12 nautical miles from the baseline store approximately 137 million tonnes of carbon in the top 25 centimetres of the seafloor²⁷.

Erosion of biomass provides natural avenues for carbon sequestration at sea (Figure 9). POC and DOC losses provide a continuous source for carbon deposition, burial, or further breakdown into the recalcitrant RDOC, which is crucial for environmental impact assessments and carbon accounting methodologies. Neves et al. (2025)²⁸ provides valuable data for future research on macroalgae cultivation and its contribution to global carbon mitigation efforts.

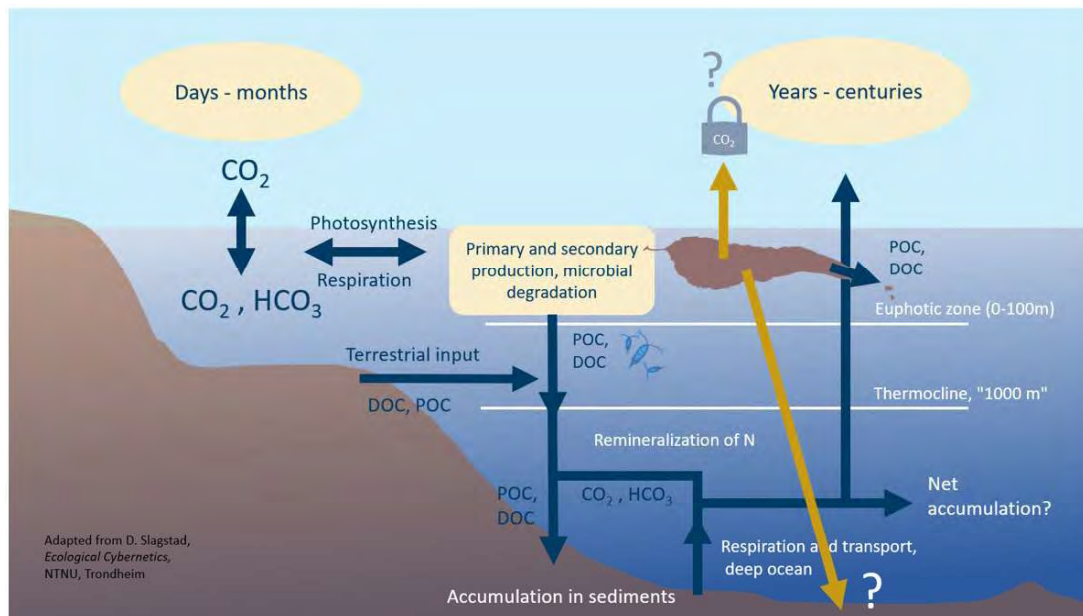


Figure 9 Simplified schematic of the ocean carbon(ate) system and how seaweed cultures interact with it.

²⁷ <https://www.regjeringen.no/contentassets/20944f0c5bf14bd5b5112ae8aa08e853/no/sved/12.pdf>

²⁸ Neves L., Broch O.J., Smeby K., Johnsen G, Ardelan M.V., Skjermo J. 2025. Carbon uptake and losses to particulate and dissolved organic pools in cultivated *Saccharina latissima* from two deployment times. *Science of The Total Environment*, Volume 982

While the harvested seaweed biomass accounts for the largest share of CO₂ uptake, RDOC and sedimentary carbon still remain relevant pools to consider for carbon project pathways. There are different methodology options for the use of harvested biomass, but no published methodology for certifying the activities of the seaweed farm itself (i.e., passive carbon pathways).

3.7.1 Seaweed Farming as a Blue Carbon Project

With the growing momentum for Blue Carbon projects, which are highly sought after in the voluntary carbon market, several organisations have collaborated with major standards, such as the Verified Carbon Standard (VCS) and the Gold Standard, to develop seaweed farming methodologies in recent years. As of now (2026), there is no published full methodology. However, standards are increasingly establishing the necessary infrastructure to publish methodologies, including working groups and industry initiatives (see [Verified Carbon Standard - Verra](#)). Furthermore, newer standards like Social Carbon, which specialise in nature-based methodologies, could become significant players due to their more agile processes.

When that's said, there are currently two VERRA methodologies under development for seaweed cultivation, including passive marine CDR:

- Methodology for Carbon Removals Through Seaweed Aquaculture
- Methodology Framework for Seaweed Carbon Projects

Developing a methodology requires a thorough quantification of carbon removals from key pools and the associated fluxes with seaweed cultivation, particularly focusing on dissolved organic carbon and carbon storage in ocean floor sediments. Although the literature has reached a consensus that seaweed farming has potential for climate change mitigation through passive carbon pathways, for it to be recognised as a viable carbon project type that properly values these passive sequestration pathways, there are still some gaps to address, despite significant progress made through SCS JIP research.

The passive CDR has been thoroughly investigated in a PhD-project within the SCS JIP, delivering three papers:

1. Neves L., Broch O.J., Smeby K., Johnsen G, Ardelan M.V., Skjermo J. 2025. Carbon uptake and losses to particulate and dissolved organic pools in cultivated *Saccharina latissima* from two deployment times. *Science of The Total Environment*, Volume 982.
2. Neves L., Aker S., Skjermo J. and Ardelan M.V.: New insights on the production, biodegradation and characterization of organic carbon from cultivated *Saccharina latissima* in Norway (manuscript)
3. Neves L., Brunsvik A., Skjermo J. and Ardelan M.V.: Production of recalcitrant dissolved organic carbon (RDOC) in a seaweed farm in Norway, with implications for carbon sequestration (manuscript)

The main conclusions from this work

- Macroalgae farming can contribute to natural carbon sequestration processes during the grow-out phase at sea through the erosional production of particulate (POC) and dissolved organic carbon (DOC). Both POC and DOC may be broken down and converted to recalcitrant dissolved organic carbon (RDOC), contributing to long-term sequestration, yet further research is needed to assess its permanence in the marine ecosystem. New data is provided for DOC release from cultivated *Saccharina latissima*, with 29% of fixed carbon being released from kelp deployed in the autumn and 12% from kelp deployed in the winter, before the progression of bryozoan biofouling. The effect of bryozoan biofouling on DOC release needs further study, along with more seasonal DOC release data.
- POC and DOC losses depend on seedlings deployment and biomass harvest times. For each tonne of kelp harvested in April, June and July, 8, 18 and 28 kg C have been lost to the environment,

respectively. These findings encourage further investigation into the dynamics and characterization of POC, DOC and RDOC in marine environments, to assess their contribution to marine biogeochemical cycles and long-term impacts on carbon sequestration.

- Future research should focus on quantifying the contribution of macroalgae farming to natural carbon capture, utilisation and storage (CCUS) processes and optimising farming practices to enhance carbon capture efficiency. A multi-purpose approach to macroalgae farming is recommended to make use of opportunities in multiple target markets, where techniques such as partial harvesting of the farm or coppicing (*i.e.* cutting the sporophytes above the meristem) of the kelp in April - May for *e.g.* food use may be applied, leaving the remaining kelp for further growth into larger amounts of biomass for harvest in June-July for use in production of feed, bio-stimulants, chemicals or CDR products.

For seaweed farming as a viable blue carbon project type that puts a value on passive marine sequestration pathways, some gaps remain despite valuable advancements through ongoing SCS JIP research on DOC/RDOC measurements and modelling. Establishing seaweed cultivation as a high-quality, reliable means for permanent carbon sequestration will require further research into marine CDR and related MRV – and it is critical quantifying the passive CDR and its permanence in a scientifically robust manner to enable methodology development.

3.7.2 SouthPole on seaweed CDR

In a feasibility assessment provided by SouthPole²⁹ it was estimated that a sea farm of 10,000 ha could add a gross carbon sequestration of 10,600 tonnes CO₂e/year if including sedimentary carbon to the total carbon budget. None of the SouthPole assessments indicated that dissolved organic carbon (DOC) and sedimentary carbon are sufficient to create net sequestration on their own but would need to be combined with other pathways, such as the use of seaweed as biochar. However, continued research will contribute to the understanding of the passive CDR pathway, which has the potential to add to the total carbon budget of seaweed CDR projects when documented and verified.

SouthPole also calculated a scenario of 1 million tonnes of biomass, if included in a project that is already a net carbon sink, the additional carbon stored in sediments could add to the value of a carbon asset as much as €318,000 to €742,000 per year if sold as European blue carbon credits. However, the current SCS JIP Scope does not cover a detailed assessment of burial into sediments, nor is there existing methodologies to certify this CDR contribution.

Some ICROA-endorsed Standards (*e.g.*, Puro.earth, Isometric) are moving towards an LCA quantification approach for carbon, which may facilitate a more holistic approach to quantifying carbon in the full seaweed value chain. *E.g.* accounting for the carbon benefits from RDOC and sediment burial within a biochar or bioplastics accounting approach). Note that this is in line with mentions in the reviewed literature by Hasselström & Thomas³⁰ who suggest integrated conceptual expressions, yet, subject to further evaluation of *e.g.* allocation details.

In order to quantify the full net carbon sequestration potential of the seaweed value chain through integration of both pathways (passive and active CDR) it would currently necessitate separate application of methodologies under separate (or potentially combined) projects, as long as processes for ensuring that no double counting takes place are established.

²⁹ <https://www.southpole.com/about-us>

³⁰ A Critical Review of The Life Cycle Climate Impact in Seaweed Value Chains To Support Carbon Accounting and Blue Carbon Financing | PDF | Life Cycle Assessment | Carbon Sequestration

3.8 Monitoring, Reporting and Verification

SouthPole also provided an assessment of the monitoring, reporting, and verification (MRV) of seaweed CDR. All carbon dioxide (CO₂) removals need to be stored but different storage methods vary in their susceptibility to releasing GHGs back into the atmosphere. When verifying and issuing carbon credits, permanence is crucial, especially for nature-based projects, as a fundamental requirement of the ICVCM Core Carbon Principles, which represent industry best practices. MRV is therefore essential to demonstrate that the project design functions as intended and that all claims made by the project can be substantiated and verified. Moreover, MRV is a key component of any methodology and is essential for determining the quantification approach of carbon removals and appropriate and adequate data sources.

While the permanence of recalcitrant and ultra-recalcitrant categories of DOC is considered reliable, risks of reversal of different organic and inorganic carbon sinks, as well as their interaction with microbial processes, are location-specific and changes in different ocean temperatures and chemistry and needs to be addressed sufficiently in a subsequent project phase.

SouthPole Conclusion

- Generally, RDOC and sedimentary carbon can be considered long-lasting sequestration by seaweed.
- MRV processes for both RDOC and sediment burial are currently resource-intensive and lack sufficient consensus on widely applicable protocols, necessitating further investigation into proxies, models, and approaches to minimum viable representation of parameters that influence the amounts in SSRs
- RDOC and sedimentary carbon can be considered long-lasting, but robust methods for traceability and risk assessment are lacking.
- Complexity in marine environments: transboundary movement of carbon presents substantial challenges for carbon accounting, necessitating new guidelines and governance frameworks to manage these carbon stocks effectively
- While the significance of each carbon pool will depend on location and farm specifics, all pools will still need to be quantified as part of the methodology development process for seaweed farming.
- The current SCS project scope does not include a detailed assessment of burial into sediments, approximations are made only via fallout.
- Moderate confidence that some of this particulate carbon ends up in long-term storage in the ocean and seabed.
- Yet, low confidence about the final destination of seaweed-derived dissolved carbon and its longevity.
- Emerging databases and models for sedimentary carbon (see e.g. MAREANO map) and scientific advancements using eDNA sequencing offer potential solutions for the identified gaps.

Key recommendations for enabling seaweed farming carbon projects in the voluntary market:

To address the highlighted gaps in the current scope of SCS (mCDR) work, in particular around sediment burial, minimum viable options for MRV (RDOC and burial) and thresholds or ranges for permanence claims for different marine conditions and farm types (scalability of methodology application in mind). Incl. The development of risk assessment tools, and exploration of the feasibility of 'shortcuts', considering scientific advancements for sampling and modelling (eDNA and/or isotope data, etc.).

3.9 Life Cycle Assessment

A complete Life Cycle Assessment (LCA) is a criterion for qualifying and registering a project under the Puro.earth Framework and Biochar Methodology. Based on the project activities performed in the SCS value chain, all emissions have been accounted for, and an overall Life Cycle Assessment (LCA) was conducted to evaluate the potential for carbon removal with the current project design. Certification pathways for certified carbon removals have been identified. Currently, the SCS project activity is conditionally eligible under the biochar methodology. The SouthPole assessment concludes that the SCS project design can be fully eligible under the Puro.earth Biochar methodology if all the eligibility criteria are met in the project design.

Although there are several benefits to farming biomass in the sea, there are also some drawbacks with today's methods, which are evident in the resource-intensive operations required to farm in exposed conditions and process the seaweed. The SCS project LCA has identified value chain emission hotspots and offers concrete recommendations for improvements.

3.9.1 Value chain emissions

The SCS project LCA examined the potential for carbon dioxide removal (CDR) using biochar produced from cultivated seaweed biomass harvested from a seaweed farm in Frohavet, outside Frøya, Norway.

Please note that these figures are based on estimates provided by the data providers. The production volumes of 500 tonnes of seaweed (fresh weight) per year at the respective farms which is assumed in this study, as well as the subsequent large-scale production of seaweed biochar, have not yet been demonstrated.

Zooming in on the biomass to biochar production, Figure 10 shows the CO₂ sequestered in 1kg of biochar compared to the emissions of producing it:

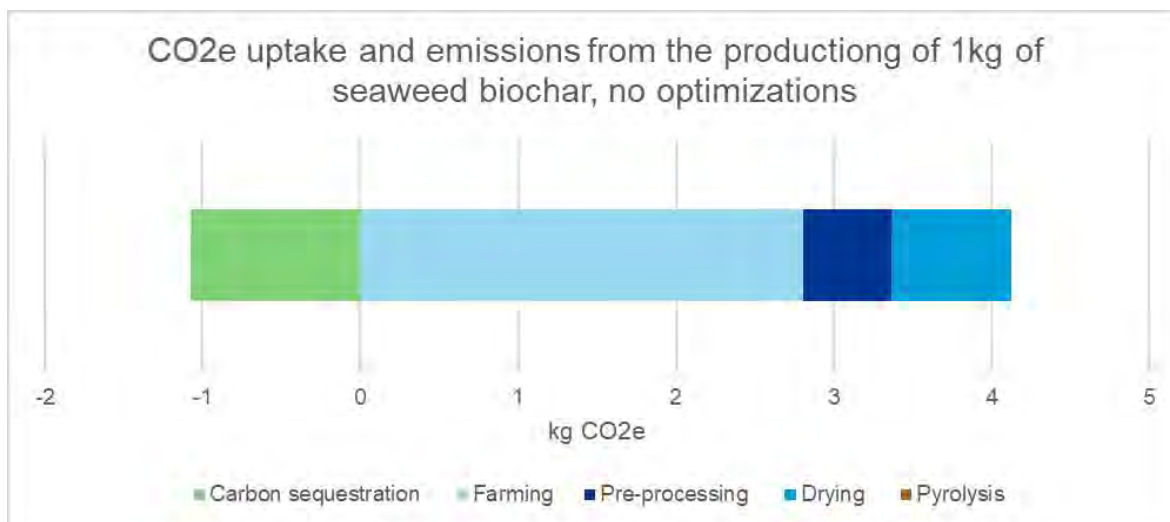


Figure 10 Net CO₂ uptake and emissions from the different parts of the seaweed biochar value chain. See section 3.10.1.2 for the LCA breakdown of annual emissions from the farm and operations at Storflua (farming).

A simplified energy balance indicates that the pyrolysis of seaweed can theoretically be self-sustaining if the moisture content is sufficiently reduced before entering the reactor. Pyrolysis is therefore not included in the LCA. However, real-world inefficiencies, including energy losses during drying and pyrolysis, must be assessed and accounted for before industrial scaling.

Since there is no established methodology for passive CDR from seaweed cultivation it is challenging to accurately estimate the total carbon potential of a seaweed farm project and the mCDR contribution is therefore excluded in the LCA. Still, we have provided new data on this contribution in this project. Therefore, there is a need for updated LCA's in the future, when this contribution is acknowledged.

3.9.1.1 Farming: Seafarm design, operations and logistics for offshore cultivation

The seaweed farm at Storflua (locality number 45189) is a state-of-the-art facility designed for farming in offshore conditions. Offshore farming can enhance seaweed yield and scalability, but it also necessitates robust infrastructure to withstand the challenging offshore environment. For a project with carbon sequestration as the main objective, SCS now has data showing that sea farm design and logistics significantly impact the LCA, which is hard to mitigate in the short term, even with high-volume production and increased CDR, especially without available vessels operating on alternative energy sources other than diesel. Still, there is a potential for scaling up the seaweed industry in Norway if cost-efficient sea farms, more mechanised and automated methods for operating the seaweed farms are developed, and, from a CDR perspective, emissions related to the design and materials are considered.

The LCA analysis reveals that the GHG impact of the Storflua farm infrastructure amounts to 14,920 kg CO₂e per year. Components made from steel accounted for 70% of these emissions, while lines and buoys contributed 30% of the emissions from the farm infrastructure. Note that some of the buoys also contain steel parts, which are the main contributor to their associated emissions.

3.9.1.2 LCA breakdown of annual emissions from the farm and operations at Storflua

The LCA breakdown of annual emissions from the farm and operations at Storflua highlights the emissions of the sea farm itself (material use) (Figure 11). It includes the emissions from the installation of the infrastructure, as well as related vessel use. The equipment and diesel consumption for installing the farm have been spread over the respective lifetime of the equipment (according to certification). Whereas logistics related to the deployment and harvest of seaweed are an annual event.

The overview of the yearly emissions from infrastructure at the Storflua farm, measured in kg CO₂ equivalents, highlights the need to rethink seafarm design, material use, and logistics. Here, the burden from the installation phase is distributed over 10 years, aligning with the expected lifetime of most farm equipment (excluding anchors and chains) and the anticipated replacement of these components. The remaining vessel operations occur for each farming cycle, which is assumed to be once a year, and are accounted for accordingly.

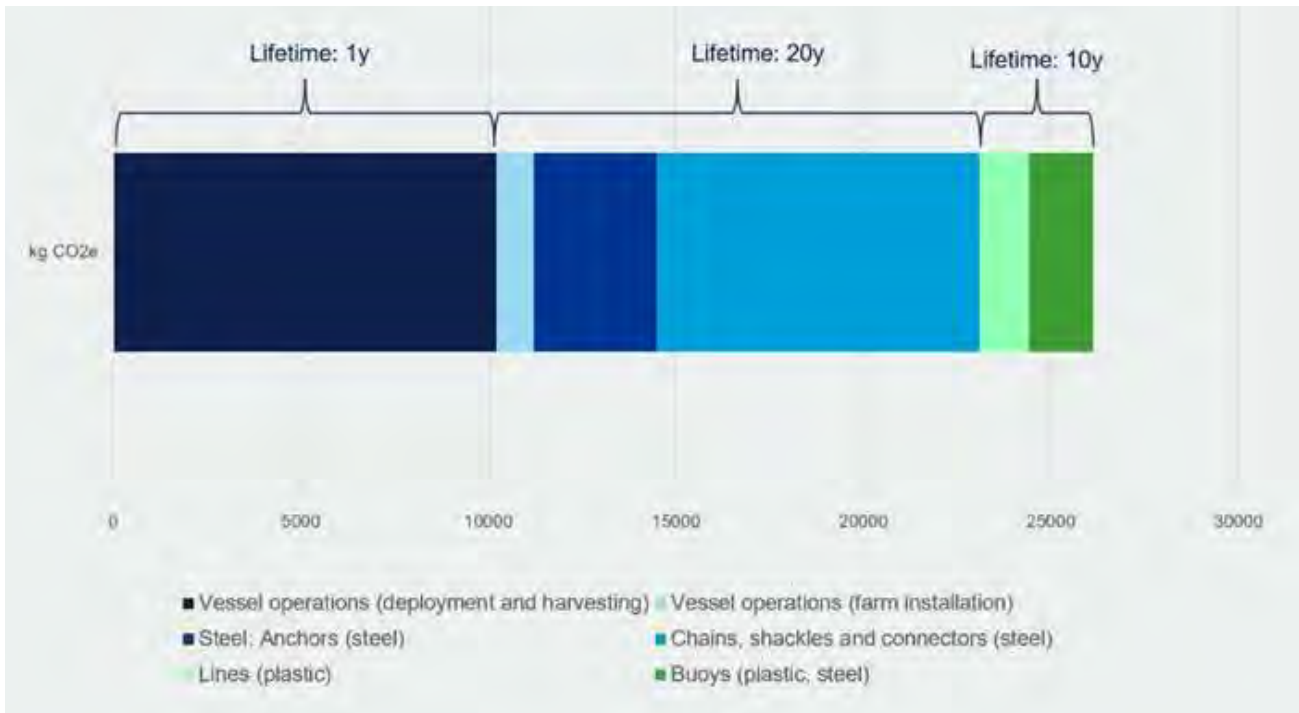


Figure 11 Annual emissions from Storflua infrastructure and operations.

3.9.2 LCA Conclusion

Based on the SCS project LCA, the value chain must optimise and demonstrate carbon-negativity to generate carbon credits from farmed seaweed. There is potential for optimisation throughout the value chain to design for minimised CO₂ emissions, thereby improving the potential for negative emissions.

Regarding CO₂ emissions, apparent hotspots in the seaweed CDR value chain are:

- 1) Material use in infrastructure associated with the seaweed farm
- 2) Diesel consumption of vessels for deploying and harvesting the seaweed and
- 3) Energy consumption needed for drying the seaweed.

Zero and low-emission vessels should be used to reduce the carbon footprint of future seaweed cultivation operations. Diesel consumption from vessel operations is currently the most significant hotspot in the seaweed biochar value chain. Switching from diesel-fuelled to electric work vessels for all operations can reduce emissions by 63% at Storflua. The transition to electric work vessels in the aquaculture sector is expected to occur in the short term, as the aquaculture industry in Norway is already transitioning to electric and hybrid-electric vessels.

Furthermore, anchors, mooring lines and other structural components constitute a significant share of the total construction cost for a seaweed farm, by further developing the hydrodynamic models for seaweeds cultivated on ropes or other substrates, more accurate and reliable estimates can be achieved, reducing conservatism and contributing to more cost-efficient and less carbon-intensive design. The project has addressed the latter steadily throughout its duration.

The drying of seaweed biomass is currently a significant contributor to emissions in the value chain. The drying process can be optimised through either sourcing energy from 100% renewable sources for drying or

by utilising excess heat from waste incineration plants, gas refineries, or other local industries. However, new technical solutions and facilities for large-scale drying will require investments and time to develop.

It is possible to generate negative emissions if a range of optimisation strategies is implemented (Figure 12). The optimisation scenario for the biomass to biochar pathway is based on the following assumptions:

- All operations with work vessels and boats are electric (including stress-testing of the farm).
- Assuming 100% renewable power has been sourced for all electric processes.
- The seaweed is dried using excess heat from other industries, assuming no additional energy input is needed for drying, but includes a transport stage by an electric boat.
- GHG burdens and benefits from the pyrolysis process are assumed to be net zero.

We see that exposed cultivation has higher farming emissions, but if all the abovementioned optimisations are implemented, biochar production has the potential to become carbon negative with the current farm design at the near-shore farm. The exposed Storflua farm has the potential to become close to carbon neutral.

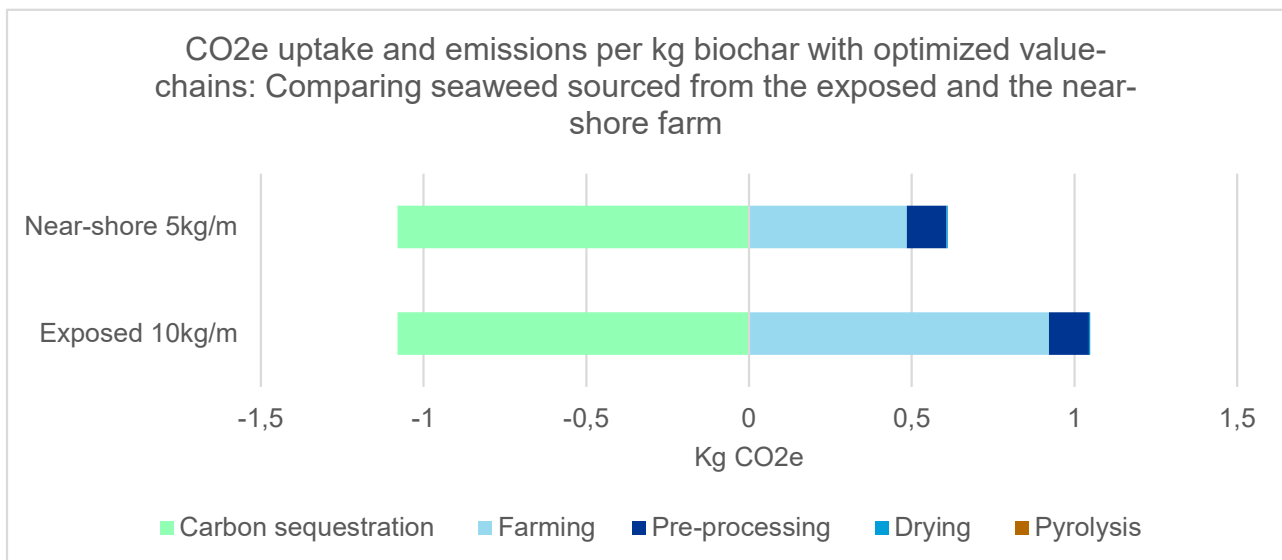


Figure 12 The CO₂ uptake and emissions per kg biochar based on seaweed from exposed (offshore) and near-shore farms when a scenario for optimisation is included.

Increasing production volumes and yield

The focus should not only be on reducing emissions but also on increasing the yield of seaweed. Higher yields will significantly impact the carbon balance, as the increased output of carbon capture and storage will help shift the equation towards carbon negativity. Although no methodology currently exists for passive CDR from seaweed cultivation, marine carbon removals (mCDR) are also expected to qualify as blue carbon removals in the long term.

3.9.3 Recommended value-chain improvements towards carbon negativity

The current value chain for offshore seaweed production and processing needs major changes to reduce CO₂ emissions.

Five recommendations for optimising the value chain:

- 1) Using electric work vessels instead of diesel or petrol-fuelled ones will have the most considerable impact on reducing value chain GHG emissions.
- 2) Reducing the use of steel components can significantly reduce emissions related to the seafarm.
 - a) Locating new seaweed farms in more sheltered areas could be a short-term solution to reducing the carbon footprint of farming operations.
 - b) In the longer term, exploring alternative materials and sea farm designs that lower GHG emissions and can withstand offshore conditions is essential. Additionally, there is an advantage to situating farms in areas with hard bottom substrates, where mooring with bolts instead of anchors is possible. However, it is important to acknowledge that obtaining a license for seaweed farming can be challenging, and farmers often do not have the luxury of selecting their ideal locations.
- 3) Ensure that the electricity mix used in energy-intensive processes, such as operating work vessels and drying, is based on renewable energy sources, both in practice and on paper.
- 4) Although it is not one of the major contributors to the GHG-impact of seaweed biochar, the pre-processing by use of sulfuric acid to ensile seaweed biomass is still at an early stage, and one can assume that there is room for improving the procedure
- 5) Drying seaweed with a high-water content is energy intensive.
 - a) The best option would be to utilise excess energy from other industries.
 - b) The second-best option is to ensure the energy used for drying is entirely renewable.
 - c) To reduce energy use and transport costs, further work should also investigate possibilities for de-watering before the drying process.



4 Discussion and final outlook to seaweed CDR

The SCS JIP was initiated to investigate the technology development needed for CDR through seaweed farming, oriented to offshore farming and opportunities for CO₂-offsetting. The project encompassed a comprehensive range of activities to advance seaweed cultivation for CDR purposes. The project's approach has been methodical and multifaceted, focusing on several key aspects outlined below:

- 1) **Location Siting and Licensing:** The project identified and secured a productive, accessible, and exposed site suitable for large-scale seaweed farming. Licensing procedures were navigated to enable operations at this optimal location.
- 2) **Sea Farm Design and Installation:** A sea farm was designed and installed to withstand the challenging conditions of the selected site, ensuring both survivability and high productivity.
- 3) **Operational Logistics:** The logistics of seaweed farming were addressed, including the deployment of seedlings and the harvesting of mature biomass, to facilitate efficient and reliable operations.
- 4) **Preprocessing and Long-Term Storage:** Trials were conducted to develop preprocessing methods for long-term storage solutions aimed at preserving the carbon content in harvested seaweed, crucial for enabling a year-round supply of feedstock for subsequent pyrolysis into biochar.
- 5) **CDR Pathways:**
 - a) **Marine CDR Alternative:** The project investigated passive carbon removal through natural fragmentation and leakage during seaweed cultivation, enabling some biomass to sink and sequester carbon in the marine environment.
 - b) **Biochar Production:** Harvested biomass was converted to biochar for soil amendment. This pathway included verification of the biochar's effects as a soil improver and carbon sink.
- 6) **Monitoring Environmental Impact:** The project incorporated systematic studies of the environmental impact resulting from seaweed farming, essential for scaling up industrial seaweed cultivation for CDR, with a scope extending beyond the pursuit of carbon credits

4.1 Further developing seaweed CDR

Overall, the CDR segment encompasses a range of project types, including biological, engineered, and hybrid methods. Hence, SCS certification pathways are relevant for further development, and in general, large-scale biomass production beyond terrestrial sources is highly sought after, strengthening the rationale for ocean-based biomass production for CDR purposes.

Following SouthPole's feasibility assessments, the project team chose not to pursue developing a project specific mCDR methodology due to both timeline constraints and the lack of acknowledged MRV technology and methods. Instead, efforts supported Silvestrum Climate Associates³¹ ongoing methodology work. MRV method development is essential since passive CDR also lacks substantiated durability data, a vital prerequisite for accreditation³². Continued research will help close the knowledge gaps and address MRV challenges for mCDR. As the SCS concept evolves, prioritising methodology progress for mCDR is key.

³¹ [Silvestrum Climate Associates | Climate](#)

³² [A-Comprehensive-Program-to-Prove-or-Disprove-Marine-Carbon-Dioxide-Removal-Technologies-by-2030_FINAL.pdf](#)

It's important to emphasise that the SCS is an R&D&I project. Marine CDR is nascent; biochar CDR is novel. Technology, standards, and methodologies are under development. Seaweed cultivation as an ocean-based carbon farming method is currently not included in the EU Carbon Removals and Carbon Farming (CRCF) Regulation. However, both SCS CDR mechanisms are recognised [as Carbon Removals and Carbon Farming - European Commission](#), and could be implemented in the future.

4.1.1 The state of CDR

Nearly 2.1 billion tonnes of CO₂ are already being removed annually, largely through conventional methods. Around 7–9 billion tonnes of CO₂ per year will need to be removed by mid-century from the atmosphere if the world is to meet the 1.5°C Paris Agreement target.

“The state of CDR - 2edition” (Smith et al., 2024)³³ also shows that only a tiny fraction of all carbon dioxide removals results from novel methods and highlights the need for innovation and scaling of new CDR methods. It also underpins the significant and urgent need to develop new CDR technologies (Figure 13).

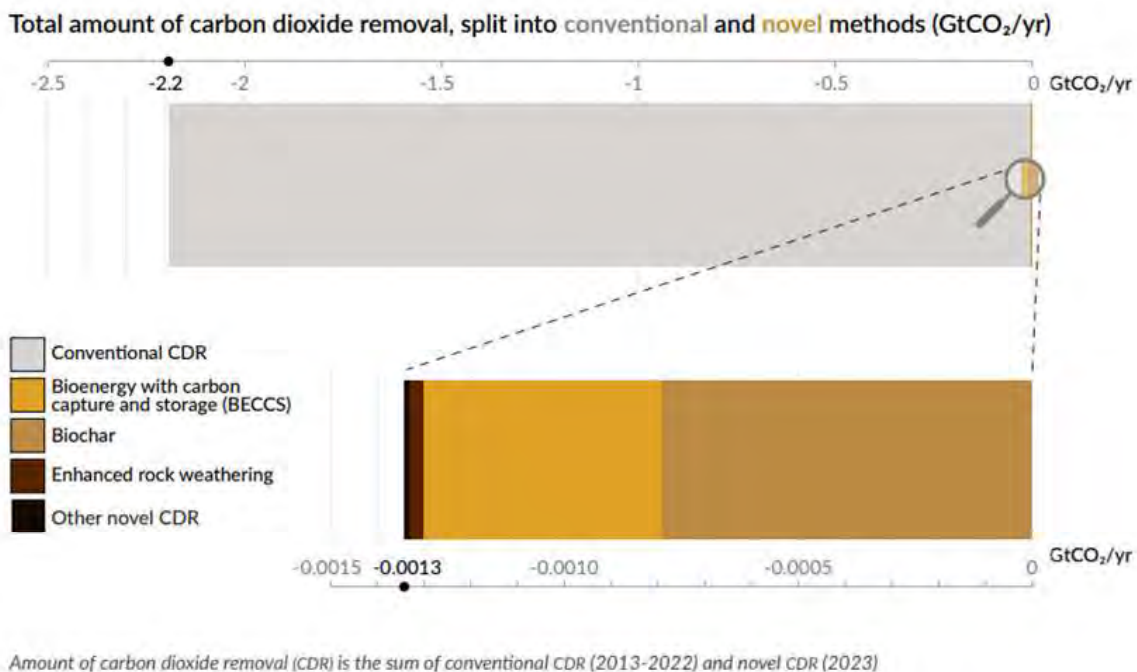


Figure 13 Total CDR by conventional and novel CDR methods (copied from Smith et al., 2024)³⁴.

To advance seaweed CDR and create viable business opportunities it is necessary to address readiness to scale, especially the regional value chain and infrastructure issues identified in the LCA and operations, along with economic analysis of potential future business models.

³³ [Executive-Summary-SoCDR-2Edition2024.pdf](#)

³⁴ Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schneuit, F., Schulte, I., Vaughan, N. E. (eds.) The State of Carbon Dioxide Removal 2024 - 2nd Edition. DOI 10.17605/OSF.IO/F85QJ (2024) The State of Carbon Dioxide Removal

4.1.2 Seaweed biomass for biochar

In 2023, more than 80,000 tonnes of biochar credits were issued in the VCM. Biochar credits comprise 90% of all CDR credits sold on the voluntary carbon market, often in the form of offtake agreements, providing predictability and derisking the scaling up for the producers. Moreover, the demand for biochar credits could rise between 15-35 times in the by 2025 (SouthPole) highlighting its role as an important CDR technology contributing to mitigating climate change in every CDR scenario to meet the Paris Agreement goals.

BiCRS utilising seaweed biochar presents a novel and innovative approach to carbon sequestration, combining nature-based solutions with technical conversion (Figure 14 **BiCRS for soil applications (copied from Energy Transitions Commission, 2022)**). Biochar is currently a more mature solution and can facilitate market access for seaweed biochar. Still, due to its nascent nature, the seaweed CDR and biomass-to-biochar value chain needs to be optimised to reduce production costs and emissions and increase volumes and yield.

High-volume biomass production requires improved efficiency and automated operations to lower the production costs, key to enable scaling of both biomass and biochar production. Although BiCRS prices have ranged between €100-180 per credit in the last two years, today, the offshore cultivation BiCRS business case is not profitable, due to the current high production costs and lack of certification.



Figure 14 BiCRS for soil applications (copied from Energy Transitions Commission, 2022)³⁵.

There is an opportunity in the short term to achieve certification using residuals for biochar production, and also in near shore cultivation (Figure 12). Furthermore, investigating cascading processing methods for the full utilisation of biomass and the extraction of high-value components before utilising the biomass residuals for biochar production, can potentially improve the business case and enable diversification of the income streams. The push towards net-zero industries, combined with expected growth in various market opportunities for biomass and biomass components, indicate a need to investigate further how an industrial

³⁵ Energy Transition Commission, 2022: Mind the Gap Report - Limiting Global Warming To 1.5°C | ETC

seaweed CDR value chain should be developed, possibly incorporating cascading processing principles alongside carbon removal strategies.

4.1.3 Emissions related to the exposed ocean cultivation and related logistics

To qualify for applicable CDR methodology the project emissions must be reduced. For the vessel use in offshore/exposed seaweed aquaculture, with no industry-specific vessels, yet, we rely on the existing marine and maritime sectors. The FHF-funded project EnerSea³⁶ states: *“It is estimated that vessels in the aquaculture industry account for around 80% of domestic greenhouse gas emissions from the industry. In short terms, only battery operation allows for the extensive use of renewable energy, thereby cutting greenhouse gas emissions for aquaculture vessels. In the longer term, alternative fuels such as hydrogen and ammonia are expected to play a larger role in the transition. Unfortunately, there are major challenges associated with transitioning from fossil to battery-electric operation of vessels. The main challenges are limitations in range and availability of charging points with the necessary capacity. The largest vessels in the aquaculture industry, such as well boats/live fish carriers, will not be able to rely solely on battery operation, but for smaller vessels – mainly service and site boats – it may be possible to achieve significant cuts in greenhouse gas emissions with proper operational adjustments, strategic infrastructure development, and smart use of range-extending solutions”*.

Takeaway messages for scaling offshore, aligned with net-zero requirements, is the opportunity to use low-emission vessels and develop low-emission sea farms. SCS knowledge should be implemented both from a LCA design and operational point of view to address emissions and including seabed bathymetry and sediment conditions in the framework for site selection as a part of the requirements for a cultivation site to reduce the need for high emission materials like steel anchors. There will probably be trade-offs, given the pressure and competition for areas that are available for aquaculture and offshore industries, including future ambition for offshore coexistence, with the requirements for conditions securing high yields and optimised CDR.

4.2 Estimates for major items in a scaling scenario

At this time, it's difficult to predict exactly how the seaweed industry could evolve alongside other offshore industries, still, the nature positive role of the offshore wind sector³⁷ and potential coexistence with other offshore industries, hence infrastructure and capacity sharing, is highly relevant topics in any future large-scale scenario. There are high uncertainties related to future design and costs at present. Therefore, the major item for a scaling scenario, in this report, is the SCS JIP sea farm. Still, as mentioned in the LCA, there is an identified need to rethink both the seafarm design itself and investigate low emission mooring solutions to reduce steel components.

To enable upscaling at a production volume of 10.000 tonnes WW, firstly, we must assume continuous funding into RnD driving overall technology development, reduction in production costs and concrete actions towards a negative emission value chain. Together with rising carbon prices and increasing decarbonisation goals, incentivising the investment towards development of low-carbon technologies, industrial scaling for offshore cultivation could develop both sustainable and responsible, however, its recommended to assess the financial perspectives through different business models. Scaling to this level will obviously require areas offshore.

³⁶ Alternative energikilder og -bærere i sjømatnæringen - Delrapport 3 i EnerSea - Tilgang på fornybar energi for sjømatnæringen fram mot 2040 - Nasjonalt vitenarkiv

³⁷ [WEF Nature Positive Role of the Offshore Wind Sector.pdf](#)

The following section presents rough estimates for scaling of sea farms, along with their corresponding biomass production, based on today’s knowledge and several assumptions. Other major items would include large-scale logistics, drying, and pyrolysis. However, access and utilisation of offshore vessels, excess heat drying facilities and prices for large-volume processing is highly uncertain, also in terms of technology readiness level and capacity, and should be further assessed before potential scaling. That said, it will be essential to continue with increased R&D towards these steps in the value chain, also to build competence and capabilities in supply chains and in processing this – in a western world perspective - novel feedstock.

The upscaled roadmap³⁸ for industrialisation industry case in Table 5 below indicates 50 sea farms like Storflua to cultivate 26,000 tonnes per year, which is the breakeven industry case in that report. However, it is unlikely a scale up would retain the same sea farm design, as both the climate footprint of the materials used and operational challenges in exposed conditions has been pronounced in the SCS project. Therefore, these estimations must be done with updated numbers when these questions are settled.

Table 5 Estimated CAPEX to establish cultivation at scale, roadmap case study by Almås et.al (2024).

Ocean cultivation Units/Seafarms	Capacity tonnes per year	Estimated CAPEX
SINTEF pilot - Storflua	500	10-12MNOK
Industry case	26,000	0,5-0,7 MRDNOK
Upscaled industry case	100,000	2-3 MRDNOK
Roadmap goal 1M tonnes	1,000,000	20-25 MRDNOK

Copied from Almås et al., 2024³⁸

The roadmap estimates a CAPEX of 5-700MNOK on sea farms with capacity to 26,000 tonnes per year. No cost reductions or cultivation optimisation included.

Example of costs estimations for scaling exposed seafarm production units

Cultivating seaweed in offshore conditions imposes specific requirements on seafarm design and mooring, which are always location-specific, resulting in variations that affect price.

Still, if we use Storflua as an example, the total cost of this research infrastructure has provided us with the foundation to estimate 10MNOK in CAPEX for the next unit, all expenses included until installation. Let's use this number to create a simple cost learning curve to estimate and illustrate a scale-up of 50 ocean cultivation units.

Assumptions in the calculations

- 1 sea farm (OCU) total cost: 10MNOK
- Material costs: 5MNOK (assumed fixed)
- Planning, labour, management: 5MNOK (variable costs, experience sensitive)

Assuming the variable costs is likely to decrease with experience applying a 15% learning rate in variable costs, by the time we install Unit 50, there is an estimated 58% reduction in these experience-sensitive costs. Material costs are likely to remain somewhat stable or reduce marginally. But let's assume that bulk ordering and supplier negotiations will enable volume discounts, resulting in a 10–15% reduction by the time we

³⁸ Almås et al., 2024. Veikart for industriell dyrking av tare i Trøndelag - SINTEF

install unit 50, adding fixed and variable costs that is 35–37% total cost reduction by unit 50 compared to the first farm, 10MNOK and approximately 6,5MNOK respectively. Then, averaging the expenses over the 50 units, as seen in the figure below, the price per unit is approximately 7.5MNOK per unit, total CAPEX 375MNOK vs 5-700MNOK.

See Figure 15 below for an illustrative example of this estimate:

- Orange line: Total cost per farm (declines from 10MNOK to around 6.35MNOK)
- Orange dashed line: Planning, labour, and management costs (experience-driven)
- Green dashed line: Material cost trend (moderate efficiency through volume purchasing/design)

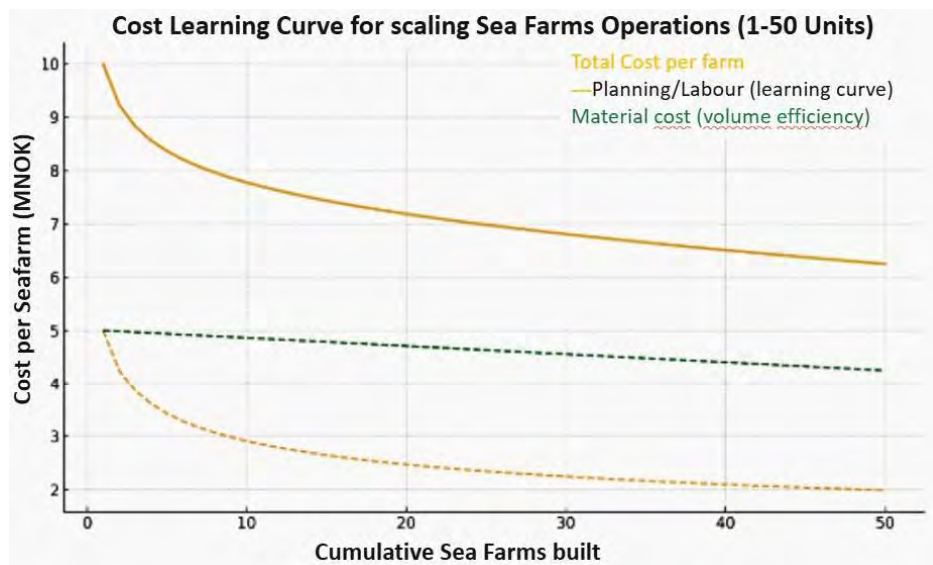


Figure 15 Cost Learning curve in scaling up to 50 Ocean Cultivation Units, corresponding to 25 modules of 2 OCUs per module.

Scaling up to 50 sea farms offers significant potential for cost reductions in experience-sensitive costs, due to cumulative learning, economies of scale, and systematisation. Looking at Figure 15 and using the average cost per unit of ca. 6.2MNOK to estimate a CAPEX of approximately 310MNOK in the industry case scenario.

Again, note that Figure 15 is for illustrative purposes only, the estimate does not consider design optimisations, nor potential revenue and increased yields, factors that can improve the business case and increase CDR, hence motivate the investment in ocean cultivation units.

4.2.1 Cost of production of biomass

The estimations of the cost of Storflua biomass production considers seed production (all equipment and suppliers involved), renting service boats from the aquaculture industry for deployment and harvest, **all operations up until delivery of fresh harvested biomass on the docks, and is approximately 11NOK per kilo (Figure 16).** The cost of production is also based on a conservative yield of 5kg per meter, still, we have demonstrated 10kg per meter of substrate with today's methods at the exposed location. Volumes and yield will affect the price.

Currently, seed production (land-based) represents more than 50% of these production costs, affecting the cost of production independently of location, and reducing this cost is therefore of interest for all biomass producers. This is expected to be achieved in the short term through automated processes.

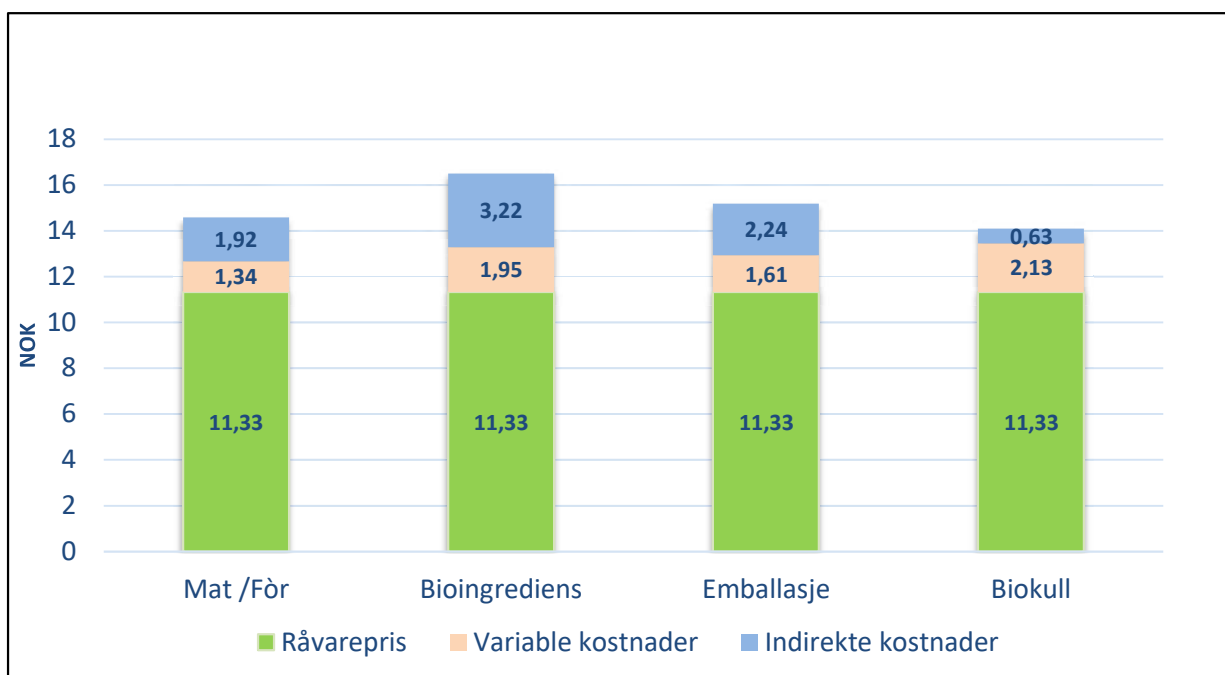


Figure 16 Cost of biomass production³⁸ and processing cost (NOK per kg WW) added for the product categories (from left) food/feed, bioingredients, packaging and biochar. Cost of production of the biomass until stabilised is assumed the same for all categories, again, based on the roadmap project (Almås et al., 2024).

The data, calculations and uncertainties of these numbers are discussed thoroughly in *Veikart for industriell dyrking av tare i Trøndelag - SINTEF*

Following the scaling example above (Table 5), no optimisations made, 500 tonnes WW capacity per unit, we estimate the annual cost of biomass production for the industry case to be between 150-300MNOK. The lower estimate assumes it's possible to reduce the cost of seed and overall production significantly. Moreover, total cost of production of biomass does not include potential future credit opportunities and diversification of income streams from full utilisation of the biomass that could potentially improve the business case.

4.2.1.1 Cost of Offshore Production in an optimised scenario – an example from Maine

A recently published paper by Moscicki et al (2025)³⁹ performed a comprehensive quantification of production costs for large-scale aquaculture and costs reduction opportunities. Their techno-economic assessment concludes that the cost of production can be reduced from USD2618 at baseline to USD383 in an improved scenario.

The authors highlight the following primary cost reduction drivers (Moscicki et al 2025):

1. Use of purpose-built, correctly sized vessels
2. Heavily mechanized operations
3. At-sea processing of harvested kelp into a slurry
4. Biomass storage in vessel holds

³⁹ Moscicki et al (2025). [Comprehensive quantification of production costs for large-scale kelp aquaculture and cost reduction opportunities - ScienceDirect](#)

5. Structural design that minimizes loads, maximizes operational efficiency and spatial productivity
6. Cultivation at maximal depths for site specific light penetration

Note that this is production cost for the raw material, processing, drying of the biomass and biochar production is not included in this assessment.

4.2.2 Multiple challenges and barriers must be addressed

The reduction in overall cost of production described above is very relevant for SCS, as we face many of the same challenges, highlighted in this report. Further, advancing into automated land-based operations can significantly reduce seed production costs. Increased yields through targeted cultivation strategies can also lower production costs by providing larger harvested volumes without expanding the scope of land-based work to prepare for the deployment. However, significant investments towards the cultivation industry are critical to realise these advancements. Certified carbon removals can offer new revenue streams and incentivise this investment.

To achieve carbon credit certification within the current SCS project design, the project must demonstrate a volume production of 500 tonnes, in addition to reducing identified value chain emissions. Said biomass volume can be produced on the existing sea farm if the capacity is optimised, or at the near shore location - as shown in the LCA scenario. However, the applicable methodology requires pyrolysis capacity, *i.e.* that the pyrolysis factory is located within 300 km from the seaweed biomass landing site. The pyrolysis knowledge exists, *e.g.* at SINTEF, and a new pyrolysis facility owned by Mære Landbruksskole was recently opened in Steinkjer.

Nevertheless, there is an option in scaling gradually and going to market product by product. By using existing cultivation licenses for CDR purposes and targeting existing markets for biomass while simultaneously doing the research, development and innovation needed to optimise, verify and establish the CDR pathways as viable business cases. Before scaling, this needs to be assessed also from a techno economic perspective to strengthen any potential CDR business case.

Building a seaweed CDR business case and value proposal must assume verified removals through viable certification pathways (passive and active), of which is not achieved in this project. The business model (and potential volumes) remains highly uncertain for offshore cultivation for CDR purposes. The SCS JIP results, however, motivate further research and development into making the offshore biomass to biochar value chain net negative, both for near shore and offshore concepts. Furthermore, investigation of the waste to biochar BiCRS pathway, including how to valorise residuals from biorefinery of the seaweed biomass for biochar production and thus unlock a full utilisation of the biomass, can create several market opportunities. An estimate of the needed research budget (The National Academies Press, 2022)⁴⁰ is shown in Table 6.

⁴⁰ A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration | The National Academies Press

Table 6 Copy from “A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration” | The National Academies Press (2022)⁴¹

Total Estimated Research Budget	\$54/yr	5–10	\$466M
Estimated Budget of Research Priorities	\$5M/yr	5–10	\$25M
Seaweed Cultivation			
Technologies for efficient large-scale farming and harvesting of seaweed biomass	\$15M/yr	10	\$150M
Engineering studies focused on the conveying of harvested biomass to durable oceanic reservoir with minimal losses of carbon	\$2M/yr	10	\$20M
Assessment of long-term fates of seaweed biomass and by-products	\$5M/yr	5	\$25M
Implementation and deployment of a demonstration-scale seaweed cultivation and sequestration system	\$10M/yr	10	\$100M
Validation and monitoring of the CDR performance of a demonstration-scale seaweed cultivation and sequestration system	\$5M/yr	10	\$50M
Evaluation of environmental impacts of large-scale seaweed farming and sequestration	\$4M/yr	10	\$40M
Total Estimated Research Budget	\$41M/yr	5–10	\$385M
Estimated Budget of Research Priorities	\$26M/yr	5	\$235M

continued

Scaling up marine CDR and the biomass-to-biochar and/or the complete utilisation of waste-to-biochar pathway will require continued and increased investments into technological advancements, as well as the demonstration of larger-scale procedures throughout the seaweed value chain. Although an example from the US in Table 6 above, this supports the experience from the Norwegian seaweed industry and research, also underpinning a global interest towards establishing seaweed cultivation for CDR. Due to the early stage development and uncertainties related to MRV, identifying investors with a longer-term perspective on returns on investment, valuing other benefits beyond monetary gains in the short term, are ideal partners to develop the seaweed CDR concept. Therefore, engaging impact investors and acquiring strategic stakeholders towards demonstrating a carbon-negative value chain is essential to verify SCS CDR.

Also considering external factors, a multitude of end users and stakeholders outside the seaweed sector is of interest, all of which are driven by the green transition, a changing geopolitical situation and the EU Net Zero Industry Act, to achieve mutual goals.

4.3 Towards 2050

By 2050, offshore cultivation is predicted to be fully automated and mechanised, and co located with offshore wind or other offshore industries. Technology is developed and implemented for monitoring and surveillance, MRV technologies are demonstrated and acknowledged, and the marine CDR is verified and credited. The value chain hotspots have been developed and transitioned to net-zero technologies, and end products and their use are designed and certified for CDR purposes.

Both large-scale and extensive seaweed aquaculture planning must consider co-existence with other marine industries, in particular in context of the “30x30”-target of 30% protection and 30% restoration of all sea and land areas by 2030 in the Kunming-Montreal Global Biodiversity Framework. The potential for IMTA

⁴¹ A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration | The National Academies Press

with salmon and kelp has been evaluated previously⁴² and though a lot of research remains along that line, we will focus on:

- Evaluating the possibility of integration with and repurposing of existing offshore oil and gas assets for seaweed aquaculture.
- Evaluating the potential benefits of integrating with offshore ocean wind energy farms.

4.3.1 Repurposing and integration of O&G assets for seaweed aquaculture

One advantage of siting large-scale seaweed aquaculture in offshore conditions is that the natural potential for biomass production seems to be greater there⁴³. The cultivation trials at Storflua indicate that this hypothesis, based on the state-of-the-art knowledge and ocean modelling, may indeed be correct. Some disadvantages are loss of accessibility and greater bottom depths. The latter is technically challenging, and both are challenging in terms of economy and the energy (carbon) requirements for farm installation and operation.

Integration of seaweed cultures with already existing O&G installations might provide mooring options that are a lot cheaper than siting aquaculture by itself. In terms of operations, already existing infrastructure and operational routines might be an advantage in O&G areas compared to other offshore regions. There might be restrictions related to safety, operations of and access to the O&G installations. Repurposing O&G facilities that will be shut down to operations would be an advantage as there will be less conflict between operations. Thus, by integrating activities, existing O&G installations may serve as operational hubs and might even offer helipads for easy (though costly) access of personnel.

There is a risk that crude oil from spills or leaks or produced water components from oil production might be taken up in cultivated seaweeds. Some seaweed species, in particular kelps, have a relatively low lipid content, so that bioaccumulation of, *e.g.*, PAHs may not be a great problem. Monitoring of the chemical composition of the biomass is necessary regardless of the locations, but maybe special care should be taken if the seaweeds are grown in the vicinity of O&G facilities.

4.3.2 Co-existence and integration of ocean energy with seaweed cultures

Co-use of ocean areas for seaweed cultivation and offshore wind has been discussed ever since “modern” (2008-present) large-scale seaweed aquaculture was first suggested. As for O&G there are many apparent advantages of co-siting apart from better area use, like common infrastructure, safety procedures, and logistics. Obvious disadvantages are the need to consider conflicts between the moorings and operations of the seaweed and wind farms. One should also consider potential stakeholder conflicts, within the ocean wind regions, between seaweed aquaculture and other marine interests and industries like fisheries.

In order to optimize technical solutions, management, logistics and area use, it is important that any area for combined seaweed and wind farming is planned as such from the beginning. Adding seaweeds as an “afterthought” will potentially diminish the added value substantially.

Ocean wind farms (OWFs) are sited offshore and hence in exposed conditions. We have seen in 3.3 that generally speaking offshore conditions may sustain a high seaweed biomass production. Presently, an area

⁴² Broch OJ et al (2013) Modelling the cultivation and bioremediation potential of *Saccharina latissima* in close proximity to an exposed salmon farm in Norway. *Aquacult Environ Interact* 4:187-206 doi: 10.3354/aei00080; Fossberg J et al (2018) The potential for upscaling of kelp (*Saccharina latissima*) cultivation in salmon-driven integrated multi-trophic aquaculture (IMTA) *Front. Mar. Sci.* 5:418; doi:10.3389/fmars.2018.00418.

⁴³ Broch OJ, Alver MO, Bekkby T, Gundersen H, Forbord S, Handå A, Skjermo J, Hancke K. (2019) Kelp cultivation potential in coastal and offshore regions of Norway. *Front. Mar. Sci.* 5:529; <https://doi.org/10.3389/fmars.2018.0059>

of around 56 000 km² is being considered for potential offshore wind siting⁴⁴. Hence there is huge potential for seaweed cultivation in ocean wind regions. Examples of the simulated kelp cultivation potential in three (more or less randomly) selected regions being considered for OWF are given in Figure 17. Allocating **1 % of the area** in each of the regions in Figure 17 to kelp cultivation might yield around 1 million t fresh weight kelp (using the average production figures from each region for the period September-June), which is enough to cover the kelp biomass needs for many years. Ocean wind turbines are sparsely distributed within their allocated area, with ~1 km or more between each. This indicates that co-siting of OWF and kelp cultures is feasible, even with ample space allocated for safety distances, operations, and logistics.

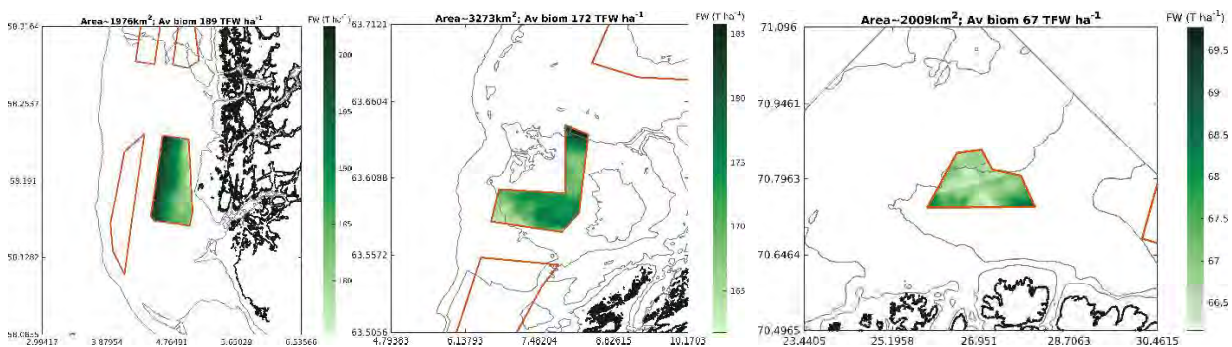


Figure 17 The simulated kelp (*S. latissima*) cultivation potential in three selected regions identified for potential ocean offshore wind siting (Source: NVE, <https://veiledere.nve.no/havvind/strategisk-konsekvensutredning-av-vindkraft-til-havs-del-1/kart/interaktivt-kart/>). Left: Vestavind G. Middle: Nordvest B. Right: Nordavind B. The areas of the regions displayed on top are not quite accurate.

In terms of carbon uptake and sequestration potential, the “1 % of the areas” may sustain a potential passive carbon sequestration of > 12,000 tonnes C in addition to the 30,000 tonnes C captured in the biomass needed to achieve 1 tonne of CO₂ stored in biochar (see Figure 3). The calculation does not account for emissions that occur within the value chain and production process. This might contribute to the total carbon balance of the OWF regions.

Seaweed aquaculture contributes several ecosystem services that might contribute to offsetting detrimental effects of OWF. These include increased O₂-concentrations, higher pH, and habitats for pelagic organisms. Whether seaweed cultures forming a temporary “artificial” habitat for marine life should be considered solely a benign effect is a matter of debate and definition.

Increasing competition for ocean space requires coordinated marine planning and Norway’s Ocean Industries Strategy and the European Ocean Pact⁴⁵ promote multi-use approaches. The forthcoming EU Circular Bioeconomy Strategy supports a regenerative, climate-neutral economy aligned with the Clean Industrial Deal, Ocean Pact, and Industrial Decarbonisation Accelerator Act. However, the seaweed stakeholders must proactively take responsibility to inform, promote and act on behalf of this emerging industry in “the race for space”.

Figure 18 presents a map with an index for the potential of cultivating sugar kelp in Trøndelag, based on coupled biophysical ocean models, and ranks the different locations according to their basic simulated

⁴⁴ See the interactive map of NVE: <https://veiledere.nve.no/havvind/strategisk-konsekvensutredning-av-vindkraft-til-havs-del-1/kart/interaktivt-kart/>

⁴⁵ EUR-Lex - 52025DC0281 - EN - EUR-Lex

cultivation potential. Assuming the most productive available areas are used, the area requirements for capturing and storing the carbon varies two-fold between optimistic (high natural sequestration, low CO₂ usage on processing) and pessimistic (low natural sequestration, high CO₂ usage in processing) scenarios⁴⁶. This stresses the need for dedication of high-productive sea area to the emerging seaweed aquaculture industry.

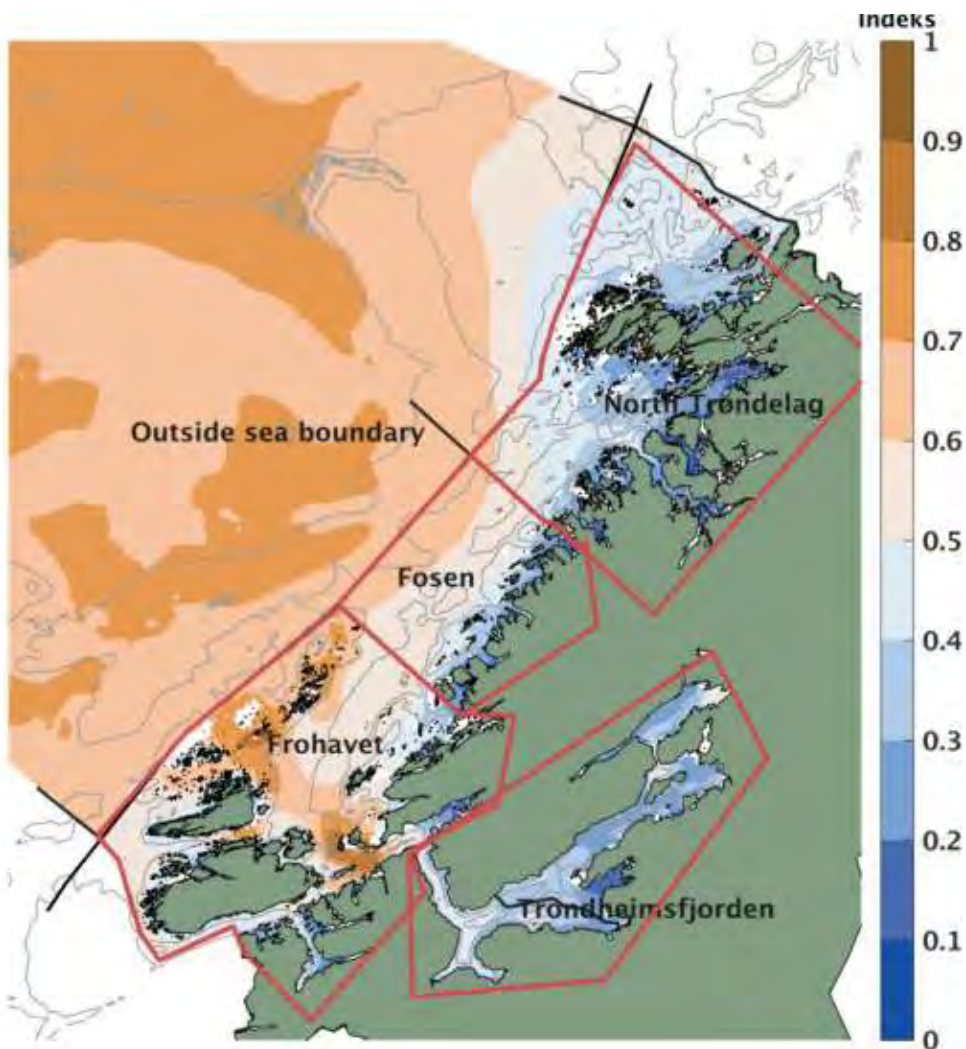


Figure 18 Areas at the coast of Trøndelag suited for sugar kelp cultivation. The red lines indicate a rough subdivision of Trøndelag into smaller regions, including the areas outside the sea boundaries (copied from Broch et al., 2017).

Norway has large areas that in theory could be used for kelp farming and CO₂ sequestration (Figure 19) and future management of areas for seaweed aquaculture, both inside and outside of the baseline, should allow for sufficient space to develop seaweed aquaculture. Sound planning will streamline the permit application process and minimize the potential for conflicts. Areal planning should consider areas suitable for seaweed aquaculture, and in particular areas that might need to have other properties than traditional finfish aquaculture. For example, seaweed aquaculture requires a sufficient supply of dissolved nutrients, an aspect not relevant for salmon aquaculture.

⁴⁶ Broch OJ, Tiller R, Skjeremo J, Handå A (2017) Potensialet for dyrking av makroalger i Trøndelag. SINTEF Ocean rapport OC2017 A-200 <https://hdl.handle.net/11250/2458072>

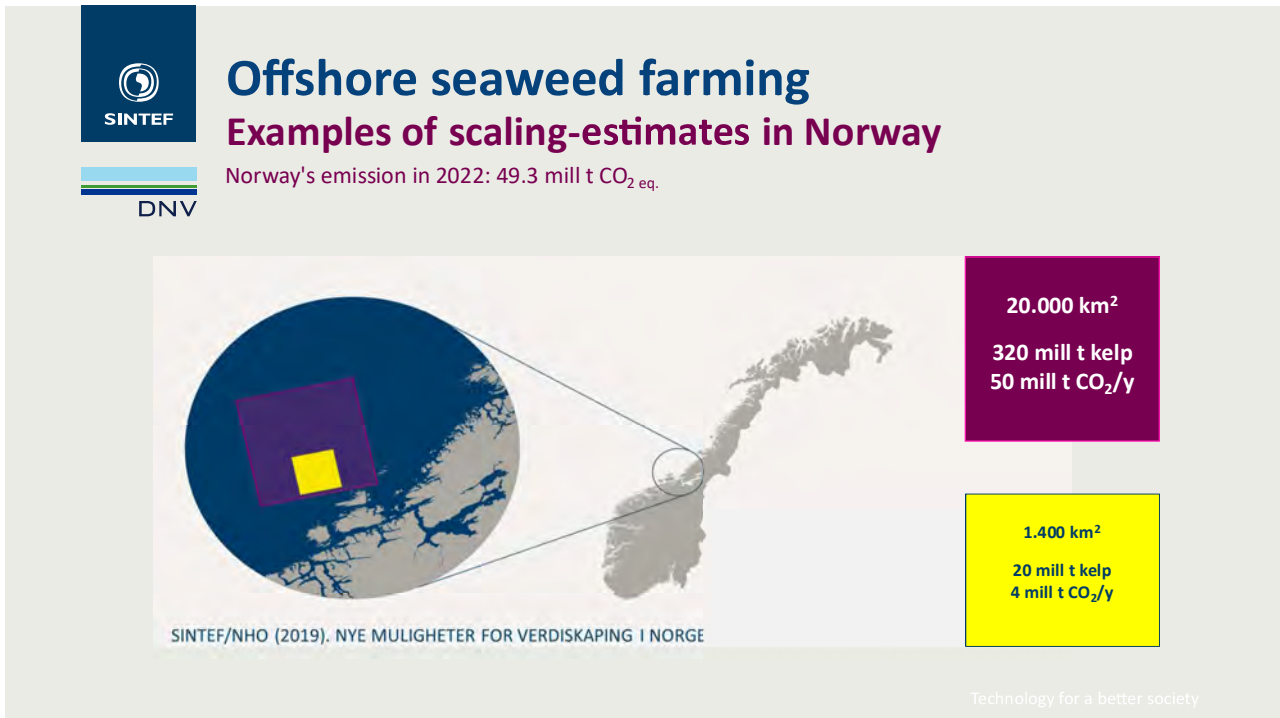


Figure 19 Scaling estimates for offshore cultivation for CDR (SINTEF Ocean).

4.4 Beyond Carbon Credits

Ocean-based climate solutions can offer a range of benefits, including employment opportunities, enhanced coastal resilience, improved biodiversity, global food security, better water quality and health, as well as improved income prospects and livelihoods in coastal regions.

While carbon credits centre on measurable greenhouse gas reductions or removals, the "beyond carbon" concept emphasises the co-benefits and risks of projects that influence ecosystems, communities, and long-term sustainability, taking a more holistic approach than solely monetary. Thus, "beyond carbon credits" involves acknowledging and valuing the wider environmental, social, and economic effects of carbon removal or reduction initiatives that are not fully captured by carbon accounting alone.

The Blue Growth Strategy promotes innovation in marine biotechnology, and seaweed offers an untapped potential for biotechnological applications, such as the development of bio-based products, biofuels, and biodegradable plastics. This presents an opportunity for new revenue streams through seaweed cultivation and resource diversification, supporting the case for establishing a large-scale seaweed industry. Moreover, there is a growing demand for sustainable, carbon-neutral inputs and ingredients in various supply chains. Seaweed biomass can be cultivated to produce valuable by-products that replace fossil fuels, as mentioned, creating carbon avoidance opportunities in other industries and value chains⁴⁷. This increases the motivation to develop and establish an industrialised seaweed cultivation value chain as part of a broader sustainable business model aimed at achieving a greater social and environmental impact. The technologies developed in the JIP SCS can help facilitate the continued development and upscaling of the emerging western seaweed industry, providing sustainable biomass for a variety of applications, including CDR purposes.

⁴⁷ Urgent need to consider how to best use biomass in Europe | Press releases | European Environment Agency (EEA)

Aligned with the Global Biodiversity Framework, it should be investigated how to implement biodiversity objectives to a larger extent in the scope of work when developing the concept, possibly from the perspective of restoration efforts, directly or indirectly, aimed at supporting long-term ocean health and climate targets. If appropriately designed and managed, seaweed cultivation could deliver more co-benefits and synergies than trade-offs⁴⁸, enabling responsible scaling.

Sustainable and Responsible upscaling

Biodiversity is essential for human well-being, a healthy planet, and economic prosperity. It provides food, medicine, energy, clean air and water, security from natural disasters, recreation, and cultural inspiration, supporting all life on Earth.

The Kunming-Montreal Global Biodiversity Framework (GBF) was adopted during the 15th Conference of the Parties (COP15). This historic framework, which supports the achievement of the Sustainable Development Goals (SDGs) and builds on the Convention's previous Strategic Plans, sets out an ambitious pathway to reach the global vision of a world living in harmony with nature by 2050.

Aligned with the GBF Global targets for 2030, the SCS has taken urgent action towards climate mitigation - and adaptation using nature-based solutions and biodiversity-friendly practices. Furthermore, biochar produced for soil improvement on land can improve agricultural productivity by helping soils retain water and nutrients and restoring degraded soils.

Considering the magnitude and significance of the emission reductions needed and the global biodiversity challenges, sustainable solutions that tackle both issues are essential. The research and development associated with developing the emerging seaweed industry could be incorporated into a more comprehensive strategy aimed at mitigating and offsetting both emissions and the adverse impacts on biodiversity, as part of corporate sustainability and environmental initiatives.

4.5 Rationale and future pathways for industrial seaweed cultivation and CDR

Biomass is expected to play an important role in reaching the goals of the European Green Deal (Box 1). It is needed for food and energy security, nature protection, pollution reduction, and climate action. However, research shows that biomass produced within the EU will not be enough to meet all these needs in the future⁴⁹. Cultivated seaweed is not yet fully included in EU biomass estimates, even though it can provide scalable annual production for bio-based industries.

Ocean-based carbon removal methods are receiving increasing attention as tools to address climate change. However, these technologies differ in how mature they are, how much they cost, and how quickly they can scale. Seaweed cultivation combined with biochar production offers a practical step forward. In the short term, carbon removals can be certified through established biochar methods. At the same time, further research can improve the monitoring and verification systems for marine carbon removal. This approach allows progress now while building knowledge for larger-scale impact in the future.

In the short term, BiCRS can be developed at existing near-coastal sites, which have lower emissions than offshore pilot sites. However, these areas have limited space and cannot support very large-scale production. In the long term, offshore cultivation offers greater potential for scaling. Offshore areas have access to natural nutrient pools from ocean currents, reduce pressure on coastal zones, and create

⁴⁸ [Co-benefits and trade-offs of climate change mitigation actions and the Sustainable Development Goals - ScienceDirect](#)

⁴⁹ [The European Biomass Puzzle | Publications | European Environment Agency \(EEA\)](#)

opportunities to share space and infrastructure with offshore energy or other marine industries. Still, the offshore value chain is not yet mature.

Scaling up seaweed farming requires careful planning. Marine space is shared with fisheries, shipping, nature reserves, recreation, offshore wind, and other industries. Offshore farming, in particular, faces high investment costs, limited technology maturity, and underdeveloped supply chains. It also relies on energy transition in the aquaculture- and related service sector, of which it currently rent and utilises different services and vessels from. The LCA from the SCS JIP shows that the exposed site design has too high emissions to qualify for certified carbon credits, today. To succeed, the industry must reduce emissions across the value chain. This includes improving farm design, mooring systems, logistics, automation, and moving toward zero-emission operations. Indisputably, the downstream part in the value-chain also needs a bigger attention, to enhance the development of low-emission products.

Despite these challenges, industrial seaweed cultivation has a strong potential to contribute to climate mitigation. With targeted research, innovation, and investment, seaweed-based carbon removal can complement existing carbon removal methods without competing for land resources. Developing Seaweed Carbon Solutions aligns with EU climate and sustainability goals and can strengthen Europe's bioeconomy. Seaweed biomass should therefore be considered an important part of Europe's future biomass strategy and net-zero transition.

The ambition remains to scale up and industrialise seaweed cultivation to make a significant impact. In general, the scale-up of emerging permanent removal methods requires overcoming technological, environmental and economic barriers⁵⁰. This applies to seaweed CDR as well. Significant investments into seaweed cultivation technologies are strongly needed to develop this into a size that matters, i.e. a removal of thousands to millions of tonnes of CO₂ per year.

Box 1 Predicted removals from cultivated seaweed in EU⁵¹.

The EU Blue Economy Report 2025 states, "Oceans are a great carbon sink, absorbing excess heat and energy released from rising GHG emissions. Seaweed cultivation can be an effective NBS, as in addition to being a source of food and energy, and having other uses, its production contributes to carbon sequestration and ecosystem restoration. Macias et al.* have assessed the environmental suitability of EU marine regions for seaweed cultivation, showing that Atlantic regions are the most suitable areas for seaweed cultivation, particularly for cold-water and intermediate-water species. Moreover, taking a precautionary approach by using only 1% of the suitable area and considering logistical constraints (water depth and distance to coast), seaweed production in Member States' waters could reach about 5.5 million tonnes, assimilating about 1.9 million tonnes of carbon, 225 000 tonnes of nitrogen and 24 000 tonnes of phosphorous per year over an area of about 1 900 km²».

⁵⁰ Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU

⁵¹ The EU blue economy report 2025 - Publications Office of the EU

Appendix A: Work package reports



SINTEF

Project memo

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JIP Seaweed Carbon Solutions WP1 Scaling, site selection and licensing

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Abstract heading


The triple planetary crisis calls for urgent measures and immediate climate action. The Seaweed Carbon Solutions project will, in its initial phase, focus on existing technologies and adapt and scale up these for ocean kelp farming and carbon sequestration.

An area outside Mid-Norway suitable for the uptake of 1 million tons of CO₂ per year will be identified and used as a case for siting ocean farms, and the technological requirements for offshore seaweed farming will be assessed.

SINTEF Ocean is responsible for Work Package 1, Including Site selection and licensing, as well as planning of the hatchery.

- a) Evaluate high productivity sea areas for site selection. Include opportunities for possible integration with ocean wind energy, mooring and logistics, and possibilities for passive and active transportation of kelp debris or biomass to large depths.
- b) Apply for licence for cultivation of sugar kelp.
- c) Plan the seeding strategy and needed hatchery capacity for kelp seedlings production, including need for access to seedlings produced by commercial suppliers.

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SINTEF

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5	2026-04-15	Unrestricted, 20 p total, otherwise same as V4



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1 Background

Seaweeds, especially the large brown kelps, grow rapidly and are highly efficient in converting $\text{HCO}_3^-/\text{CO}_2$ dissolved in seawater into biomass through photosynthesis. For example, cultivating 1,400 km² of offshore sea area can produce approximately 20 million tons of kelp (wet weight) annually, which will take up 4 million tons of CO₂ from the seawater. This corresponded to 8% of Norway's annual CO₂ emissions in 2020.

To contribute substantially to CO₂ removal, a thorough scale-up of seaweed cultivation is needed. Due to the need for large cultivation areas, cultivation should be performed offshore, where the productivity is higher and potential conflicts with other activities and uses are fewer. The development of large-scale seaweed farming must be based on both existing knowledge of offshore technology, a good understanding of natural seaweed ecosystems, and how seaweed aquaculture interacts with the marine environment.

Highly productive offshore areas (Fig. 1) have been identified along the Norwegian coast, representing a significant potential for carbon sequestration through seaweed farming.

A biophysical ocean model (SINMOD) with a module for seaweed growth, carbon uptake- and composition have been used to find suitable best cultivation sites.

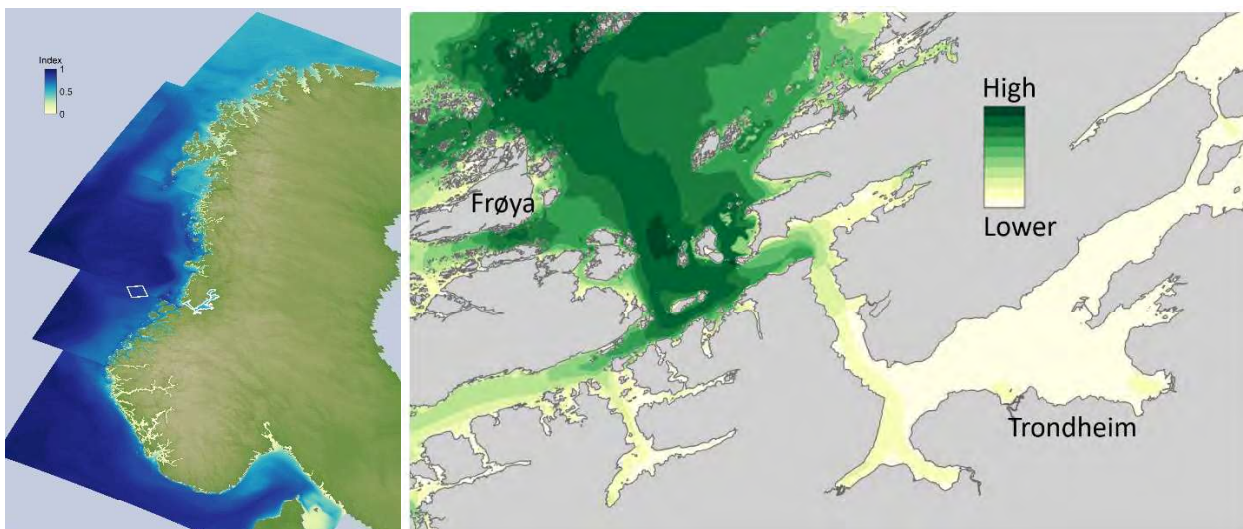


Figure 1 Left: Index for the kelp biomass production potential in Norway. The darker colors (blue) indicate a higher kelp production potential, while the brighter colors (yellow) indicate a lower potential. The white square has an area of approx. 1440 km², equal to the area of the Trondheim fjord, also outlined in white (middle of image). Right: high resolution image of the kelp cultivation index for the Trondheim fjord and Frohavet. See: Broch OJ et al (2019) Kelp cultivation potential in coastal and offshore regions of Norway. *Front. Mar. Sci.* 5:529; <https://doi.org/10.3389/fmars.2018.0059>



The model results indicate that the cultivation potential increases as one moves away from the coast (Fig. 1). The reason for this is that offshore, in Atlantic waters, we find more stable temperatures (higher in winter, lower in summer), longer periods of higher nutrient concentrations, and better optical properties of the water than in coastal waters. This argument applies to the northern part of the North Sea and the Norwegian Sea, but in the southern part of the North Sea the terrestrial nutrient loading from e.g. the Rhine is so great that nitrate concentrations are significantly higher nearshore than offshore. Details on the model system¹ and its application to seaweed cultivation potential mapping can be found in Broch et al. (2019)²

2 Preparations for offshore farming experiments

As illustrated in Fig. 1, an area outside Mid-Norway has been identified as suitable for the uptake of millions of tons of CO₂ per year by seaweed cultivation. The following will elaborate further on the site selection methodology, choice of location, and the application process to obtain a permit.

2.1 Site Selection Methodology

The seaweed cultivation potential of any site depends not only on the biophysical conditions, but also on the choice of technology, cultivation strategy, skill and experience of the site operators. It is impossible to ascertain the actual potential without trial. Assuming “all other factors being equal” (such as the choice of technology), biophysical modelling (without going into details about choice of model and numerical implementation) or a detailed (and costly) site survey (or ideally a combination of both) are the only options to assess the suitability of a site without trial.

For selection of our cultivation site, we used an approach of gradually narrowing down from general to more specific conditions:

- Biophysical conditions (currents, nutrients, light, temperature etc)
- Technological considerations (bottom depth, relevant for e.g. mooring systems; currents for structural design)
- Operational considerations (e.g. inside/outside baseline, safety considerations, economic considerations)
- Governance/legal considerations (area plans)
- Stakeholder interactions.

One might go from the bottom up, but it is important at least to avoid biologically unsuitable sites, so the first point on the list must be considered in some way. It is further difficult to foresee all potential objections from stakeholders in the public consultation audited by the county authority (which grants licenses). The county authority might call for archaeological surveys to avoid conflicts between operations and cultural heritage sites like shipwrecks etc.

² Broch OJ, Alver MO, Bekkby T, Gundersen H, Forbord S, Handå A, Skjermo J, Hancke K. (2019) Kelp cultivation potential in coastal and offshore regions of Norway. *Front. Mar. Sci.* 5:529; <https://doi.org/10.3389/fmars.2018.0059>



The assessment of the biophysical conditions was made based on previous work by SINTEF Ocean financed in part by the Research Council of Norway and in part by Trøndelag and Møre og Romsdal County authorities. Further modelling of significant wave height was performed by SINTEF Ocean in the project “The Norwegian Continental Shelf: A Driver for Climate-Positive Norway (NCS C+)” funded by the Research Council of Norway (328715) under the green platform program. Part of the license application process was further financed by resources made available in the Norwegian Seaweed Centre national infrastructure project financed by the Research Council of Norway.

2.2 Site Selected

Ideally, a genuinely offshore site would have been selected. Offshore sites are expensive to operate since they cannot be safely accessed or run without seagoing vessels, and mooring might likewise be prohibitively expensive at great bottom depth. Therefore, it was decided to map sites that lie inside the maritime baseline, yet still retaining some of the properties of a proper offshore site. While the interpretations of “offshore” and “exposed” may depend on the situation, our conditions included: a site with

- good vertical mixing for good supply of nutrients;
- relatively high water current speeds;
- relatively high wave exposure.

Frohavet (Fig. 2) generally has many suitable locations supporting these conditions. Analyses based on coupled kelp-biology-physics models (Section 1) indicate that there is a particularly high cultivation potential around the Froan archipelago (Fig. 1). A site that is well expose to currents and waves was selected south of Gjøesingen (Fig. 2).

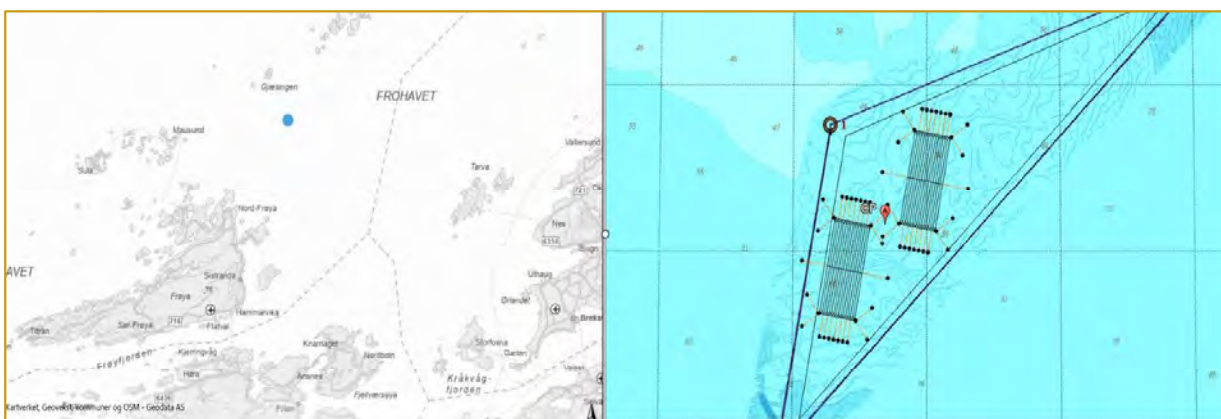


Figure 2 Site selected and initial planned sea farm module



2.3 Location choice

In early 2022, SINTEF Ocean was in dialogue with Møre og Romsdal Fylkeskommune (MRFK) about utilising their planned aquaculture license for seaweed cultivation at Grip (Møre og Romsdal), but when the MRFK application process was significantly delayed, and one of the seed suppliers experienced delivery issues, the plan to use the MRFK site and license was abandoned. Instead, the SCS timeline aligned with the that of a permit application for the RI Seaweed Project, a seaweed infrastructure project providing an exposed site for cultivation for the next 10 years in Trøndelag.

Motivated by both logistical and overall SCS project economy reasons, a strategic decision to be a part of the Norwegian Research Council’s seaweed value chain in Trøndelag for long term perspectives and predictability related to value chain infrastructure and competence - the steering committee made a formal decision to change the location from Grip to Frohavet and execute the SCS JIP in the Trøndelag region, not investing in the sea farm in the SCS project, but renting and using the RI seaweed’s ocean cultivation unit (offshore sea farm) in the pilot phase.

After the final decision was made to change the location, the Storflua application process was initiated.

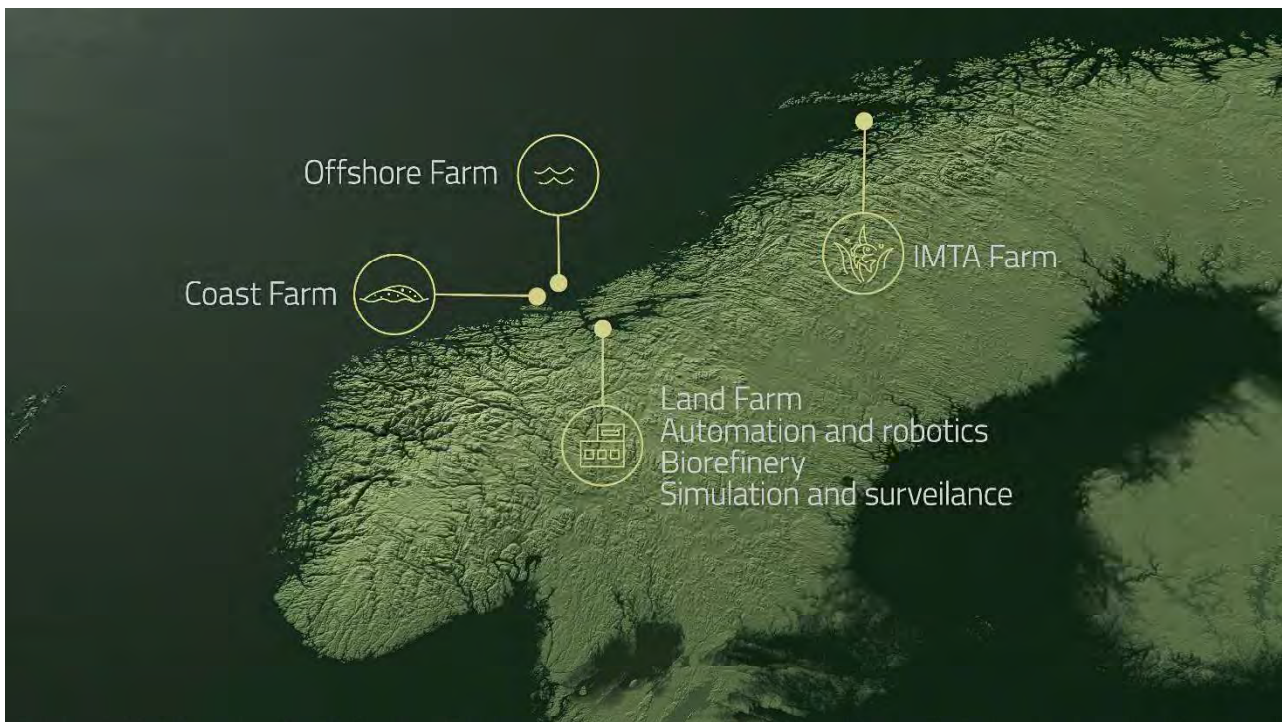


Figure 3 RI Seaweed Infrastructure. Source: norwegianseaweedcenter.com



2.4 Detailed Timeline and Application Process

22.02.2022 RI Seaweed meeting with Trøndelag Fylkeskommune to assess possibilities for exposed seaweed aquaculture in the region as part of the research infrastructure.

30.08.2022 SINTEF Ocean attended a dialogue meeting with Frøya Municipality to initiate and notify the stakeholders about our plans and the coming process. Attending were also representatives from the local fishermen's association; Frøya&Hitra, Mausund and Sørburøy;

The fishermen's association identified the Storflua area, out of the proposed locations, as a location that would have minimal impact on existing fisheries. However, they preferred a placement as far to the northeast as possible to avoid conflict with gillnet fishing (Fig. 4 below).



Figure 4 Proposed placement for seaweed cultivation - blue square

Following the meeting with the Municipality and fishermen's association, dialogue was initiated in early September with the Coastal Authorities to clarify which of the proposed potential areas discussed in the previous meeting they recommend based on their expertise. The Coastal Authorities came with clear recommendations:

- A location that avoids conflict with the white zone for marine traffic and with heavily trafficked areas
- Points to **Storflua** as the most ideal site in the Gjæsinghavet area
- The Norwegian Coastal Administration will approve the placement of the facility within the designated area (triangle)
- Requires the facility to be placed east of the white zone from Svartskjæret (minimum 50 meters)
- Wants sufficient distance from Storflua for safe maritime navigation
- Requests that the facility be positioned parallel to the dominant direction of marine traffic (a relatively trafficked area)

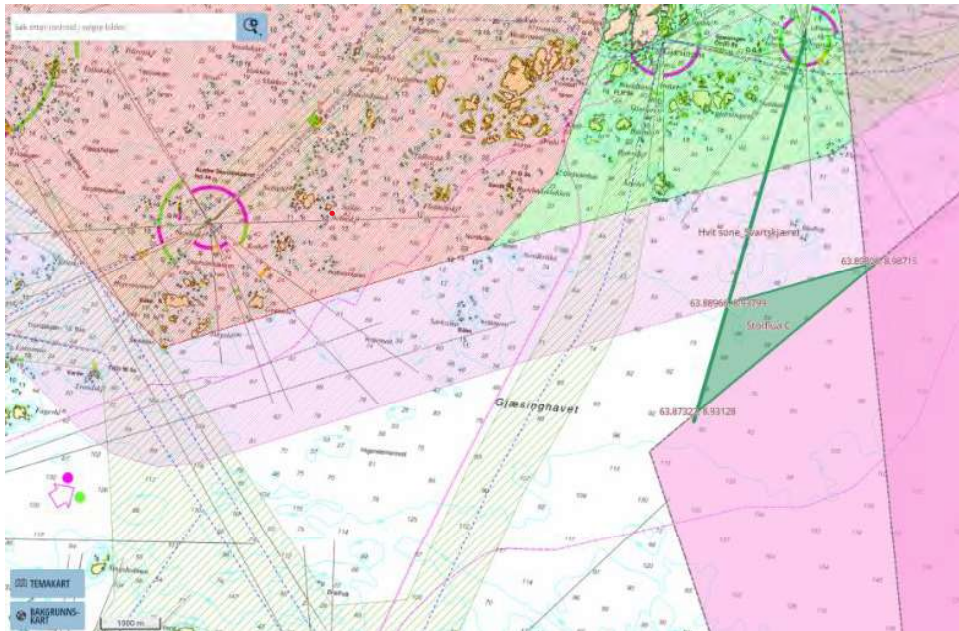


Figure 5 Identified new placement of location - green triangle

Fig. 5 above shows the area pointed out and aligned with both fisheries interests, nature reserves, military regions and coastal traffic, northeast of the location initially identified and proposed in Fig. 4

15.09.2022 meeting with the County governor (Statsforvalter)

- The County Governor is opposed to establishing the facility within the wildlife reserve. The area has RAMSAR status. Anchoring within the wildlife reserve may be permitted, provided there is sufficient justification.
- The County Governor will assess the facility following Section 49 of the Nature Diversity Act, "waste in protected areas." Information must be provided about where the seaweed biomass will end up. This assessment can be made based on current site measurements. The evaluation must be carried out if the facility is located near the protected area.
- County Governor is generally positive toward the project but is opposed to the facility encroaching on the protected area and prefers that the facility be shifted toward the military's area.

06.10.2022 Meeting with Norwegian Defence Estates Agency (NDEA), followed by an application for the release of part of area T15 (Fig. 6) for the establishment of aquaculture, which was **denied on 26.01.2023**. The motivation behind this application was to safeguard areas for scaling up the seaweed cultivation in the same location in Frohavet. The refusal to expand operations within T15 in Frohavet, an area of several stakeholders and a conflict of interest, will have consequences for future plans of scaling:

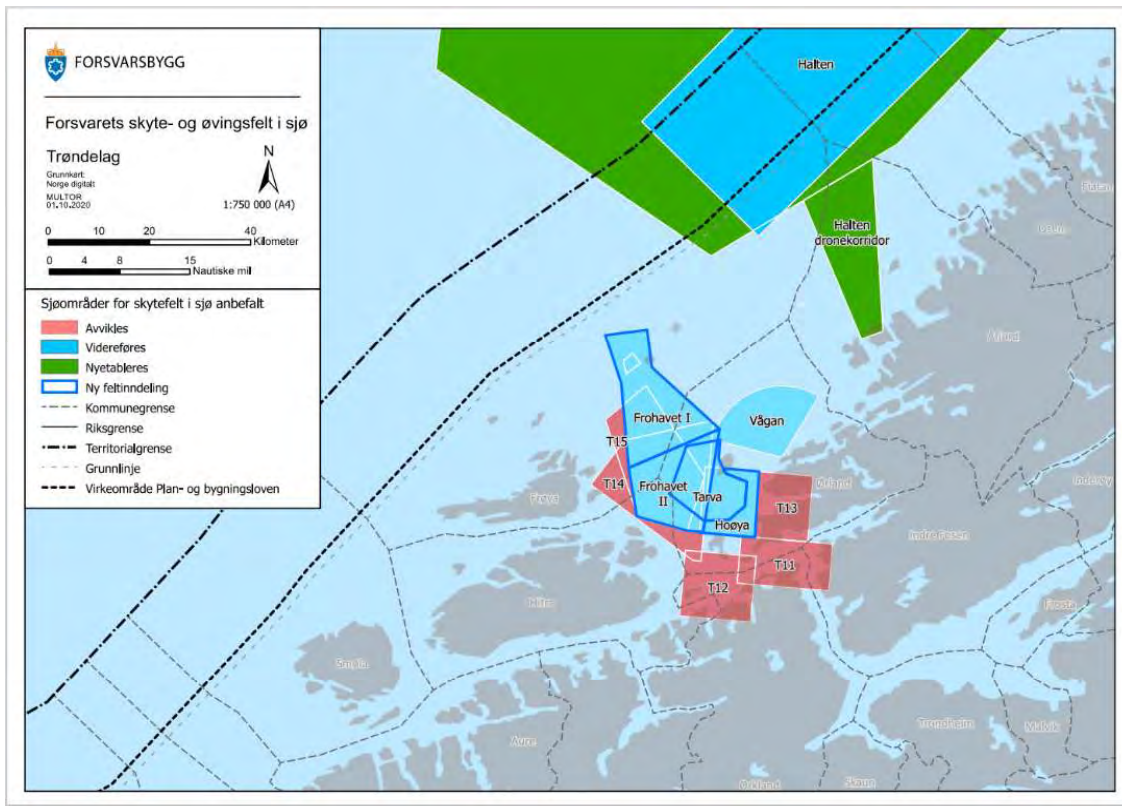


Figure 6 T15 area for possible expansion of Storflua license, denied

18.10.2022 Meeting with TFK (Trøndelag County authorities/Fylkeskommunen) to provide an update on the process and status so far, in preparation for the final and submitted application. TFK was informed about plans to expand the cultivation area. However, the Military had denied our request at this stage – T5 could be made available for seaweed aquaculture when the agreement to discontinue military operations there was formally agreed.

25.10.2022 The RI Seaweed application for an offshore cultivation license in Frohavet was submitted to Trøndelag Fylkeskommune (TFK), which promptly quality assured the application and forwarded it to Frøya Municipality and the relevant sector authorities.

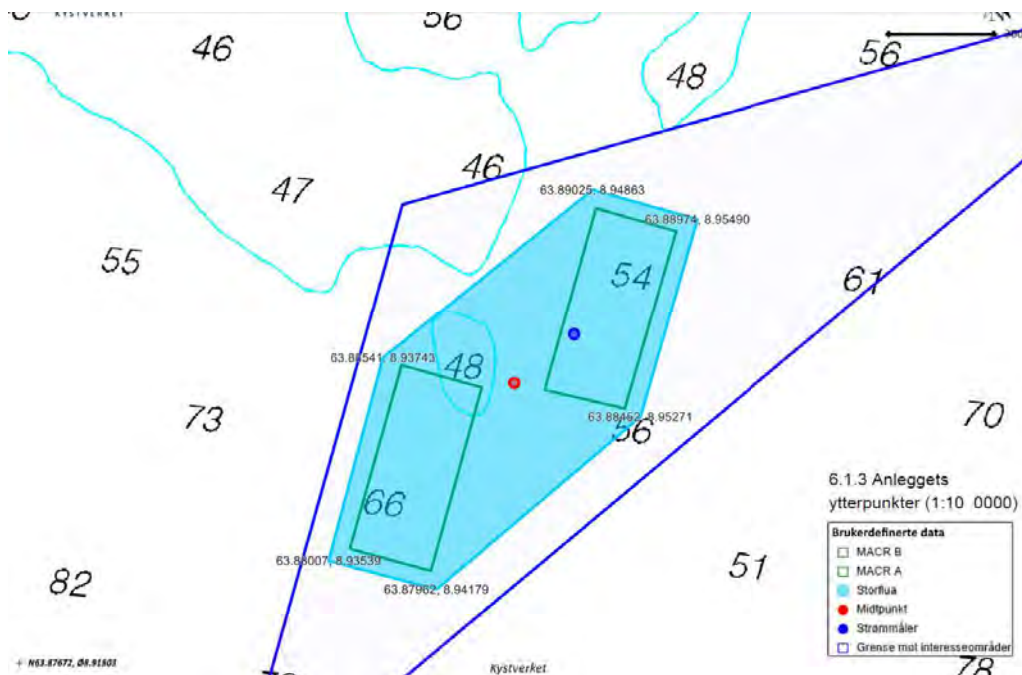


Figure 7 Proposed location (Storflua) and rig placement as applied for shown in cyan inside the triangle outlined in Fig.5 with two rigs/seafarms

04.11.2022 Frøya Municipality made the application available for public consultation for four weeks.

The public consultation provided comments from the local fishermen's association, followed by a Unanimous Decision by the Main Committee for General and Technical Services in Frøya Municipality on 13.12.2022

- Frøya Municipality recommends that SINTEF Ocean AS be granted permission to establish a site at Storflua, but that the facility be relocated approximately 1,000 meters northeast toward Storflua.
- Coexistence with the fishing industry is encouraged (as mentioned in the statement from the Fishermen's Association of Mid-Norway).
- Cleanup required after 10 years of operation.

Assessment:

Frøya Municipality views this project very positively and wishes for SINTEF Ocean AS to have the opportunity to carry out their project. Still, considerations must be made for the fishing industry. Therefore, it is recommended that the facility be moved approximately 1,000 meters northeast toward Storflua. However, it must not be moved so far northeast that it ends up within the protected area (Froan Wildlife Reserve) or the military firing range.

Due to the remarks from the local fishermen's association, SINTEF had to follow up on that.

12.01.2023 SINTEF meets with the local fishermen's association to discuss the remarks from the Local Fishermen's association during public consultation and find common ground.

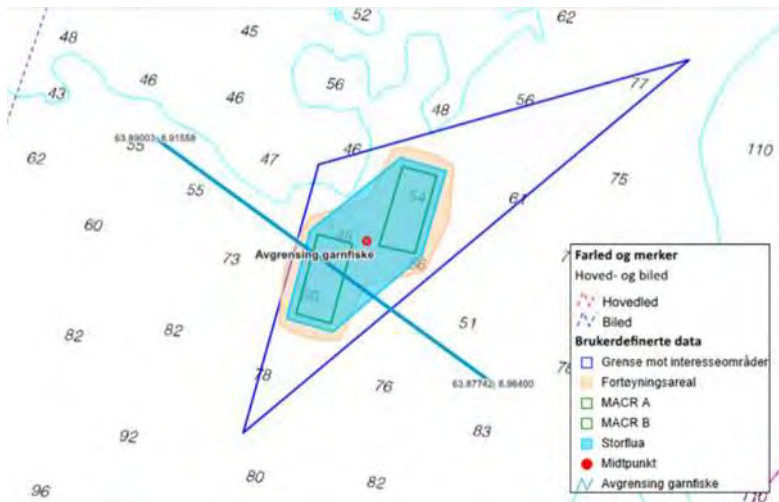


Figure 8 Fishermen's associations proposed a reduction in the area marked by the blue line

- SINTEF Ocean does not want to move the facility into the protected area, or in any other way come into conflict with the protected area (see Figure 5)
- SINTEF Ocean will look at opportunities to push/adjust the facility's actual location within the applied area, to reduce the loss of fishing grounds (especially applies to gillnet fishing in the southwest). This will be discussed in detention.
- SINTEF Ocean is open to looking at the possibility of opening up for fishing closer to the facility than 100 m (§18 general fishing bans up to 100 m from aquaculture facilities)
- Choice of anchor: SINTEF Ocean will investigate the possibility of using anchors that do not hook easily into nets. Will consider using eye bolts instead of T-bolts when fastening in rock. Will use plough anchors on soft bottom; this has few hook points if appropriately mounted.

After the public consultation, the sector authorities, per procedure, have 4 weeks to process the application. However, the County governor can apply for an extension, which they did in this case, with a formal notification received on **24.01.2023**, with an unknown date for finalisation on their end. Based on experience, this extension can last between 3 and 6 months.

01.02.2023: Another meeting with the Norwegian Fishermen's Association to follow up on remarks and previous dialogue, focusing on finding solutions to accommodate their request to relocate the seafarm infrastructure north for the blue line shown in Figure 8 above.

05.05.23 SINTEF's proposed solution, shown in Figure 9, moves the southwestern most part of the kelp farm and seabed area approximately 250 meters northeast, thus accommodating about 50% of the Fishermen's Association's request. Rigs A and B have been reduced in width and/or length and shifted toward the northeast. The seabed area has been reduced from 80 ha to 74.5 ha and has been shifted northeast.

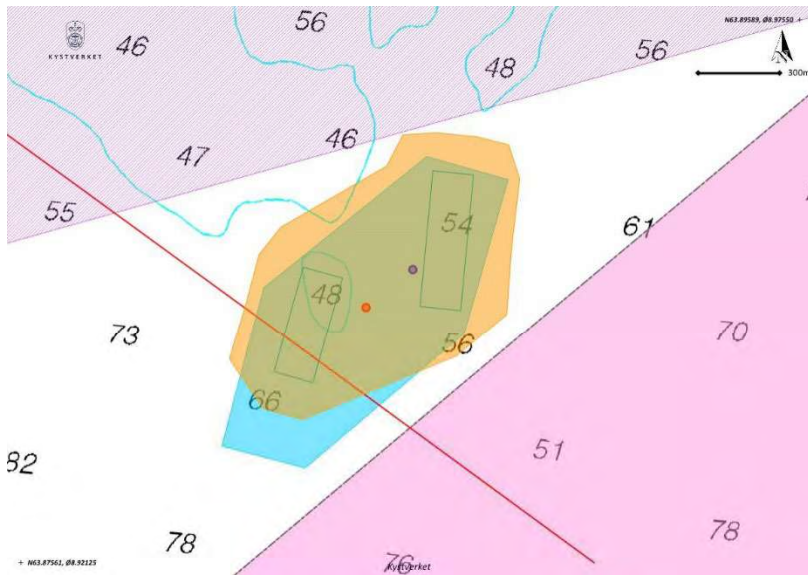


Figure 9 The red Line shows the boundary and requirement set by the Fishermen's Association.

The figure above shows the applied surface area (blue shape), revised seabed area (orange shape), revised positions for rig A (south) and rig B (north) (green outline), centre point of the facility (red dot), and the location for measurements of currents (blue dot). The line indicating the Fishermen's Association's preferred boundary for the facility's location is shown with a red line. On the base map, the area for the Froan Wildlife Reserve is marked with a buff area in the northwest, and the military area is shown with a pink area in the southeast.

The Norwegian Fishermen's Association did not accept our proposal, and the dialogue continued into June 2023 before we reached an agreement.

16.06.2023 SINTEF notified Trøndelag county authorities about the final changes agreed with the Fisheries Association to be formally implemented in the application, allowing the licensing process to proceed.

The area after the adjustment is shown in the Figure below. The adjustment involves the removal of the southern facility rig (Rig 1 in Fig 8) and a corresponding reduction in the applied surface and seabed areas. The adjustment has been made to accommodate the request from Nord Fiskarlag to avoid conflict with gillnet fishing taking place south of the red line indicated in Fig. 9.

The surface area has been reduced from 64 hectares to 20.5 hectares, and the seabed area has been reduced from 74 hectares to 36.6 hectares.

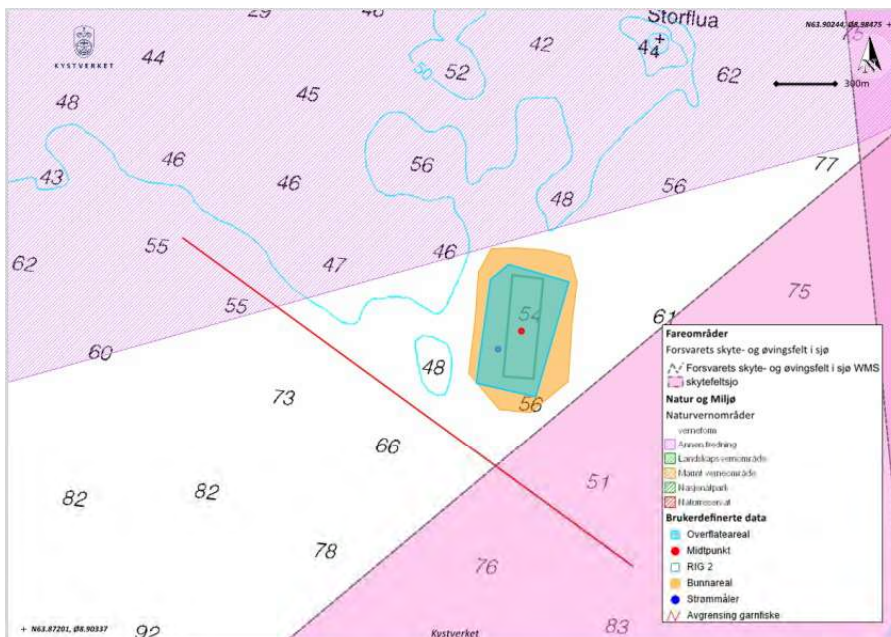


Figure 10 Final adjustment and reduction to the applied area for seaweed aquaculture

The result was a reduction in the size of the licence, and moving away from the module concept left only the physical space to install one seafarm, also referred to as Ocean Cultivation Unit (OCU).

2.5 License approval

25.07.2023 [Tildeling av tillatelse til etablering av lokaliteten Storflua](#)

Other species

In its decision dated March 6, 2023, the Directorate of Fisheries granted an exemption from the prohibition on holding multiple species under the same permit. The exemption applies to the following species:

- **Sugar kelp** (*Saccharina latissima*)
- **Winged kelp** (*Alaria esculenta*)
- **Oarweed** (*Laminaria digitata*)
- **Laver/Nori** (*Porphyra/Pyropia spp.*)
- **Dulse** (*Palmaria palmata*)
- **Irish moss** (*Chondrus crispus*)
- **Sea lettuce** (*Ulva sp.*)

In addition to the process with the fishermen's association, several additional requirements were imposed by sector authorities during the licensing process.



2.6 Required monitoring and surveys

Environmental monitoring program at Storflua

The Tøndelag County Authority, in consultation with the County Governor, may require environmental investigations before site allocation and during operation. Storflua kelp farm was granted “Permit for activities under the Pollution Control Act” by the County Governor of Trøndelag in 2023. The permit states the following requirements:

- In the area of influence outside the immediate zone of the kelp farm, the status of the deep water, soft-bottom fauna and sediment must be ‘good’ (status class II) or better according to the Water Framework Directive.
- Deposition or loss of organic material must not lead to negative changes in biodiversity at or near the farm.
- The beach zone in the vicinity of the facility must not be visibly affected by discharges or other pollution from the facility.

NIVA and SINTEF designed a monitoring program in line with the requirements specified in the permit, which also included a more detailed survey of the biodiversity related to the kelp farm as an artificial habitat. The program was sent over to the County Governor, who commented on the position of some of the monitoring stations but had no further comments. Please see the technical report for WP5 for the details.

Additional surveys

Additional surveys were carried out before kelp farm deployment as a part of the license application process, including the following elements:

- Current measurements (Åkerblå 2022)
- Bottom mapping with multibeam (Åkerblå 2022)
- Investigation of sediment characteristics (Åkerblå 2022)
- Mapping of seabed/natural habitats with ROV at anchor points (Åkerblå 2023)
- Modelling of organic particles from the kelp farm (SINTEF 2022)

The seabed in the areas affected by the anchor points was surveyed using a remotely operated vehicle (ROV) to map the presence of vulnerable species and habitat types.

Marine archaeological survey

On November 15, 2022, the NTNU University Museum submitted a request for a marine archaeological survey in connection with SINTEF Ocean AS's application for the establishment of an aquaculture facility at the Storflua site in Frøya Municipality.

This Survey was postponed until the conflict with the fishermen’s association was resolved. On June 28, 2023, Nordic Subsea AS conducted a remotely operated vehicle (ROV) survey of the anchor points for the planned facility. On July 9, 2023, NTNU University Museum was given access to the video footage from the



study for review, to assess the presence of underwater cultural heritage. NTNU University Museum has reviewed the video material and has not identified any underwater cultural heritage or anomalies that could represent such.

In addition, on 02.02.2023, we received a notification concerning future applications for aquaculture.

Risk Assessment in Aquaculture Applications – Corals and Vulnerable Biodiversity

“The County Governor of Trøndelag and Trøndelag County Authority wish to strengthen the knowledge base regarding the impact on vulnerable species and habitats in connection with the processing of aquaculture applications. Current knowledge about the presence of valuable and vulnerable species in the marine environment is very limited. We therefore require that future applications include an assessment of the risk that the aquaculture facility may conflict with vulnerable species and habitats. The result of the risk assessment will determine whether a physical survey is necessary”.

2.7 Scaling estimates

Please see the Final Report JIP Seaweed Carbon Solutions for a discussion around estimated costs of scaling the seafarm to accommodate a biomass production towards the demonstration scenario of 10.000t/WW

Table 1 Estimated CAPEX for scaling the ocean cultivation units towards a 1M/tonnes sceanrio

Ocean cultivation Units/Seafarms	Capacity tonn/y	Estimated CAPEX
SINTEF pilot - Storflua	500	10-12 MNOK
Industry case	26,000	0,5-0,7 MRDNOK
Upscaled industry case	100,000	2-3 MRDNOK
Roadmap goal 1Mtonnes	1,000,000	20-25 MRDNOK

Copied from Almås et al. [Veikart for industriell dyrking av tare i Trøndelag - SINTEF](#)

Applying an optimised sea farm capacity of 500 tonnes WW, and based on SCS JIP data, the next offshore cultivation rig is estimated to cost 10MNOK installed .

Budget estimations for major items (sea farm and biomass production) in a demonstration phase with a production of 10.000tonnes WW is included, based on the data we have from the JIP Seaweed Carbon Solutions project, note that these are not commercial prices.

In dialogue with a commercial producer, outsourcing the production of 500 tonnes WW over 2years (250t/Y), the cost of production until acid preserved at the dock, would cost approx. 11.5MNOK in a first estimate. Leaving us with a current price of 23NOK/kg for near shore cultivation. The estimate does not include any optimisation of yield or technology, hence possible cost reductions, scaling this as is to 10.000tonnes will



result in a total cost of 230MNOK for the produced biomass. By comparison, the Roadmap for industrialisation of seaweed cultivation in Trøndelag³ estimates, based on quite a few assumptions, a cost of production of biomass of approximately 11NOK/kg WW.

However, both significant technological advancements and cost reductions are to be expected as the industry develops, through optimised sea farm design and utilisation, cultivation methods, increased yields and cost of production, enabling scaling and exploiting economies of scale.

All SCS JIP numbers (RnD) should be reviewed and compared with realistic market prices before any significant scaling can be justified.

3 Changes and amendments

- 10.11.2022 The formal decision to change the location was voted on in the JIP Steering Committee ([Endringsordre](#)) From MRFK to TFK
- Reduced area and sea farm adjusted to meet requirements from stakeholders during the licensing process

4 Discussion

4.1 License application, site and upscaling

The license application had to be adjusted and changed several times during negotiations with the Fishermen's Association. The final version, dated June 23, 2023, is the version approved by Trøndelag County authority. Storflua is approved for an area of 20.5 ha, and the permit is limited to "emissions" from the cultivation of macroalgae corresponding to an annual production of 800 tonnes WW at the site. Still, this represents a significant reduction from the initial plans for the SCS project, both in terms of size and related production volumes.

The permit allows for the cultivation of several species at the site. The permit does not allow for areal expansion of the site without a further application and licensing process. Expanding the surface area of the farm involves taking into consideration areal conflicts with marine protected areas and possible future expansion of these, as well as military activities (cf the report from WP2). Requirements from the County Governor, applying to future license applications and applications for expansions of the site, further involve mapping impacts of seaweed cultivation on corals and other vulnerable species.

The biomass yield from Storflua seems to be relatively high, but there might be other exposed sites that are more easily operated. Selection of a new site involves LCAs for design, construction, and choices of materials, and thus involve substantial costs even in planning.

³ [Veikart for industriell dyrking av tare i Trøndelag - SINTEF](#)



4.2 Potential for seaweed aquaculture with offshore wind/energy and repurposing of existing offshore O&G assets

Both large-scale and extensive seaweed aquaculture planning must consider co-existence with other marine industries, in particular in context of the “30x30”-target of 30% protection and 30% restoration of all sea and land areas by 2030 in the Kunming-Montreal Global Biodiversity Framework. The potential for Integrated Multi-Trophic aquaculture with salmon and kelp has been evaluated previously⁴ and though a lot of research remains along this line, we will focus on

- Evaluating the possibility of integration with and repurposing of existing offshore oil and gas assets for seaweed aquaculture.
- Evaluating the potential benefits of integrating with offshore ocean wind energy farms.

4.2.1 Repurposing and integration of O&G assets for seaweed aquaculture

One advantage of siting large-scale seaweed aquaculture in offshore conditions is that the natural potential for biomass production seems to be greater there⁵. The cultivation trials at Storflua indicate that this hypothesis, based on the state-of-the-art knowledge and ocean modelling, may indeed be correct. Some disadvantages are loss of accessibility and greater bottom depths. The latter is technically challenging, and both are challenging in terms of economy and the energy (carbon) requirements for farm installation and operation.

Integration of seaweed cultures with already existing O&G installations might provide mooring options that are a lot cheaper than siting aquaculture by itself. In terms of operations, already existing infrastructure and operational routines might be an advantage in O&G areas to other offshore regions. There might be restrictions related to safety, operations of and access to the O&G installations. Repurposing O&G facilities that will be shut down to operations would be an advantage as there will be less conflict between operations. Thus, by integrating activities, existing O&G installations may serve as operational hubs, and might even offer helipads for easy (though costly) access of personnel.

There is a risk that crude oil from spills or leaks or produced water components from oil production might be taken up in cultivated seaweeds. Some seaweed species, in particular kelps, have a relatively low lipid content, so that bioaccumulation of, e.g., PAHs may not be a great problem. Monitoring of the chemical composition of the biomass is necessary regardless of the locations, but maybe special care should be taken if the seaweeds are grown in the vicinity of O&G facilities.

4.2.2 Co-existence and integration of ocean energy with seaweed cultures

Co-use of ocean areas for seaweed cultivation and offshore wind has been discussed ever since “modern” (2008-present) large-scale seaweed aquaculture was first suggested. As for O&G there are many apparent advantages of co-siting apart from better area use, like common infrastructure, safety procedures, and

⁴ Broch OJ et al (2013) Modelling the cultivation and bioremediation potential of *Saccharina latissima* in close proximity to an exposed salmon farm in Norway. *Aquacult Environ Interact* 4:187-206 doi: 10.3354/aei00080; Fossberg J et al (2018) The potential for upscaling of kelp (*Saccharina latissima*) cultivation in salmon-driven integrated multi-trophic aquaculture (IMTA) *Front. Mar. Sci.* 5:418; doi:10.3389/fmars.2018.00418.

⁵ Broch OJ, Alver MO, Bekkby T, Gundersen H, Forbord S, Handå A, Skjermo J, Hancke K. (2019) Kelp cultivation potential in coastal and offshore regions of Norway. *Front. Mar. Sci.* 5:529; <https://doi.org/10.3389/fmars.2018.0059>



logistics. Obvious disadvantages are the need to consider conflicts between the moorings and operations of the seaweed and wind farms. One should also consider potential stakeholder conflicts, within the ocean wind regions, between seaweed aquaculture and other marine interests and industries like fisheries.

In order to optimize technical solutions, management, logistics and area use, it is important that any area for combined seaweed and wind farming is planned as such from the beginning. Adding seaweeds as an “afterthought” will potentially diminish the added value substantially.

Ocean wind farms (OWFs) are sited offshore and hence in exposed conditions. We have seen in Section 2 that generally speaking offshore conditions may sustain a high seaweed biomass production. Presently, an area of around 56 000 km² is presently being considered for potential offshore wind siting⁶. Hence there is a huge potential for seaweed cultivation in ocean wind regions. Examples of the simulated kelp cultivation potential in three (more or less randomly) selected regions being considered for OWF are given in Fig. 11, based on the same data as Fig. 1. Allocating 1 % of the area in each of the regions in Fig. 11 to kelp cultivation might yield around 1 million t fresh weight kelp (using the average production figures from each region for the period September-June), which is enough to cover the kelp biomass needs for many years. Ocean wind turbines are sparsely distributed within their allocated area (~1 km or more between each). This indicates that co-siting of OWF and kelp cultures is feasible, even if ample space is allocated to safety distances, operations and logistics.

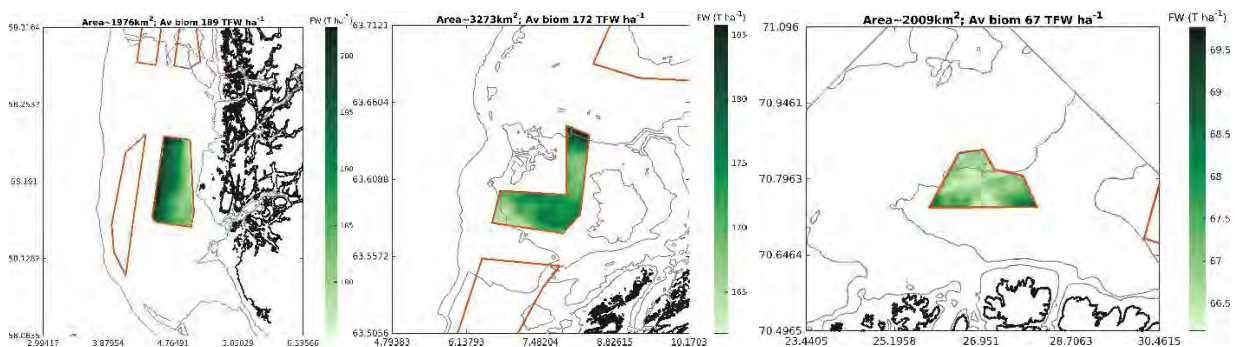


Figure 11. The simulated kelp (*S. latissima*) cultivation potential in three selected regions identified for potential ocean offshore wind siting (Source: NVE, <https://veiledere.nve.no/havvind/strategisk-konsekvensutredning-av-vindkraft-til-havs-del-1/kart/interaktivt-kart/>). Left: Vestavind G. Middle: Nordvest B. Right: Nordavind B. The areas of the regions displayed on top are not quite accurate.

In terms of carbon uptake and sequestration potential, the “1 % of the areas” may sustain a potential carbon sequestration of > 12, 000 t C in addition to the 30,000 t C captured in the biomass (Table 1). This might contribute to the total carbon balance of the OWF regions.

Seaweed aquaculture contributes several ecosystem services that might contribute to offsetting detrimental effects of OWF. These include increased O₂-concentrations, higher pH, and habitats for pelagic organisms.

⁶ See the interactive map of NVE: <https://veiledere.nve.no/havvind/strategisk-konsekvensutredning-av-vindkraft-til-havs-del-1/kart/interaktivt-kart/>



Whether seaweed cultures forming an “artificial” habitat for e.g. small fish etc should be considered solely a benign effect is a matter of debate and definition.

Table 1. The potential for biomass cultivation yields, carbon uptake and -turnover for the three regions indicated in Fig. 1. The calculations for “passive” release of C to the ocean are based on Neves et al (2025)⁷

Using ~1 % of the areas in Fig. 1	
Wet weight biomass cultivation potential (harvested/harvestable)	1,000,000 t FW
Dry weight biomass (assuming 10 % dry matter content)	100,000 t DW
Carbon in biomass at harvest (assuming 30 % C in dry matter)	30,000 t C
CO₂ equivalents in biomass at harvest	110,000 t CO₂
Particulate Organic Carbon released to the ocean during cultivation “passives”	7,800 t C
Dissolved Organic Carbon released to the ocean during cultivation, “passives”	5,000 t C
Total carbon released to the ocean during cultivation	12,800 t C
Total CO₂ equivalents released to the ocean during cultivation, potentially sequestered	46,000 t C

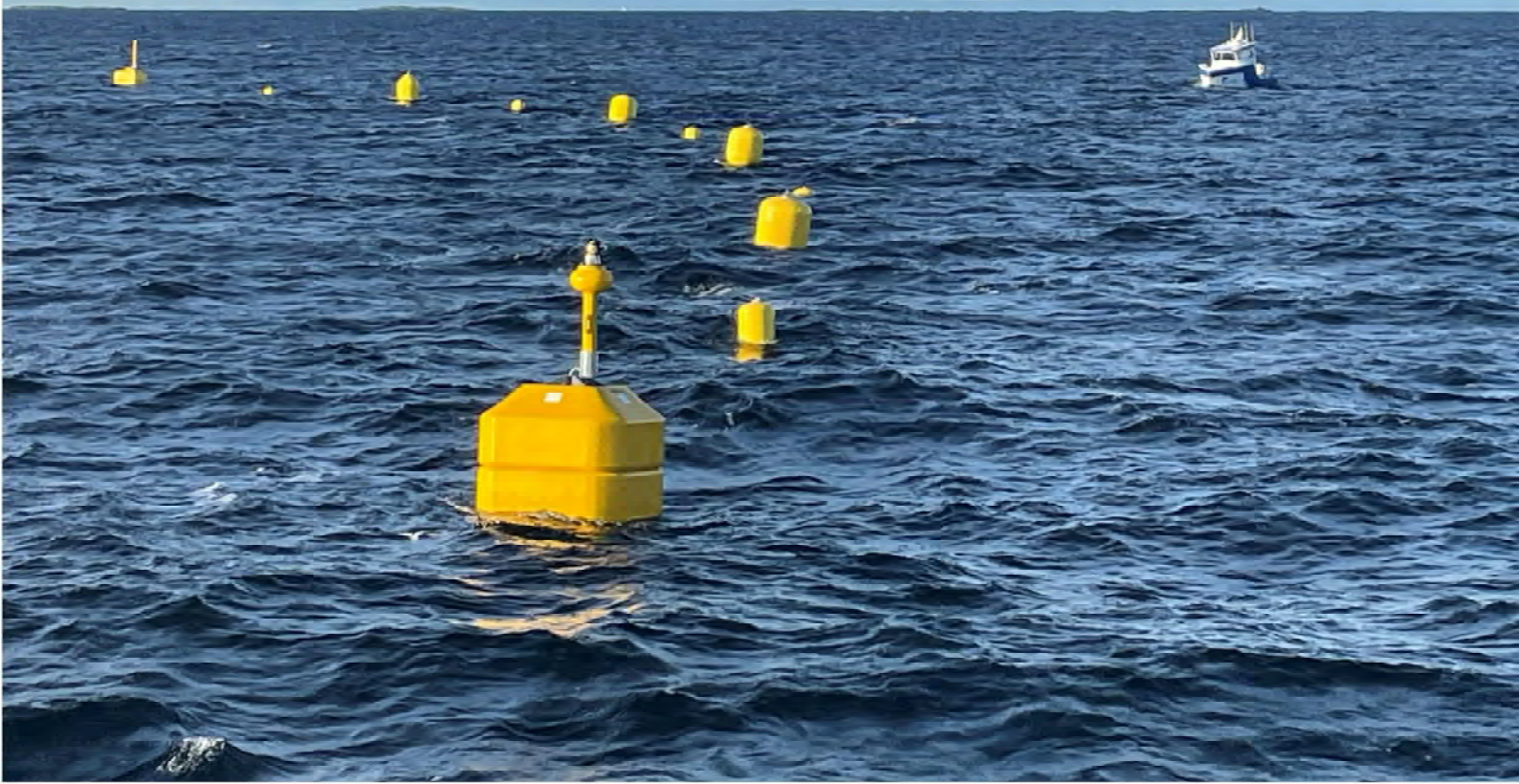
5 Outlook and Recommendations

- Future management of areas for seaweed aquaculture, both inside and outside of the baseline, should allow for sufficient space to develop seaweed aquaculture. Sound planning will streamline the permit application process and minimize the potential for conflicts.
- Areal planning should consider areas suitable for seaweed aquaculture, and in particular areas that might need have other properties than traditional finfish aquaculture. For example, seaweed aquaculture requires a sufficient supply of dissolved nutrients, an aspect not relevant for salmon aquaculture.
- Co-use of areas for, e.g., seaweed aquaculture and ocean energy production should be considered. Benefits are easier handling of logistics, safety, and infrastructure, and a better use of the allocated areas.
- One to a few percent of the area in each of the regions presently being considered for ocean offshore wind are sufficient for production of the seaweed biomass needed in the foreseeable future, not taking into account specific properties (e.g. nutritional content) of the biomass.

⁷ Neves L, Smeby K, Broch OJ, Johnsen G, Ardelan MV, Skjermo J (2025) Particulate and dissolved organic carbon losses in high latitude seaweed farms *Sci. Tot. Env* 982:179677 <https://doi.org/10.1016/j.scitotenv.2025.179677>



SINTEF



Report

JIP Seaweed Carbon Solutions WP2 Offshore pilot farm design, installation and operations – FINAL REPORT

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WP2 Offshore pilot farm design, installation and operations – FINAL REPORT

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SUMMARY

This report covers the work performed in work package 2 (WP2) of the JIP Seaweed Carbon Solutions project. The purpose of this report is to document and describe the rationale, criteria, principles, assumptions, and constraints used for the engineering, procurement, construction and installation activities for the seaweed cultivation rig for location "Storflua". Furthermore, the report describes the current methods for operating the Offshore Cultivation Unit (OCU) at Storflua and the operational challenges. Finally, the report addresses the areas for improvement and proposes solutions for further improvement of cultivation technology and operational methods.

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1 Introduction

The seaweed cultivation rig at Storflua is part of the research infrastructure in the Norwegian Seaweed Centre (RI Seaweed). SINTEF Ocean has received funds from the Research Council of Norway (RCN) to establish a research infrastructure for seaweed cultivation and utilization technologies—RI Seaweed, Figure 1. The research infrastructure includes an offshore (exposed) seaweed cultivation unit. The cultivation area is located in the ocean area Frohavet outside the coast of Trøndelag, Mid-Norway.

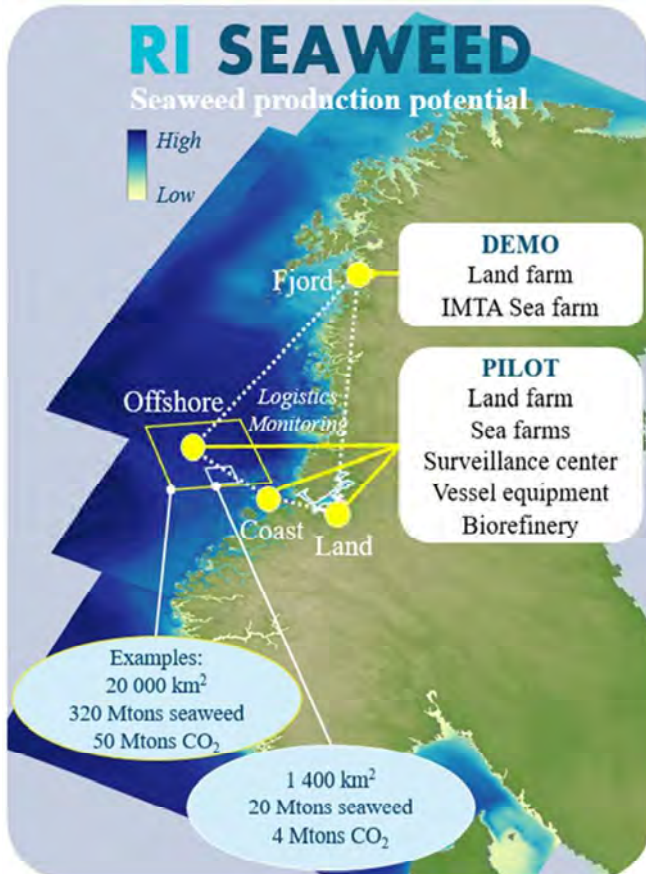


Figure 1: Index for seaweed production potential, geographical placement of RI SEAWEED nodes and examples of area requirement.

Cultivation models for seaweed, developed at SINTEF Ocean, show that there are very good growth conditions for seaweed along the Norwegian coast (Broch et al., 2019). The combination of more favourable light conditions, lower summer temperature and access to nutrients in open sea areas (no stratification, upwelling, etc.) improves growth and reduces the risk of unwanted fouling based on the experience gained in the Faroe Islands at the exposed cultivation sites. The open ocean cultivation with better growth and less fouling allows for an extended cultivation season and potentially multiple annual harvests, and thus better utilisation of farm infrastructure and ocean space. Cultivation in open sea areas will require development and testing of new robust and cost-effective seaweed farms concepts, both in terms of structural integrity of the facilities and in performing cost-efficient operations under demanding weather conditions.

The research infrastructure in the RI Seaweed project will be made available for users from research, education, and industry for cultivation experiments. The joint industry project (JIP) Seaweed Carbon Solutions (SCS) will be the first user of the seaweed cultivation rigs. The SCS project aims to demonstrate

reduction of atmospheric GHG through offshore ocean seaweed farming and conversion to climate positive products or solutions.

The JIP Seaweed Carbon Solutions is a project that will design, build, operate, and assess offshore large-scale seaweed production for carbon capture and storage as a climate-positive solution. The project aims to develop a framework and model for sustainable and efficient carbon extraction from the biosphere and explore alternatives for permanent storage on land or at sea.

Seaweed Carbon Solutions is a "joint industry project" (JIP) funded by partners SINTEF, DNV, Equinor and Lundin Energy. See project webpage for more information about the project:

<https://www.sintef.no/en/projects/2021/seaweed-carbon-solutions-jip/>

Furthermore, the Seaweed Carbon Solutions project aims to further develop the seaweed farm concept for industrial seaweed cultivation. This includes possible modifications to rig arrangement and development of mechanised and (semi) automated solutions for seeding/deployment and harvesting seaweed. Further, the project will test and evaluate sensors and instrumentation to be used for monitoring environmental conditions, biomass growth, and structural integrity of the rigs.

This report covers the work performed in work package 2 (WP2) of the JIP Seaweed Carbon Solutions project. The purpose of this report is to document and describe the rationale, criteria, principles, assumptions, and constraints used for the engineering, procurement, construction and installation activities for the seaweed cultivation rig for location "Storflua". Furthermore, the report describes the current methods for operating the Offshore Cultivation Unit (OCU) at Storflua and the operational challenges. Finally, the report addresses the areas for improvement and proposes solutions for further improvement of cultivation technology and operational methods.

2 Design and engineering of seafarm

2.1 Site location – Storflua

The cultivation site is located in Frohavet outside the coast of Trøndelag county, Norway, Figure 2. The cultivation area is bound by a nature reserve in the north, a white sector, i.e., a lighting sector that define safe routes for marine traffic from the navigation light at "Gjæsingbogen", on the west side and a military training area in the south. The military training area is planned to be abandoned, opening for a future expansion of the cultivation site towards south. The current area restrictions leave a triangular area available for cultivation of seaweeds, Figure 3.



Figure 2: Location of cultivation site Storflua (indicated by red dot)

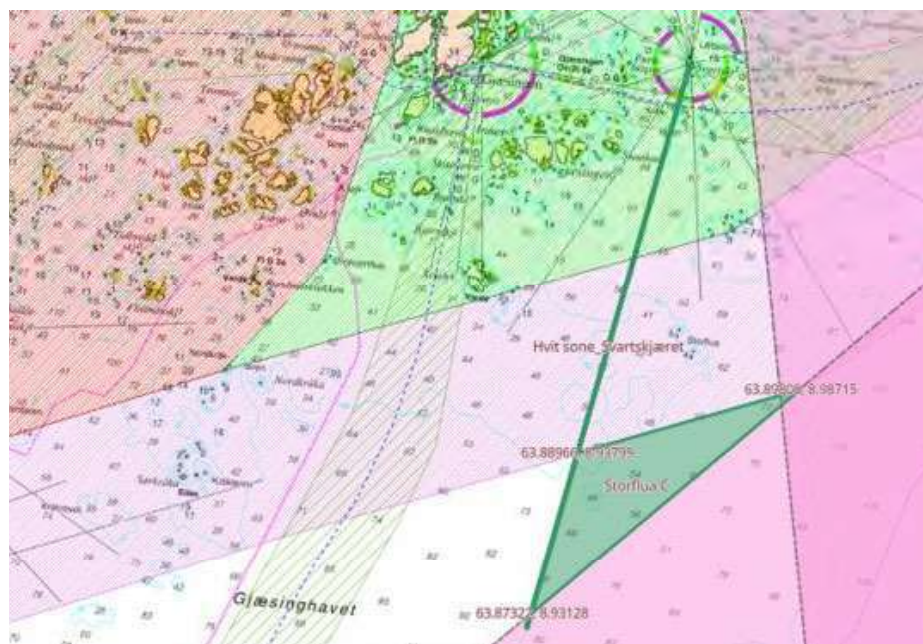


Figure 3: Available cultivation area – green triangle

Coordinates for triangular area:

WGS 84 DD.MM.MMM:

N 63 53.379 Ø 8 56.280

N 63 52.393 Ø 8 55.877

N 63 53.885 Ø 8 59.229

2.2 Concept selection and feasibility study

2.2.1 Identification of seaweed farm concepts for exposed areas

Seaweed farms for scaled industrial seaweed cultivation does not exist in Norway. The existing Norwegian seaweed farms requires various degree of manual work operations, which will not be cost-efficient for large scale production. There is a potential for scaling up the seaweed industry in Norway if cost-efficient seafarms and more mechanized and automated methods for operating the seaweed farms are developed. A further description of various available cultivation technologies could be found in the report from the Akvalab-project, (Lona et al., 2020).

The existing Norwegian seaweed farms are placed in relatively sheltered waters. The semi-rigid arrangement of these seaweed farm concepts, with tensioned cultivation ropes in the most wave affected zone, may make these concepts unsuitable at more exposed locations. The cultivation rig used by Ocean Rainforest (ORF), with vertical cultivation ropes, has been demonstrated for rough weather conditions. In addition to potentially reduce spatial occupation, another advantage with this concept is that the rig partly enters into a "survival mode" in rough weather conditions, by allowing the vertical cultivation ropes to partly deflect in rough weather conditions. This effect likely reduces the total hydrodynamic loading on the seafarms, which means the seafarms potentially could be designed with fewer and smaller anchors and reduced rope dimensions compared to seaweed farm concepts with horizontal ropes and similar biomass.

2.2.2 Concept selection

The seaweed cultivation rig for the exposed test site at Storflua is based on Ocean Rainforest's cultivation rig system, the Macroalgal Cultivation Rig (MACR), which is a well proven concept for seaweed cultivation in harsh weather conditions (Bak et al., 2018).

As stated by Ocean Rainforest, *"The offshore MACR has proven itself to be the 'first of its kind' open ocean seaweed cultivation system in the world with higher growth rates and lower costs than other known offshore systems for similar seaweed species"* (Bak et al., 2020). The system is scalable. Over the years, modifications to the original system have been made to meet site specific characteristics, to reduce the number of anchors and chains used and to reduce spatial occupation (Marsman et al., 2023). A further description of the MACR, hereafter denoted Storflua OCU (Offshore Cultivation Unit) is given in Section 2.4.

2.2.3 ORF feasibility report

A feasibility study was conducted by ORF concluding that seaweed cultivation with the MACR were feasible at the Storflua site. Further details could be found in (Marsman et al., 2023).

2.3 Design basis

A design basis outlining the design criteria, principles, assumptions, and constraints for design, planning and installation of seaweed cultivation rigs for the location "Storflua", was established prior to the design phase (Lona, 2022).

The following aspects are considered in the design specification:

- Description of the cultivation site
- Environmental design conditions
- Soil conditions and bathymetry
- Design code, design principles and governing regulations
- Project specific HSE (Health, Safety and Environmental) requirements

The guidelines and requirements outlined in this design specification were used as basis for the final design and planning of installation activities to ensure that relevant regulations and project specific requirements were met.

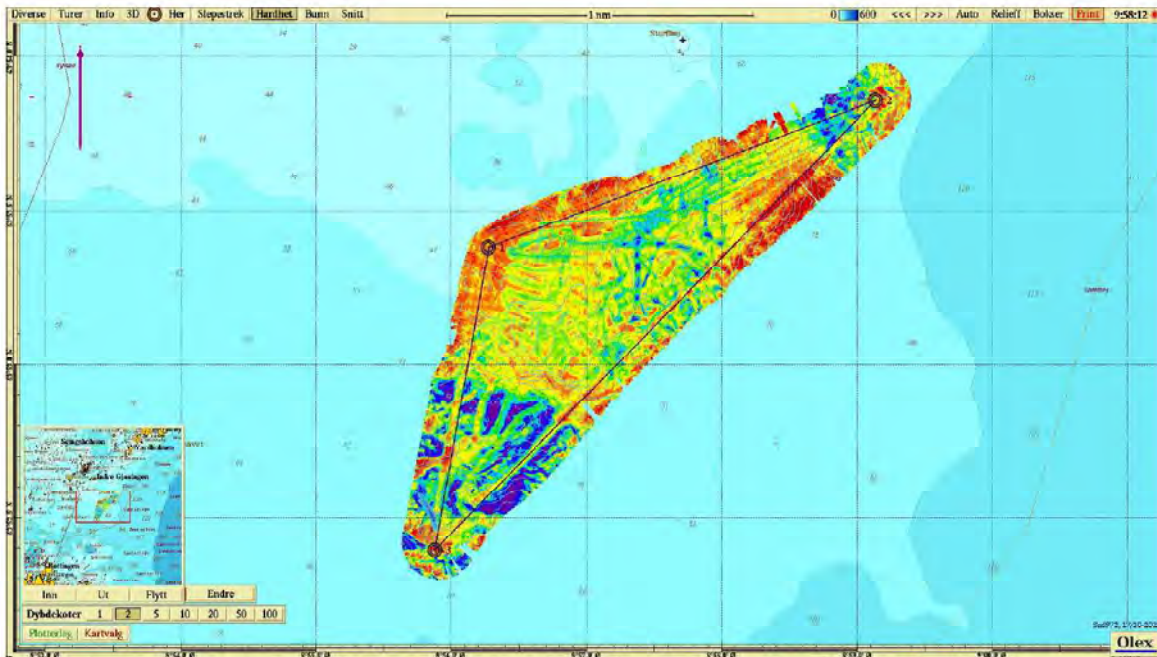
2.3.1 Seabed bathymetry and soil conditions

Seabed surveys have been performed by the company Åkerblå, (Åkerblå AS, 2022a, 2022b), including bathymetric mapping and seabed grab samples. The seabed depth varies from 46 to 91 m within the triangular area. See report for details (Åkerblå AS, 2022a).

The multibeam surveys indicate that the seabed sediments are relatively hard (illustrated by warm colours) in the majority of the area, whereas the area in the south appears to be softer (indicated by purple colour), Figure 4. See multibeam survey report (Åkerblå AS, 2022a) for details.

In addition, a survey of the seabed sediments was performed, and a total of 20 grab samples were collected. 10 samples consisted mainly of calcareous sand (Norwegian: skjellsand), with elements of gravel and sand. 9 of the samples consisted of small rocks, and 1 sample consisted of hard rock. See report (Åkerblå AS, 2022b) for details.

The hearing process for the permit application resulted in a requirement for an additional survey concerning cultural monuments, i.e., shipwrecks. The survey involved a visual survey of the seabed along the anchor positions/trajectory with an ROV equipped with scanning sonar. This survey concluded that: «the sediment in the area consists mainly of gravel, sand and shell sand, with some sparse occurrence of larger rocks», see report (Åkerblå AS, 2023) for details.



Figur 3.4. Kartlegging av relative sedimenthardhet. Relativ hardhet er representert ved fargekoder hvor rød farge indikerer 100% hardhet, mens lilla indikerer 0% hardhet.

Figure 4: Seabed hardness (red colour indicates 100% hardness, purple colour indicates 0% hardness), Figure: Åkerblå AS

2.3.2 Waves and current

2.3.2.1 Wave conditions at Storflua

The wave conditions have been estimated based on using the third-generation wave model SWAN and detailed bathymetry of the area. The basis for estimating extreme waves for 10- and 50-years return periods is based on the Annual Maxima method, based on 10 years data (2010-2019), see Appendix A for details.

Return values of H_s (m) for 10- and 50 years:

Table 1: Estimated design waves (5m depth)

Return period	10-year	50-year
Wave height - H_s [m]	5.9	6.8

2.3.2.2 Current conditions at Storflua

According to NS9415:2021, design currents for the location should be established based on measurements.

A current meter, type RCM Blue 5430 from Aanderaa AS, was installed to measure current profiles in the period 08.09.22 - 13.10.22. The Aanderaa RCM Blue is a single point ZPulse recording current meter based on the Doppler principle (Table 2).

Table 2: Estimated design current based on current measurements (Åkerblå AS, 2020b)

Return period	10-year	50-year
Current velocity [m/s] – 5m	1,24	1,39
Current velocity [m/s] – 15m	1,08	1,21

The values for 10- and 50-years return periods for current are based on the recommendations in the Norwegian standard for fish farms NS9415:2021 "Floating aquaculture farms - Site survey, design, execution and use". According to this standard, the dimensioning value for current needs to include a multiplication factor if the measuring period is less than one year. For short measuring periods, one month in this case, the multiplication factors applied are 1,65 and 1,85 for 10- and 50-years return periods respectively, which may give unrealistic high design values. The project will investigate how to justify use of lower design values for current.

2.3.3 Rules and regulations for design of seafarm

There is no specific standard that sets requirements for the design of seaweed farms. In lack of a specific standard for seaweed farms, the common practice in Norway is to adopt relevant requirements from the governing standard for fish farms, NS9415:2021, "Floating aquaculture farms - Site survey, design, execution and use" (Norsk Standard, 2021). The purpose of this standard is to reduce the risk of escape as a result of technical failure and wrong use of marine fish farms.

Other relevant design standards for offshore and coastal structures:

- DNVGL-OS-E301 (2018): Det Norske Veritas. «Position mooring»
- BV NR 493: Bureau Veritas. «Classification of mooring systems for permanent and mobile offshore units».
- ABS - American Bureau of Shipping. «Guide for Position Mooring Systems», including ABS Guidance Notes on the Application of Fiber Ropes for Offshore Mooring (Fiber Rope Guidance Notes)

Storflua rig design is based on a combination of NS9415 and ABS, based on Ocean Rainforest's experience with rig design on the Faroe Islands and in California. The main difference between the ABS standard and NS9415 for this application, are that the ABS standard allows for a reduced safety factor on ropes compared to NS9415. On the other hand, NS9415 allows for reduced conservatism in design of anchor holding force, if anchors are proof load tested, and the ABS standard has stricter requirements to anchor design. The implementation of the different standards is further discussed in Section 2.4.

2.3.4 Marking and Aids to Navigation for Storflua seaweed farm

Seaweed farms shall be marked according to the Norwegian Coastal Administration's requirements for marking of aquaculture sea farms. The relevant legislation is "Kystverkets forskrift av 19. desember 2012 nr. 1329 - Forskrift om farvannsskilt og navigasjonsinnretninger" (Samferdselsdepartementet, 2013). (English: requirements for aids to navigation).

The legislation requires that the extremities of the seaweed farm should be marked with buoys with lights, and in some cases, Automatic Identification System (AIS) are required. In this case, where the seaweed farm will be placed close to the white sector of a nearby lighthouse (i.e., close to a safe sailing route for maritime traffic), for the Storflua seaweed farm, Kystverket (Norwegian Coastal Administration) requires that the farm shall be equipped with AIS. In addition, the facility is marked on electronic sea charts, as described in Section 3.3.2

In general, there is no requirement to mark aquaculture facilities with AIS. The project was in dialogue with the Norwegian Coastal Administration regarding the application for a cultivation permit at Storflua. The Norwegian Coastal Administration was then unsure whether they should require AIS for this facility, but they ultimately concluded that it would be appropriate to use AIS: "*Since the facility is placed in open waters where an installation is not expected, it would be appropriate for safety reasons to mark the facility with AIS.*" With two AIS transmitters, there will in principle be sufficient redundancy, provided that

inspection and maintenance of the AIS transmitters are well performed. At Storflua, the use of AIS requires batteries, and there are few suppliers of this type of solution. AIS and lights are supplied by Ovun AS (formerly Partnerplast AS), which is a recognized supplier of equipment to the Norwegian aquaculture industry. The Storflua seaweed farm aids to navigation are indicated in Figure 5.

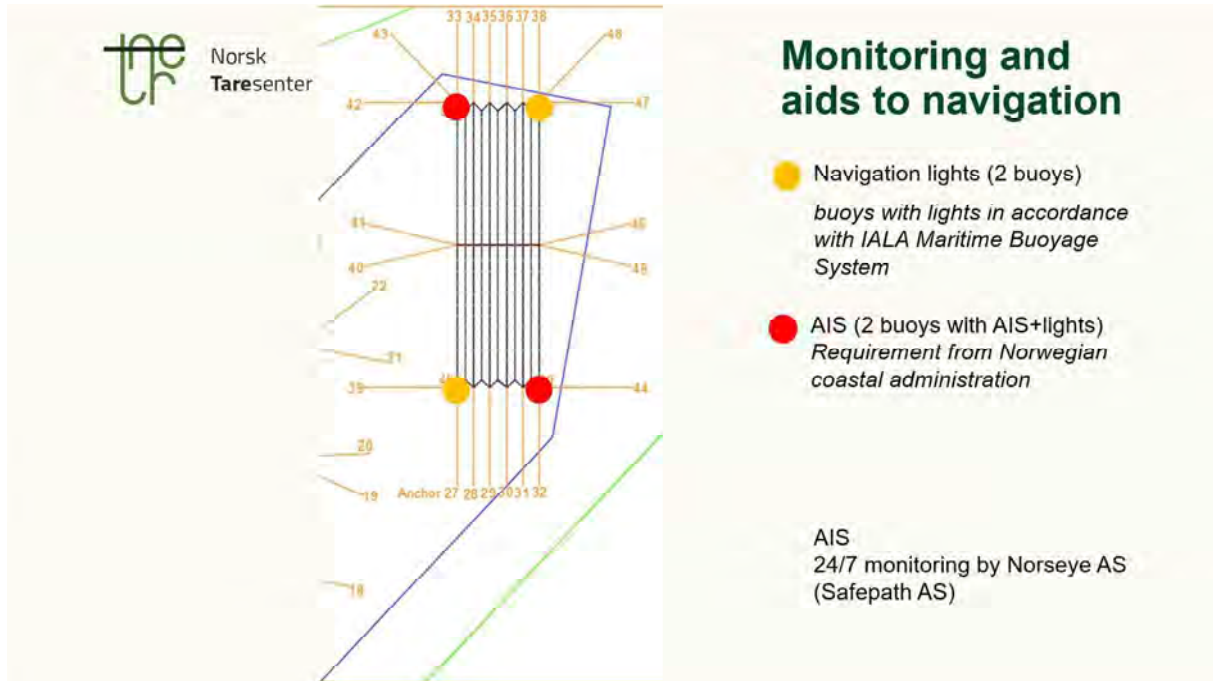


Figure 5: Aids to Navigation for Storflua seaweed farm

2.4 OCU Design and local adaptation

2.4.1 Design and engineering

Ocean Rainforest (ORF) was selected as the supplier of the OCU. The OCU design was based on ORF's MACR-3 (MacroAlgae Cultivation Rig) design, Figure 6.

The subcontract with Ocean Rainforest included:

- Engineering and consultancy services for design, installation and commissioning of a macroalgae cultivation rig (MACR) at SINTEF Ocean's cultivation location "Storflua" in Frohavet, in accordance with the established design specification (Lona, 2022).
- Delivery of all necessary materials for the macroalgae cultivation rig (MACR).

2.4.2 Ocean Cultivation Unit (OCU) general arrangement

The Storflua OCU concept use vertical cultivation lines. The cultivation ropes are suspended between the main line at 10m depth and a support line at the surface. There are a total of 11 main lines / support lines, which are connected to backbones in each end and a midbone at the centre. The mooring system consists

of 22 plough anchors. The length of the OCU is 500m and the separation between each line is 15 m, resulting in a total width of 150m. The length of each anchor line is typically three times the water depth.

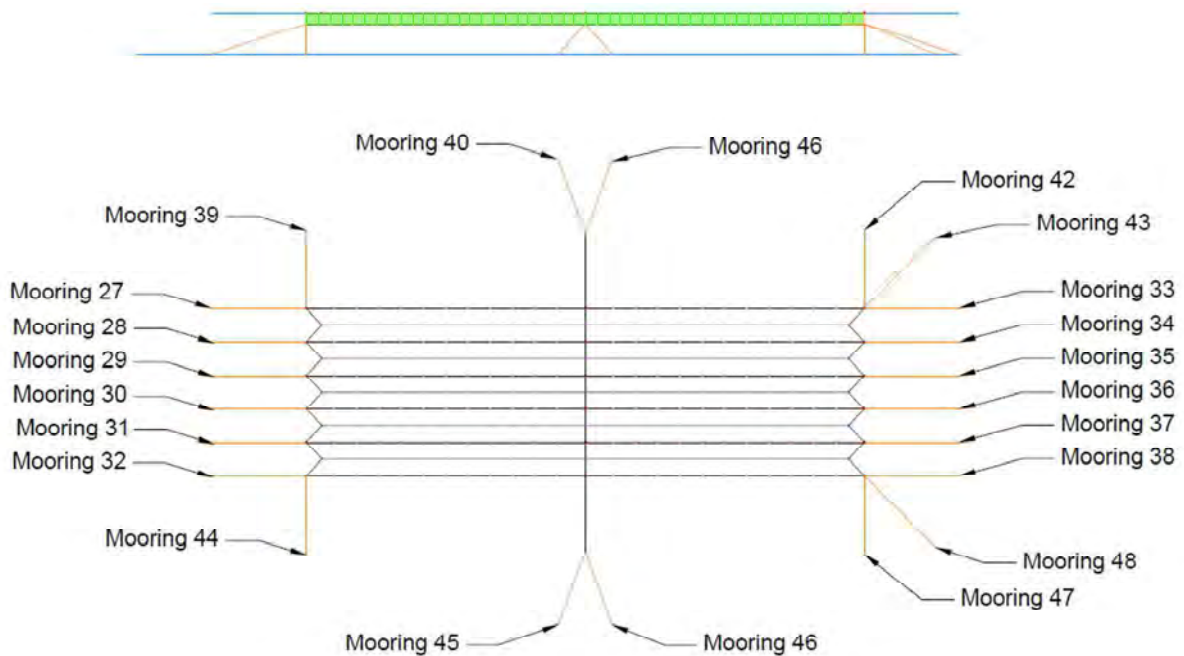


Figure 6: Storflua OCU (GA Drawing by Ocean Rainforest)

2.4.3 Positioning and orientation of the rig

The initial plans for Storflua cultivation area included 2 MACR units, with maximum utilisation of the available cultivation area, Figure 7 . ORF generally use 15-25m spacing between the mainlines depending on site conditions and local adaption of the actual cultivation unit deployed. In order to maximize the production potential at Storflua, it was decided to use 15m spacing between the mainlines for the Storflua MACR units.

“The position of the rigs is optimized 1) respecting the buffer zones, 2) having an angle around 45° from the direction at maximum current speed, and 3) no overlapping or interfering of the mooring systems. The strongest current has most often a direction from North-West to South-East or opposite. This results in the positioning of the rigs at an 55° angle from the NW-SE line, parallel to the Western border. Given these restrictions, it was only possible to fit two systems in the selected area”, (Marsman et al., 2023).

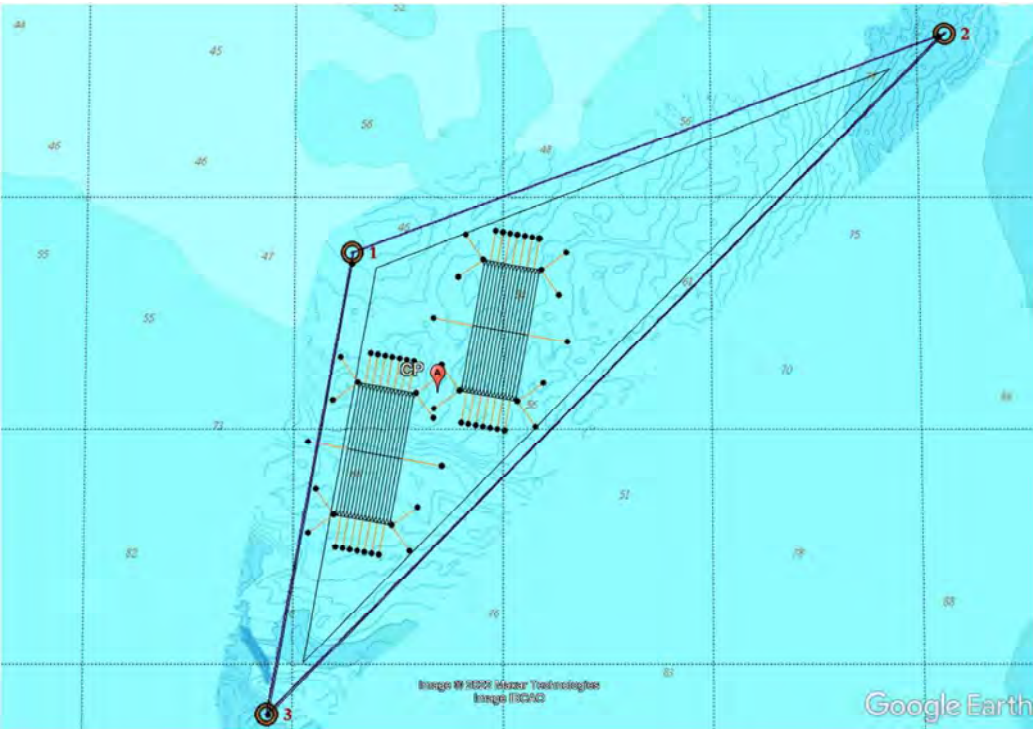


Figure 7: Initial plans for Storflua seaweed farms

Due to complaints from local fishermen that claimed to have valuable fishing activity in the southern part of the area, on the south side of the blue line indicated in Figure 8, it was decided to abandon the southern rig and to only install the northern rig, to avoid further delays in the permit application process. A repositioning of the remaining rig or any of its anchors would also have resulted in additional delays in the permit application process. Hence, it was decided to install the northern rig as-per initial plans.

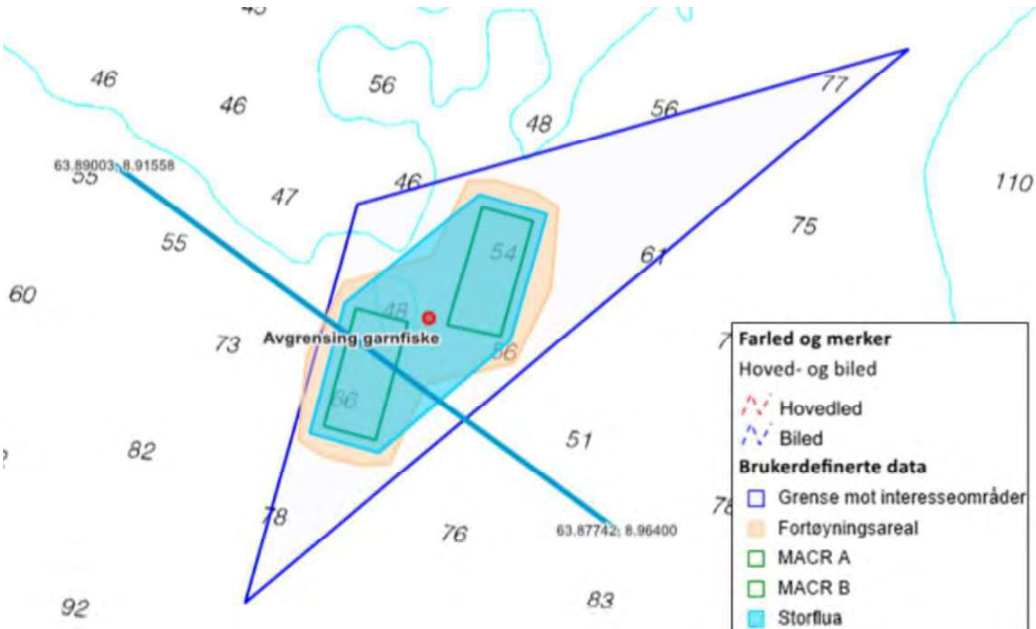


Figure 8: Abandonment of southern rig due to fishing activity

2.4.4 Mooring analyses report

The initial mooring analyses report from ORF's subcontracted engineering company showed dimensioning anchor line loads for the OCU above 100 tonnes for several of the mooring lines. These loads would have resulted in extremely large mooring line components. In addition, it was necessary to investigate ways to reduce the loading, to achieve dimensioning anchor line loads that resulted in anchor, chain and rope sizes that were possible to handle with a typical aquaculture service vessel.

Several iterations of the mooring analyses were conducted to achieve acceptable loads and compliance with nationally recognised design standards and industry practice. The following adaptations were used as basis for the revised mooring analyses:

- Maximum allowable anchor load limited to 30 tonnes – to ensure reasonable size of anchors and to allow for proof load testing of anchors according to NS9415 standard (50% of design load).
- Increased size of corner buoys (equipped with AIS) to ensure positive freeboard in storm conditions.
- Seasonal growth data combined with seasonal wave statistics implemented to reduce design loads.

2.4.5 OCU Capacity – as-installed

Maximum cultivation capacity of the OCU was reduced from 55 km of seeded lines to 30 km seeded lines, to reduce the hydrodynamic loads on the OCU and the corresponding mooring line loads. I.e. spacing between each vertical cultivation rope increased from 1m to 1.8m.

2.4.6 OCU Capacity – adjusted based on operational experience

There is a small distance between the main lines/support lines, only 15m between each line. During deployment, harvesting and maintenance operations the vessels need to work between the lines. The tight separation between the lines increases the risk of getting ropes in the propellers, especially in strong currents and winds, also considering the fact that the available vessels do not have any propeller guards. This imposes additional weather restrictions to the operations. For the 2024/2025 cultivation season, it was decided to remove every other support line, meaning that the separation between the lines currently is 30m, in order to be able to operate vessels in a safer manner. With 5 of 11 support lines removed from the cultivation unit, the cultivation capacity was reduced correspondingly.

3 OCU installation

3.1 Installation specification

An installation specification describing the background and the scope of work related to installation of cultivation rig at Storflua, was established prior to the installation works, (Lona, 2023). The guidelines and requirements specified in this installation specification were used to ensure that relevant regulations and project specific requirements were met.

3.2 Installation works and identified challenges

Operational challenges related to installation were specifically related to environmental conditions.

- Exposed location, high waves and strong currents.
- Weather limitations for installation and operation of OCU limited by:
 - 1) anchor installation/lifting of anchors above deck,
 - 2) lifting and handling of buoys, connection plates, main lines and support lines
 - 3) vessel manoeuvring and rope entanglement with thrusters.

3.3 As-built

The Ocean Cultivation Unit (also referred to as the sea farm) was deployed in November/December 2023.

3.3.1 As-built ROV survey,

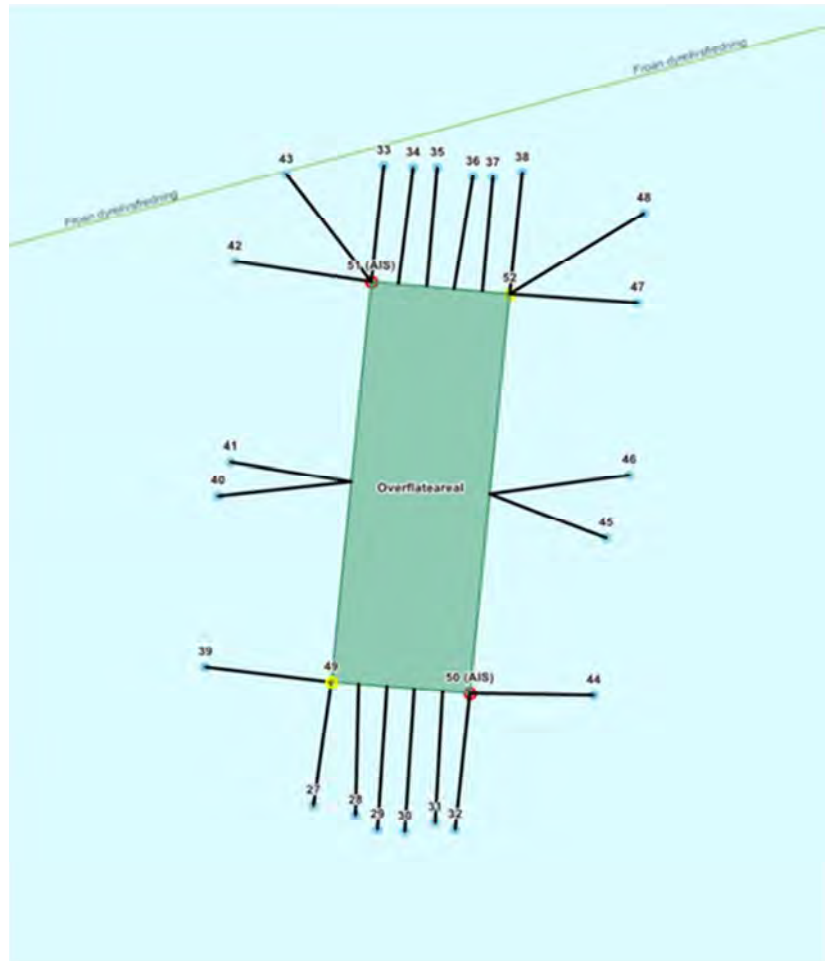
The as-built documentation of the Storflua OCU was documented by the installation contractor (Frøy Akvaservice AS, 2024).

3.3.2 Anchor positions – Norwegian Mapping Authority

As-built positions of anchors and corner buoys have been reported to the Norwegian Mapping Authority (Kartverket). The positions are included in official Norwegian Electronic Navigational Charts (ENC) that are issued for navigational use by the vessel's ECDIS system (Electronic Chart Display and Information System). As-built positions of anchors and corner buoys are shown in Table 3.

Table 3: Storflua OCU as-built positions

	North	East
Bøye 49	63*53.118	8*56.932
Bøye 50	63*53.118	8*57.135
Bøye 51	63*53.388	8*56.932
Bøye 52	63*53.388	8*57.135
Anker 27	63*53.034	8*56.923
Anker 28	63*53.030	8*56.986
Anker 29	63*53.022	8*57.021
Anker 30	63*53.022	8*57.060
Anker 31	63*53.030	8*57.103
Anker 32	63*53.027	8*57.133
Anker 33	63*53.466	8*56.933
Anker 34	63*53.466	8*56.976
Anker 35	63*53.468	8*57.012
Anker 36	63*53.464	8*57.064
Anker 37	63*53.465	8*57.094
Anker 38	63*53.470	8*57.135
Anker 39	63*53.120	8*56.748
Anker 40	63*53.235	8*56.741
Anker 41	63*53.259	8*56.753
Anker 42	63*53.393	8*56.731
Anker 43	63*53.454	8*56.793
Anker 44	63*53.124	8*57.313
Anker 45	63*53.231	8*57.310
Anker 46	63*53.274	8*57.334
Anker 47	63*53.390	8*57.320
Anker 48	63*53.450	8*57.317



4 Operation of OCU

This section describes the experiences related to operation of the OCU at Storflua. It covers the organisational framework, the methods for operating the OCU and the operational challenges associated with the OCU at Storflua.

4.1 Risk management and HSE and QA

An overall Risk register has been developed, which is regularly visited and maintained by the project management throughout the project.

The project is executed in accordance with SINTEF’s governing procedures. In addition, a project specific HSE Plan has been developed.

4.1.1 Health, Safety and Environment (HSE) requirements

A HSE plan outlining the HSE requirements for the project has been prepared. The HSE plan specifies that prior to any field activities at Storflua, a risk assessment shall be performed. Prior to commencement of operations, a Safe Job Analysis (SJA) shall be performed together with all involved personnel.

4.1.2 Emergency preparedness – operations at site

SINTEF Ocean has prepared an emergency preparedness plan for the seaweed farm that address the necessary actions to be taken in case of a contingency situation during activities at sea. The emergency preparedness plan will be made available to any subcontractors prior to commencement of any field activities at Storflua.

4.1.3 Monitoring of seafarm

The Storflua seaweed farm is monitored 24/7 by Norseye AS. Norseye is tracking the signal of the two AIS transponders, and they are instructed to report if the AIS signals fall outside the specified geographical range or if the signal disappears.

4.2 Vessel requirements

A vessel with large crane capacity is needed for deployment and harvesting operations, as well as for maintenance. At the same time the vessel must be suitable for operating within the seafarm in terms of size and manoeuvring capacity. In addition, the vessel must have sufficient deck space, especially for the deployment and harvesting operations. These criteria points towards service vessels from the aquaculture industry.

An estimation of required lifting force to raise the main line from 10m depth to a point 2m above the water, is shown in Table 4. The values are indicative but may be used to characterize the vessel requirements to be used during farm operations.

Table 4: Required lifting force to raise main lines

Line	Lifting Location from End of Line (m)	Required Lifting Force (metric tons)
Outer Backbone	0	3.13
	125	0.45
	250	4.95

When defining the required crane capacity, the term “lifting moment capacity” is normally used. "Lifting moment capacity" refers to the force of the load multiplied by the load arm. For the Storflua OCU, the vessels need to be able to lift minimum 5 tonnes at approx. 5 m radius, resulting in a moment of 25 tonne-meters (t/m). Hence, vessels operating at Storflua need to be equipped with minimum 25 t/m cranes, to be able to lift the mainline.

4.3 Available vessels and vessel operators in the Frøya region

There are few service vessel owners with capacity and availability in the Frøya region. Frøy Akvaservice was the only company that had a large number of vessels operating in the area. The availability of vessels is strongly depending on the seasonal demand in the aquaculture industry, mainly driven by the increase in sea lice populations during warmer months, and the subsequent need for de-licing activities. Frøy Akvaservice has their home base at Frøya. Other service vessel companies in the region, like Abyss, AQS and FSV, presently have few or no vessels in the area on fixed contracts. Renting a service vessel is expensive. In addition there were challenges in 2024 with ISA (Infectious Salmon Anemia) restrictions around Frøya (Mattilsynet, 2024), resulting in reduced availability of vessels and extra costs associated with cleaning and disinfecting vessels entering and exiting the ISA zone around Frøya.

4.4 Vessel crew and familiarisation

Service vessels are normally manned with a captain and two seamen. A challenge with the service vessels used in the project, is the lack of continuity and experience transfer between the vessel crews. The project often ended up with a new boat and a new crew for each field trip to Storflua. Crew familiarisation and risk assessment is carried out prior to each job, but still this factor imposes additional risk to the project.

For improving the efficiency and reducing the operational risk in the project, it would be preferable to have a stable crew that could gain experience with the location, the farm design and with the associated operations such as deployment, monitoring, harvesting and maintenance. Knowledge and experience about the local weather conditions at Storflua is also critical.

4.5 Operational challenges – vessel operations at Storflua

Storflua is an exposed location with frequent strong winds, high waves and strong currents, meaning that there are few available weather windows. The exposed conditions create unpredictability and challenges for all operations at Storflua.

4.5.1 Farm design and intervention operations

The operational challenges related to the Storflua OCU are mainly related to vessel intervention operations, involving work on the mainline/supportline and handling of the cultivation lines.

As described in Section 2.4.6, the small separation between the main lines/support lines imposes challenges for vessel operations. Hence, it was decided to remove every other support line, increasing the separation between the support lines from 15m to 30m, in order to be able to operate vessels in a safer manner.

Handling cultivation ropes involves "fishing" up the mainline from 10m depth while maintaining the vessel's position (Figure 9). This is a critical operation and there is high risk of getting rope in the propeller, especially when the separation between the lines is only 15 m and the width of the service vessels are typically 8-10 meters. Once the mainline/support line is lifted in the rope rollers on the side of the vessel, the vessel is partly restricted from moving sideways and from rotating. Hence, this is a more stable situation. On the

other hand, high tension in the mainline exerts large forces on the rope rollers during this operation which needs to be accounted for in the design of the rope rollers.



Figure 9: Lifting the mainline into the rope rollers

4.5.2 Weather limitations for vessel operations at Storflua

Stable weather from the east is normally associated with good weather conditions in Trøndelag. However, winds from the east presents challenges at Storflua as large waves build up over Frohavet. The fetch length from SE to NE is typically more than 30 km, meaning that large waves will develop from these wind directions. The Storflua site is more sheltered from western winds by the Frøya archipelago.

Actual wind conditions at Storflua are often stronger than the weather forecast indicates and the operations often need to be interrupted or cannot be started due to strong wind and heavy waves. A typical weather limitation criterion, based on experience from performed operations, is 7-8 m/s wind, but strong currents and/or wind from the east can cause operations to be interrupted even in weaker wind conditions.

4.5.3 Vessel Operations – General

Vessel manoeuvring within the farm is a critical factor. There is always a risk of getting a rope stuck in the propeller. Service vessels lack propeller protection, which is more common on fishing vessels. Lack of propeller protection also limits the vessel's heading during the deployment of cultivation ropes, i.e. depending on the current conditions, the vessels may be restricted to only work backwards.

There is also a high risk of damaging marker lights and AIS when these buoys need to be handled in bad weather, e.g., during repair or battery replacement. The response time for incidents requiring repairs is relatively long as this depends on vessel availability and acceptable weather conditions.

It is beneficial to have an ROV onboard to be able to inspect the farm moorings, infrastructure and biomass.

4.5.4 Deployment of seeded lines

An operating procedure for deployment of seeded growth lines was developed by Ocean Rainforest and handed over to the project (Christiansen et al., 2023). The procedure has been followed on the deployment campaigns in the project, and it has also been useful for familiarisation of new personnel.

Entanglement issues

The deployment operations are dependent on a favourable current direction, perpendicular to the mainline/supportline to avoid entangling of cultivation ropes during deployment (Figure 10). In cases where the current direction is in-line with the mainline/supportline, the project experienced significant amounts of entanglement, meaning that the cultivation ropes are either entangled into each other or around the mainline/supportline.

When deploying the lines, Figure 10, it's crucial to ensure they don't get tangled with the mainline or support lines when going out. When they are deployed, they need to go either straight down or drift away from the mainline and support lines. This is quite challenging. Both the current direction and the wind must align for successful deployment.

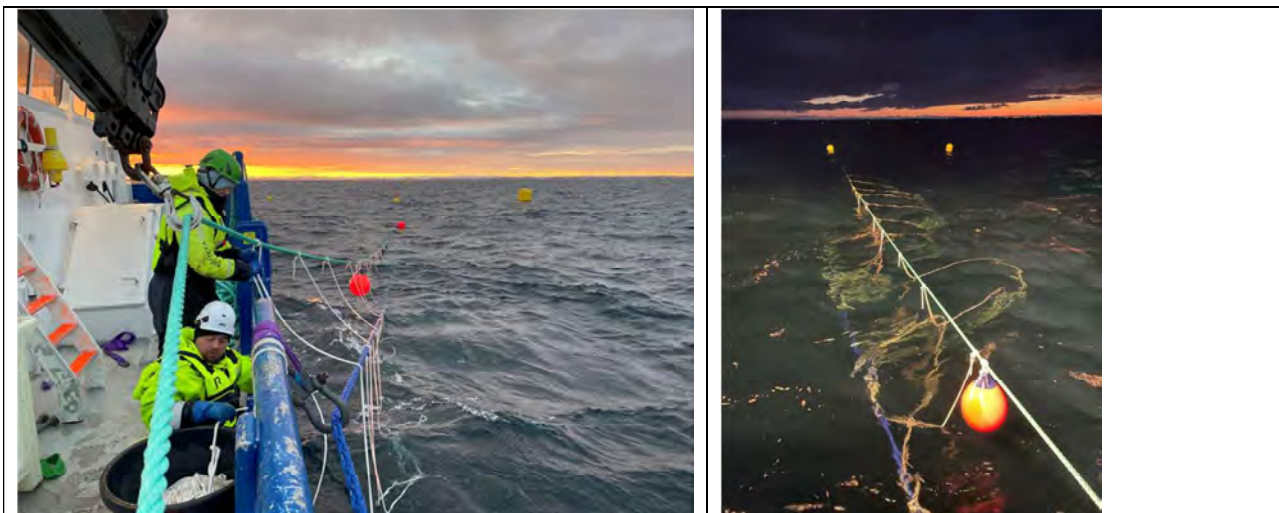


Figure 10: Entanglement issues

Vessel manoeuvring

Due to lack of propeller guards, the service vessels prefer to reverse when deploying the cultivation lines. They avoid going forward because they don't want to risk damaging the propellers. It's always easier to follow and work going forward. The need for reversing makes the operation more challenging.

Attachment/tying method for 10m vertical ropes

The cultivation ropes are tied to the mainline and supportline as the vessel moves along the mainline. Knotting is a labour-intensive and manual process. It is also time consuming to handle individual 10m cultivation ropes.

To avoid the mainline and support line to touch during the growing season, due to hydrodynamic forces on the growth lines, the mainline is equipped with sinkers and the support line with floats. A sinker and a buoy are tied to, respectively, the mainline and the support line for every 20 meters (Christiansen et al., 2023).

4.6 Seafarm structural integrity

The Storflua OCU has successfully survived the weather conditions at Storflua throughout two cultivation seasons. It should be noted that the full cultivation capacity of the OCU has not been utilized.

The project experienced damage to one of the main buoys at the OCU. Due to the OCU design, the innermost centre buoys will experience small loads. The loads are especially small during the winter months when the biomass is low. It is believed that the low loading of the buoy resulted in significant snatch loads, which caused damage to the buoy.

4.7 Supporting equipment

The corner buoys are equipped with lights and AIS. This equipment suffers significant wear in the demanding conditions at Storflua. The project experienced damaged marking lights, internal breakage in the cable of the marking lights, and some moisture inside the AIS.

This is due to the challenging weather conditions, where the leeward side of the farm structure is experiencing low tension, causing the buoys to float high in the water and undergo significant pendulum movement, whereas the buoys on the weather side may experience occasional full submergence.

5 Challenges, areas for improvement and innovation needs

As described in Section 4, there are several challenges associated with the operation of the Storflua OCU. This section describes general areas for improvement and innovation needs related to seaweed farming at weather exposed locations.

5.1 Seafarm layout and operability

Seaweed farm concepts should be designed based on a holistic approach, considering all phases of the cultivation process, including construction, seeding, operation, monitoring, maintenance and decommissioning. Design of future seaweed farms should facilitate a high degree of automation, which makes seaweed farming cost-efficient. Handling and operation procedures for seaweed cultivation and harvesting must consider personnel safety.

5.2 Prediction of hydrodynamic loads

Anchors, mooring lines and other structural components constitute a significant share of the total construction cost for a seaweed farm. Uncertainties in theoretical models are normally handled by adding conservative safety factors to the design. When safety factors are added to the environmental loads, to the load effects and finally in the structural design, the result could be that the final design is over-dimensioned, resulting in unnecessarily high costs and excessive material use. By further developing the hydrodynamic models for seaweeds cultivated on ropes or other substrates, better and more reliable estimates that reduce conservatism and contribute to more cost-efficient and less carbon intensive design could be achieved.

5.3 Dimensioning and design standards

NS9415:2021 is based on the partial safety factor method for structural design. The partial safety factor method is a design method by which the target safety class is obtained as closely as possible by applying load and resistance factors to characteristic values of the governing variables. The governing variables consist of (1) loads acting on the structure or load effects in the structure, and (2) resistance of the structure or strength of the materials in the structure. In other words, load factors are applied to the estimated characteristic environmental loads and material factors are applied to the various structural components to obtain the desired safety level.

For the design of seaweed farms, a future design standard should consider if it is acceptable to apply a lower target safety level than for fish farms based on the following mitigating factors:

- the consequences of technical failures are significantly lower for a seaweed farm, compared to a fish farm where the main risk is escape of fish. The potential consequences for nearby marine traffic due to structural failures of seaweed farms must however be considered.
- most fish farms are operated on a daily basis, which means that structural failures also impose a risk for injury to personnel.
- the period for maximum biomass in the seaweed farms is outside the window for when the maximum environmental loads occur (typically late spring to autumn when light intensities are highest).

The above mitigating factors may justify use of reduced load- and material factors for design of seaweed farms compared to design of fish farms. Reduced conservatism will contribute to more cost-efficient design of seaweed farms (Lona et al. 2020).

5.4 Anchor and mooring system design

Mooring systems in the Norwegian aquaculture industry are generally made up of the following components, Figure 11: 1) anchor, 3) anchor chain with shackles (2,4) in each end, 7) mooring rope with thimble in each end (5,8), 10) connection plate, 13) chain between connection plate and buoy, 11) buoy and 15) mooring frame rope. A similar system is used for the Storflua OCU.

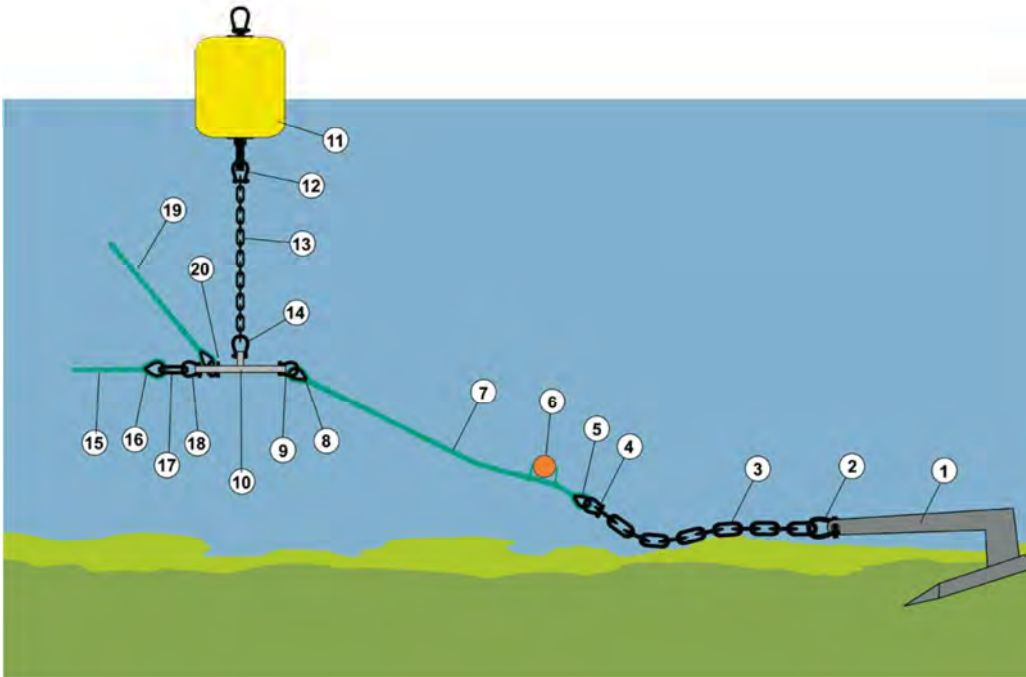


Figure 11: Mooring system for aquaculture (Figure: Eiva-Safex AS)

Mooring of seaweed farms in Norway are normally carried out the same way as for fish farms. The current dominant concept for farming of Atlantic salmon is flexible floating net-cage systems where several net-cages are mounted into a rope-based frame-mooring system (Bjelland et al., 2015). The mooring systems consists of several mooring points. The mooring line design loads are moderate and allows for using fluke or plough anchors installed by relatively small service vessels in seabed consisting of marine sediments. Rock bolts are used in rock seabed, which is a seabed type that is more common in near shore areas. For installing rock bolts, a drilling unit that could be operated by a standard work-class ROV is normally used.

A major part of the seabed area in Norwegian coastal and offshore waters consist of marine sediments. The seabed sediments form a veneer on the underlying bedrock. The seabed sediments are particles of varying sizes and shapes, ranging from boulders to clay. The thickness of the seabed sediments varies but generally the thickness increases with increasing distance from shore.

One of the main challenges in anchoring of aquaculture farm systems is not considered to be the lack of appropriate anchors, but the lack of knowledge on geotechnical conditions and choosing the appropriate anchor for the actual geotechnical conditions on the site. Anchoring in marine sediments consisting of boulders is a known challenge.

Geotechnical surveys and geotechnical engineering are costly and are normally not used in the aquaculture industry. A visual ROV survey of the anchor positions is normally carried out to determine whether fluke or plough anchors could be used or not. In lack of knowledge on geotechnical conditions, it is common

practice to assume anchor holding force based on the anchor weight. Normally, the maximum anchor holding force is taken as 20 times the anchor weight (Certex Norge AS, 2019).

In order to document the anchor holding force, NS9415 requires that the anchors are load tested. NS9415 requires a proof load test of each installed anchor at 50% of dimensioning load for 15 minutes. In practical terms, the proof loading requirements limits the maximum dimensioning force of each anchor line to typically 25-30 tonnes, as most of the typical Norwegian service vessels have a maximum bollard pull less than 15 tonnes.

There is a need for developing low-cost geotechnical surveys and efficient tools to document anchor holding force to reduce cost for anchor installations and to reduce uncertainty in anchor holding force.

5.5 Sensors and monitoring

Monitoring of structural integrity and seaweed biomass

Methods for real time monitoring of seaweed biomass, environmental conditions and structural integrity of seaweed farms is essential for continuous monitoring and reduced need for personnel.

Wireless subsea load sensor technology is available. One of the main challenges is that transmission of data requires a surface module. It could be possible to integrate this hardware into the mooring buoys together with battery power supply. This should be further investigated.

5.6 Materials and reuse - environmental sustainability

Ropes used in seaweed farms should preferably be made of eco-friendly materials that minimize environmental impact, e.g. natural and/or biodegradable material.

Ropes – Material Selection

Ropes are classified according to the type of material they are made from or the way they are manufactured. The raw materials for ropes come from the main groups: plant fibres, synthetic fibres, or metals. Natural ropes made from plant fibres or synthetic ropes are most relevant in this context. Generally, ropes are made from thin fibres that are twisted together. The most common type is the so-called three-strand rope, which consists of three strands twisted to the right (Petersen & Ording, 2020).

Natural Ropes

Natural rope is made from plant fibres such as hemp, cotton, manila, coconut, and sisal. Natural rope is made from many short fibres twisted together to form yarn (Petersen & Ording, 2020).

Synthetic Ropes

Synthetic ropes are traditionally made from polyethylene (PE), polypropylene (PP), polyamide (nylon), and polyester. Unlike natural ropes, synthetic ropes have fibres that run the entire length of the rope. This makes the rope stronger, and it is not necessary to twist the fibres to keep the rope together. Therefore, synthetic ropes can be braided or woven. Mooring lines for ships are usually made of polypropylene, braided together from eight or twelve strands. The most common and affordable synthetic rope is still the regular three-strand rope (Petersen & Ording, 2020).

Synthetic ropes come in many types with different properties. However, they are generally much smoother than natural ropes. Synthetic materials have higher resistance to rot and may also withstand the effects of

acids and alkalis without being significantly weakened. They retain their breaking strength even when wet because they generally do not absorb much water. By blending fibres, the best properties of the materials can be combined into one product. "Danline" and "Megaline" are ropes made from polypropylene (PP) and polyethylene (PE) and are widely used in fishing and aquaculture industries.

The breaking strength of synthetic ropes is significantly higher than that of natural fiber ropes of the same dimension. When using natural ropes, the rope dimension must be increased, or alternatively, the length of the rope span must be reduced. If the rope is designed for a shorter lifespan, e.g. if the rope is designed to last only one cultivation season, reduced material factors can likely be used, allowing for smaller dimensions.

New Synthetic Rope Types

New synthetic rope types with extremely high breaking strength include ropes made from aramid fibres (e.g., Kevlar) or high-modulus polyethylene (e.g., Dyneema). However, these types of ropes are very expensive.

Biodegradable Ropes

Biodegradable ropes are also under development. Biodegradable nets are used in the development of fishing and trapping gear to reduce the risk of ghost fishing (Grimaldo et al., 2012). Ideally, biodegradable materials should break down completely into water and carbon dioxide by microorganisms, but they can also break down into microparticles and toxic substances.

Ropes made from macroalgae

It is also possible to produce biodegradable ropes from phycocolloids from macroalgae. The advantage of this is that a marine bioresource is used as raw material to create polymer materials (i.e., materials that can be used in various plastic products). Polymer materials from phycocolloids appear to be able to be produced with high mechanical strength and resistance to moisture. The material is believed to have sufficient durability and mechanical properties for use at sea and is also biodegradable as it can break down in soil (Chaudhary et al., 2015).

Ropes – re-use or single use

It is considered appropriate that the frame construction itself is designed for a service life of 10 years, as for aquaculture facilities. For seaweed cultivation ropes, it can be considered whether they should be reused after each harvest cycle or if the ropes should be for single use. Single-use ropes must be brought ashore for proper waste management.

Single-use ropes can either be made of natural fibre or biodegradable materials. Biodegradable ropes currently have a relatively high price, but it can be expected that the price will decrease as the demand for this type of material increases (Grimaldo et al., 2012). The development of biodegradable nets and other fishing gear is expected to contribute to the development of these types of materials.

Costs related to cleaning ropes, recycling, or waste management must also be included in the cost-benefit assessments.

5.7 Vessel design

5.7.1 Seaweed cultivation vessel

Specialised cultivation vessels that could handle large volumes at low operating costs are assumed to play an important role in the development of a future seaweed industry in Norway. Since seaweed cultivation is seasonal and currently has a limited production volume, it is relevant to consider the adaptation of vessels used in other industries, in an early phase in the seaweed industry. When assessing required characteristics, the following vessels are considered relevant:

- Seaweed trawlers
- Service vessels from the aquaculture industry
- Mussel vessels
- Smaller fishing vessels from the coastal fishing fleet
- Other types of vessels

Most of these vessels can be categorized as cargo ships with a length of less than 24 meters according to the regulations of the Norwegian Maritime Authority.

Service vessels generally have large working decks that make it possible to perform varied tasks. They are also equipped with powerful cranes, winches, and some vessels have cabin capacity. This makes the service vessels well-suited for tasks related to seaweed cultivation and also enables the installation of modular deployment and harvesting solutions on board. This does not exclude that vessels aimed at fishing, mussel farming, or other types of vessels may also be relevant for adaptation and equipment with seaweed cultivation functions (Lona, 2021).

5.7.2 Zero- and low emission vessel operations

Zero and low-emission vessels should be used to reduce the carbon footprint of future seaweed cultivation operations. The potential for using zero and low-emission vessels for seaweed cultivation, could be illustrated by the status and ongoing developments on zero- and low emission vessels in the aquaculture fleet.

It is estimated that vessels in the aquaculture industry account for around 80% of domestic greenhouse gas emissions from the industry (Slette et al., 2024). In short terms, only battery operation allows for extensive use of renewable energy, and thus cuts in greenhouse gas emissions, for aquaculture vessels. In longer terms, alternative fuels such as hydrogen and ammonia, are expected to play a larger role in the transition. Unfortunately, there are major challenges associated with transitioning from fossil to battery-electric operation of vessels. The main challenges are limitations in range and availability of charging points with the necessary capacity. The largest vessels in the aquaculture industry, such as wellboats/live fish carriers, will not be able to rely solely on battery operation, but for smaller vessels – mainly service and site boats – it may be possible to achieve significant cuts in greenhouse gas emissions with proper operational adjustments, strategic infrastructure development, and smart use of range-extending solutions.

Already today, there are many battery-hybrid vessels in the aquaculture industry. Enova has supported battery installation on 180 site boats, service vessels, and passenger transport boats. The median battery capacity is 350 kWh for vessels under 15m and 730 kWh for vessels over 15m (Norwegian Maritime Authority, 2023). There are currently being built service vessels with batteries up to 2 MWh, which can be enough for a few days of work at a fish farm or a few of hours of sailing. However, such a battery pack would typically only provide a range of around 2% of what can be expected with fossil operation. Both fish farm

sites and quay facilities can be used as charging points for vessels. At the beginning of 2024, 44% of fish farm sites are connected to shore power while the rest use diesel generators (Lunde et al., 2024). An additional 20% are planned to be connected to shore power. The challenges with establishing charging points at fish farm sites or at adjacent land-based quay facilities is that grid capacity is often low and operational activities at fish farms, such as feeding, will be prioritized. The lack of charging infrastructure mean that today's battery use is mainly limited to peak-shaving. This indicates that there is untapped potential for increased emission reductions for existing and new vessels un the aquaculture industry.

5.8 Storing and preservation of biomass

Once harvested the seaweed degrades quite rapidly. This means that the seaweed must be harvested and transported effectively to onshore facilities for further processing, or it must be preserved onboard the vessel. Seaweed cultivation and harvesting will be a seasonal activity. Hence, methods for preserving the seaweed to allow for continuous utilisation of land-based processing equipment are essential. For short-time storage onboard the vessel, temporary storage in air is an alternative. Storage in seawater, onboard the vessel or in net pens in the sea, gives prolonged shelf life. For conservation onboard the vessel, ensiling is considered the most favourable method. Ensiling of seaweed could be used for a range of end products. It will ensure necessary preservation of quality, and the method is energy efficient. The level of processing and preservation onboard the vessels depend on the intended application areas (Lona, 2021).

6 Project research and innovation work

WP2 has focused on the research and innovation tasks in line with the project objectives, while addressing the project specific operational challenges at Storflua, described in Section 4.

Main overall objectives of WP 2:

- a) Design and construction of a robust ocean farm of pilot scale for the selected site, with mechanised and automated solutions for operations.
- b) Testing of materials to be used in the farm, as growth substrate and mooring systems.
- c) Testing of the farm in SINTEF Ocean's ocean laboratories and optimising of the construction.
- d) Deploy the pilot farm at the selected site.

6.1 Vessel equipment and methods for cultivation operations

6.1.1 Rope rollers

A set of rope rollers has been developed in the project (Figure 12). The purpose of the rope rollers is to stabilize the mainline and the support line along the vessel side during deployment, harvesting and maintenance operations on the OCU.

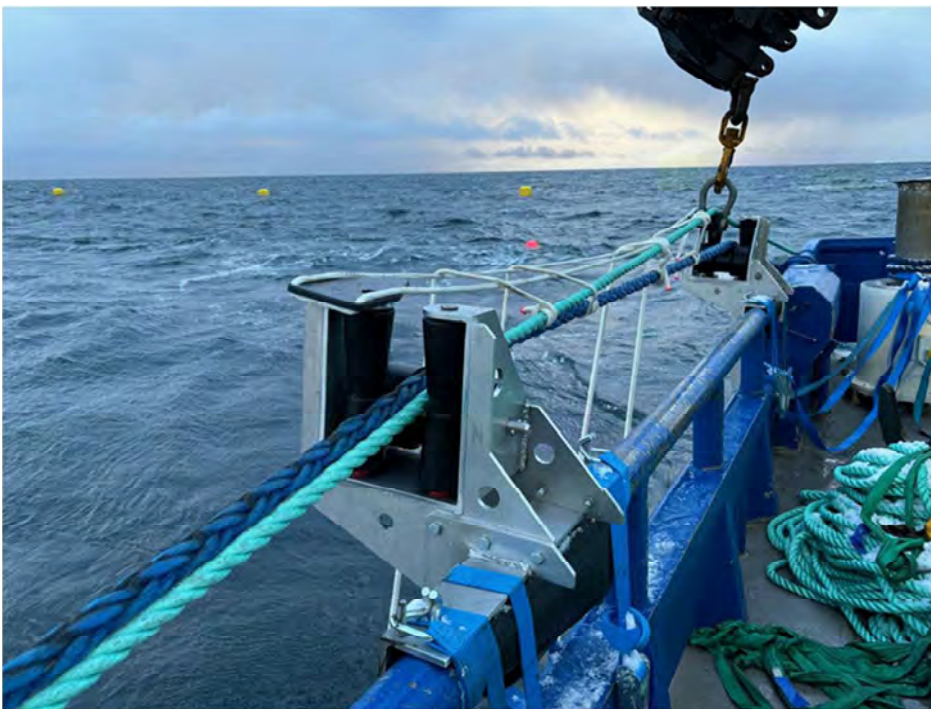


Figure 12: Rope rollers

6.1.2 Rope cleaner

The project experienced significant amount of biofouling on the anchor lines, main lines and support lines. A rope cleaner, Figure 13, has been bought, but unfortunately it has not been tested by the project yet. The rope cleaner is planned to be tested on the load carrying lines at Storflua and it should also be tested whether the rope cleaner provides satisfactory cleaning for the reuse of cultivation ropes.



Figure 13: Rope cleaner (Figure: SHM Solutions AS)

6.1.3 Deployment operations

The deployment operations are dependent on a favourable current direction, perpendicular to the mainline/supportline to avoid entangling of cultivation ropes during deployment. When deployed, the cultivation ropes need to go either straight down or drift away from the mainline and support lines. This is quite challenging. Both the current direction and the wind must align for successful deployment. Hence, it is essential to develop means and methods to reduce the entanglement, even in unfavourable weather conditions.

The project has tested using sinkers on the cultivation ropes and has discussed if it is possible to design and install an “anti-entanglement device”, a device that separate the main line and support line as the cultivation ropes leaves the vessel.

A test with continuous empty longlines, in a zigzag pattern between the mainline and supportline, was also performed during the 2024/2025 season. One of the challenges with this solution is to design a suitable attachment device for attaching the longline to the main line and the support line.

6.1.4 ROV for inspection and maintenance

The project has used ROV's for various tasks at Storflua. A set of operational requirements has been defined considering the experiences from completed field operations at Storflua.

- ROV should have low weight to allow hand carriage to ease transport and deployment without the need of large vessel with crane.
- ROV must have sufficient thruster capacity to be able to operate in strong currents present at the Storflua site.
- ROV should have a user-friendly interface to allow for easy set-up and operation.
- ROV should facilitate mounting of grab arm and rope cutter (grab arm required for collecting samples and cutter needed for harvesting & maintenance operations).
- ROV should facilitate mounting of other sensors (future research needs).

6.2 Model testing in ocean basin

Author: Per Christian Endresen

The main goal of the experimental investigations performed on scaled cultivation lines was to document the suitability of scaled experiments to quantify the hydrodynamic loads on seaweed farms elements. This was achieved by performing a set of tests in currents or waves alone with two different line configurations (horizontal/vertical) in the Ocean Basin. The force-speed relationship originated from a towing experiment previously performed at SINTEF in seawater with live seaweeds was used together with simple calculations within FhSim to validate the outcomes of the current tests. More complex processes such as roll-up and Vortex-Induced-Motions were identified as having a potential significant impact on the dynamic forces experienced by the cultivation lines. Under both regular and irregular waves, we characterised a lower force response (drag and lift) on the wave harmonic for the vertical set-up compared to horizontal set-up, but an enhanced response for both very low frequencies and higher second wave harmonics. Overall, the generated dataset is calling for further investigations in integration with field measurements and/or more elaborated simulations of the key hydrodynamic processes to better predict the loads on such flexible farm structures (Henry, 2024).

6.3 Numerical analyses

Author: Per Christian Endresen

Having adequate understanding of forces on sugar kelp growth lines in current and waves as well as numerical methods that are able to model and simulate the effect of the most dominant contributing factors to loading on kelp farm components are crucial to efficiently and reliably be able to design and make changes to kelp farm designs in order to meet requirements for structural integrity, economic viability as well as addressing operational concerns.

Numerical modelling of physical problems is an important tool for design and dimensioning of marine floating structures. It often enables evaluation of concepts and design changes for relevant environment conditions as well as estimating behaviour during operations. Floating flexible rope structures for kelp farming should not be an exception, and thus numerical tools able to reliably estimate the forces a kelp farm is exposed to would be valuable for design of seaweed farms. Numerical tools/codes able to estimate forces which is close to the forces expected may be beneficial as it has the potential to enable the construction of more reliable and possibly more cost-effective designs for seaweed farms.

A typical seaweed farm consists mainly of interconnected ropes, whether it be a farm with horizontal growth line layout, or a layout with vertical risers such as Storflua OCU. Simulating these layouts, which may consist of thousands of metres of ropes, require a numerical code with suitable numerical models (structural models) for cables or ropes. Assuming the structural model is adequate, the hydrodynamic load model must be able to predict forces on the ropes both for ropes without and with kelp. The forces on ropes grown with kelp have been shown to behave differently to variations in fluid flow velocity and fluid flow direction compared with some methods used for ropes. This means that numerical codes applied to model the hydrodynamic forces on, and response of kelp growth ropes should have hydrodynamic load models suited to the purpose. Tests performed in this, and previous projects show that drag forces on ropes grown with sugar kelp do not increase with a factor proportional to the velocity squared, but with a factor proportional with velocity to the power of a number slightly less than two. This means that by for instance modifying the drag coefficient one may only produce expected results for a limited velocity range with standard drag models, which makes it challenging to estimate forces for different current conditions or in waves. Model tests on both horizontal kelp ropes and vertical kelp risers (both with kelp surrogates) were performed in the current project, and analysis of the model test results indicate that the drag forces on these kelp surrogate ropes do not vary with relative inflow angle in the same manner as is used under

for instance crossflow assumptions. Rather, the tests and subsequent analysis indicate that the drag forces may vary more similarly to how the drag forces on net panels vary with inflow angles. These results have both increased the knowledge on drag forces on kelp growth ropes, as well as emphasised the need for increased knowledge and further research on the topic. Increased knowledge is also important for future implementations of load models in numerical tools which may enable further improvements in modelling.

Other factors that are important for modelling of kelp lines is the lift forces on the lines, meaning the forces transversal to the velocity vector. In addition, the lines may have high biomass when grown. This mass, and the hydrodynamic effect called added mass, needs to be investigated. The latter is challenging to quantify due to the complexity and flexibility of the plants and their configurations, but may be important to model correctly. Wake, or shadow effect, used in modelling of net cages in aquaculture, where the water current component of fluid flow is reduced when passing through the net (slow-down of velocity) may also be something that needs to be modelled in kelp farms. In addition, wave attenuation (wave damping) is a topic that should be investigated for kelp farms. The goal of a farm design is to make it safe and reliable while fulfilling its purpose and being able to be operated and serviced for a predetermined percentage of the time. The design should also be as cost effective as possible without compromising at least safety, but also other factors deemed important. In order to achieve this, it is therefore paramount to improve knowledge on hydrodynamic loads on kelp growth lines as well as implementing and testing new knowledge in available numerical codes.

The mentioned considerations and aspects of modelling hydrodynamic forces on kelp ropes indicate that the creation of reliable numerical models for kelp growth lines may not be as straight forward as using methods intended for other applications, at least not without adequate adaptations and knowledge of the properties of what are to be modelled. This may for instance lead to erroneous estimations of forces on components in kelp farms, which in the worst case may lead to failure.

Kelp farms consisting mainly of ropes and floats may have the ability to comply with the environment conditions exerted on it. The compliance may for instance enable passive reactions to high environmental loads if design and layout of the farm and the size of floats permit it. Future work could investigate these properties and whether design could aid load reducing compliance of the farm structure while at the same time considering operability of the farm as well as legislative requirements (Endresen, 2025)

7 Summary and discussion

7.1 Vessels and equipment

As of today, there are no specialized seaweed farming vessels for industrial cultivation of seaweed, although some prototypes exist. Seaweed cultivation is seasonal and currently has a limited production volume, and hence it is relevant to consider the adaptation of vessels used in other industries in an early phase in the seaweed industry. Vessels from aquaculture industry are suitable for seaweed farming operations, but the period for harvesting coincides with high vessel activity at the Norwegian salmon farms. This situation affects both the availability and the costs for renting a vessel. The adaptation of vessels used in other industries, should be further investigated.

Propeller guards are protective devices designed to prevent damage caused by propellers. Typically, the propeller guards will reduce the risk of getting fixed and free-floating ropes into the propellers. Propeller guards are common among fishing vessels and some of the site boats used on the aquaculture farms, but propeller guards are rarely seen on service vessels. The possibility for having interchangeable propeller guards, to be used for the vessels operating at the Storflua OCU should be further investigated.

7.2 Farm design and operations

The operational challenges related to the Storflua OCU are mainly related to the intervention operations on the mainline/supportline and handling of the cultivation lines.

The Storflua OCU design relies on vessels with large crane capacity for handling the mainline. In practice, this narrows the adaption of vessels from other industries down to service vessels from the aquaculture industry. Possible re-design or modifications to the OCU, to reduce the need for service vessels with large crane capacity, need to be prioritized in order to reduce the operational costs for seaweed farming at Storflua.

There is a small distance between the main lines/support lines, only 15 meters between each line. The original design proposal from Ocean Rainforest was 25 m separation, but to maximize cultivation capacity on the allocated area, it was decided to reduce the separation to 15 m. The tight separation between the lines imposes additional weather restrictions to the operations. For the 2024/2025 cultivation season, it was decided to remove every other support line, meaning that the separation between the lines currently is 30 m. It should be noted that this reduces the total cultivation capacity of the rig. Ideally, the OCU design for a site like Storflua should be based on minimum 25 m separation between the lines.

Use of knots is a safe and reliable method for attaching the cultivation lines. It avoids the use of metal or plastic connections that may degrade and/or lead to wearing of rope. There is no CAPEX involved in knotting. However, knotting is a labour-intensive and manual process which intensifies with quantities. Knotting is time consuming, with high OPEX. Available weather windows are short, and vessel and personnel costs are high. Hence, it is essential to be able to deploy faster, without manual knotting operations. It is also time consuming to handle individual 11 m cultivation ropes. Continuous rope is preferred to ease handling operations, and continuous ropes are also favourable for potential re-use of ropes. The use of continuous ropes should be the preferred option for future developments.

The deployment operations are dependent on a favourable current direction, perpendicular to the mainline/supportline to avoid entangling of cultivation ropes during deployment. When deployed, the cultivation ropes need to go either straight down or drift away from the mainline and support lines. This is

quite challenging. Both the current direction and the wind must align for successful deployment. It is possible to wait during the day for the conditions to improve. However, available weather windows are short, and vessel and personnel costs are high. Hence, it is essential to develop means and methods to reduce the entanglement, even in unfavourable weather conditions.

7.3 Farm design and optimization of mooring analyses

Anchors, mooring lines and other structural components constitute a significant share of the total construction cost for a seaweed farm. By further developing the hydrodynamic models for seaweeds cultivated on ropes or other substrates, better and more reliable estimates that reduce conservatism and contribute to more cost-efficient and less carbon intensive design could be achieved. The project has worked steadily with these issues throughout the project.

The existing OCU design has some limitations. The system with vertical cultivation ropes seems to contribute to adequate survivability of the rig in harsh weather conditions. On the other hand, the vertical cultivation ropes impose operational challenges. It needs to be further investigated, how longlines could be incorporated into the existing design, alternatively new concepts with horizontal cultivation lines for exposed weather locations should be explored.

The existing OCU design has few anchors taking load in transverse direction, i.e. perpendicular to the mainlines. This results in that a few of the anchors have high utilisation. It could be investigated whether introducing a second midbone and possibly extending the length of the rig by 250 m could have the potential to reduce the mooring line loads on the most utilized anchors. Reducing individual mooring line loads have the potential for allowing a better utilisation of the OCU's cultivation capacity.

The current and potentially the wave forces on the rig may pull the rig down. In principle, this effect could be beneficial as the increased submergence and deflection away from the wave zone may contribute to less loads on the rig, i.e. we could say the existing rig design has the potential to enter a survival mode in harsh weather. On the other hand, the corner buoys are equipped with lights and AIS which needs to be operational at all times. To ensure positive freeboard on the main buoys in extreme conditions, the main buoys need to be very large, and this partly restricts the OCU from submergence. The large corner buoys also contribute to increased cost of the OCU. A possible solution to this could be to have separate marker buoys that are not attached to the OCU itself.

Wear and tear of equipment and components in the OCU is dominated by wave forces, creating snatch loads and subsequent potential for damage to components. It needs to be ensured that the main buoys on the OCU are designed for conditions with small nominal loads, typically during the winter months when the biomass is low. This could be achieved by using buoys with large waterplane area, as opposed to the taller buoys that are mainly used on the Storflua OCU.

7.4 Organisation and manning

Changing crew members frequently presents challenges the operations. It is preferable best to have the same crew from both SINTEF team and from the vessel provider. For improving the efficiency and reducing the operational risk in the project, it would be preferable to have a stable crew that could gain experience with the location, the farm design and with the associated operations such as deployment, monitoring, harvesting and maintenance. Knowledge and experience about the local weather conditions at Storflua is also critical.

8 Conclusions and recommendations for JIP Phase 2

8.1 Changes to farm design and operational procedures

The cultivation rig used by Ocean Rainforest, with vertical cultivation ropes, has been demonstrated for rough weather conditions. In addition to potentially reduce spatial occupation, another advantage with this concept is that the rig may partly enter into a "survival mode" in rough weather conditions, by allowing the vertical cultivation ropes to partly deflect in rough weather conditions. This effect likely reduces the total hydrodynamic loading on the seafarms, allowing for a rig design with fewer and smaller anchors and reduced rope dimensions compared to seaweed farm concepts with horizontal ropes.

On the other hand, the concept of single vertical 10 m cultivation ropes gives significant operational challenges. Handling cultivation ropes involves "fishing" up the mainline from 10 m depth while maintaining the vessel's position. This is a critical operation and there is high risk for getting rope in the propeller. Once the mainline/support line is lifted in the rope rollers on the side of the vessel, the vessel is in a more stable situation, partly restricted from moving sideways and from rotation. The cultivation ropes are then tied to the mainline and supportline as the vessel moves along the mainline. Harvesting is done in a similar manner. Knotting is a labour-intensive and manual process. It is also very time consuming to handle individual 10 m cultivation ropes. There is a strong need for developing methods and equipment that allows for integration of continuous longlines to the existing OCU design. This would significantly ease both the deployment and harvesting operations.

8.2 Refined numerical analyses and possible design changes

The current and wave forces on the rig may pull the rig down. In principle, the increased submergence may contribute to less loads on the rig. However, the corner buoys are equipped with lights and AIS which needs to be operational also in extreme conditions. This requirement results in very large corner buoys that restricts the OCU from submergence. A possible solution to this could be to have separate marker buoys that are not attached to the OCU itself and thereby allow the rig to enter a survival mode in harsh weather.

The existing OCU design has few anchors taking load in transverse direction, i.e. perpendicular to the mainlines. This means that a few of the anchors have high utilization. The effect of introducing a second midbone and possibly extending the length of the rig by 250 m could be investigated to evaluate how this may change the utilization of the anchor lines. Reduction of forces on individual mooring lines may allow better utilisation of the OCU's cultivation capacity.

8.3 Vessel and seaweed farm crew

Having a stable crew that could gain experience with the location, the farm design and with the associated operations such as deployment, monitoring, harvesting and maintenance is crucial for being able to operate seaweed farms in a safe and efficient manner. Building knowledge and experience about the local weather conditions is also critical.

Due to the existing seaweed farm design, involving the need for lifting the mainline during deployment and harvesting operations, vessels with large crane capacity are needed. At the same time the vessel must be suitable for operating within the seafarm in terms of size and manoeuvring capacity and the vessel must have sufficient deck space. These criteria points towards service vessels from the aquaculture industry. With a different seafarm design, where the load bearing structure of the seaweed farm could remain in place during deployment and harvesting, smaller vessels with smaller cranes could potentially be utilized.

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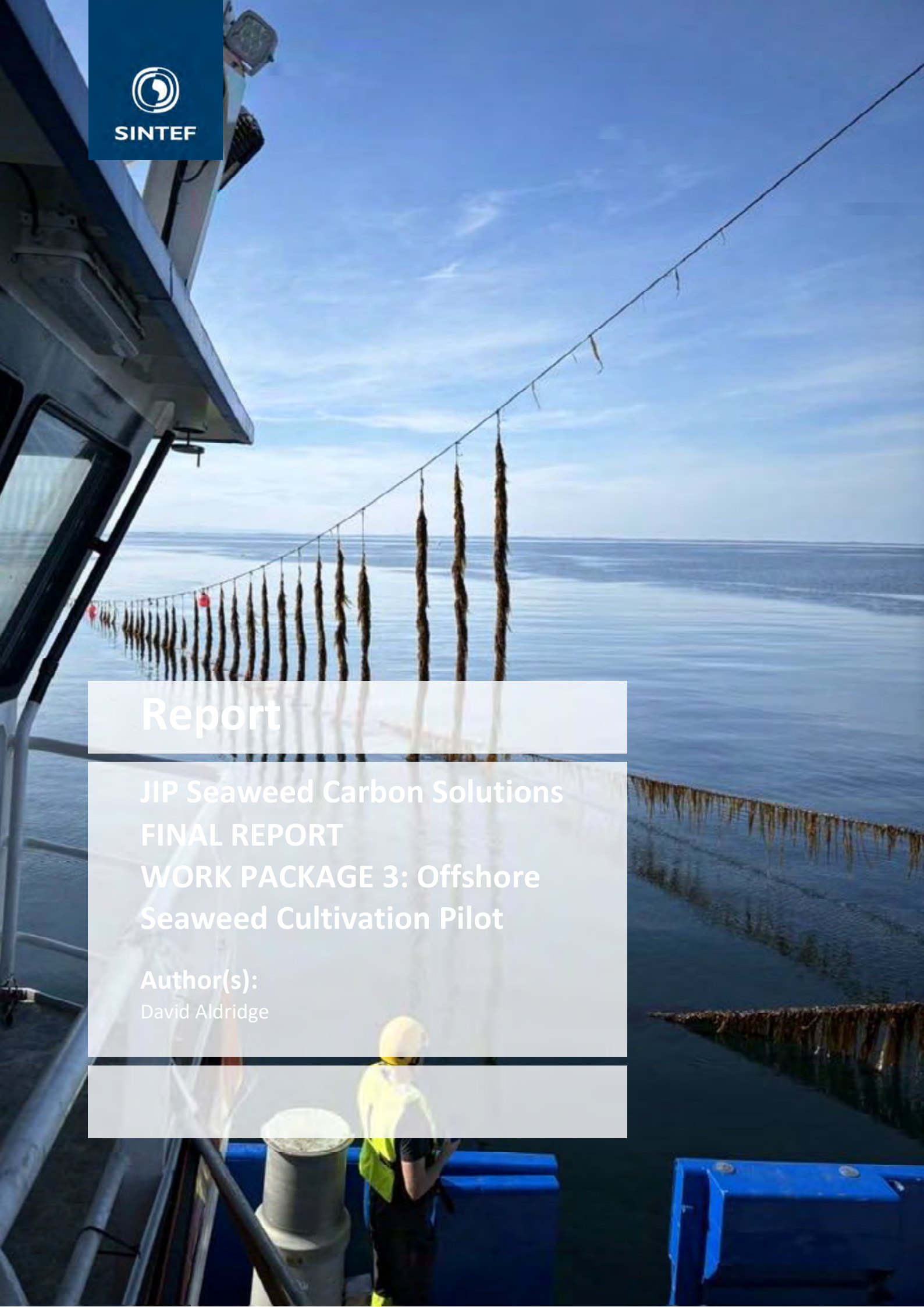
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Report

JIP Seaweed Carbon Solutions FINAL REPORT WORK PACKAGE 3: Offshore Seaweed Cultivation Pilot

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SUMMARY

Abstract

This report presents the findings for Work Package 3 of the JIP Seaweed Carbon Solutions project, investigating the optimisation of large-scale offshore seaweed farming. Through two cultivation seasons, the project compared an exposed, offshore farm (Storflua) with a sheltered, inshore farm (Skarvøya) in the Trøndelag region of Norway. Results consistently demonstrate that the offshore site produces significantly higher biomass yields, attributed to more favourable environmental conditions (light, nutrients, temperature) arising from this dynamic environment. The study evaluated different seeding methodologies, finding twine seeding and high-density direct seeding to be most reliable. However, significant operational challenges in deployment and harvesting were encountered in the exposed environment, highlighting the need for innovation, such as continuous line systems, to improve efficiency.

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1 Introduction to offshore seaweed farming

The impetus to transition farms to exposed, offshore environments is multifaceted. This move is crucial for scaling production, maximising the climate and environmental benefits that kelp offers (including for carbon capture and storage, CCS), and alleviating conflicts with other ocean users in crowded nearshore areas (Boderskov et al., 2021; Forbord et al., 2020; Kerrison et al., 2020; Umanzor et al., 2020; Wilding et al., 2025).

1.1 Experiences and challenges in farming offshore

1.2 Seeding methodologies

The optimal choice of seeding technique for offshore kelp cultivation is highly context dependent. It is influenced by factors such as the specific kelp species being cultivated, the prevailing environmental conditions of the farm site (e.g., current exposure, water depth, and turbidity), and the desired scale of the operation. For small-scale cultivation sites located in relatively dynamic, open-coast environments, twine seeding has generally demonstrated superior biomass yield (Forbord et al., 2020; Kerrison et al., 2020; Umanzor et al., 2020; Wilding et al., 2025).

However, for large-scale offshore operations, where the substantial labour and hatchery costs associated with twine seeding become significant economic barriers, direct seeding's cost-effectiveness and scalability potential make it an attractive alternative. Despite its current limitations in productivity, further development and optimisation of direct seeding methods are warranted. The success of cultivation on various substrates, such as nets, is also heavily reliant on water conditions like depth and turbidity, which directly impact light availability and, consequently, kelp growth. Deeper lines, for instance, may experience lower biomass yield due to reduced light penetration and self-shading effects.

The inherent trade-off between the higher biomass yield and reliability of twine seeding versus the lower labour and hatchery costs of direct seeding presents a critical strategic decision point for offshore kelp farmers. This choice directly impacts the economic viability and scalability of operations, requiring a careful balance between maximising output and minimising operational expenditure, especially as farms move to larger, more exposed sites. Furthermore, the variable success of direct seeding, particularly its lower yield in current-exposed locations (Boderskov et al., 2021), underscores the critical importance of precise site selection and advanced hydrodynamic modelling in offshore farm design. Optimising these factors could significantly enhance the suitability and performance of direct seeding, potentially enabling its wider adoption for large-scale offshore farms despite its current productivity limitations.

Table 1: Comparison of Seeding Methodologies (Twine vs. Direct seeding)

Feature	Twine Seeding	Direct Seeding
Process Description	Hatchery-grown juveniles on twine, then fastened to grow lines.	Juvenile sporophytes/gametophytes directly applied to cultivation substrate.
Labor Intensity	High (manual attachment)	Low (bypasses large part of hatchery phase)

Hatchery Requirement	Yes (controlled environment)	Gametophyte/sporophyte production only
Initial/Operational Cost	Higher (hatchery, labour)	Lower (reduced hatchery operations, less labour)
Biomass Yield (Relative)	Higher (for <i>S. latissima</i>)	Lower (for <i>S. latissima</i>)
Reliability	High (established, consistent)	Mixed (variable results)
Suitability for Exposed/Current-Exposed Environments	Good (more robust initial growth)	Variable/Challenging (lower yield in currents)
Current Adoption	Most Common in Europe	Novel/Emerging

1.3 Deployment of seedlings

At temperate latitudes, kelp is usually deployed in autumn/winter. It is desirable to deploy as early as possible in order to maximise growth time and yields (Sæther et al., 2024). However, high summer sea temperatures and low nutrient (E.g. nitrate) concentrations in surface waters, due to thermal stratification, prevent summer deployments (Sæther et al., 2024). The optimal timing is therefore following the breakdown of water column stratification that occurs with reduced sea temperatures in the autumn.

1.4 Harvesting of biomass

The optimum time to harvest is in late spring/ early summer. The annual spring phytoplankton bloom utilises nutrients in the surface ocean (euphotic zone), which slows down the growth of the seaweed. Around the same time as growth begins to slow, fouling organisms (typically bryozoans) cover the seaweed (Saunders and Metaxas, 2007), negatively affecting the quality of the biomass, also making it brittle and prone to erosion. For these reasons, seaweed in Norway is generally harvested between May and July, depending on latitude (Sæther et al., 2024).

In the Faroe Islands, Ocean Rainforest achieve multi-year seaweed harvests from the same seeded lines by “cropping” the biomass at harvest and allowing it to regrow. The unique location of the Faroe Islands, with relatively stable year-round conditions, and regular upwelling of nutrients into surface waters, is likely factors that make this strategy feasible.

1.5 Monitoring of the environment and the biomass

A. Environmental Monitoring Protocols

Environmental monitoring is critical for understanding the factors that influence growth, yield and biofouling at seaweed farms. The ultimate goal is to use this knowledge to optimise operations (e.g. deployment/harvest timing, farm design) in order to maximise yield and biomass quality.

Key Parameters and Importance:

- **Water Temperature:** Kelp species typically thrive within a specific temperature range (e.g., 5-20°C for many species). Temperature directly influences metabolic processes such as photosynthesis and

nutrient uptake; deviations outside the optimal range can negatively impact kelp growth and survival (Broch and Slagstad, 2012; Kerrison et al., 2015; Sæther et al., 2024; Simonson et al., 2015).

- **Salinity:** As a fundamental water quality parameter, appropriate salinity levels are essential for kelp health and optimal growth (Kerrison et al., 2015).
- **Light:** Light intensity and penetration is a critical factor, as it decreases with increasing water depth and turbidity (variable throughout the year), directly affecting kelp growth. High irradiances are also damaging to kelp, which can become an issue in the summer months (Broch and Slagstad, 2012; Heinrich et al., 2012; Kerrison et al., 2015).
- **Nutrients (nitrate and phosphate):** These nutrients are critical for growth and vary throughout the growing season (Broch and Slagstad, 2012; Forbord et al., 2021; Kerrison et al., 2015; Rugiu et al., 2021; Sæther et al., 2024). Seaweed is also highly efficient at absorbing dissolved nitrogen and phosphorus from the water. This nutrient uptake helps to improve water quality and can remediate ocean eutrophication, especially near coastal areas and in the vicinity of other aquaculture operations like fish farms.
- **Chlorophyll-*a*:** This is the photosynthetic pigment found in algae. Its concentration in the water column is used to approximate the abundance of microalgae/phytoplankton. The variation in phytoplankton abundance throughout the year (lowest in winter, peaking in spring) impacts seaweed growth by taking up nutrients in the water column and reducing their availability to seaweed (Larsen et al., 2004). High abundances also increase water turbidity and reduce light penetration to cultivation depths. Phytoplankton are also the base of the marine food web, so their concentration also impacts the abundance of biofouling organisms.
- **Current Speed:** Water flow is crucial as it influences the delivery of nutrients to the kelp (Broch and Slagstad, 2012) and can impact the attachment and survival of seedlings, particularly for direct seeding methods (Boderskov et al., 2021).
- **pH (Acidity/Alkalinity):** Kelp absorbs carbon dioxide (CO₂), via photosynthesis, which can lead to a localised increase in pH during daylight hours. In the dark, respiration rates exceed photosynthesis and there is net production of CO₂ (Krause-Jensen et al., 2016).

Monitoring Technologies and Methods:

- **Sensors:** Automated sensors are widely deployed to continuously measure key environmental parameters such as water temperature, pH, salinity, fluorescence (chlorophyll-*a*), nutrient levels, and light intensity (above and below the water). These sensors can log data frequently, providing continuous insights into environmental conditions.
- **Direct Visual Surveys:** Regular direct observations of cultivation lines and farm infrastructure are conducted, often by pulling lines onto a research vessel. These surveys assess both growth and epibiont assemblages (fouling organisms), colonisation by other algal, hydroid, and bryozoan species, and the composition of wild seaweed species settling on cultivation lines. Underwater cameras (used from a boat or on surface or underwater remotely operated vehicles) can also be used to assess the kelp underwater in situ without the need to lift the lines.
- **Water Samples:** Water samples are collected at various depths throughout the growth season and are analysed for nutrient concentrations (nitrate, ammonium, phosphate).
- **Remote sensing (satellites):** A range of sensors fitted to satellites orbiting the Earth give high temporal resolution data about the oceans, including sea-surface temperature, salinity, chlorophyll-*a* (phytoplankton), turbidity, surface light intensities and light attenuation (reduction in light intensity as it travels through seawater). This data is openly available from organisations such as Copernicus and NASA. Although temporal resolution is high (daily/weekly), spatial resolution is generally low (100s to 1000s of meters) and data from high latitudes is often poor or missing during winter months due to low sun angle and persistent cloud cover (Purkis and Chirayath, 2022).

2 Plan and establish a large-scale seedlings production to serve the ocean farm, with genetic material from the same region.

2.1 Task description

We sourced seedlings from two commercial producers: **Seaweed Solutions AS** in Norway and **Hortimare BV** in the Netherlands, while spools for twine seeding were produced using a “spooling machine” developed at SINTEF (Fig.2.1). Seaweed Solutions was selected for its proficiency with twine-seeded substrates, while Hortimare was chosen as a leading industry supplier of materials and expertise for direct seeding. Both suppliers sourced their seedling material locally in the Frøya region. In total, material for 36 km of seeded line was produced across two seasons (30 km in season one and 6 km in season two).



Fig. 2.1 Spools produced using a “spooling machine” (left and centre) at SINTEF Ocean and seeded by Seaweed Solutions (right).

2.2 Future consideration

The quantity of seedlings was not a limiting factor for our operations as both seedling providers were able to deliver seeds that exceeded what we were able to deploy. The main challenge was in coordinating travel and logistics with Hortimare in relation to the weather windows at Storflua. For this reason, using local seedling suppliers would be an advantage for large scale operations.

3 Out-planting of the seeded substrates, either pre-cultivated seeded lines or ropes/materials seeded directly at out-planting.

3.1 Task description

We faced significant operational challenges in **season one** after missing the optimal deployment window in late autumn. Winter storms, combined with the exposed conditions at Storflua and a shortage of suitable vessels, severely limited our opportunities to work. This forced us to deploy much of the material in poor conditions, which resulted in line entanglements (Fig.3.1). Ultimately, we deployed only 5-10 km of the 30 km of seeded line we had produced. On a positive note, we

successfully deployed the R&D lines, which allowed us to proceed with our comparative analysis of different seeding techniques.

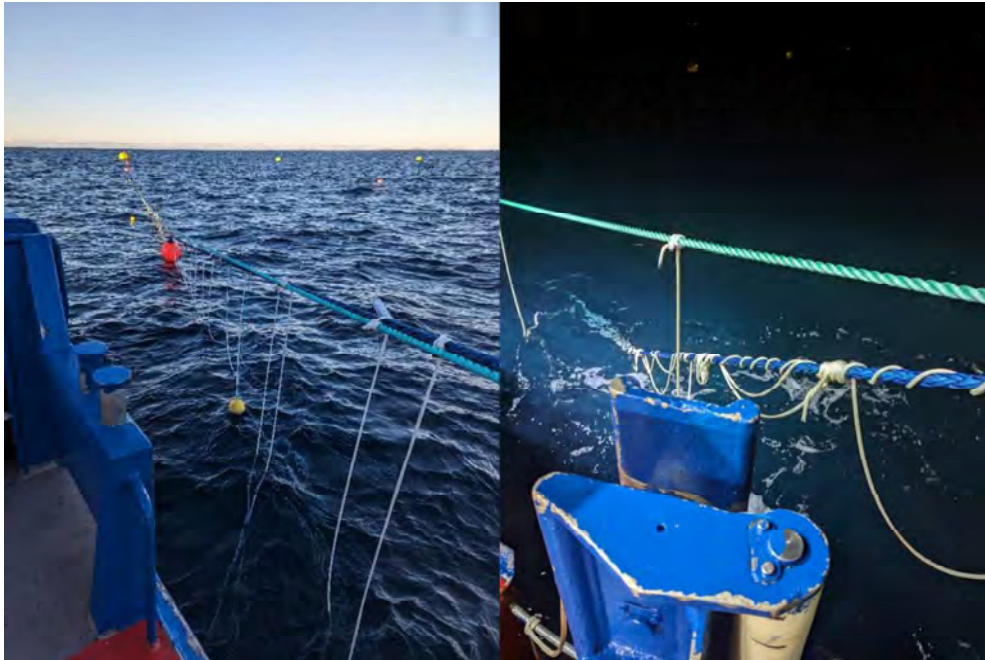


Fig.3.1. Deployment of seeded lines in February 2024 at Storflua, showing non-tangled (left) and tangled (right) lines.

In October 2024, we successfully deployed 2.5 km of seeded line under very good weather conditions. To minimise entanglement risk, we deployed the lines in sections. In February 2025 we further deployed several hundred meters of R&D tests, albeit under challenging sea conditions. This deployment included R&D tests of a new species, winged kelp (*Alaria esculenta*), and new seeding methods. Additionally, we trialled an alternative "free-floating" cultivation system, where cultivation lines are weighted at the bottom and attached only to the top line (see Fig.3.2), a design intended to simplify deployment and harvesting by avoiding the need for large vessels. This method has been successfully used by Ocean Rainforest at their most exposed site, but when we checked the lines in June 2025 all the lines were entangled.

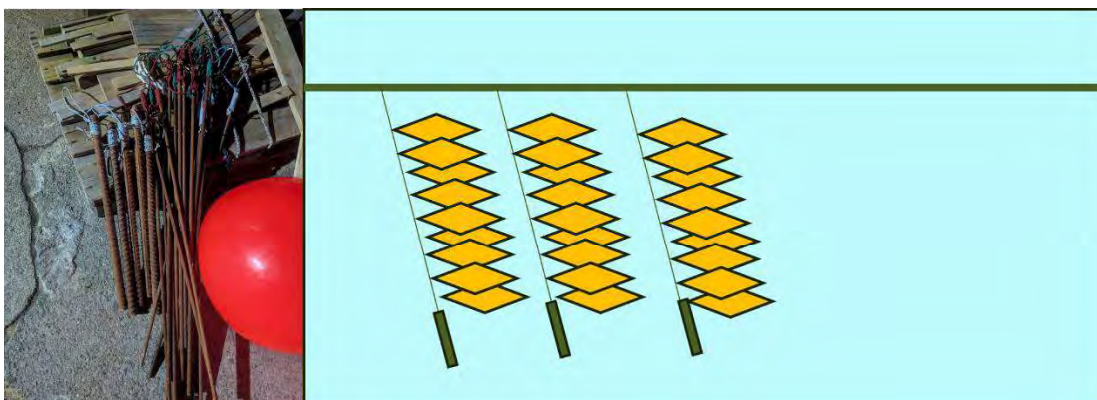


Fig.3.2. Alternative line deployment method using lines that are free-floating at the bottom. This would reduce the need for large boats for harvest and deployment but may lead to entanglements.

3.2 Future consideration

The current deployment process faces three key limitations: slow operational speed, constraints imposed by sea conditions, and high costs and emissions from vessel dependency:

1. **Slow Speed:** The use of individual 10-meter cultivation ropes is a primary bottleneck, preventing continuous workflows for both onshore seeding and at-sea deployment.
2. **Sea Conditions:** Rough seas pose a significant safety risk to boat-based operations, limiting viable work periods. While systems less prone to entanglement—such as those previously discussed—could widen this deployment window, they do not solve the underlying issue.
3. **Vessel Dependency:** Reliance on large vessels elevates operational costs and the carbon footprint of cultivation.

To fundamentally improve efficiency, a shift towards a continuous line system (e.g., in a zig-zag pattern) is recommended. This would require developing innovative attachment points that are rapid to install, durable enough for the growth season, and simple to detach during harvesting. This would have another major advantage by facilitating the reuse of rope for the next cultivation season (following cleaning), which would reduce costs and environmental impact.

4 Follow up of the operations needed for quality evaluation and strategy for harvesting

4.1 Task description and observations

In June 2024, a complete harvest production line, from biomass retrieval to acid preservation, was successfully implemented (see Fig. 4.1).

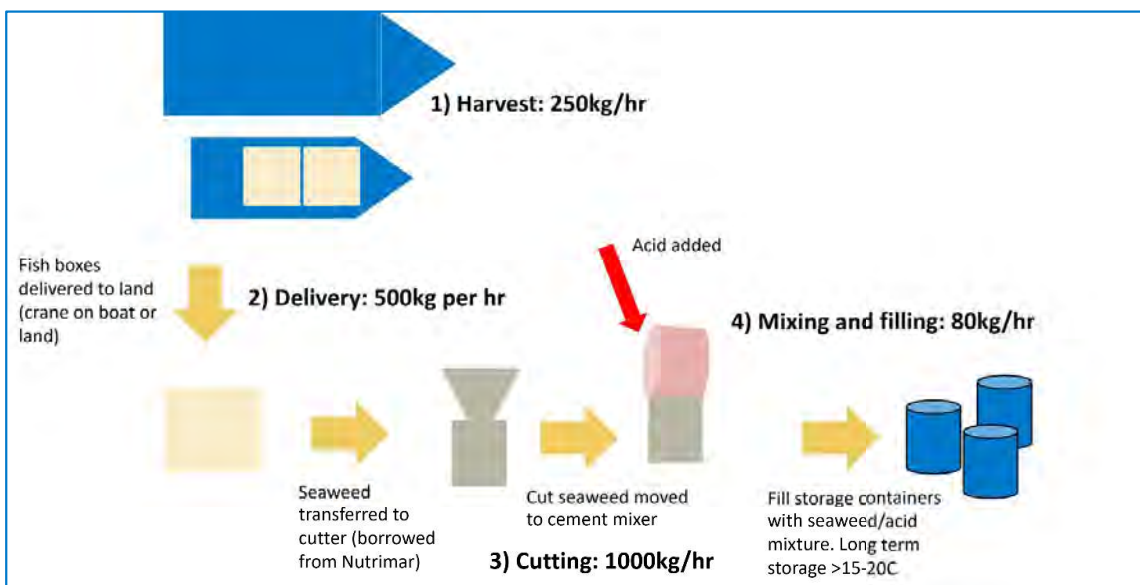


Fig. 4.1. Schematic of harvesting and processing logistics.

Harvesting Operations

The main operational challenge was the unavailability of suitable workboats with a crane of sufficient lifting strength to raise the cultivation lines. To mitigate this, a custom rope cutter was developed by Mausund Feltstasjon, enabling harvest from a small vessel by severing cultivation lines at depth (Fig.4.2). While this method was slower than would be expected from a large workboat, it achieved a harvest rate of 0.25 tonnes per hour and was not the major bottleneck in the production line.

Processing and Bottlenecks

The main bottleneck in the production line was the acid preservation stage (following cutting), which included mixing and filling of containers. This process operated at a relatively slow rate of 80 kg per hour. However, this processing speed could be substantially increased in future operations through the implementation of larger-capacity cement mixers for mixing the seaweed and acid.



Fig 4.2. Seaweed line cutter (left), cut seaweed line (center) and harvested seaweed in an insulated fish box (right).

4.2 Future consideration

With a larger service boat, it is likely that we could achieve a harvesting rate of around 1 ton per hour, based on the rates achieved by Ocean Rainforest in the Faroe Islands. Further improvements would likely require a move towards a continuous line system, as discussed in section 2.2.2 in this report. This would allow continuous harvest operations without the stopping and starting of short 10m sections of rope.

5 Testing of strategies for a prolonged harvest season

5.1 Task description and observations

Biofouling observations were made at harvest at both the inshore (Skarvøya) and offshore (Storflua) farms. Following harvest, lines were left at the farm in both 2024 and 2025 to see if the seaweed survived through the summer. Our observations following harvest revealed:

1. **Extended Harvest Window:** During the harvest in late June 2024 and 2025, biofouling by bryozoans was observed at Storflua, but this biofouling was less severe than that observed at Skarvøya (sheltered farm) a few weeks earlier. This suggests that one of the advantages of exposed seaweed farming may be a prolonged growth season, enabling higher yields of biomass.
2. **Likely Non-Viability of a Second-Year Crop:** Lines were left over the summer of 2024 to assess the potential for a second-year crop but showed complete die-off by August 2024 (Fig.5.1). The loss is attributed to summer stressors (high temperature, high irradiance, low nutrients). A second-year crop would likely only be possible if the cultivation system were submerged into colder, darker (possibly more nutrient rich) waters, where the seaweed would be under less physiological stress.



Fig.5.1. The poor state of the seaweed lines in Autumn 2024 (left) compared to in May (right), suggesting that a 2nd year crop is not possible without modifications to the farm design (e.g. adjustable depth).

5.2 Future considerations

A second-year crop would be advantageous in several ways. Firstly, it would open up the possibility for multiple harvests from the same lines, reducing costs and the environmental impact of the materials, energy consumption etc. Secondly, it would likely increase the content of high value compounds such as fucoidan, therefore increasing the value of the biomass.

The reason that this is not achievable at most seaweed farms is due to a combination of high temperatures, low nutrients and very high light intensities over summer. This combination of stressors often leads to the death of the seaweed. Lowering the farm to deeper in the water column, however, could help mitigate this stress. In deeper waters there will be reduced light intensities, lower temperatures and also possibly increased nutrient concentrations (depending on the depth and the location). Testing this possibility in a simple way, prior to developing the farm technology, would be a logical next step for a future project.

6 Farm state assessment (biomass, biomass composition) by a coupled monitoring-modelling (w/work package 4) approach, and monitoring of operational variables (currents, waves, light, temperature, nutrients)

6.1 Task description and observations

6.1.1 Season 1 – 2024/25

Deployments and harvesting

Deployments were carried out at both farm locations in November 2023 and February 2024. Harvest and data collection of final biomass took place at both locations in late June. However, many of the lines from November failed due to lack of growth leading to mostly naturally attached seaweed. For this reason, we decided to focus only on February 2024 deployments in our analysis. For the analysis, we have measurements from various depths on the line (1-2m, 2-3m, 5-6m and 9-10m), but for ease of analysis these have been split this into “Upper line” (0-5m) and “Lower line” (5-10m). The real depth of these sections, accounting for the depth of the longlines at the farm beneath the surface (2m below surface), are 2-7m and 7-12m.

Seeding methods compared were twine seeding (twine), direct seeding from Hortimare (Hort.), high density direct seeding from Hortimare (Hort. (HD)), direct seeding using SEAWISER’s “SEASEEDER” (SeaS.) and high-density direct seeding using SEAWISER’s “SEASEEDER” (SeaS. (HD)). The aim was to see which methods could deliver the best and most predictable yield. However, seedlings used across the methods were not the same, with Seaweed Solutions providing the twine seeded line as well as the seedlings for direct seeding with the SEASEEDER. Hortimare provided their own seedlings for their direct seeding attempts.

Site and method comparison

Analysis of harvest data showed that overall yields, across multiple seeding methods, were greater at the offshore Storflua site compared to the inshore Skarvøya site (Fig.6.1, left panel). Interestingly, this was not a result of larger individual plants, as metrics for plant length and area were comparable when measuring 10 individual seaweeds at random between the two farms.

The yield on the lower cultivation lines at Skarvøya was very low (<0.5kg/m compared to 2-3kg on the upper lines), and the average size of the seaweed seems to be one reason for this. The lower lines at Storflua had similar yields to the upper lines at Skarvøya (up to around 2.5 kg/m), with almost double the yield on the upper lines (up to 4.5 kg/m). However, sizes were comparable, pointing to other factors explaining the differences in biomass yield.

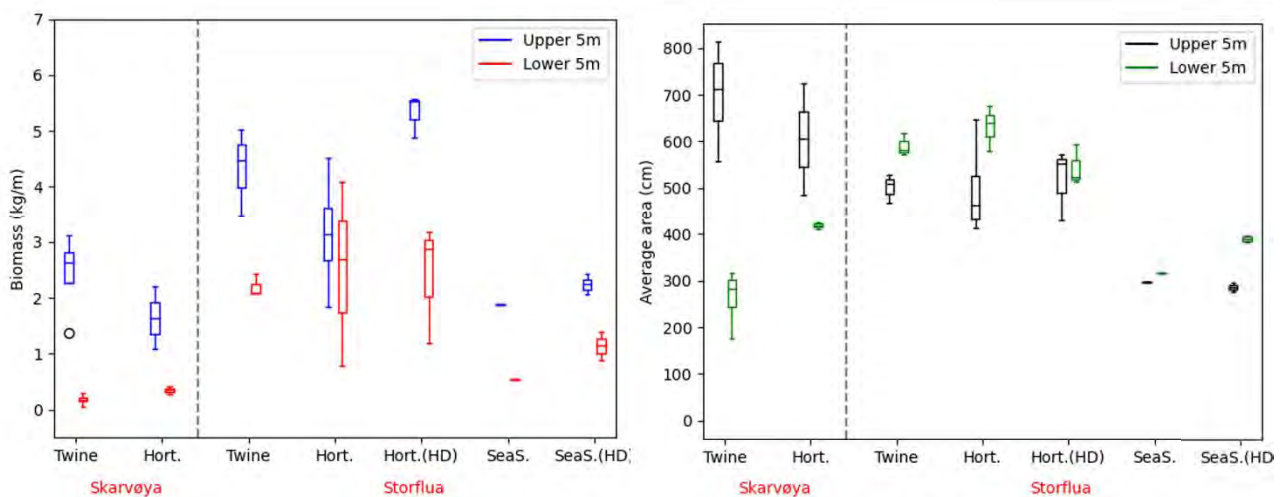


Fig 6.1. A comparison of how site, depth and seeding method affect the biomass (left) and average size (area) of seaweed during cultivation in Season 1 of the field trials.

Given that individual seaweed size was not the determining factor, the superior yields at Storflua must be attributed to higher plant density, greater plant thickness (thallus), or both. Visual inspection during the harvest supports the conclusion that plant densities were lower on the lower lines (Fig 6.2).

The differences observed may, therefore, reflect the ability of the offshore site to support a higher density of seaweed rather than promoting faster individual growth. A possible mechanism for this is that increased water movement offshore improves light distribution throughout the entire canopy, thereby reducing the effects of self-shading and allowing a denser crop to flourish. This would also explain the higher densities closer to the surface, if greater water movement near the surface had the same effect.



Fig 6.2. Visual inspection of seaweed growth at Storflua (Hort.) at three different cultivation depths.

When it came to seeding method, both the “twine” and “Hort. (HD)” gave the best yields and reliability (low variability). Although they had similar yields, we need to be careful when comparing the twine and Hort.(HD) directly, as they used different seedlings (collected separately by Seaweed Solutions and Hortimare), and factors such as genetic differences could influence size and densities. This is perhaps hinted at when looking at the length and width data, where Hortimare direct seeded trials had a lower length/width ratio (Fig 6.3) than the methods using Seaweed Solutions seedlings (Twine and SeaS.). Looking at the raw data, it seems generally that the seaweed seeded with SES seedlings were longer but thinner than Hortimare seeded methods, also possibly suggesting greater densities with the latter –

although we don't have the density data needed to confirm that. The main conclusion is that twine gives reliable results, but if using direct seeding it is advantage to use slightly seeding densities than normal to ensure good density and yield. It would also be expected that twine can be deployed earlier, and achieve greater yields, than direct seeding due to the higher vulnerability of direct seeding to sub-optimal environmental conditions in autumn.

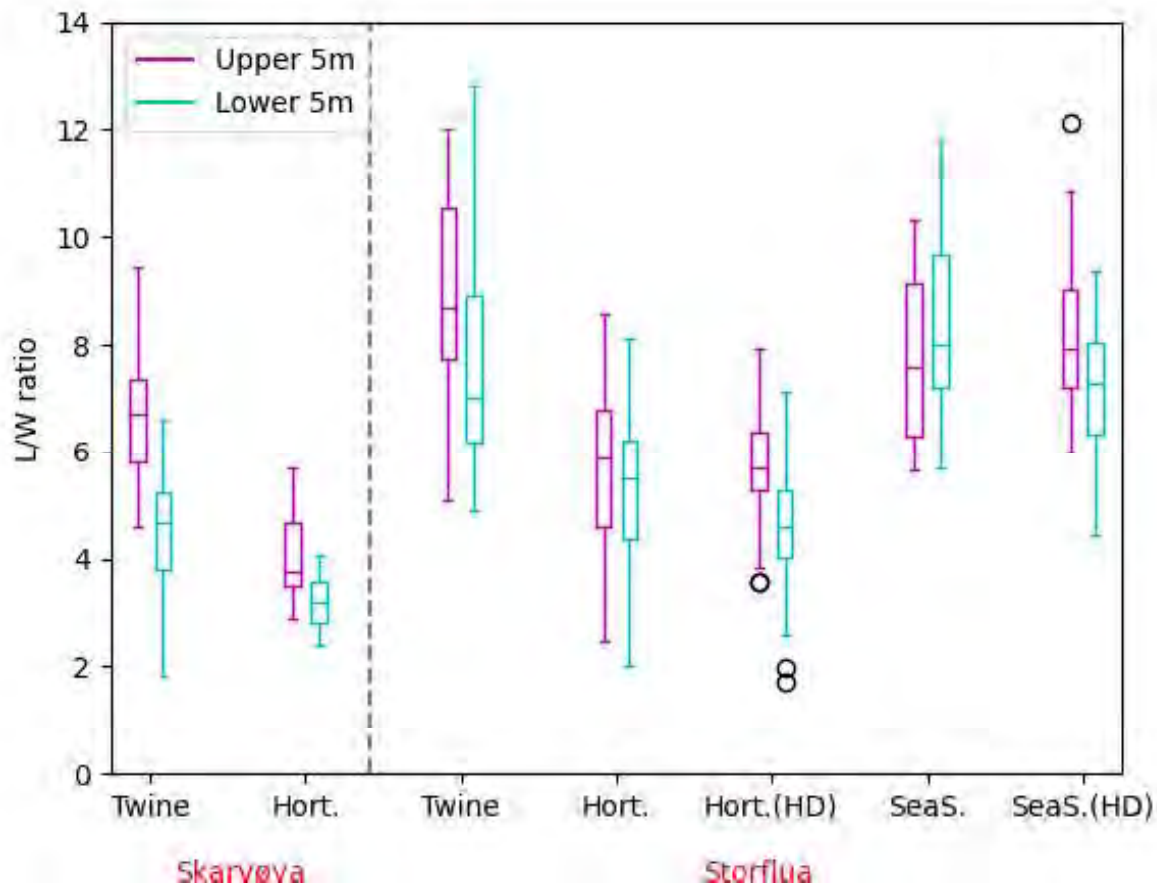


Fig 6.3. Length to width ratios across the different sites, depths and seeding methods.

6.1.2 Season 2 – 2024/25

Deployments were done at Storflua in late October 2024 and at Skarvøya in late November 2024. Harvest and data collection of final biomasses took place at both locations in June (early June at Skarvøya and late June at Storflua). At each site we took biomass and size measurements at 3-4m and 5-6m below the surface. At Storflua, where the first season demonstrated ok yield down to 12m, we also took samples at 7-8m. We were planning to focus only on the most reliable seeding methods (“twine” and “Hort. (HD)”), but due to a succession of storms during the winter and autumn, it was only possible to deploy twine.

Site comparison

Average (median) yields at Storflua were over two times greater than at Skarvøya (Fig.6.4) both at 3-4m depth (8.6kg/m vs 3.7 kg/m) and at 5-6m depth (5.6kg/m vs 2.3kg/m), consistent with the trend in season one and with yields decreasing with depth. The overall yield (accounting for the full 10m of growth line) could be estimated as the yield at the mid-point of the 10m growth line, which would equal around 4.6kg/m.

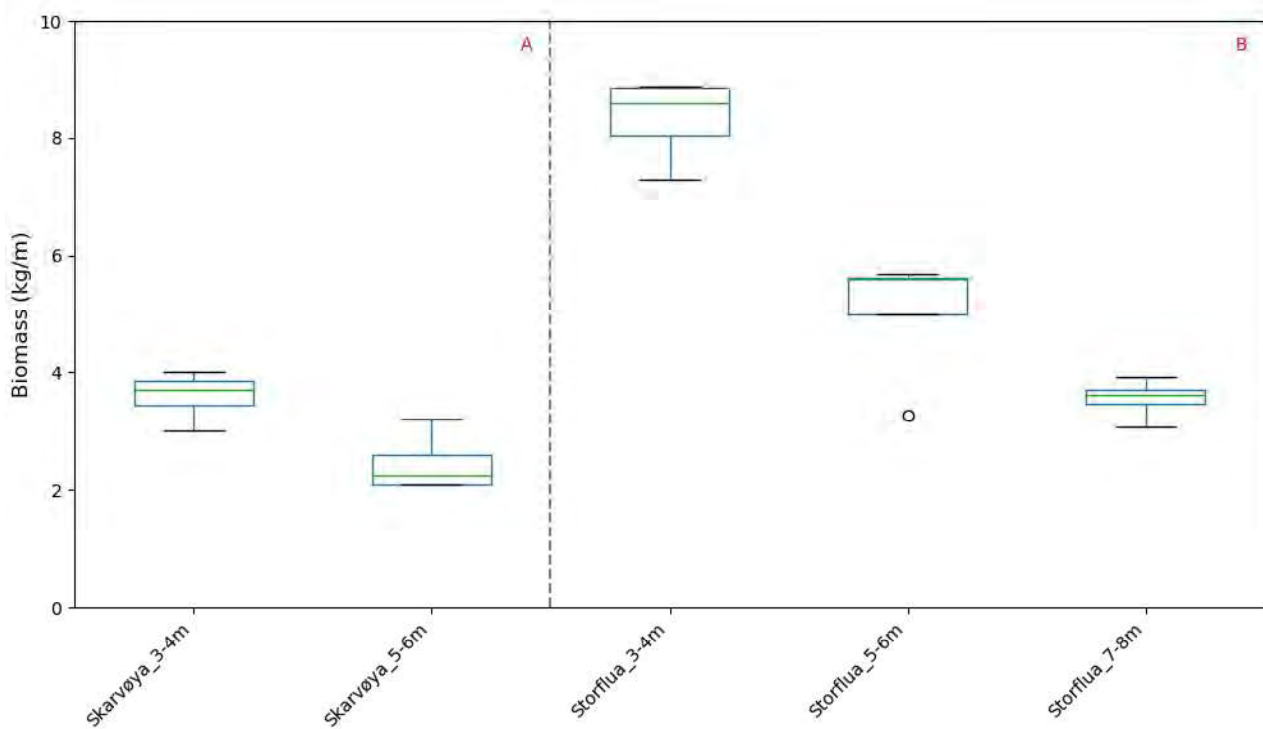


Fig 6.4. A comparison of how seaweed biomass varies with site and depth in the Season 2 (2024/25) field trials.

In contrast to season one, the biomass differences were not due to density differences, where there was no relationship between overall density and biomass (Fig. x, $R^2=0$). The average length (of 10 individuals) was only loosely correlated (Fig. x, $R^2=0.21$). However, the best correlation was between the density of individuals over 60cm in length (Fig. x, $R^2=0.67$), suggesting that it is the relative abundance of large individuals that lead to the high yields at Storflua. In simpler language, this site can support a higher number of large seaweeds.

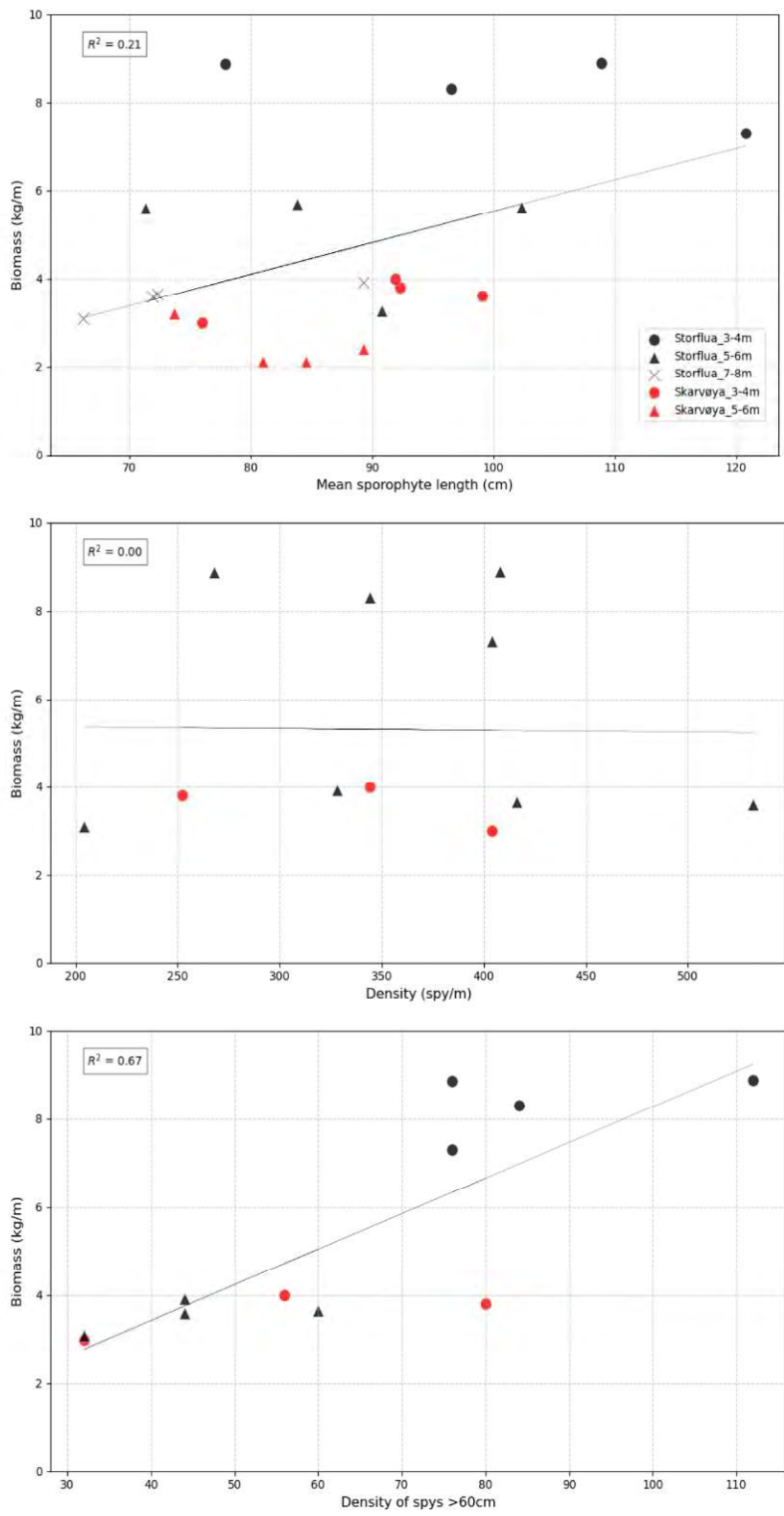


Fig 6.5. The relationship between “mean sporophyte length” (upper, $R^2=0.21$), “total density” (middle, $R^2=0$) and “density of sporophytes >60cm” (lower, $R^2=0.67$) with seaweed biomass.

6.2 Future considerations

- High yields are achievable, even without optimised deployment timing.
- Unsure how early we can deploy, but favourable nutrient dynamics likely mean we could deploy earlier than at sheltered sites.
- Growth close to the surface was considerably higher, so ideally you would want a farm design to take advantage of this.
- The differences in factors determining yield between season 1 and 2 (density vs size) may be explained by deployment timing and low light in winter which allows the “surface seaweed” to get a head-start over the deeper seaweed.

7 Develop and test possible remote monitoring of environmental parameters (currents, waves, light, temperature, nutrients).

7.1 Task description and observations

7.1.1 Overall Seasonal Trends

Both Storflua and Skarvøya exhibit strong, largely predictable seasonal patterns in environmental conditions driven by changes in light and temperature. These data, primarily sourced from satellite observations (Fig.7.1), are incredibly powerful for understanding regional, large-scale patterns and seasonal trends. However, their coarse spatial resolution (typically around 1 km²) makes them less reliable for pinpointing the exact environmental conditions at a specific, complex coastal location, as a single pixel represents an average value over a large area, which is why we supplement this with *In situ* data from CTD profiles of the water column throughout the year from both Skarvøya (Fig.7.2) and Storflua (Fig.7.3). The general seasonal cycle observed from this data is as follows:

Winter (approx. Nov - Feb): This period is characterised by the lowest Sea Surface Temperature (SST) and Photosynthetically Active Radiation (PAR). Nutrient concentrations, specifically nitrate, are at their highest due to reduced biological uptake and increased water column mixing. Chlorophyll (Chl-a) concentrations are low, indicating low phytoplankton biomass.

Spring (approx. Mar - May): As PAR and SST rapidly increases this triggers the spring phytoplankton bloom, visible as a sharp spike in Chl-a concentration. The bloom consumes available nutrients, causing a steep decline in nitrate.

Summer (approx. Jun - Aug): SST reaches its peak, while PAR is also high. The water column becomes stratified, limiting nutrient replenishment from deeper waters. Consequently, nitrate concentrations remain very low, which in turn limits phytoplankton growth, causing Chl-a concentrations to decrease after the spring peak.

Autumn (approx. Sep - Oct): SST and PAR begin to decline. Cooling surface waters and increased storm activity can break down summer stratification, starting to replenish nitrate in the surface layer.

7.1.2 Comparison Between Locations

While the overall satellite patterns are similar, *in-situ* data from CTD profiles reveals critical differences in the hydrographic structure and stability of the water column between Skarvøya and Storflua, which have direct implications for biological processes.

Spring Bloom Timing: The satellite data suggests the spring bloom at Skarvøya may begin slightly earlier and is more prolonged compared to Storflua, where the Chl-a peak appears more concentrated in May. This could be one explanation for later biofouling at Storflua, as bryozoan larvae are dependent on phytoplankton as a food source (Winston, 1977); a delayed spring bloom would likely delay their development.

Temperature and Salinity: Contrary to satellite data suggesting only minor variations, *in-situ* CTD profiles reveal two distinct hydrographic regimes. Skarvøya demonstrates clear characteristics of a coastal system, with significant freshwater input creating a pronounced low-salinity surface layer during parts of winter (sometimes dropping below 25 during) and colder deep-water temperatures of <6°C. In contrast, Storflua maintains higher salinity throughout the water column, year-round, and exhibits warmer deep-water temperatures of approximately 7°C during winter, indicative of a stronger influence from offshore Atlantic water masses. The warmer winter sea temperatures at Storflua could be advantageous for growth, as photosynthesis is limited at lower temperatures. In late spring/summer, temperatures at Storflua were lower than Skarvøya (greatest in May 2024, where Storflua was up to 2°C colder (7 vs 9 °C). Low temperatures are known to limit biofouling pressure (Saunders and Metaxas, 2007) which could be part of the reason why biofouling was reduced at Storflua compared to Skarvøya).

Nitrate Levels: While satellite data indicates little difference in surface nitrate, the distinct water masses identified by the CTD profiles suggest potentially different nutrient dynamics. Storflua's connection to warmer, saltier Atlantic water may provide a more consistent or slightly larger nutrient reservoir heading into the productive season.

PAR Variability: The PAR curves show significant divergence between 2m and 12m depth during the summer months at both sites. This indicates strong light attenuation in the water column, which is typical when phytoplankton is abundant and/or turbidity is high due to suspended particles. The greater currents at Storflua likely cause the longlines to separate horizontally, ensuring a more even distribution of light to the deeper sections of the cultivation lines.

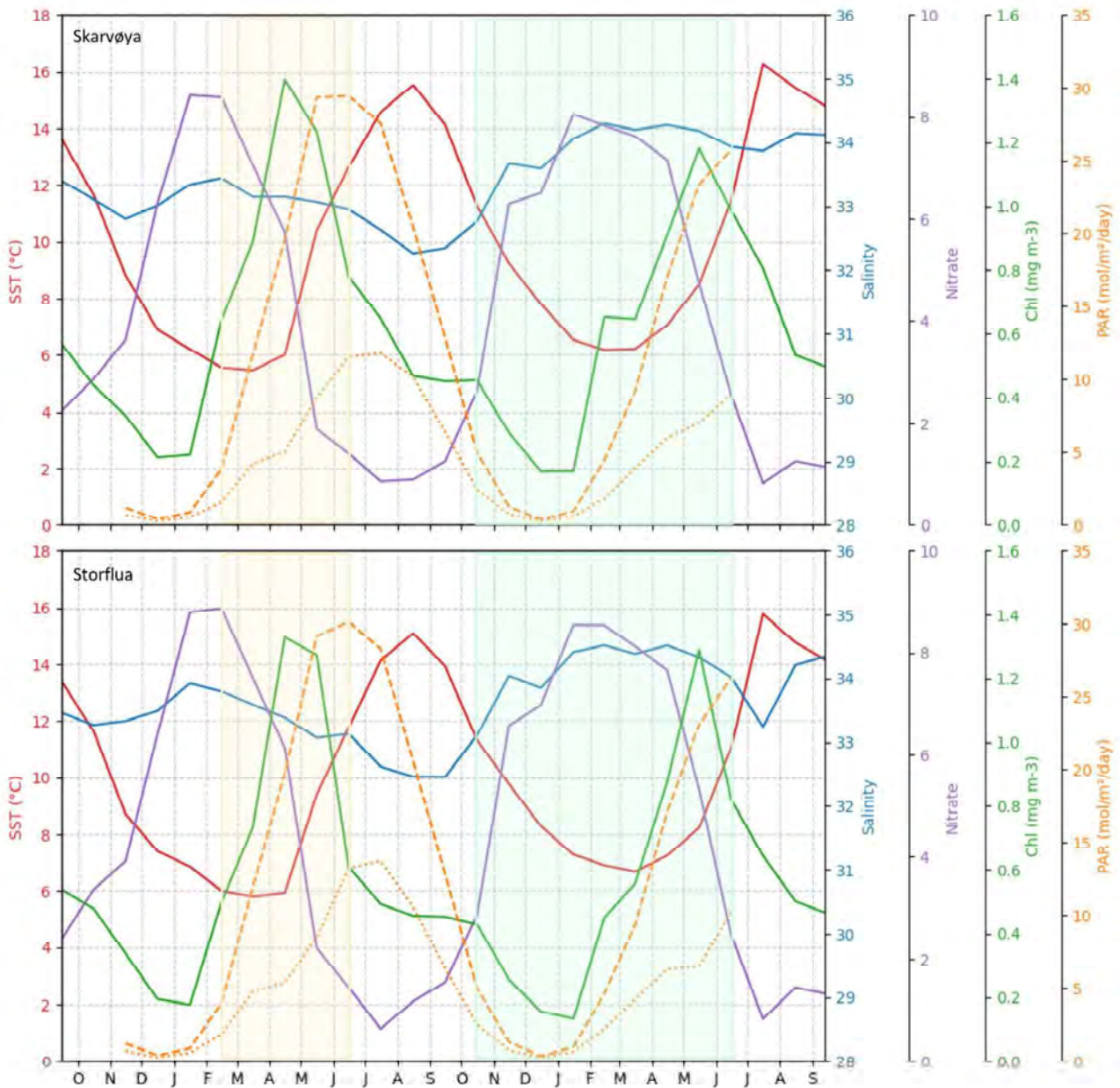


Fig.7.1. Remote sensing satellite data of various relevant environmental variables over the project duration for Season 1 (yellow shading) and Season 2 (green shading) at both Skarvøya (upper panel) and Storflua (lower panel). Data includes SST (red line), salinity (blue line), modelled nitrate concentrations (purple line), chlorophyll-a (green line) and PAR at 12m (yellow dotted line) and 2m depth (yellow, dashed line). PAR data was accessed from NASA ([NASA POWER | Data Access Viewer \(DAV\)](#)) and all other data from Copernicus ([Copernicus Marine Data Store | Copernicus Marine Service](#)).

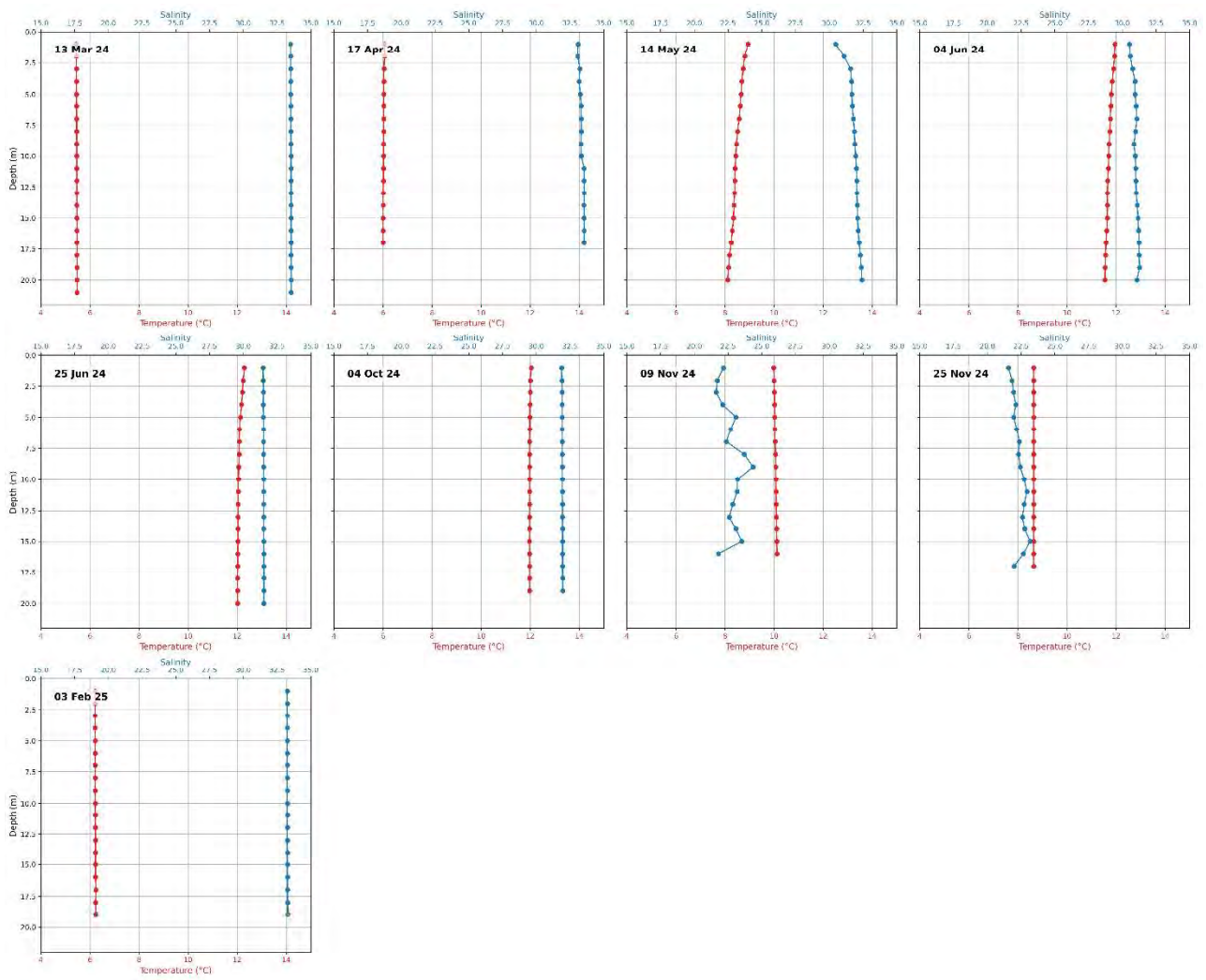


Fig.7.2 CTD water profiles from Skarvøya showing depth profiles of salinity and temperature during different times of the year (2024-2025).

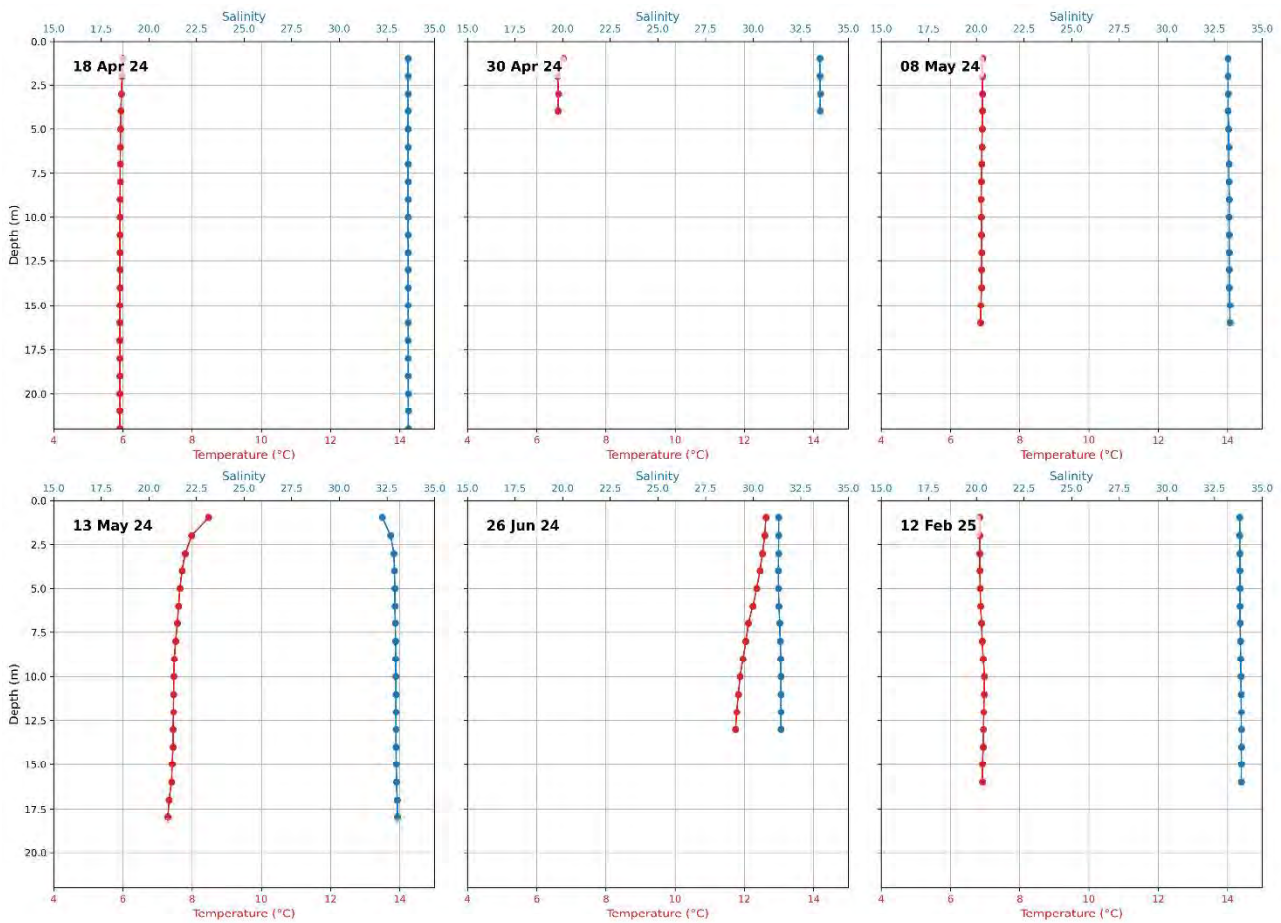


Fig.7.3. CTD water profiles from Storflua showing depth profiles of salinity and temperature during different times of the year (2024-2025).

7.1.3 *In situ* nitrate measurements

Testing of *in situ* nitrate measurements: A marine nitrate sensor (part of RI Seaweed infrastructure), developed by ClearWater Sensors (UK), was deployed in October 2024 and provided high resolution nitrate data over 3 days. Comparison with wind speed data shows how the exposed location likely benefits from increased N concentrations during storms, when N-rich deep water is mixed into the surface ocean. This sensor was redeployed in February 2025 and will be collected in November 2025 to provide insights into the nutrient dynamics at Storflua.

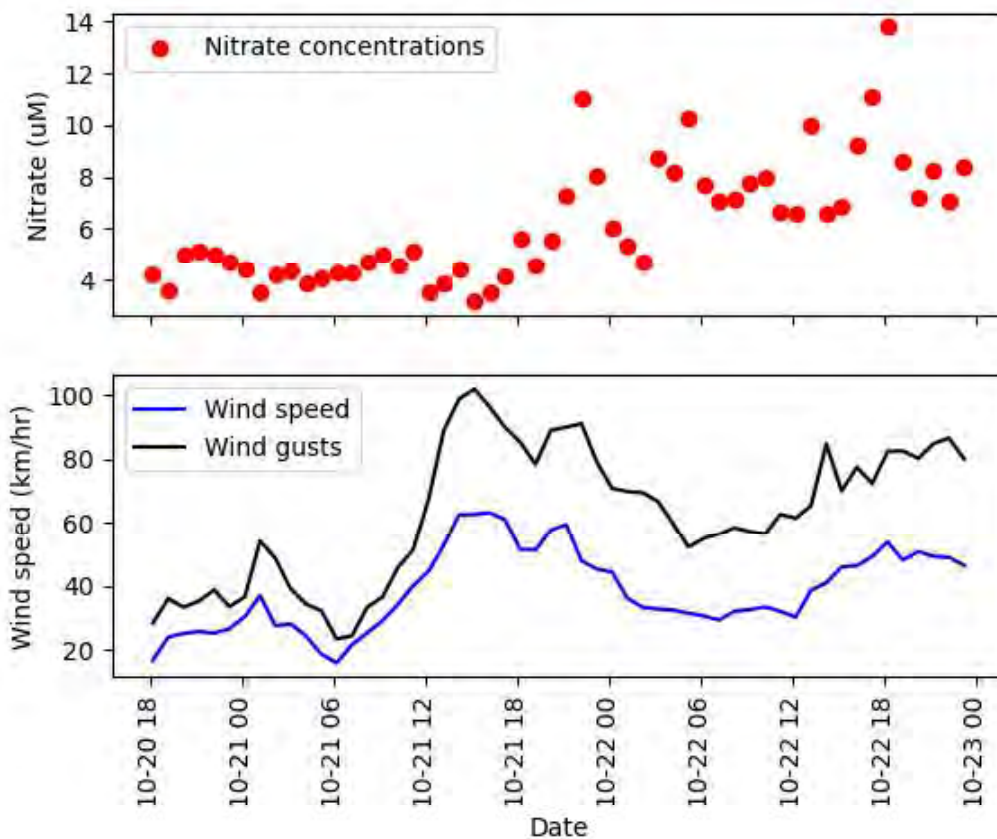


Fig.7.4. High resolution in situ nitrate data from October 2024 plotted against wind speeds and gusts (from [Weather Query Builder | Visual Crossing](#)).

8 Develop and test possible remote monitoring of biomass growth and biofouling by machine vision/biometry/AUV

8.1 Task description and observations

In a collaborative effort with F&Z Solutions (Trondheim), the feasibility of remote monitoring for seaweed biomass and biofouling was explored using a proprietary unmanned surface vehicle (USV) named 'Pamela'. The primary objectives of the demonstration were to evaluate the USV's ability to safely navigate for complete coverage within the farm, to assess the potential of its underwater camera imagery for developing biomass estimation tools, and to confirm the viability of automated data collection via GNSS-based navigation. Initial trials at Storflua were impeded by a weak mobile network signal combined with strong currents. However, a subsequent demonstration at the Skarvøya site proved successful, meeting all initial objectives and resulting in a qualitative biomass map of the farm (Figs. 8.1 and 8.2).

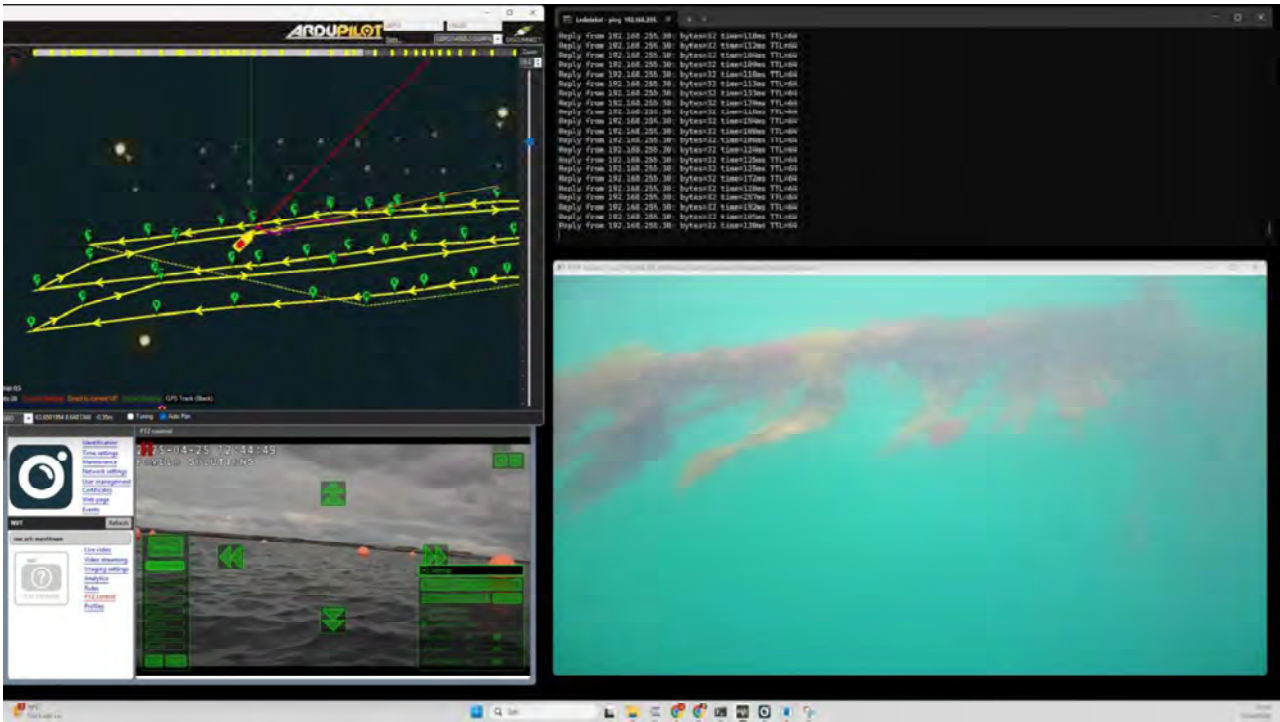


Fig.8.1 Upper left: satellite image (map) with automatic transect overlay and vehicle tracking Lower left: Above water camera. Lower right: underwater camera feed.

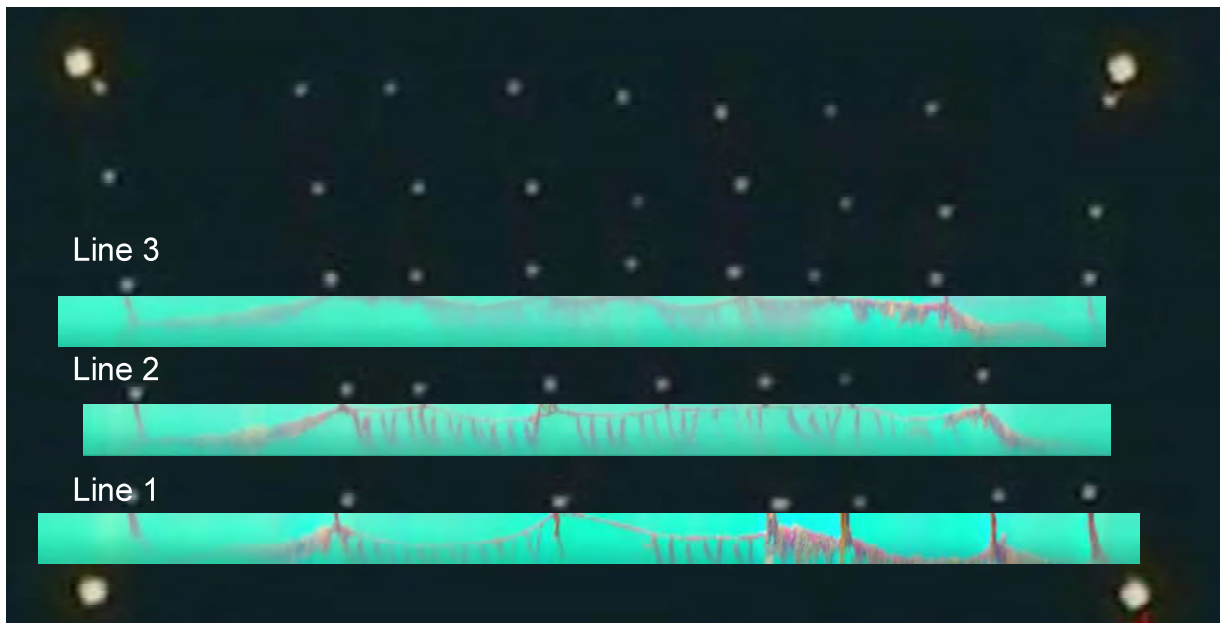


Fig.8.2. Visualisation of underwater feed for assessment of seaweed growth, biofouling and biomass.

9 Conclusions and Recommendations

Offshore Cultivation Potential: Moving seaweed farms to exposed, offshore environments would be crucial for scaling up production for carbon capture and storage (CCS) and minimizing conflict with other marine activities. The offshore Storflua site consistently produced significantly higher biomass yields than the inshore Skarvøya site across both seasons (24/25 and 25/26). This advantage is attributed to factors like higher seaweed density in the first season and a greater abundance of large seaweeds in the second, likely driven by superior environmental conditions such as improved light distribution and nutrient availability resulting from a more dynamic offshore location. However, there are still substantial logistical and technical challenges that need to be solved.

Seeding and Deployment:

- **Seeding Methodology:** A critical trade-off exists between high-yield, reliable twine seeding and the more cost-effective, scalable direct seeding method. Twine seeding and high-density direct seeding delivered the best results. However, direct seeding's success is more variable and requires further optimisation.
- **Logistics:** The project highlighted significant logistical challenges related to deployment in exposed offshore conditions. If adverse weather conditions delay deployment, then the optimal deployment time will be missed, and yields will be reduced. Using local seedling suppliers is recommended to simplify logistics and better align with narrow weather windows. Further improvements for deploying in adverse weather conditions are required, and these likely require a rethink of the farm design.
- **Recommendations for Improvement:** The current method of deploying a large number of individual 10-meter ropes is a major bottleneck as it restricts attempts to implement continuous operations and reuse rope. It is recommended to shift to a continuous line system (e.g., in a zig-zag pattern) to improve operational speed, reduce vessel dependency, and facilitate the reuse of materials, thereby lowering costs and environmental impact. Alternative farm designs should also be explored (e.g. horizontal longline systems), especially with regards to facilitating deployment logistics in adverse conditions.

Harvesting and Season Extension:

- **Operations:** A full harvesting and processing pipeline was successfully tested, although the processing operations (acid preservation) was identified as the primary bottleneck. A custom-developed rope cutter allowed harvesting to proceed without a large crane vessel. With a larger boat and optimised processing (e.g., larger mixers), harvest rates could be significantly increased.
- **Season Length:** The offshore site showed less severe biofouling, suggesting a potentially longer harvest season compared to inshore locations (likely due to higher nitrate concentrations and lower temperatures). However, attempts to achieve a second-year crop failed due to the seaweed dying off during the summer, suggesting nutrient-limitation in these months. One way around this would be to explore possibility of submerging the farm into deeper, colder water during summer to mitigate environmental (high light, low nutrient) stress and potentially enable a second harvest.

Monitoring:

- **Environmental:** While satellite data is useful for observing broad seasonal trends, *in-situ* monitoring is essential to capture critical differences between farm sites. *In-situ* data revealed that the offshore site likely benefits from higher stability, with warmer seawater during winter, colder temperatures in summer, and increased nutrient entrainment into surface waters (Fragoso et al., 2021), likely contributing to the higher yields.

- **Biomass:** The use of an Unmanned Surface Vehicle (USV) for remote monitoring was successfully demonstrated, proving its capability to navigate the farm and generate qualitative biomass maps from underwater imagery. This technology should be explored further, also with a view to using underwater robots to perform basic farm operations in addition to monitoring.

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SINTEF

Report

JIP Seaweed Carbon Solutions WP4 – Long term carbon calculus

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Report No:

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JIP Seaweed Carbon Solutions

WP4 – Long term carbon calculus

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SUMMARY

This study explores kelp cultivation as a marine carbon dioxide removal (mCDR) strategy using the SINMOD ocean model and a simple dynamical model for carbon budgets in a kelp farming operation. Simulations show kelp farms can reduce surface fCO_2 , and provide ecosystem services like increasing pH and oxygen levels and nutrient uptake. Long-term carbon sequestration is feasible if biomass is stabilized, e.g., via biochar. However, emissions from farm construction and operation significantly affect net carbon removal. Scenario analyses suggest a 40% reduction in emissions and improved yields are needed for viability. The study identifies key knowledge gaps, including life cycle assessments and ocean-atmosphere feedback, emphasizing the need for further research and technological development.

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1 Introduction

Due to the flux of CO₂ through the ocean-atmosphere interface, the oceans have taken up around 24 % of the anthropogenic carbon released since the mid-19th century (Friedlingstein et al., 2022). Removal of CO₂ from the ocean may therefore lower atmospheric CO₂ concentrations. Various biologically based/nature-based solutions have been suggested for *Carbon Dioxide Removal (CDR)* from the ocean (Tanzer et al., 2019) (marine CDR, mCDR). For example, cultivation of macroalgae or restoration of kelp forests and habitats have been heralded as two possible solutions (Duarte et al., 2021). Regardless of the technical implementation, the goal of such CDR initiatives is either:

- i. to increase the primary production and the vertical flux of carbon in the ocean, or
- ii. to increase primary production and stabilize the carbon in such a way that it is not immediately degraded and released to the atmosphere-ocean system (e.g. production of biochar).

The idea behind this is that the difference in partial pressure of CO₂ ($p\text{CO}_{2,\text{atm}}$ in the atmosphere, $f\text{CO}_2$ in the ocean surface) between the ocean surface and the atmosphere leads to either flux of CO₂ from the atmosphere to the ocean, or the other way around, following the equation:

$$J_C = K_{\text{Airsea}}(f\text{CO}_2 - p\text{CO}_{2,\text{atm}})$$

A *negative* sign of this quantity (when $p\text{CO}_{2,\text{atm}} > f\text{CO}_2$) means that the ocean is taking up CO₂, while a *positive* sign (when $f\text{CO}_2 > p\text{CO}_{2,\text{atm}}$) means that the flux goes from the ocean to the atmosphere. The gas exchange rate K_{airsea} depends on the wind speed, the water temperature, and ice cover. See Wanninkhof (1992) for the details. It is important to note that even when there is a flux from the ocean to the atmosphere ($f\text{CO}_2 > p\text{CO}_{2,\text{atm}}$) increased primary production (biological uptake of CO₂) will contribute to reduce atmospheric $p\text{CO}_2$ in the sense that the flux to the atmosphere is decreased. Some of the processes involved are illustrated in Fig. 1 below. The equation above has been simplified here to avoid unnecessary notation and introducing numerous additional concepts.

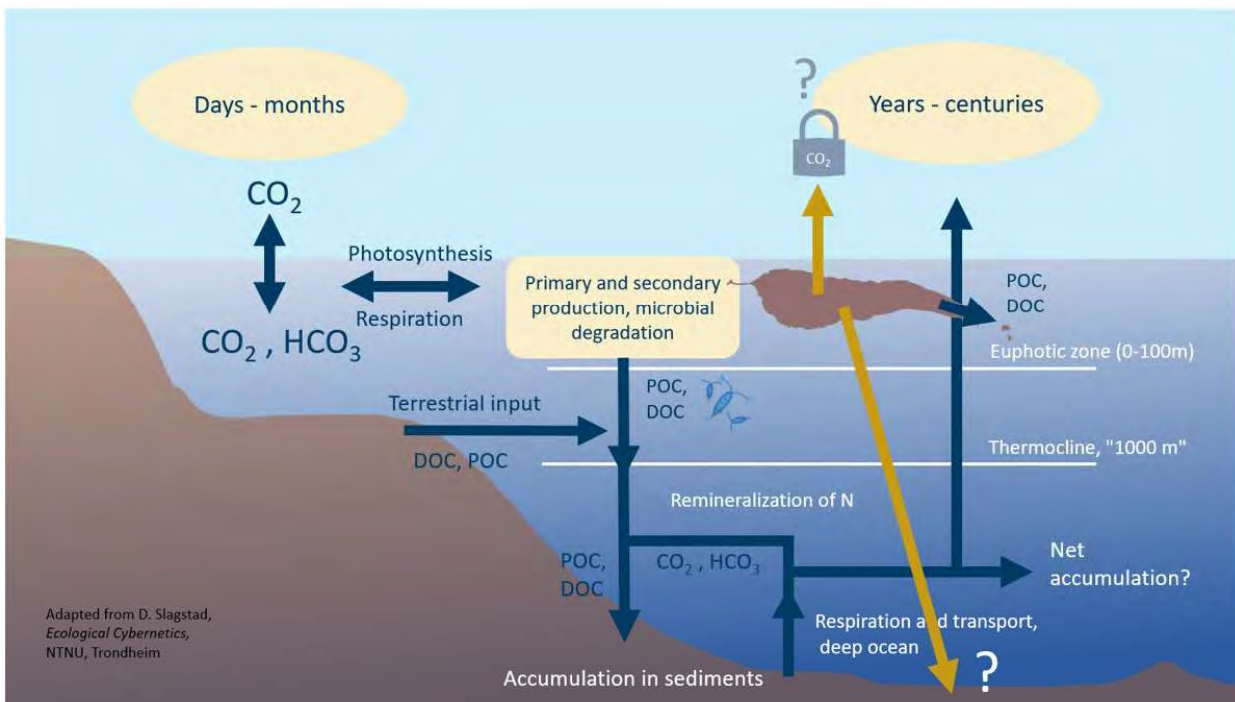


Figure 1. Simplified schematic of the ocean carbon(ate) system and how seaweed cultures interact with it. The schematic also provides a simplified overview of the processes involved in the ocean model SINMOD's carbon system module and its interactions with the biogeochemical loop (nutrients, bacteria, plankton). The two yellow arrows indicate stabilized carbon through biochar production (or similar) and "active deposition" of seaweed biomass on the ocean floor.

1.1 WP4 Objectives (according to project description)

The complete carbon uptake and sequestration, as well as the large-scale environmental interactions, of the/a kelp farm can only be properly quantified by *upscaling calculations*. Upscaling calculations may be made in different ways. Here, we have used the SINMOD ocean model framework as a basis for the calculations. The framework couples the most important processes shown in Fig. 1 in addition to the physical environment (ocean water currents, salinity, temperature); nutrients (nitrate NO_3 , ammonium NH_4^+), light, and ecosystem interactions through a basic food web model; kelp growth, composition, and biomass through a kelp growth model; the ocean carbon and oxygen system through a carbon module, including ocean-atmosphere CO_2 exchange.

Specific tasks in WP4:

- a. Update the model based on the data from the other sub projects, by including new parameters and rates and by including new variables and processes
- b. Quantification of gross carbon captured by photosynthesis and the CDR (w/sub-project 6) on a large scale
- c. Simulation of changes in alkalinity (counteracting "acidification"), the carbon system and the oxygen concentrations in the long term
- d. Quantification of the large-scale and long-term impacts on dissolved nutrient concentrations
- e. (*Planned for the original suggestion for Phase 2 of the project, so will not be described here*) Coupling [the ocean model] with atmospheric climate model(s) for quantification of the climate impact of seaweed CDR (involve atmospheric modellers)

We have approached tasks a. to d. by running *scenarios* using the model system. This is one of the strengths of dynamical modelling: that we may assess the effects of perturbing the system in different ways by running simulations with and without the perturbations. In the present work we have introduced large-scale kelp cultures in the model and coupled the kelp model two-way with the physical-biological-biogeochemical model. The SINMOD system is a four-dimensional model system (the three spatial dimensions + time) and we therefore get insight into not only how much, but where and when changes/effects are taking place. The downside of spatially explicit ocean models is that they require a lot of computations that might take a long time to finish.

To assess the long-term CO_2 uptake and storage potential by kelp aquaculture by handling the biomass in different ways (biochar, others), including the passive carbon storage (see WP6), we have combined the simulation results with a *carbon calculus model* that calculates the long-term carbon storage in the marine system an otherwise, depending on how the biomass is used.

A comparison between SINMOD simulation results and observational data is made in a paper in preparation.

2 Methods

2.1 Ocean model framework and setups

The ocean model framework SINMOD was used to simulate the interactions between seaweed cultures and the marine environment (Figures 1, 2). The model simulates physical, biological, and geochemical processes in the ocean and how they interact. There is a carbon(ate) system module and seaweed growth module for the model framework. See, e.g., Broch et al. (2019) for the kelp growth model and how it is used with the biogeochemical model.

SINMOD's lower trophic levels ecosystem module is a simplified model for the lower trophic levels in the marine food web (Fig. 2). The main currencies of the food-web model are nitrogen and silicate, and a fixed C/N-ratio (Redfield ratio) is applied (Wassmann et al., 2006). The module is run fully coupled with the hydrodynamic model (two-way feedback). The ecosystem module simulates key variables such as light availability, nutrient concentrations (nitrate, ammonium), phytoplankton production and concentrations, oxygen, zooplankton and detritus. Importantly, processes such as remineralization of ammonium NO_4^+ into nitrate NO_3^- are included. A detailed overview is provided in Wassmann et al. (2006). An assessment of results from the ecosystem module is given in Lee et al. (2016), while recent results from the model can be found in Vernet et al. (2021).

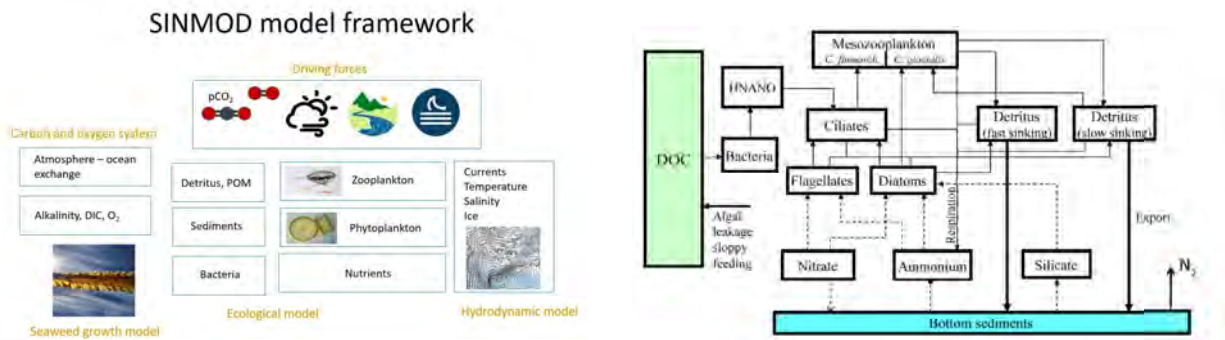


Figure 2. *Left*: Overview of the SINOMD Ocean model framework. *Right*: Structure of the lower trophic level food web model (Wassmann et al., 2006).

Total carbon C_T and alkalinity A_T are the main states (prognostic variables) in the carbon system module uses. There are further corresponding states for total carbon and alkalinity of the sea ice. Calculations of equilibrium constants and f_{CO_2} follow Dickson et al. (2007), while ocean-atmosphere exchange of CO_2 follows Wanninkhof et al. (1992). The dynamics of C_T and alkalinity A_T are determined by the processes indicated in Fig. 1. We will not give a complete and rigorous formulation of the equations here, but refer to Wassmann et al. (2006) for the general link between biogeochemical processes (like uptake of nitrate and ammonium in phytoplankton and excretion of ammonium) and the advection-diffusion operators, and to Wolf-Gladrow et al. (2007) for remineralization of nitrate and ammonium, with ensuing consequences for the alkalinity. Results from an earlier version of the carbon module have been compared against data for the arctic (Wallhead et al., 2017).

Model setups in horizontal resolution ranging from 20,000 to 160 m were used (Fig. 3). In the present work, z-layers were used, i.e. each vertical layer had a fixed thickness, except the surface and bottom layers. The 20 km resolution model domain covers the Arctic and north Atlantic, with specified boundary conditions from the World Ocean Atlas (WOCE). The sea ice model and results are described in detail in Ellingsen et al. (2009) and Slagstad et al. (2015). The model was nested in 3 steps to a model domain of 160 m for the coastal areas of Central Norway (Romsdal, Northern Møre, and Southern Trøndelag). Atmospheric forcing was applied using ECMWF's ERA-Interim data (Dee et al., 2011). Forcing by freshwater from rivers and land was implemented by using data from the Norwegian Water Resources and Energy Directorate (www.nve.no), generated by a version of the HBV-model (Beldring et al., 2003). Further river data comes from SMHI hype.

Previous studies have shown that the model system is able to approximate the local current system at scales of e.g. the region around aquaculture sites in a realistic manner (Broch et al., 2020). On a larger scale, the model has been shown to reproduce the circulation dynamics at the Norwegian Shelf outside Northern Norway (Skadhamar et al., 2005).

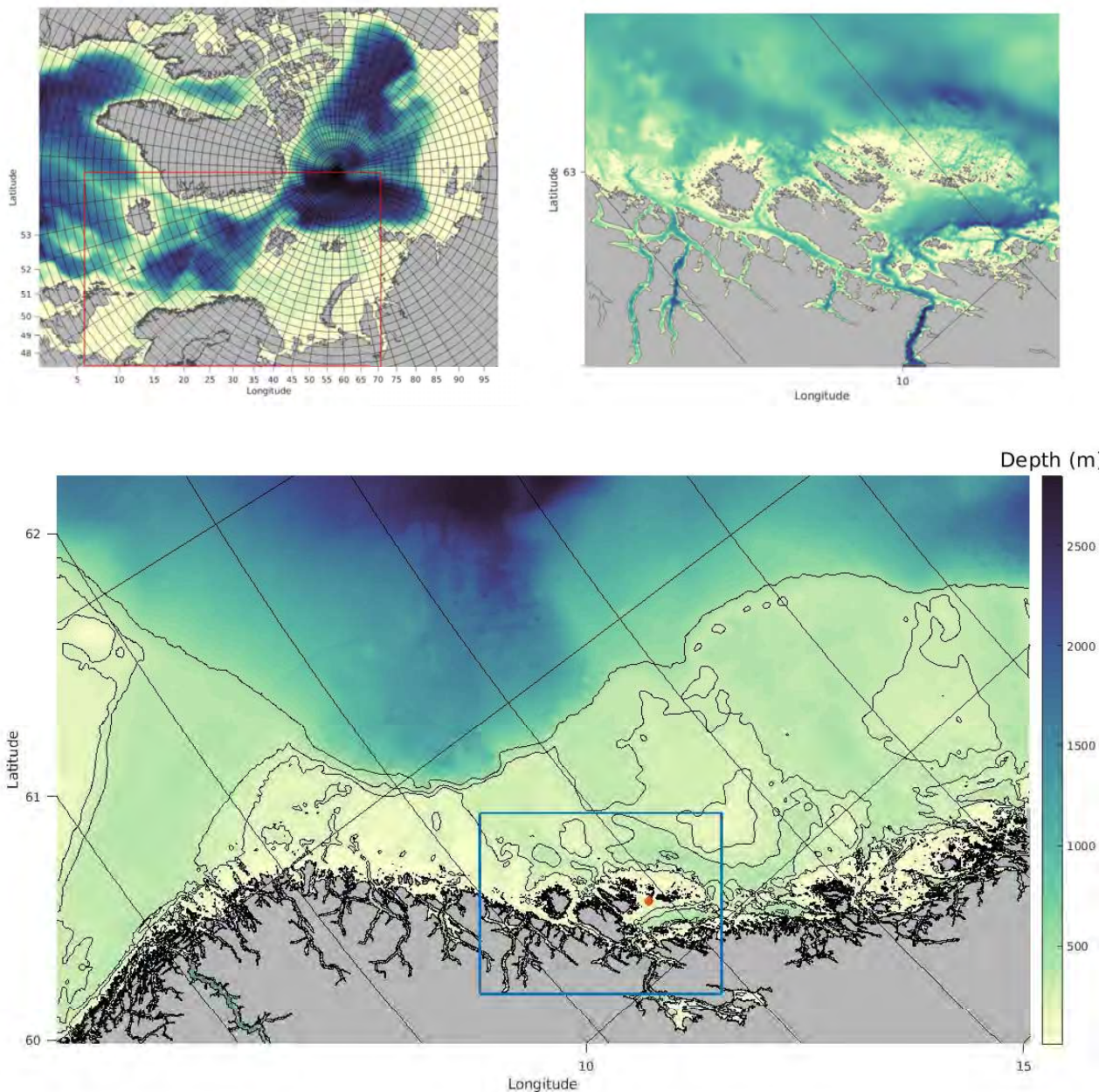


Figure 3. Model domains in 20,000 (top left) and 160 (top right) m horizontal resolution used in the simulations. Note the orientation of the right figure: north points upward towards the right. Bottom: 800 resolution model indicating the cultivation site at Storflua (red dot).

The 20 km resolution model was run for the period 1996-2022 following a 25-year spinup from 1980. Output data were stored in a 1 week to 1 day resolution over this period. The model was forced with atmospheric CO₂ concentrations from the Mauna Loa observatory via NOAA (Tans and Keeling), with local seasonal overlay based on data from Station M (previously located in the Norwegian Sea at 66° N, 2°W).

2.2 Local deposition study, Storflua

A 160 m horizontal resolution model domain for the coast of Central Norway was used for detailed deposition studies (Fig. 3). See Broch et al. (2022) for details on the model setup and the deposition calculations. Four detritus/POC compartments were used with sinking speeds of $v_1 = 5 \times 10^{-3}$, $v_2 = 1.5 \times 10^{-2}$, v_3

$= 2.5 \times 10^{-2}$, and $v_4 = 5 \times 10^{-2} \text{ ms}^{-1}$. These sinking speeds were selected from empirical laboratory studies by M. Bondø, L. Neves and S. Forbord (SINTEF Ocean, unpublished) in a project funded by SINTEF's Global Climate fund, and have not been previously published. The kelp detritus followed a realistic release pattern based on the data in Fieler et al. (2021); see also Broch et al. (2022). The results in Neves et al. (2025) on POC release from kelp farms corroborate the findings of Fieler et al. (2021). In simple terms, a greater fraction of the organic matter generated through photosynthesis is released late in the season (June-July) than earlier on in the season. For this reason, we ran simulations for a 2-month period (May-June), which is the period when 90 % of the particulate organic carbon is released. Note that these simulations described here considered physical **dispersal and sinking only**. Degradation of the organic matter was *not* taken into account.

2.3 Local interactions with the biogeochemical system

Model domains of 160 and 800 horizontal resolution were used for simulations with the fully coupled physics-biology-kelp model system (Fig. 3). The purpose of the simulations was to investigate the interactions between the kelp farm and the local biogeochemical system, focusing on the (important) variables:

- Nutrient (nitrate concentrations)
- Oxygen
- pH.

Again, simulations were run for the relevant late-spring-summer period (May-July). Before this, the biomass is very small, with only minor impact on the variables considered here. The uptake of nutrients and carbon by the kelp and production of oxygen was included.

2.4 Larger-scale and long-term simulation scenarios

The larger scale 20 km resolution model was used to study a scenario in which large amounts of kelp were cultivated over a longer time-period. The coarser model was used to allow for both a longer time-period and a larger region covered by the simulations.

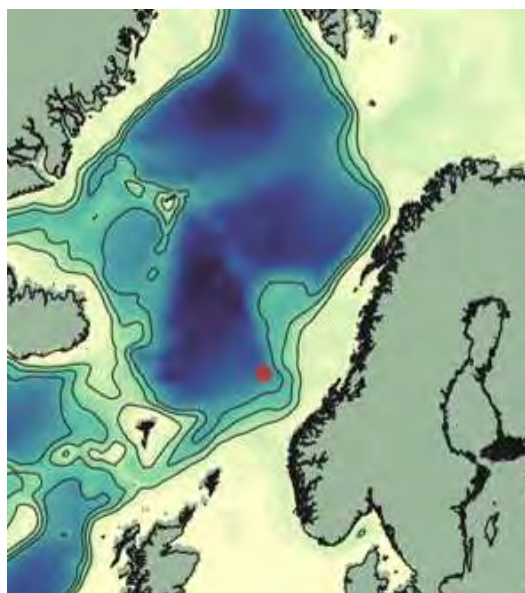


Figure 4. Large-scale and long-term cultivation scenario. The red dot indicates the position of a hypothetical large-scale kelp (*S. latissima*) cultivation region of 20 x 20 km. The black curves are 500, 1000, and 1500 m depth contours, so the hypothetical cultivation region lies well beyond the Norwegian continental shelf.

Two simulation scenarios were run.

Baseline scenario. Here we ran the model from 1996-2022 with the standard forcing (rivers, atmospheric data, pCO₂) as described in section 2.1, without any perturbations from kelp cultures.

Kelp scenario. The same time period was simulated, using the same external forcing and the same initial conditions, as in the baseline scenario. In addition, **cultivation and deposition of kelp biomass was introduced in the model.** The following assumptions were made

- A target biomass of ~300 000 t FW kelp was cultivated and deposited in year 1, linearly increasing each year to a target biomass of ~ 7 500 000 t FW kelp cultivated and deposited in the final year 2022- 2023
- Deployment: end of September (28)
- Deposition: end of June (28)
- Bottom depth ~2200 m
- Region covering 400 km² (20 × 20 km), approx. what is allocated to seaweed cultivation in China.

There was two-way feedback between the kelp model and the marine ecosystem model. Thus, for example, the nutrients or carbon taken up from the surface waters through the growth of the kelp lead to a decrease in the nutrient concentrations and $f\text{CO}_2$.

The long-term ocean model simulation scenarios were run before data on POC, DOC, and rDOC release were ready, so the degradation rates of the organic matter released from the hypothetical kelp farm were assumed to enter the standard POC and DOC compartment of the ocean model, with similar rates.

The matter assumed to be deposited on the sea floor after cultivation can be interpreted either as matter actively deposited, or as detritus released from the cultivation region.

2.5 Carbon calculus

We establish some basic relations and equations between the amount of carbon in cultivated biomass, the amount stored passively or actively, from a **500 T wet weight per year kelp cultivation unit**. We introduce degradation rates (compare the half-life of radioactive matter) of some of the carbon fractions to investigate the accumulated efforts of seaweed cultivation and biomass use, including production of biochar and other methods stabilizing the seaweed carbon. Table 1 summarizes the quantities involved in the mathematical relations and calculations.

We make the assumption that the fraction of C not used for active deposition or passive export is transferred back to the CO₂ pool. This will be a neutral budget. Likewise, we disregard seaweed respiration as this is a neutral budget. However, CO₂ expenditure during cultivation, processing or other activities might render the activities carbon positive (a net release of CO₂ to the atmosphere).

Table 1. Definitions of and notation for concepts and variables used in the carbon calculus. In the present scenarios all rates and fractions are annual fractions in terms of the amount of net photosynthesized carbon. If not explicitly stated otherwise, all the numerical values of the parameters are *based* on Neves et al. (2025) or Neves pers. comm.

Symbol/notation	Numerical value where relevant	Explanation
C	Variable	Total carbon present in a 500 T kelp cultivation unit at time t .
C_{NPP}	Variable	NPP (carbon) of the farm annually
C_G	Variable	Total <i>gross</i> carbon stored by kelp cultivation: $C_G = C_P + C_A$. Gross: carbon expenditure during cultivation, harvesting or any other parts of the value chain have <i>not</i> been accounted for
C_S	Variable	Total amount of stable carbon from the cultivation efforts at time t .
C_P	Variable	Total passively deposited carbon stored kelp cultivation. This includes POC (Particulate Organic Carbon), DOC (Dissolved Organic Carbon, fast degrading) and rDOC (recalcitrant Dissolved Organic Carbon, slowly degrading): $C_P = C_{POC} + C_{DOC} + C_{rDOC} + C_{SED}$
C_{POC}	Variable	Total amount of POC from the cultivation operations present in the environment (at time t)
C_{DOC}	Variable	Total amount of DOC from the cultivation operations present in the environment (at time t)
C_{rDOC}	Variable	Total amount of POC from the cultivation operations present in the environment (at time t)
C_A	Variable	Total actively stabilized carbon. This is a (not necessarily fixed) fraction of C .
C_{PROC}	Variable	Carbon stabilized through processing of harvest biomass. Examples are carbon stabilized in biochar or stabilized by active deep-sea deposition.
C_{SED}	Variable	Amount of sedimented carbon at time t
k_{DOC}	-8.3178	Annual specific degradation rate of DOC, based on L. Neves, pers comm.
k_{rDOC}	-0.1155	Annual specific degradation rate of DOC, based on L. Neves, pers comm.
k_{POC}	-1.825	Annual specific degradation rate of POC, based on Boldreel et al. (2023)
f_{DW}	0.1198, 0.1396 0.1593	Dry matter fraction of wet weight biomass, in resp. April, June, July
f_C	0.2651, 0.2677 0.2611	Carbon fraction of dry matter in resp. April, June, July
f_{P2D}	0.5	Fraction of POC transferred to DOC annually
$f_{POC2SED}$	0.2	Fraction of POC transferred to sediments annually
f_{POC}	0.09, 0.26, 0.46	Fraction of C produced annually released as POC with harvest in, resp., April, June, July
f_{DOC}	0.7	Fraction of C produced annually released as DOC
f_{rDOC}	0.3	Fraction of DOC released as RDOC or transferred to RDOC
E_{CULT}	Variable	Amount of carbon released by cultivation – land phase, deployment, farm design and production, harvest. Per unit of C cultivated
E_{FARM}	726.4, 3257.5	kg C released by farm establishment of 500 t WW unit annually (resp. nearshore, offshore)
E_{SUB}	0.015	kg C released per m seeded rope
Y	Depending on scenario	Biomass yield per m rope/substrate
E_{PROC}	Variable	Amount of carbon released by processing into products like biochar or other products, depending on the scenario. Per unit of C cultivated
C_{BC}	Variable	Amount of carbon bound from biochar production per kg WW kelp
E_{BC}	0.0073	Amount of carbon emitted through biochar production per kg WW kelp

The quantities in Table 1 are calculated as follows (where the time step is 1 year):

$$C_{\text{POC}}(t + 1) = e^{k_{\text{POC}}}C_{\text{POC}}(t) + (1 - f_{\text{POC2SED}})f_{\text{POC}}C_{\text{NPP}}(t) - 0.5f_{\text{DOC}}C_{\text{POC}}(t) \quad (1)$$

$$C_{\text{DOC}}(t + 1) = e^{k_{\text{DOC}}}C_{\text{DOC}}(t) + (1 - f_{\text{DOC2SED}})f_{\text{DOC}}C_{\text{NPP}}(t)(1 - f_{\text{rDOC}}) + 0.5(1 - f_{\text{rDOC}})f_{\text{DOC}}C_{\text{POC}}(t) \quad (2)$$

$$C_{\text{rDOC}}(t + 1) = e^{k_{\text{rDOC}}}C_{\text{rDOC}}(t) + (1 - f_{\text{DOC2SED}})f_{\text{DOC}}C_{\text{NPP}}(t)f_{\text{rDOC}} + 0.5f_{\text{rDOC}}f_{\text{DOC}}C_{\text{POC}}(t) \quad (3)$$

$$C_{\text{SED}}(t + 1) = C_{\text{SED}}(t) + f_{\text{POC2SED}}f_{\text{POC}}C_{\text{NPP}}(t) + f_{\text{DOC2SED}}f_{\text{DOC}}C_{\text{NPP}}(t) \quad (4)$$

$$E_{\text{CULT}}(t) = E_{\text{FARM}}(t) + \frac{500,000}{Y}E_{\text{SUB}}(t) \quad (5)$$

$$E_{\text{PROC}}(t) = 500,000E_{\text{BC}} \quad (6)$$

$$C_{\text{PROC}}(t) = 500,000C_{\text{BC}} \quad (7)$$

$$C_{\text{A}}(t + 1) = C_{\text{A}}(t) + C_{\text{PROC}}(t) \quad (8)$$

$$C_{\text{BUDGET}}(t) = C_{\text{POC}}(t) + C_{\text{DOC}}(t) + C_{\text{rDOC}}(t) + C_{\text{SED}}(t) + C_{\text{A}}(t) - E_{\text{CULT}} - E_{\text{PROC}} \quad (9)$$

Some important assumptions:

- Half as much of the POC carbon is released as DOC as from the full fronds.
- The emission from producing 1 unit of cultivation substrate (rope) is independent of the yield.

3 Results and discussion

3.1 Local deposition study, Storflua

The pattern of deposition of the kelp POC is shown in Fig.5 for the **four different sinking speeds** used. In this simulation, using the high resolution 160 m model domain (Fig. 3), no degradation of carbon was included. As one would expect, the dispersal patterns are quite sensitive to the sinking speed, in particular at a site with relatively high current speeds (average 0.2 ms^{-2}) such as this. **In all cases, the deposition is heaviest in the immediate surroundings of the farm.** It is also clear that lower sinking speeds lead to wider dispersal of detrial matter and hence lower sediment concentrations. Furthermore we see indications that in the case of the lowest sinking speeds (Fig.5, upper left, letter ``C") the highest concentrations are found *outside* the farm area, in contrast to the case with the highest sinking speeds where most of the matter deposits within the farm area.

Regardless of which of the four sinking speeds we use, we see that there are some locations prone to accumulation of sediments (A, B C in Fig. 3) a bit away from the immediate farm surroundings.

The deposition depth also varied with the sinking speed (Fig. 6). The lowest sinking speed ($v_1 = 1.5 \times 10^{-3} \text{ ms}^{-2}$) stands out, with more than 50 % of the matter depositing below 75 m depth in this case, while more than 50 % of the matter deposits above 60 m depth in the other three cases. More than 15 % deposited below

100 m in the slow sinking scenario, with only negligible amounts from the three other compartments depositing at these depths.

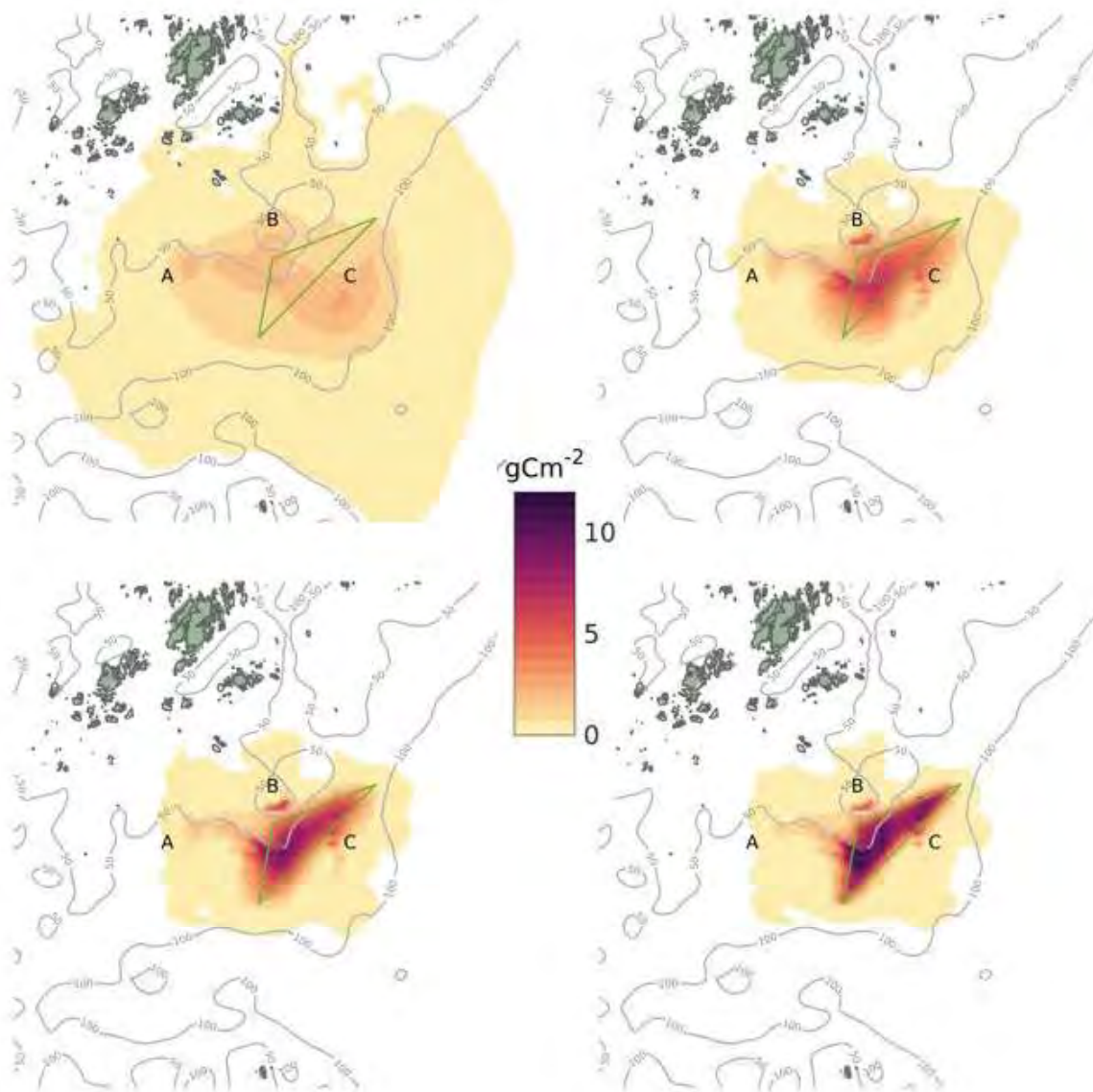


Figure 5. Left: Simulated deposition of POC from cultivated kelp over a period of 2 months (May-June) for four different sinking speeds: $v_1 = 5 \times 10^{-3}$, (upper left) $v_2 = 1.5 \times 10^{-2}$ (upper right), $v_3 = 2.5 \times 10^{-2}$ (lower left) and $v_4 = 5 \times 10^{-2} \text{ ms}^{-1}$ (lower right).

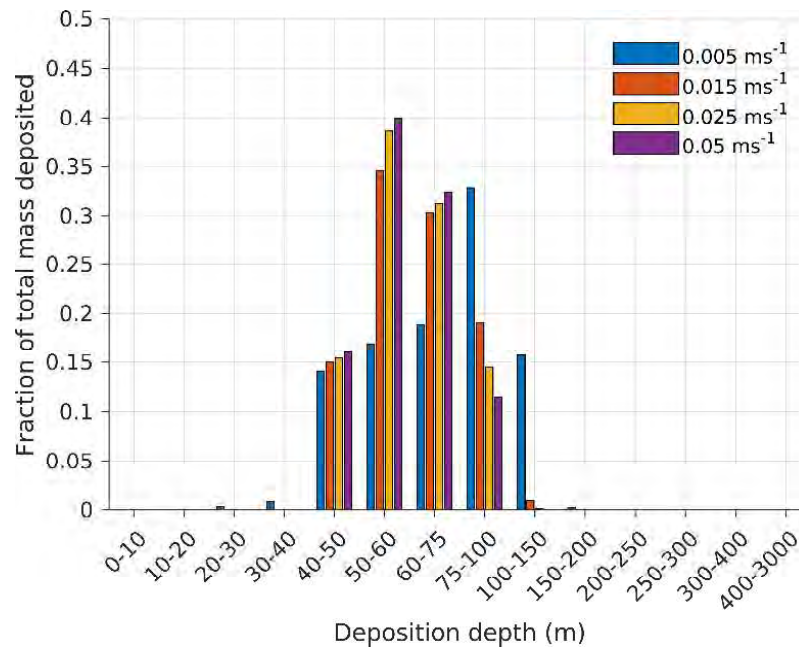


Figure 6. Distribution of simulated deposition depth of POC from cultivated kelp over a period of 2 months (May-June) for four different sinking speeds (see legend in panel)

Though we can simulate the dispersal and deposition of detritus/POC from kelp farms, the results so far have used the four sinking speeds presented above, based on empirical laboratory experiments. The assumed properties of the POC (like the sinking speeds) impacts the distribution and density of POC deposits. As the exact distribution of kelp POC between different compartments (different properties, sizes, sinking speeds) is not presently known, this is probably an uncertainty of greater impact than the sinking speeds themselves.

3.2 Ecosystem services of a large-scale kelp farm at Storflua and in Frohavet

If anyone needs convincing of the fact, the ability of the kelp cultures to absorb CO₂ and produce O₂ is evident from time series of simulated oxygen concentrations and pH at the farm site (Fig. 7). There was a strong daily signal in the changes in pH and O₂, showing that the changes quickly revert to the background concentration. Still, from the baseline to the 1500 T production scenario the trend indicates an increase in pH from 8.12 to 8.14 in the beginning of June. Likewise, the oxygen concentration increased from 320 to 337 mmol O₂ m⁻³. While an increase from 8.12 to 8.14 may seem irrelevant, a long-term time series of pH in the North Atlantic indicates a decrease from around 8.12 to 8.08 from 1990 to 2010 (Lauvset and Gruber, 2014). The change in fCO₂ due to CO₂ uptake by the kelp farm had an impact on a considerable area (Fig. 8), depending on the distance from the farm.

The results presented here are based on simulations with an 800m horizontal resolution model. Some of the changes in biogeochemical variables may be underestimated very close to the farm due to numerical dilution: that fact that we represent space in “boxes” of, say, a volume of 800x800x2 m³ that represent an average value of the pertinent variable in that box. In a higher resolution the concentration of O₂ or other variables may be impacted more. On a greater spatial scale, such as the one presented in Fig. 8, this does not matter (Broch et al., 2013). Also note that the *total amount* of e.g. O₂ or CO₂ is conserved regardless of the resolution. It is just the concentration that might be impacted by the resolution.

Even a low biomass might impact on the ecosystem through other variables than the ones we have considered. The kelp farm, and in particular the farm structure, might still be a vector for bifouling, disease, and the spread of invasive/unwanted species (Bekkby et al., 2023).

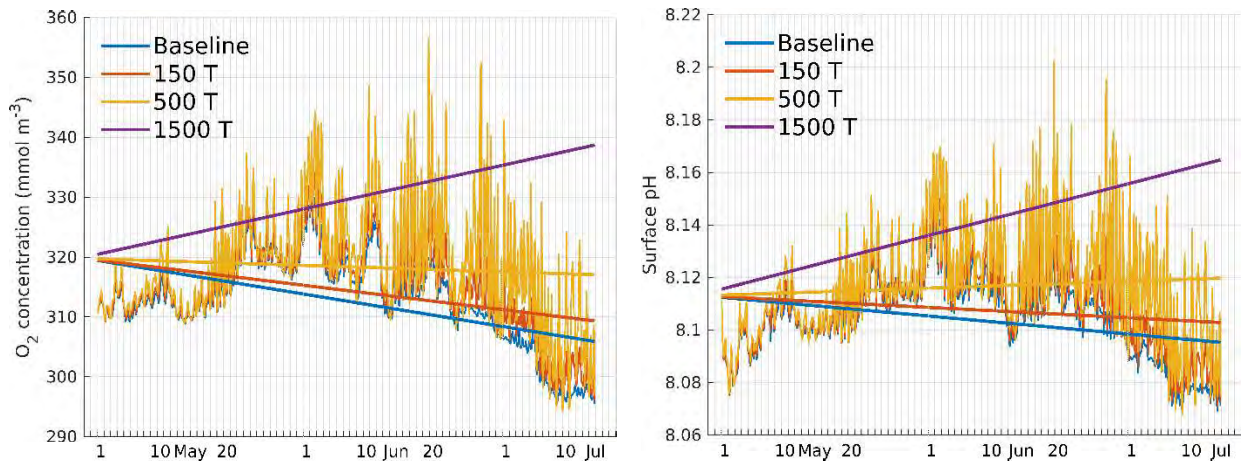


Figure 7. Timeseries of simulated surface oxygen concentrations (a) and pH (b) for four different scenarios (0, 150, 500, and 1500 T seaweed biomass production) at the farm site indicated in Fig. 3. Note that only the trend lines are plotted for the 1500 T scenario for the sake of graphic clarity.

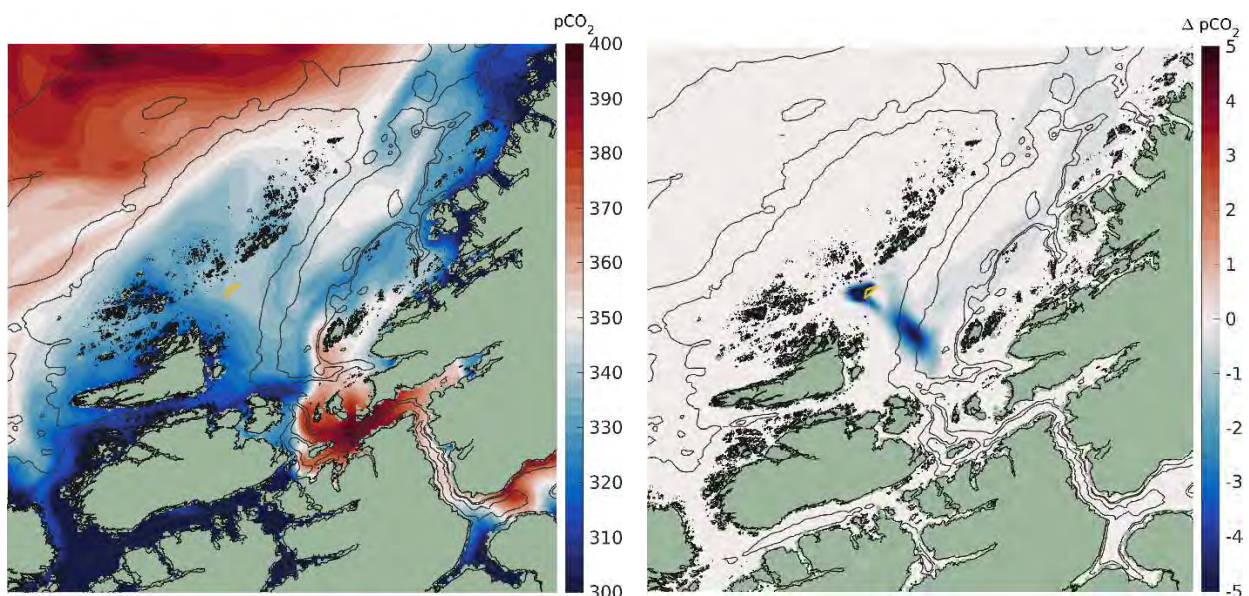


Figure 8. Snapshot (at a specific time) of the simulated surface $f\text{CO}_2$ (left) and change in surface $f\text{CO}_2$ due to kelp cultivation at Storflua (right). These are results from a simulation using 160 m resolution model (Fig. 3).

3.3 Large-scale and long-term

There was not much interannual variation in the large-scale kelp production (Fig. 9). The deviation from the 1997-2022 trend line was up to, generally a lot less, than 17 %. The same applies to the net CO₂ taken up in the biomass. Reasons for the low interannual variation in kelp biomass are stable water temperatures (ranging about 7-13°C, Fig. 10) and little interannual variation in nitrate concentrations and their seasonal pattern.

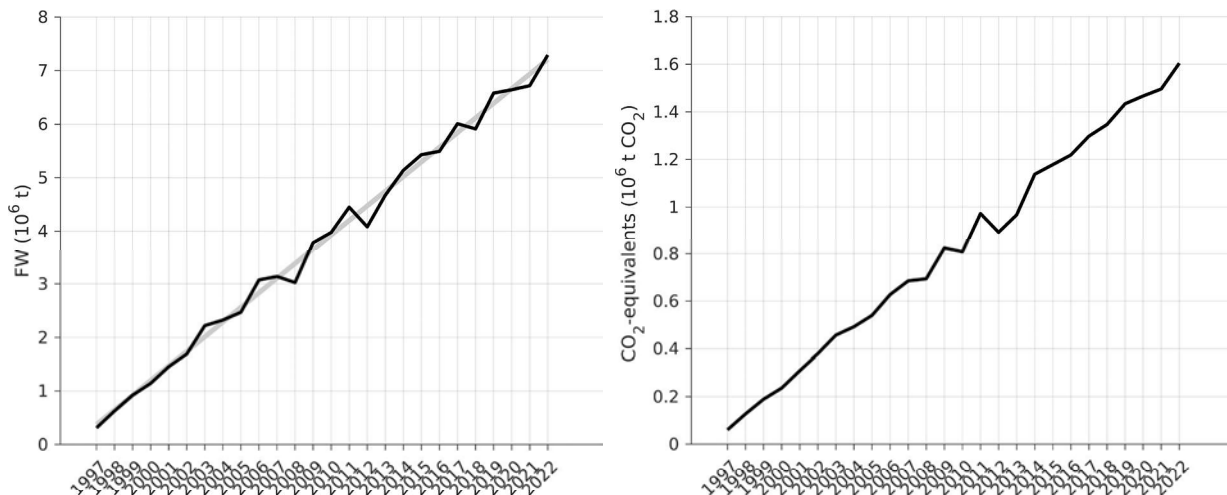


Figure 9. Results from the simulation scenario described in section 2.4. *Left*: wet weight biomass. *Right*: net CO₂ taken up in the biomass. This is based on the carbon present in the biomass at harvest only, and does not include any of the carbon released as POC or DOC.

These long-term simulations were run before empirical data on POC and DOC release were completely ready, so we have avoided presenting results on this. However, it is interesting to see how this very large scale kelp cultivation might otherwise impact the marine environment. Note that the volumes considered here are very large. A large kelp cultivation region (20x20 km, with biomass volumes as in Fig. 9) with such high volumes increased the pH significantly, at least at the times of the year before the harvest (Fig. 10, top). Interestingly, the pH quickly returned to the baseline values after “harvest” or deposition on the ocean floor. Harvest entailed deposition on the bottom in this case. Another interesting result is how the cultures at the Southern location in Fig. 10 impacted the pH at the Northern location, with a significant time lag. This is linked with the general circulation pattern along the Norwegian continental shelf and explains why the increased pH at the Southern (cultivation) location is diluted quickly. These results need further study, but hint at a certain potential for kelp large-scale and extensive cultures to provide significant ecosystem services over considerable time periods and spatial scales.

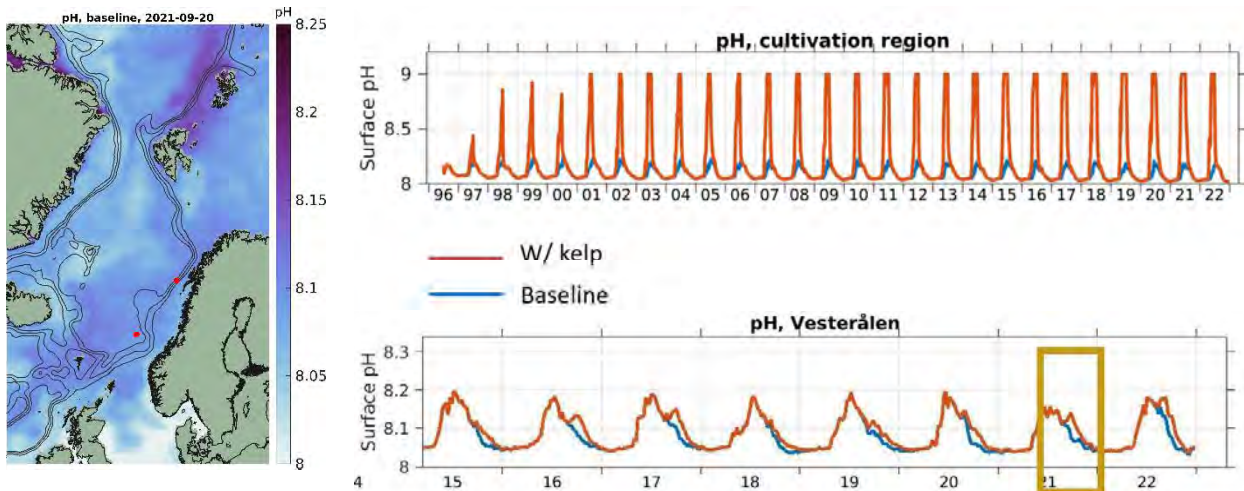


Figure 10. *Left*: Snapshot (September 20, 2021) of simulated pH in the Norwegian, Barents and Arctic seas from the long-term baseline scenario (see sec. 2.4). *Right*: Time series for simulated pH in the baseline (blue curves) and kelp cultivation (red curves) scenarios. The upper time series is extracted from the Southern location indicated in the left panel (approximately at Station M, 66°N, 2°E). The lower time series is extracted from the Northern location outside Vesterålen. The scale has been cut off at pH 9, so in some cases (for the scenario with kelp, red curves, lower panel) the simulated values are higher than indicated.

3.4 Carbon calculus

Equation (9) was used to calculate the net carbon removal or emission from operating 500 t WW farm modules from 2025 to 2100 for all combinations of the following assumptions:

- Cultivation near-shore or offshore
- Harvest of the biomass in May, June, or July (Neves et al., 2005)
- Yield of 5 or 10 kg WW per meter rope culture
- Whether the harvested biomass was used in biochar production or not.
- Whether the present emissions from farm establishment and deployment, cultivation, and harvest were used (high, present emissions) or lower (future) emissions based on improved technologies were used.

In all the scenarios including biochar production, the carbon emissions during the biochar production have been assumed to be the same, based on WP8/9. It has further been assumed that the farm/module is replaced every 10 years (report from DNV, WP10). This carbon expense has been paid over annual carbon budgets rather than stepwise every 10 years, which is fine for long-term considerations. Scenarios in which carbon emissions from manufacturing and deploying the farm structures and for production, deployment, and harvest of the seeded ropes have been reduced are considered as well. These low emission “future” scenarios assume that the manufacturing and deployment of the farm structure is reduced by 50 %, while the emissions of producing, deploying, and harvesting 1 m of cultivation rope is reduced by 70 %. A final assumption regarding technology (development) is the final biomass yield per meter rope structure. For the present scenarios, 5 kg per m rope in the nearshore and 10 kg per m rope in the offshore cases have been assumed. It has been assumed in some scenarios that a yield of 10 kg per m rope is possible also in the nearshore case, thus further reducing the emissions per unit of biomass.

The results from these scenarios all end up in the light green shaded regions in Fig. 10. Values *above* the abscissa (time) axis indicate the total cultivation activities up to that time point has a net carbon negative

effect (carbon removal). The shaded regions should be interpreted as a probable space of events. The event space spans a wide range in the long term up to the year 2100.

Four specific scenarios have been singled out: two scenarios based on the present state of cultivation technology, with high carbon emissions during farm manufacturing, farm deployment, and cultivation (scenarios 1 and 2 in Table 2); and two scenarios based on improved technologies with lower emissions during farm establishment and cultivation (scenarios 3 and 4 in Table 2).

It is highly probable that significant emission reduction is possible. The emissions used for the present high emission scenarios (in the offshore case) are based on the research facility at Storflua for which a lot of the activities have been necessary from a research point of view, but completely unnecessary from a commercial one.

Table 2. Carbon calculus scenarios. All scenarios are based on a single production module with a total annual yield of 500 t WW kelp (*Saccharina latissima*) operating from 2025 to 2100

Scenario	Description			
	Farm location	Harvest time	Yield (kg per m rope)	Cultivation emissions
1	Nearshore	July	5	High (present)
2	Offshore	July	10	High (present)
3	Nearshore	July	10	Low (future)
4	Offshore	July	10	Low (future)

The results of simulating these four scenarios are shown in Fig. 11. In the long term (up to 2100) the present technology is not a viable option (Fig. 11, top, scenarios 1 and 2) for carbon removal. The emissions during farm manufacturing and cultivation are too high. Reducing emissions and increasing the yield (per unit substrate) leads to viable scenarios (Fig. 11, bottom, scenarios 3 and 4). In all scenarios it is presently a necessary assumption that the biomass is used for biochar production. Otherwise, without stabilizing the biomass in some way or another, the emissions during farm construction, deployment and cultivation must be compensated by the passive carbon removal during the cultivation phase (Fig. 11, dashed purple lines in all scenarios). Note that there will not be net emissions before the line crosses the time axis. This means that short-term storage may be achieved even using the present technology.

Other scenarios can be constructed in which the biomass is used to replace biomass produced by higher emissions (replacements). The net effect would be similar, depending on the product.

How much must we reduce emissions in the farm construction and cultivation phase to ensure that the long-term budget will be carbon negative (net removal)? Here we assume that the biomass is used to produce a stable carbon product. Figure 12 shows scenario 1 (green line, which is bound to cross the 0-axis and hence in the long-term will increase emissions) with an improved scenario (black line) in which 1) emissions during deployment, cultivation, and harvest of the biomass remain the same as with the present technology and 2) the emissions during manufacturing and deployment of the cultivation rig have been reduced by 40 %. A reduction of around 40 % of the emissions of the farm manufacturing and deployment process is sufficient.

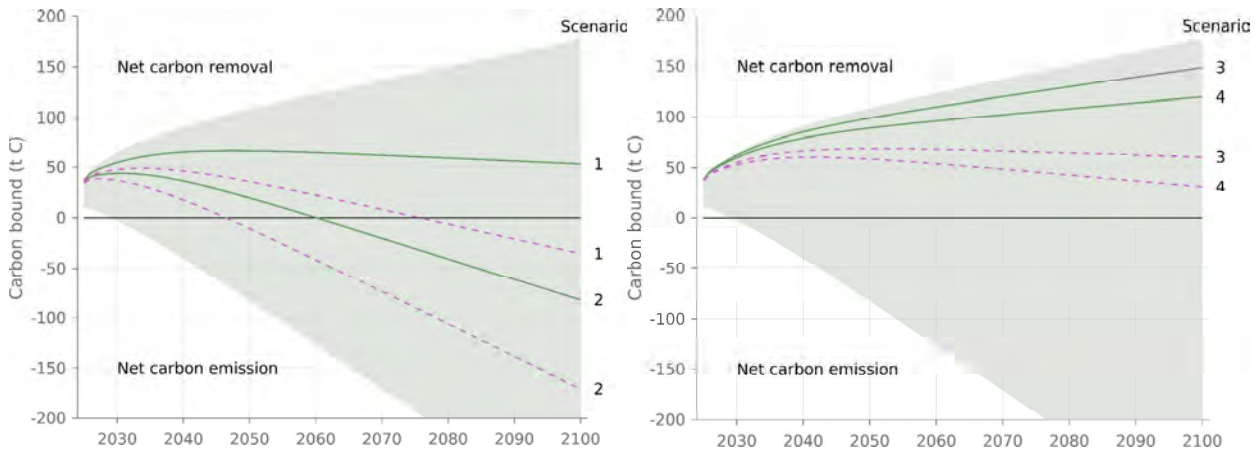


Figure 11. The solid, green lines represent the net carbon budgets when the harvested biomass is used for biochar production. The dashed purple lines represent the budgets for the corresponding scenarios when biomass is *not* used for biochar. The scenario numbers refer to those in Table 2.

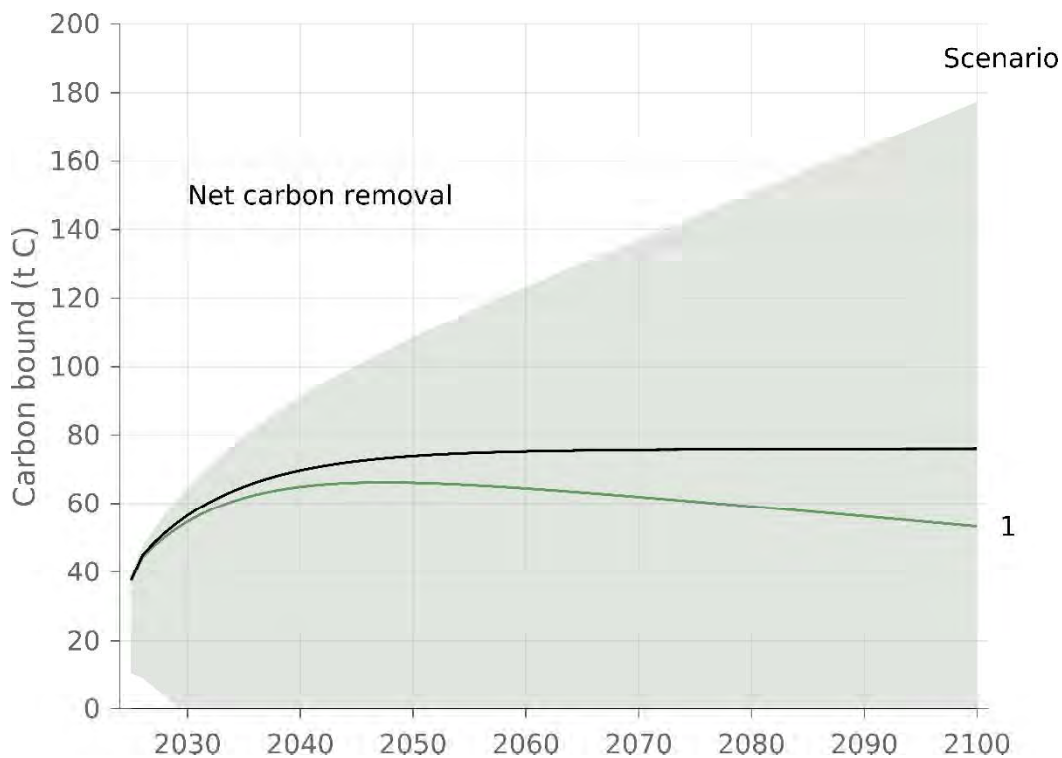


Figure 12. Green line: scenario 1 (Table 2). Black line: the necessary adjustment to the emissions in scenario 1 to ensure a net carbon negative budget – “how much must the technology be improved to avoid emitting more than is bound.

If the present technology in the long run will lead to increased emissions, is it better to wait until the technology is ready? Fig. 13 illustrates how postponing until technology has improved (10 years until 2034 in this case) might lead to slightly greater carbon removals in the long run compared to a scenario in which the present technology is used for 10 years and then replaced by improved technologies (compare black and dashed green curves in Fig. 13). However, any lack of large-scale seaweed cultivation initiatives might

postpone technological development as well. Incremental improvements to technology is also an argument for starting early.

The continued operation of the farm on or above the break-even budget ensures that in the long run a fixed amount of carbon remains bound. In this sense the farm serves the same purpose as a natural kelp forest: the overall carbon budget remains balanced, while an amount of carbon is bound in the standing biomass.

Considering the farm area use of 7.5 ha, the dashed green scenario in Fig. 13 leads to a sequestration of 1.8 kg C⁻² over 75 years, or on average a removal of 24 gC m⁻² year⁻¹. This is significant compared to the average global annual net primary production of the oceans at ca 110 g C m⁻² year⁻¹ (Woodward, 2007).

We have used present technology data for all calculations involving biochar and have not assumed that emissions during pyrolysis may be reduced.

Offshore cultivation offers huge potential for biomass production. This is corroborated both by simulation results (Broch et al., 2019) and empirical results from Storflua (see report from WP3). In the present calculations we have been conservative about the possibilities for reducing emissions, especially in the offshore case. We have also been conservative regarding the yield per cultivation substrate unit. This means that the potential for seaweed CDR by offshore cultivation is possibly substantially higher than what is indicated here. In particular, proper physical load models will provide a basis for designing and building farms suitable for an offshore environment and high biomass yields, while still keeping the climate gas emissions at a minimum.

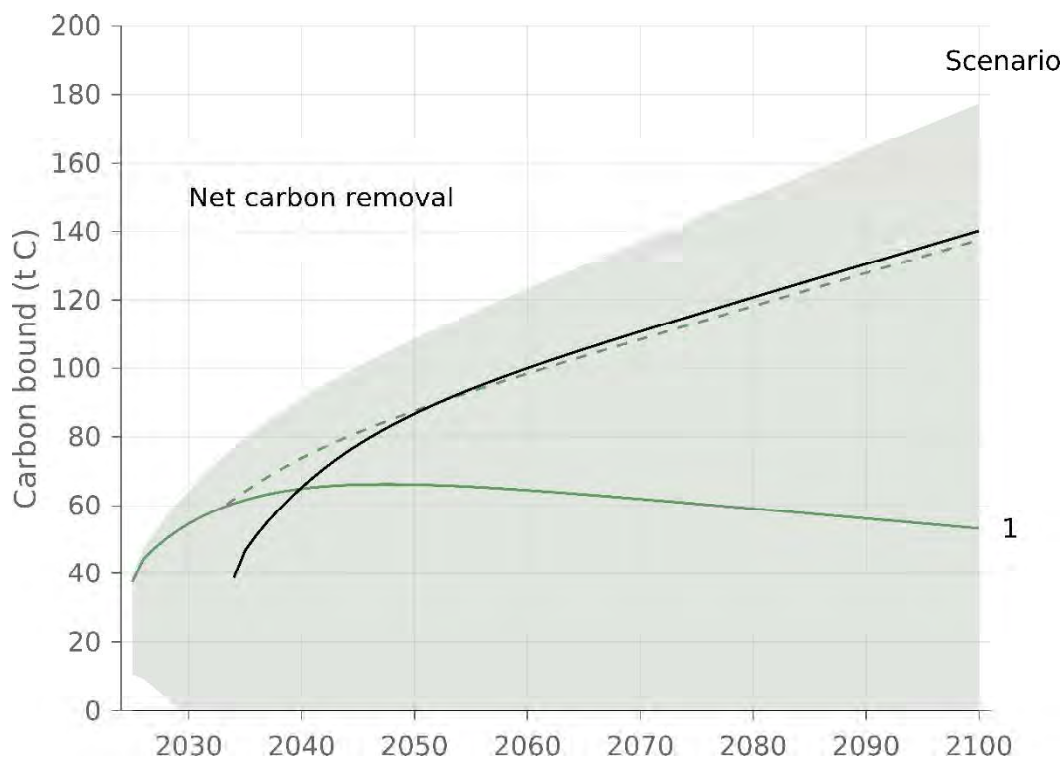


Figure 13. Solid green line: scenarios 1. Dashed green line: improved technology with reduced emissions used from year 11 (compare scenario 3 in Fig. 7). Black line: scenario 3 postponed 10 years.

4 Conclusions

The following conclusions are based on the simulations made here, and not directly on empirical results. Empirical results from this project and other research were used to estimate key parameters for the simulations and the other calculations and considerations.

4.1 Main findings

Seaweed CDR potential. The emissions during the cultivation process (including hatcheries, deployment and harvest) and farm design, construction, and deployment, are very important for the overall seaweed CDR potential. **Reducing the emissions during farm production and deployment by 40 % is enough to ensure that seaweed CDR is a carbon negative solution when the harvested biomass is used for biochar.** Farm design better adapted to the local environmental conditions is necessary to avoid over design and unnecessarily high emissions. This entails developing good physical load models as well as processes for re-use and re-purposing of aquaculture equipment.

Ecosystem services. In addition to carbon sequestration and the valuable biomass in itself, seaweed cultures provide a number of ecosystem services like nutrient uptake (a potential benefit in eutrophic systems), O₂ production, and an increase in pH linked to the carbon uptake. The large-scale and long-term simulation results indicated a substantial increase in pH over a great area.

4.2 Knowledge gaps and further research

LCA from operational farms. Present results for LCA and carbon emissions during farm production and cultivation are based on *research* facilities and not operational/commercial farms. This very likely contributes to higher emissions used in our calculation than what might be the case for an operational scenario.

Ecosystem services. The longer term and larger scale benefits (and potential adverse effects) of the ecosystem services provided this should be studied in more detail. The impact on increased pH in the large-scale and long-term simulations should be revisited to account for potential degradation of POC and DOC, partially counteracting some of the effects on heightened pH.

Atmospheric feedback/two-way ocean-atmosphere feedback. In the simulation results presented here, there was assumed a one-way coupling between the atmospheric CO₂ concentrations and the ocean carbonate system. Observations of global atmospheric CO₂ concentrations with local and seasonal overlay were used to force the model and had an impact on the ocean surface *f*CO₂ (Fig. 3). However, the atmospheric data were not adjusted according to the draw-down to or release of CO₂ from the ocean surface layer. An online linking of an atmospheric model with the ocean model would have been needed. This was initially suggested work for Phase 2 of the project. See Objective e. in Sec. 1.1.

Long term carbon removal and storage. There is still some uncertainty about rates for sedimentation for POC and degradation of RDOC. The long-term fate of RDOC is not completely understood.

4.3 Updating results

The simulation results presented here were based on preliminary empirical results. The fraction of RDOC of total DOC, for example, has been assumed to be 30 % (Table 1). The actual fraction is certainly higher, maybe up to 60 %. These results under processing may be implemented in an updated version of the report.

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**JIP Seaweed Carbon Solutions:
Monitoring and assessing
environmental interactions (WP5)**

FINAL REPORT

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Abstract

This report presents the findings from an environmental assessment of macroalgae cultivation at the Storflua kelp farm near Frøya, Norway. The study was conducted under the JIP Seaweed Carbon Solutions project, focusing on three main environmental interactions: the release of particulate organic matter (POM), nutrient uptake by cultivated kelp, and the role of the kelp farm as a temporary habitat. The main conclusion is that Storflua kelp farm poses no environmental risk, but also no clear ecological benefit.

Keywords: Macroalgae cultivation, environmental assessment

Emneord: Taredyrking, miljøovervåking

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Preface

This report presents the findings from an environmental assessment of macroalgae cultivation at the Storflua kelp farm near Frøya, Norway. The study was conducted under the JIP Seaweed Carbon Solutions project led by Sintef, focusing on three main environmental interactions: the release of particulate organic matter (POM), nutrient uptake by cultivated kelp, and the role of the kelp farm as a temporary habitat.

The work package “Monitoring and assessing environmental interactions” (WP5) was led by Gunhild Borgersen, and the study designed by Kasper Hancke, Adam Jon Andrews and Gunhild Borgersen. Field work was done by Gunhild Borgersen and Adam Jon Andrews (NIVA), and Emil Lange and Emma Ulvær (students from University of Oslo), with assistance from Odd Arne Arnesen and staff at Mausund Field Station. All biological analysis were done at NIVA, and molecular analysis at The Arctic University of Norway (UiT).

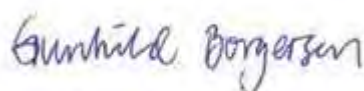
The report has been through quality assurance by NIVAs research manager for the Marine Biology section, Paul R. Berg.

This report was first published as a confidential report in October 2025. Confidentiality was revoked and the report was opened in February 2026, in accordance with the client. New results have been added to this version, in addition to some changes in the text after comments from the clients.

A handwritten signature in blue ink that reads "Paul Berg".

Oslo, 16.02.2026

Work package leader Gunhild Borgersen

A handwritten signature in blue ink that reads "Gunhild Borgersen".

Summary

This report presents the findings from a comprehensive environmental assessment of macroalgae cultivation at the Storflua kelp farm near Frøya, Norway. The study was conducted under the JIP Seaweed Carbon Solutions project, focusing on three main environmental interactions: the release of particulate organic matter (POM), nutrient uptake by cultivated kelp, and the role of the kelp farm as a temporary habitat. The monitoring program was developed by NIVA and Sintef in accordance with regulatory requirements and included baseline and follow-up surveys between 2023 (prior to kelp farm deployment) and 2025 (after 2 years of kelp production).

The Storflua kelp farm is located in Frohavet, a dynamic and relatively exposed coastal area. The farm covers 205 decares of surface area and 366 decares of bottom area, with a permit to produce up to 800 tonnes of kelp (ww) annually. However, actual harvests were significantly lower, with only 1 tonne harvested in 2024 and 200 kg in 2025. The monitoring program included ROV surveys of the seafloor, sediment and benthic fauna sampling, eDNA analysis from water and lumpfish stomach contents, and traditional fish and invertebrate sampling.

The ROV survey conducted prior to kelp deployment revealed no vulnerable species or habitats, although only a limited portion of the seafloor was surveyed. Sediment and benthic fauna sampling showed high species diversity and very good ecological status both before and after kelp cultivation. The slight reduction in species and individuals observed in 2025 was attributed to sampling limitations rather than environmental degradation. Sediment analysis confirmed coarse-grained substrates with low organic carbon and nitrogen content, indicating minimal organic enrichment from kelp detritus.

Nutrient uptake by cultivated kelp was assessed through literature review. Macroalgae and microalgae both depend on nitrogen and phosphorus for growth. While there is concern that large-scale kelp farming could limit nutrients for phytoplankton, studies show that microalgae are more efficient at nutrient uptake and can thrive even at low nutrient levels, unlike kelp. Field studies in Norway found no significant differences in nutrient levels or phytoplankton biomass near kelp farms, suggesting minimal ecological impact. However, green algae like *Ulva* and *Enteromorpha* may outcompete phytoplankton under high nutrient conditions, as shown in mesocosm experiments.

Kelp farming may also help mitigate eutrophication by removing excess nutrients from coastal waters. The effectiveness depends on scale, biomass production, and local nutrient loads. While kelp can absorb substantial nitrogen, large areas are needed to offset emissions from aquaculture or land-based sources. Seasonal mismatches between kelp growth and nutrient release from fish farms may limit direct nutrient recycling.

The role of the kelp farm as a temporary habitat was evaluated through fish and invertebrate surveys. Fish diversity and abundance were lower at the kelp farm compared to natural kelp forests, with lumpfish being the only species consistently observed. eDNA results are pending but are expected to show limited biodiversity differences based on experience from other kelp farms. Invertebrate richness was higher on long-term structures such as buoys and ropes than on cultivated kelp, suggesting that early harvesting limits habitat complexity. The presence of the alien amphipod species *Caprella mutica* was noted, highlighting the potential for artificial structures to facilitate the spread of non-native species.

While Storflua kelp farm did not negatively impact the environment, it also did not provide significant ecological benefits. The limited habitat provisioning suggests that current kelp farming practices may not replicate the ecological functions of natural kelp forests. However, the absence of negative effects

aligns with sustainability goals and supports the development of low-impact aquaculture. The report calls for further research and policy development to enhance the environmental contributions of kelp farming, particularly in relation to biodiversity, nutrient cycling, and alien species management.

In conclusion, the Storflua kelp farm was found to pose no environmental risk, but also no clear ecological benefit. The benthic fauna remained stable and habitat provisioning was limited. It is not likely that the nutrient uptake from kelp cultivation at Storflua will outcompete the local phytoplankton. These findings underscore the importance of site-specific assessments and the need for continued monitoring and research to guide sustainable macroalgae cultivation in Norway.

Conclusions:

- Storflua kelp farm poses no environmental risk, but also no clear ecological benefit.
- Benthic fauna remained stable.
- Fish and invertebrate diversity at the farm was limited.
- Nutrient uptake will most likely not affect the local phytoplankton negatively.
- Environmental impact of kelp cultivation is site-specific and depends on scale, hydrodynamics, and local conditions.

1 Introduction

1.1 Environmental effects of macroalgae cultivation

Macroalgae cultivation, or seaweed farming, is a growing industry with significant potential for sustainable food production, biofuel, and environmental benefits. Production is expected to rise both in Norway and globally, and increased cultivation volumes and larger areas covered by macroalgae may lead to both positive and negative impacts on the natural environment (reviewed in Hasselström et al. 2018, Campbell et al. 2019, Hancke et al. 2021, Norderhaug et al. 2021, Evenset et al. 2023, DNV 2023). However, environmental effects of macroalgae cultivation have been less investigated than those of for example finfish production, and there are fewer studies and data directed specifically at effects of macroalgae production, especially at large-scale cultivation outside of Asia. Most of the studies that do exist originate from parts of the world with higher production, higher density of production sites, different cultivated macroalgae species, or production situated in more sheltered areas than most of the production sites in Norway. More studies from macroalgae cultivation in Norway is therefore needed to increase our understanding of how the seaweed farms interact with the surrounding environment.

Potential environmental impacts (both positive and negative) of macroalgae cultivation on the marine environment are summarized in **Table 1**. Spread of genes, disease/parasites and genetic material are considered the most severe impacts, because the effects are regional and to a large degree more or less irreversible (Norderhaug et al. 2021). In this project we have focused on the local effects associated with the release of particulate organic matter, nutrient uptake and the role of Storflua cultivation rig as a temporary habitat:

Particulate Organic Matter

During the production period, macroalgae biomass is exported away from the production site through natural loss or detachment (Fieler et al. 2021, Hancke et al. 2021). These particles are carried by currents and deposited on the seabed, where they can serve as a food resource for benthic fauna, potentially increasing biodiversity (Renaud et al. 2015). However, the addition of organic material does not necessarily enhance overall biodiversity; it can also lead to increased production or biomass of a few opportunistic species rather than supporting a broader range of taxa. Whether the input of macroalgal detritus results in positive or negative effects therefore depends on both the quantity of material and the capacity of the local environment to assimilate it. Excessive organic material can lead to organic overload, increased microbial activity, and reduced oxygen levels in the sediment, causing hypoxia and reduced biodiversity (Pearson & Rosenberg, 1978). Results from studies on seaweed cultivation impact on benthic infauna suggest little to no negative impact during normal operations (Hancke et al. 2021, Walls et al. 2017, Zhang et al. 2009, Zhang et al. 2020, Visch et al. 2020a), but negative effect of large quantities reaching the seafloor (Hancke et al. 2021). The impact thus depends on the quantity of settled material as well as physical conditions like water circulation and temperature.

Nutrient uptake

Both macro- and microalgae need nutrients like nitrogen and phosphorus for photosynthesis and growth. Nutrient uptake by cultivated macroalgae could potentially limit nutrients for microalgae in phytoplankton, potentially outcompeting local phytoplankton production. However, field measurements from Norway (Hancke et al. 2021) and Sweden (Visch et al. 2020a) showed no effect on nutrient concentrations near kelp cultivation sites, likely because microalgae have a more efficient nutrient uptake compared to macroalgae. The nutrient uptake from the surrounding seawater by macroalgae

may potentially reduce nutrient load in eutrophic coastal areas and mitigate eutrophication effects (Jiang et al. 2019).

Artificial Structures

Kelp cultivation infrastructure consists of hard material frames, moorings, buoys, and long lines, representing artificial structures in the marine environment. Such artificial structures have been found to support significantly different faunal communities than those of adjacent areas (Mineur et al. 2012), and they may favor establishment of alien species and provide steppingstones for their dispersal (Bulleri & Chapman 2010, O'Shaughnessy et al. 2020, Norderhaug et al. 2021, Bekkby et al. 2023). The establishment of an alien species may cause large-scale, regional and irreversible effects on local ecosystems (Kumschick et al. 2015). However, the kelp farm may also function as a temporary habitat, attracting and providing prey sources for mobile fauna like fishes, aid dispersal for species with pelagic dispersal stages, and represent habitat (refugium) for species that have lost their natural habitat and have the potential to enhance the productivity of certain species.

Table 1 Overview of potential environmental impacts of macroalgae cultivation.

	Positive effects	Negative effects	Severity of negative effects
Nutrient uptake	Macroalgae absorbs nutrients from surrounding seawater, potentially reducing nutrient load in eutrophic coastal areas and mitigating eutrophication effects	Competition for nutrients may lead to reduced phytoplankton growth	Local and reversible effects
Release of POC/DOC	Kelp cultivation acts as a carbon sink, taking up carbon dioxide from the water and permanently removing some carbon from the cycle by natural processes	The release of particulate organic matter may lead to organic overload on sea bottom, affecting benthic fauna and sediment chemistry	Local and reversible effects
Artificial habitat	Cultivated kelp can serve as artificial habitats, increasing local biodiversity, aiding species dispersal, and contributing to habitat restoration for species that have lost their natural habitats.	Artificial structure may facilitate the spread of alien species, spread of disease/parasites, causing potentially large-scale impacts on marine ecosystems	Regional and irreversible effects
Spread of genetic material		Negative effects on local macroalgae	Regional and irreversible effects
pH increase	Kelp photosynthesis increases seawater pH, potentially reducing local ocean acidification.		Local and reversible effects
Shading effect		Reduced primary production (phytoplankton, eelgrass beds)	Local and reversible effects

1.2 Monitoring environmental effects at Storflua kelp farm

Currently, there is no established monitoring program for macroalgae cultivation. Suggested monitoring strategies vary by production scale and may include current measurement, surveys of natural kelp and local habitats, alien species monitoring, and potentially benthic and pelagic ecosystem monitoring (Hancke et al. 2021). Monitoring the impact of macroalgae particulate matter on benthic ecosystems has so far been adapted from salmon industry standards, in the absence of specific regulatory framework for the macroalgae industry.

Macroalgae cultivation in Norway is regulated by the Aquaculture Act (no: Akvakulturloven), which mandates ‘environmentally sound practices’. The County Municipality (no: Fylkeskommunen), in consultation with the County Governor (no: Statsforvalteren), may require environmental investigations prior to site allocation and during operation. Storflua kelp farm was granted “Permit for activities under the Pollution Control Act” by the County Governor of Trøndelag in 2023. The permit states the following requirements:

- In the area of influence outside the immediate zone of the kelp farm, the status of the deep water, soft-bottom fauna and sediment must be ‘good’ (status class II) or better according to the Water Framework Directive.
- Deposition or loss of organic material must not lead to negative changes in biodiversity at or near the farm.
- The beach zone in the vicinity of the facility must not be visibly affected by discharges or other pollution from the facility.

NIVA and Sintef designed a monitoring program in line with the requirements given in the permit, but also including a more detailed survey of the biodiversity related to the kelp farm as a temporary habitat. The program was sent to the County Governor, who commented on the position of some of the monitoring stations but had no further comments. An overview of the monitoring program is given in **Table 2**, and more details are found in Chapter 2 Methods.

The monitoring includes:

- ROV survey of the seafloor prior to deployment, to map marine biodiversity and habitat types on the seabed under and near the facility. This survey supplemented the survey already carried out at the anchors points and focused on mapping threatened and near-threatened habitats and species, poorly mapped habitats, habitats with important ecological function and habitats with international obligations.
- Survey of benthic fauna before and after kelp farm deployment, which can give an indication of whether the amount of particulate organic matter (kelp biomass) that falls to the seabed will have a negative effect on benthic fauna in the vicinity of the farm.
- Survey to map the biodiversity of the eukaryotic food web at the kelp farm pre-and post-harvest and at nearby kelp forests. Water samples for eDNA analysis were taken also prior to deployment.

Table 2 Monitoring program at Storflua kelp farm. The baseline study (benthic fauna and sediment, and water samples for eDNA) was conducted in September 2023, and the follow-up survey in May and June 2025.

Habitat	Survey type	Prior to deployment	After deployment	
			Before harvest	After harvest
Seafloor	ROV survey of the seafloor	Around anchor point (Åkerblå 2023) Below the kelp farm (NIVA, Sept. 2023)		
	Benthic survey	Sampling for sediment and benthic fauna near kelp farm	Sampling for sediment and benthic fauna near kelp farm	
Kelp farm as temporary habitat	Biodiversity study	eDNA sampling (water) near kelp farm and near natural kelp forest	eDNA sampling (water) near kelp farm and near natural kelp forest Netting or trapping of fish, underwater cameras, netting of epifauna	eDNA sampling (water) near kelp farm and near natural kelp forest Netting or trapping of fish, underwater cameras, netting of epifauna
Water masses	Desk top study: Effect of nutrient uptake			

The environmental impact of kelp cultivation on benthic fauna is dependent on farm size and production volumes. Suggested monitoring strategies for different-sized kelp farms are given in Hancke et al. (2019). With biomass production in the range of 15 - 30 tonnes in 2024 and 2025, the Storflua kelp farm is in the category of a ‘small’ kelp farm (30 – 300 tonnes per year). A kelp farm of this size does not require extensive marine monitoring, and the suggested monitoring scheme in Hancke et al. (2019) includes:

- mapping of currents
- potentially mapping of natural kelp in the area
- registrations of alien species on/near the cultivation rig
- if loss of large quantities of biomass: monitor effect on sea floor

The monitoring program originally designed for Storflua was based on an assumption that the farm would produce biomass on a much larger scale and be in the category ‘large’ kelp farm (10 000 to 30 000 tonnes per year). Monitoring the effect on the benthic fauna is not recommended for small kelp farms unless large quantities of kelp biomass fall to the seafloor. However, the permit given by the County Governor of Trøndelag in 2023 states that ‘in the area of influence outside the immediate zone

of the kelp farm, the status of the deep water, soft-bottom fauna and sediment must be ‘good’ (status class II) or better according to the Water Framework Directive’ and that ‘deposition or loss of organic material must not lead to negative changes in biodiversity at or near the farm’. This requirement can only be met by designing and conducting a traditional survey of benthic fauna as we have done.

2 Methods

2.1 Area description

The Storflua kelp farm is located in the water body Frohavet Sør (0321000032-10-C). Frohavet Sør is a relatively large water body stretching from Gjøesingen in the west to Lauvøya in the east (832 km²). The water type is Open exposed coast (H1). According to Vann-Nett, the overall ecological status is ‘moderate’. This is mainly due to some river basin specific pollutants in sediments above threshold values. The ecological status of benthic fauna, phytoplankton, oxygen and nutrients is ‘good’ to ‘very good’. Chemical status is ‘poor’ due to priority substances in sediment above threshold values. The status assessment is based on measurement results from surveys around salmon farms (C-surveys) and carried out mainly in the east of the water body. No surveys have been carried out where the Storflua kelp farm is located. The nearest survey was located just south of Risøya.

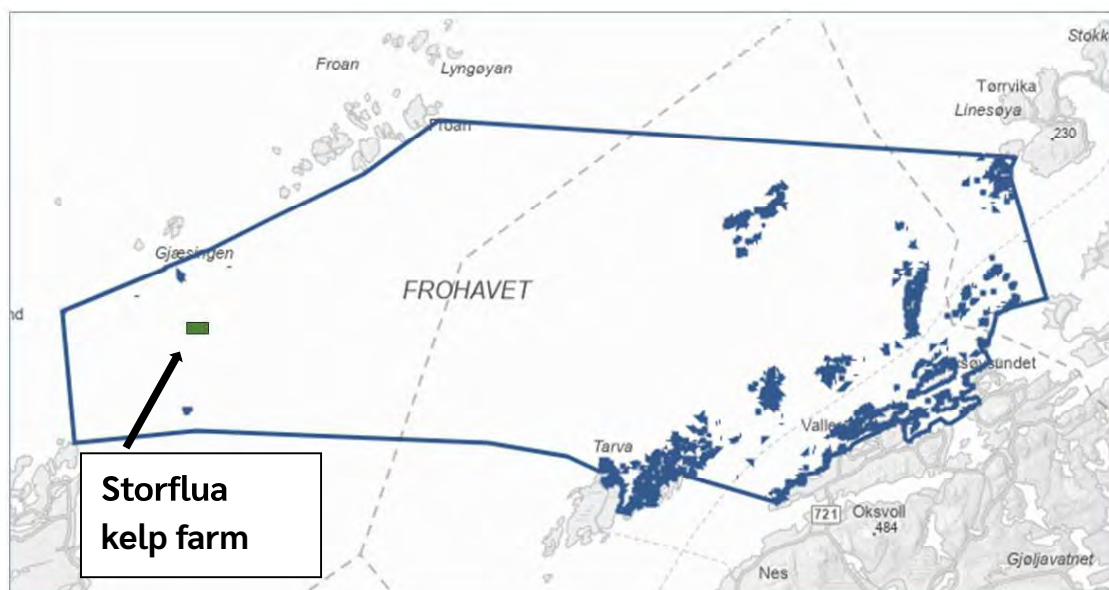


Figure 1 Waterbody Frohavet Sør (0321000032-10-C) with approximate location of the kelp farm (green square, not to scale)

The kelp farm at Storflua covers a surface area of 205 decaire (bouys and lines) and 366 decaire of bottom area (lines and anchors extending beyond the area covered by the farm at the surface) and has a permit for growing 800 tonnes kelp (wet weight) per year. In 2024 the farm produced sugar kelp biomass somewhere between 15-30 tonnes, of which around 1 tonne was harvested. In 2025 production was approximately in the same range, but harvesting was limited to 200 kg in late June. The area is relatively shallow, with bottom depths ranging from 50-60 m.

Several surveys were carried out prior to kelp farm deployment as a part of the license application process, including the following elements:

- Current measurements (Åkerblå 2022)

- Bottom mapping with multibeam (Åkerblå 2022)
- Investigation of sediment characteristics (Åkerblå 2022)
- Mapping of seabed/natural habitats with ROV at anchor points (Åkerblå 2023)
- Modelling of organic particles from the kelp farm (Sintef 2022)

Current measurements indicated main current direction towards west, south and south-east, and a high current velocity at all depths. The sediments at the Storflua site were very coarse with sand and gravel, which is also indicative of strong bottom currents. The visual survey with an ROV at the anchor points had no registrations of red-listed species or vulnerable habitats. The dispersion model of kelp particles showed that the fastest sinking particles will deposit under the southern part of the kelp farm or directly southeast of the farm, and on the south side of the 50m depth contour (**Figure 2**). More finely distributed material is dispersed further and deposited at lower concentrations.

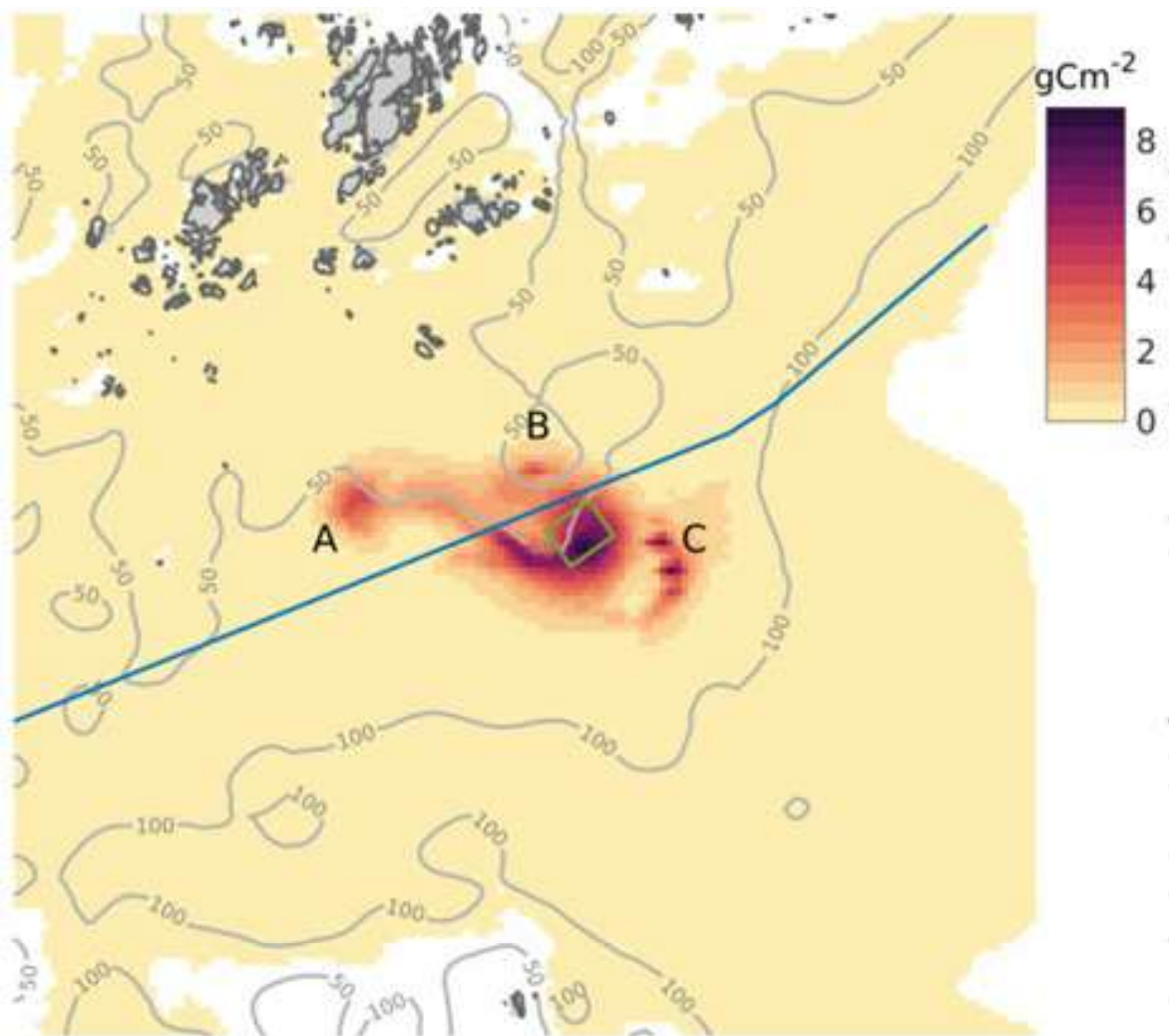


Figure 2. Simulated organic material concentration from the kelp farm (first half of July), in $g C m^{-2}$ (Sintef 2022).

2.2 Seafloor

2.2.1. ROV seafloor survey

An ROV-survey using a Ffish underwater camera (**Figure 3**) was conducted at Storflua in September 2023 by NIVA, supplementing the Åkerblå survey already carried out at the position of the anchor points. The survey was designed to map marine biodiversity and habitat types on the seabed right under the kelp farm and focused on mapping threatened and near-threatened habitats and species, poorly mapped habitats, habitats with important ecological function and habitats with international obligations.

Methodology for mapping seafloor for aquaculture site allocation is given in Husa and Kutti (2021) and Husa and Kutti (2022), for deep waters and shallow waters (0-50 m depth), respectively. The methodology recommends that 3-4 % of the area covered by aquaculture installment should be mapped by a seafloor ROV survey. However, following this methodology completely was not feasible due to the difference in area cover between a salmon farm and a kelp farm. An average salmon farm covers around 2 decares (and a large up to 10 decares), whereas the Storflua kelp farm covers a surface area of 205 decares and 366 decares of bottom area. Mapping 3-4 % of such a large area would demand a disproportionate amount of time and expenses. A reduced design where six areas on the seafloor below the allocated farm site were surveyed were implemented (**Figure 4**). However, due to malfunctioning of the camera, only four of the areas were surveyed. The four completed surveys nevertheless covered the full range of depths and seabed characteristics beneath the kelp farm, which are assumed to be relatively homogenous (based on the multibeam mapping and investigation of sediment characteristics (Åkerblå 2022)).



Figure 3. Ffish ROV used for sea floor mapping.

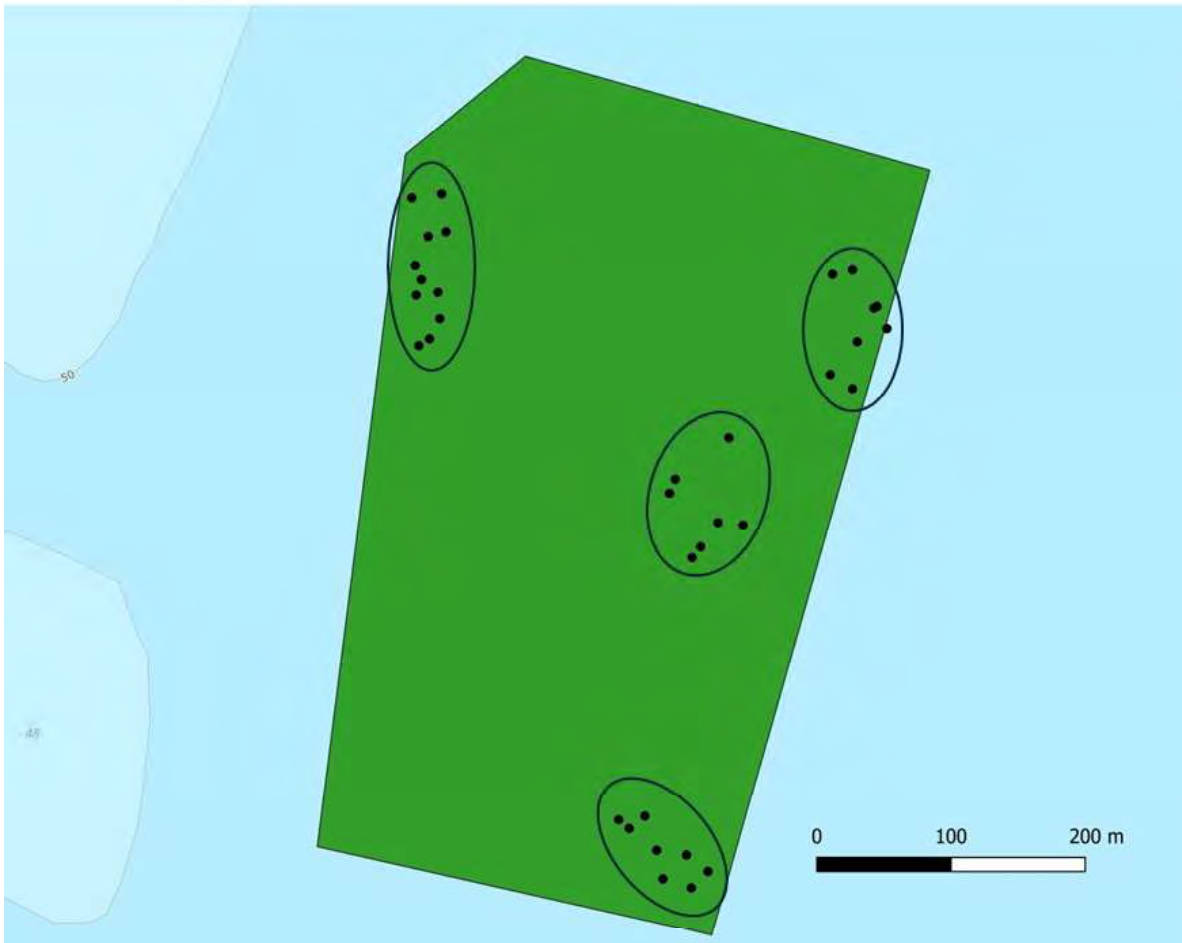


Figure 4. Map of the ROV-survey conducted under the kelp farm (green square) before kelp farm deployment. Black dots indicate GPS waypoints that were taken at regular intervals during the survey.

2.2.2. Sediment and benthic fauna

Field sampling of benthic fauna and sediment for the baseline study was conducted on 7th and 8th of September 2023. A total number of 6 stations in the vicinity of the kelp farm were sampled (see **Table 3** for coordinates and sampling depths). The position of the sampling stations were determined based on the dispersion model in areas where the kelp particles are most likely to settle (**Figure 2** and **Figure 5**). Benthic fauna and sediment were sampled at four of the stations, and only sediment at two stations. Station 7 was located closest to the kelp farm, approximately 65 m away from the south-west corner of the farm (**Figure 5**). Station 2 was located farthest away, approximately 1200 m southeast of the farm. Sampling depth ranged from 52 to 80 m. Station 4 is in an area where the dispersion model predicts accumulation of particulate organic matter from the farm, even though it is quite a distance from the farm.

Field sampling of benthic fauna and sediment after kelp farm deployment was conducted on 9th of May 2025, before limited harvesting (200 kg) was conducted on 27 June. The four fauna stations (station 7, 2, 4 and 14) were sampled for fauna and sediment (**Table 3**). Because the vessel provided by Mausund Field station was small and had a pot hauler without sufficient hauling power, we could not use the extra weights necessary to penetrate the coarse sandy sediment at Storflua. As a result, the volume of sediment sampled was less than in the baseline study, and often below the requirements set by the ISO-

standard, which is a minimum of 5 L of sandy sediments. Only 4 out of the 11 grab samples had 5 L or more of sediment.

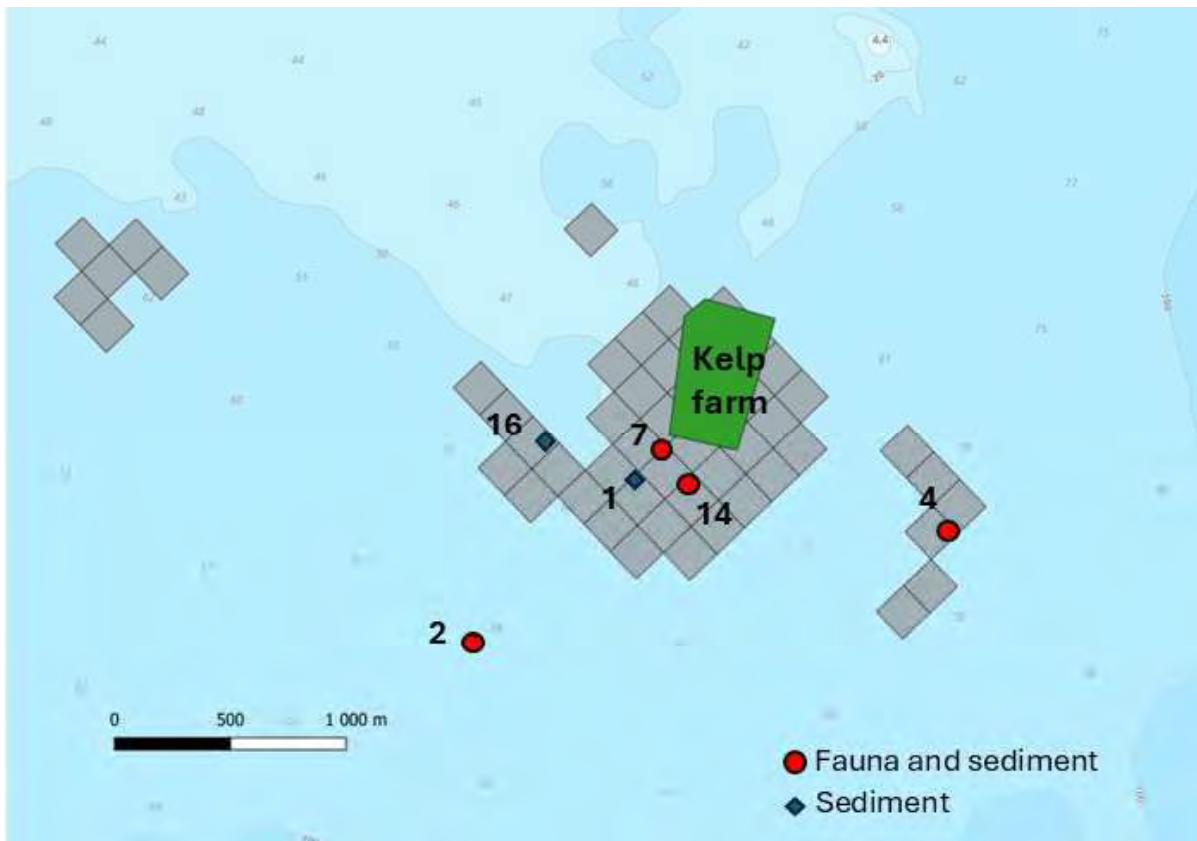


Figure 5 Map of sampling stations for benthic fauna and sediment in Storflua in September 2023 and May 2025 (station 1 and 16 were not sampled in 2025). Grey areas indicate where kelp detritus from the farm are most likely to settle on the sea floor according to the dispersion model (Sintef 2022, see also Figure 2)

Table 3 Sampling of benthic fauna and sediment at Storflua in September 2023 and May 2025. Geographical coordinates are given in decimal degrees (WGS84).

Date	Station name	Station id	Depth (m)	Latitude	Longitude	Parameter
07.09.2023 09.05.2025	Bløt nær	7	53	63,8843	8,9462	Benthic fauna, sediment
07.09.2023	Bløt 1	1	60	63,8830	8,9440	Sediment
07.09.2023 09.05.2025	SED7	14	52	63,8829	8,9491	Benthic fauna, sediment
07.09.2023	SED9	16	60	63,8842	8,9358	Sediment
08.09.2023 09.05.2025	Bløt4	4	66	63,8823	8,9719	Benthic fauna, sediment
08.09.2023 09.05.2025	Bløt2	2	80	63,8763	8,9312	Benthic fauna, sediment

Three grab samples for analysis of macrofauna and one grab sample for sediment analysis were collected at each of the faunal stations using a van Veen grab with a surface area of 0.1 m². The material in the grab was sieved onboard with a 0.5 mm and 1 mm mesh sieve. The sieve residue was preserved in 4 % buffered formalin for analysis of benthic fauna. The samples for sediment analysis were taken from a separate grab: samples for TOC/TN were taken from the top 1 cm layer of the sediment and samples for grain size analysis were taken from the upper 5 cm layer.



Figure 6 Field sampling of benthic fauna and sediment using a standard van Veen grab with a surface area of 0.1 m² and washing the material through sieves submerged in water for gentle treatment of the fragile animals.

The macrofauna from the 1 mm sieve residues were sorted and identified in the laboratory to the lowest taxonomic level possible (mostly species level) and all individuals counted (**Figure 7**). Sediment total organic carbon (TOC) contents were measured using a CHN (i.e. carbon, hydrogen and nitrogen) elemental analyzer after removal of inorganic carbon by acidification. The silt-clay fraction was determined by wet sieving and calculated as a proportion of total sediment dry weight.



Figure 7 Left: sieve residue that was fixed with formaldehyde and brought back to the laboratory for sorting and species identification. Right: all individuals were identified to species level (if possible) and counted using a stereo microscope.

Based on number of species and individuals, five benthic indices used in the Water Framework Directive (WFD) monitoring system for Norwegian coastal waters (Direktoratsgruppa for vannforvaltning, 2025) were calculated:

- the Shannon-Wiener diversity index ($H' \log_2$; Shannon & Weaver, 1963)
- Hurlbert's diversity index (ES100; Hurlbert, 1971)
- the Norwegian Quality Index (NQI1; Rygg, 2006)
- the Indicator Species Index (ISI2018; Borgersen et al., 2019)
- the Norwegian Sensitivity Index (NSI2018, Borgersen et al., 2019).

Ecological quality ratios (EQR) were calculated for each index as a weighted ratio of the observed to reference condition values and normalized. Status classification for a site is based on the arithmetic mean of the normalized EQR-values (nEQR) for the five indices. The classification system has five classes ranging from very good to very bad ecological status.

Table 4 Status class boundaries for soft bottom indices for water type H1 ("open exposed coast"). NQI1=Norwegian Quality Index; H'=Shannon's diversity index; ES100=Hurlbert's diversity index; ISI2012=Indicator Species Index; NSI=Norwegian Sensitivity Index, nEQR=normalized Ecological Quality Ratio. Table from Guide for classification of environmental status in coastal and freshwater, dated 28.1.2025 (Direktoratsgruppa for vannforvaltning, 2025)

Index	Water type H 1-3				
	Very good (I)	Good (II)	Moderate (III)	Bad (IV)	Very bad (V)
NQI1	0,90 - 0,72	0,72 - 0,63	0,63 - 0,49	0,49 - 0,31	0,31 - 0
H'	5,5 - 3,7	3,7 - 2,9	2,9 - 1,8	1,8 - 0,9	0,9 - 0
ES100	46 - 23	23 - 16	16-9	9-5	5 - 0
ISI2018	10,2 - 6,6	6,6 - 6	6 - 4,9	4,9 - 3,6	3,6 - 0
NSI2018	34 - 29	29 - 23	23 - 17	17 - 11	11 - 0

Sediment grain size and organic content

Total organic carbon (TOC) is a supporting parameter that provides information about the degree of organic load at the station. The sediment fraction provides information on how coarse- or fine-grained the sediment is, which is important for the composition of the fauna and can be used when interpreting the results.

The content of TOC in the sediment can be given a status class according to SFT guideline 97:03 (Molvær et al., 1997) but is not included in the final status classification of soft-bottom fauna. The classification of TOC is based on fine-grained sediment, and the TOC value is therefore standardized for theoretical 100 % fines according to the formula:

$Normalized\ TOC = measured\ TOC + 18(1-F)$, where F is the proportion of silt-clay fraction (particle size < 63 µm). Status class boundaries for TOC are given in **Table 5**.

Table 5 Status class boundaries for normalized total organic carbon (TOC) from guidance SFT97:03 (Molvær et al 1997). TOC is a supporting parameter and is not included in the final classification of ecological status.

	Parameter	Status class				
		Very good (I)	Good (II)	Moderate (III)	Bad (IV)	Very bad (V)
TOC	Organic carbon (mg/g)	0-20	20-27	27-34	34-41	41-200

2.3 Nutrient uptake by cultivated kelp

A literature review was conducted to identify and synthesize existing knowledge on the effects of kelp nutrient uptake. Scientific articles, reports, and guidelines were collected primarily through searches in Google Scholar, and additional references were identified by reviewing citations in relevant papers.

Publications were screened based on relevance to the research question, publication year (with emphasis on studies from the more recent years), location of study site if field study (with emphasis on studies from temperate regions and near to Norway), and scientific quality. Both peer-reviewed articles and grey literature (e.g. reports from regulatory authorities and international organizations) were included when directly relevant.

2.4 Kelp farm as temporary habitat

2.4.1. Field Sites

Field work was conducted during two main periods, from 8-11 May and 7-10 June 2025, that were initially aimed to be one before and one post-harvest. Eventually, limited harvesting (200 kg) was conducted on 27 June. One kelp farm along the Norwegian west coast was studied i.e. the 'Storflua' site near to Mausund (Trøndelag, **Figure 8**). Storflua cultivated *Saccharina latissima* and *Alaria esculenta* at depths of ca. 2-10 m, over bottom depths of ca. 55 m and cultivated ca. 10-20 tonnes in the year of sampling (**Figure 8C**). Two habitat types were studied as control sites; these were one mixed *S.latissima/L. hyperborea* 'kelp forest' (ca. 5-10 m bottom depth), and one 'pelagic' control (approx. 30 m bottom depth). Given that exposure is an important determinant of species abundance and diversity, sites were selected such that the exposure was as similar as possible between all three habitat types; this resulted in control sites being some distance away from Storflua.

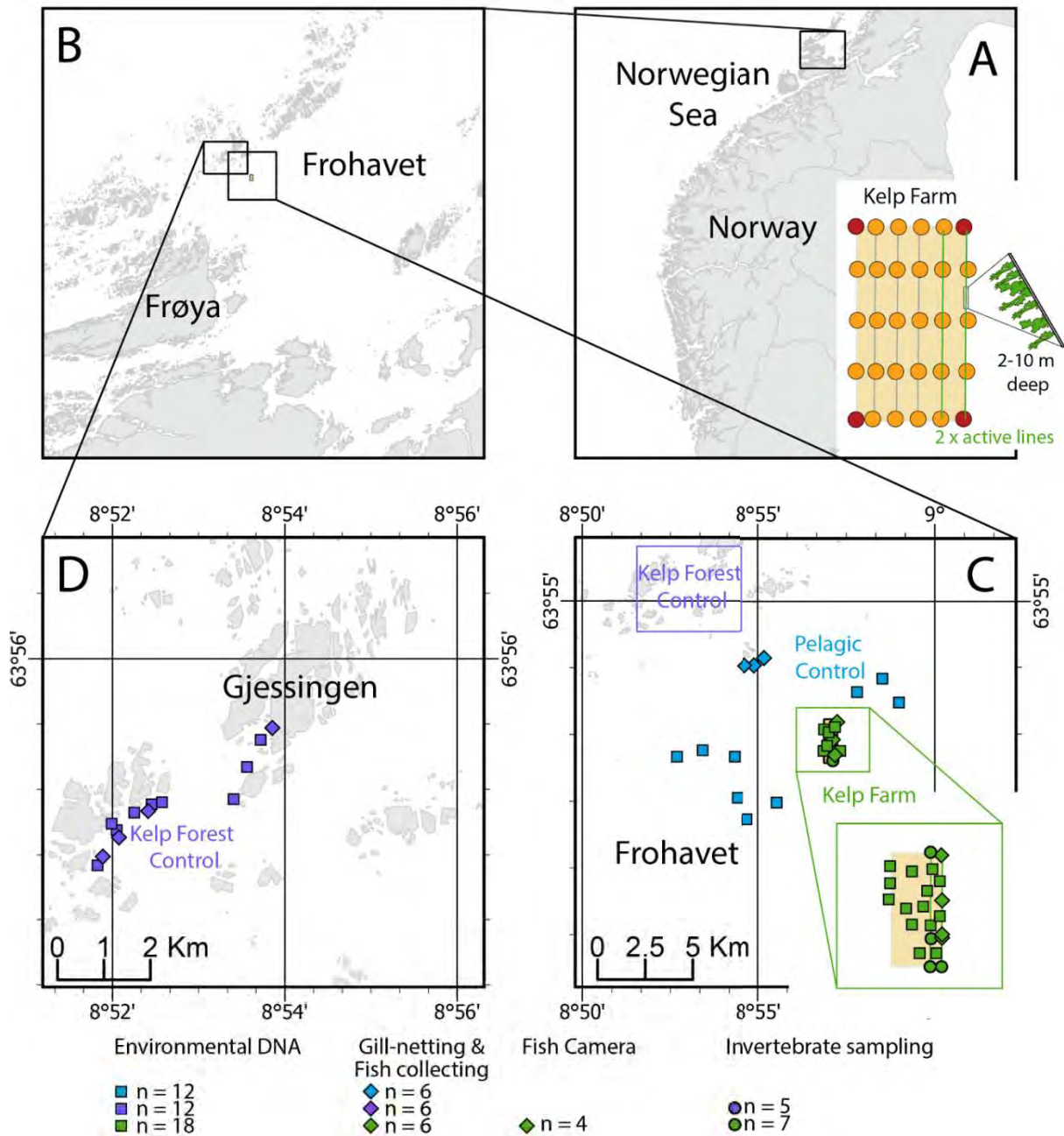


Figure 8 Map of biodiversity sampling sites and habitat types at two Norwegian kelp aquaculture locations. (A, B) Overview maps showing the locations of the study site: ‘Storflua’ near Frøya (Trondheim), along the Norwegian west coast. (C, D) Detailed site maps indicating the placement of the Storflua kelp farm (cultivating *Saccharina latissima* and *Alaria esculenta*), natural kelp forest controls (*S. latissima*/*Laminaria hyperborea*), and pelagic control sites. Inset on (A) shows a schematic of the approximate kelp farm design, illustrating the relative depths of kelp cultivation and active lines (green). Numbers of samples for each sample/survey type are shown at the bottom of the figure using squares to depict environmental DNA water samples, diamonds to represent fishing and fish camera installations, and circles to represent epifauna invertebrate sampling.

2.4.2. Fishing and fish observations

Fishing was conducted with multi-mesh gill-nets (NORDIC gill-net) that were 30 m long and 1.5 m deep; divided in 2.5 m panels with mesh sizes 43.0, 19.5, 6.5, 10.0, 55.0, 8.0, 12.5, 24.0, 15.5, 5.0, 35.0, and 29.0 mm. Three nets were placed horizontally at a depth of 2–4 m in all three habitats; kelp farm, kelp forest control and pelagic control. Fishing occurred over the day and night (24 h) for four days and nights. Fish were released from the nets and killed early morning. Species identification and total length (TL) and weight measurements were recorded for each. All fish representing different nets in the same habitat type and mesh sizes were lumped and called one sample catch. In addition, lumpfish presence on kelp during the sampling campaign and at harvest (26 June) was noted with a subset being hand-collected and preserved at -20°C to enable TL measurement at a later date. In addition, two cameras were deployed at the kelp farm to capture fish diversity and behaviour during daylight hours using GoPro Hero 10 Black cameras, recording a photo every 10 seconds. In addition, baited fishing traps were placed at the kelp farm and kelp control sites through the May sampling period.

No statistical analyses were performed on fishing or fish camera data given these data types were semi-qualitative. Instead, barplots of observation counts were generated for visual interpretation. Pairwise differences between sample type were tested using Wilcoxon rank-sum tests with Benjamini-Hochberg (BH) correction for multiple comparisons (Benjamini and Hochberg, 1995). Significant differences were annotated on the plots using the `ggpubr` package.

2.4.3. Invertebrate collection and identification

Epifauna were collected during both sampling periods on *S. lattissima* blades and holdfasts and 30 cm scrapes of production rope, structural rope (approximately 2 m depth) and floating plastic buoys (approximately 1m depth). *S. lattissima* blades and stipes were also collected at natural habitats in May and June as controls, but these were not analysed because they were too few to be representative of local natural habitats. The kelps and rope scrapes were collected from boat, placing samples into plastic bags and subsequently freezing at -20°C . Sampled kelps and rope/buoy scrapes were rinsed in freshwater, and captured fauna was retained in a 250 μm sieve (Christie et al., 2003; Bekkby et al., 2023) and preserved on 70 % ethanol. The species were identified to the lowest possible taxonomic level using a Leica TL5000 Ergo Transmitted Light Base magnifier, based on the identification literature described in Bekkby et al. (2023). The nomenclature used in the species list is in accordance with the database ‘Worlds Register of Marine Species’. The number of individuals were approximated for Copepoda. No statistical analyses were performed on invertebrate data given these data were semi-qualitative. Instead, summaries were made of family richness per substrate type and overall. In addition, Treemaps from `treemapify` package in R were created to visualize invertebrate families with and without Copepoda.

Prey items present in lumpfish stomach contents were collected from a subset of 59 lumpfish available and studied in the same manner as epifauna.

2.4.4. eDNA collection via water filtering

To obtain eDNA from the environment, triplicates of seawater samples (1.2 l) were collected at each habitat type (kelp farm, kelp forest control and pelagic control) from 2 m depth using Niskin bottles during the two sampling events and two in between events at 28th of May and 3rd of June 2025 by a local sample provider. To better capture spatiotemporal biodiversity seawater samples were taken at varying locations between sampling events, upstream of kelp farms. All sampling equipment was sterilized with 10 % bleach before each sampling event and thoroughly rinsed with seawater from the sampling point area before each use. All samples were collected and processed while wearing newly donned protective equipment such as nitrile gloves to prevent risk of contamination between samples or from outside

sources. Seawater samples were maintained cool (4°C) with no direct exposure to sunlight and were filtered within 5 hours of collection.

Seawater was filtered on site through 0.22 µm Sterivex filter units (Merck KGaA, Darmstadt, Germany) using a peristaltic pump. Pump hosing was cleaned by passing 10 % bleach followed by 100 ml MilliQ Ultrapure water and then 200 ml of sample seawater, before beginning filtration of sample through the Sterivex unit. A total of 1 l of water was filtered through each of the triplicate filters from each location to ensure a standard volume between samples. After drying the filters by pumping air through using a sterile 50/60 ml syringe from BD Plastipak, the filters were placed in pre-labeled sterile 50 ml Falcon tubes (Thermo Fisher Scientific, Waltham, MA, United States), and pre-labeled bags for transport to UiT The Arctic University of Norway (UiT) and were maintained at –20°C in an eDNA dedicated freezer. The syringes were changed, and operators' hands were meticulously sterilized, between each sample using 10 % bleach solution to limit contamination. A control blank was run on each sampling day to quantify contamination during the filtering process by filtering 0.5 l MilliQ Ultrapure water through a filter and drying the filter in the same manner as the samples.

2.4.5. eDNA laboratory analyses

The Sterivex filters used for water sampling underwent DNA extraction in over-pressured eDNA clean-labs at the Arctic University of Norway (UiT). In-house protocols were compiled that relied on vigilant care for cleanliness within and outside of the eDNA laboratories and avoidance of potential contaminant sources at UiT and personal life during the weeks of eDNA extraction lab use. Airborne DNA contamination risks were mitigated through use of a pressure positive eDNA extraction rooms and airlocked changing and sample preparation rooms. eDNA extraction protocols were meticulously followed for the modified use of DNEasy Blood and Tissue® (Qiagen, Hilden, Germany) kits. In short, a total of 500 µl of lysis buffer were added to each Sterivex filter, sealed with sterile caps at both ends, and incubated 24 h on a rotary wheel placed in a 56°C incubator oven to ensure full lysis of the particulates captured within the filter membrane. The lysed solution was then centrifuged out of the filter casing and into 2 ml Eppendorf tubes and the rest of the extraction followed the standard protocol. Subsequently each sample was eluted in 75 µl elution buffer, of which 20 µl was aliquoted for library preparation and sequencing.

A multiplexing approach was used for sequencing the 43 samples and 4 blank controls on an Illumina MiSeq next-generation sequencer (Illumina, San Diego, CA, United States). Amplicons were COI, and 12S. The partial COI Leray-XT fragment (313 bp) was amplified using the mlCOIintF-XT/jgHCO2198 primer pair (Wangensteen et al., 2018), while the 12S rRNA fragment (163-185 bp) was amplified using the MiFish primer pair (Miya et al., 2015). Samples included three PCR blanks as well as field blanks for each sampling event. 8-base tags were used to uniquely label each sample as in Wangensteen et al. (2018). PCR amplifications were conducted in 20 µl reactions containing 2 µl of DNA template, 10 µl of AmpliTaq Gold Master mix, 0.16 µl of Bovine Serum Albumin (20 µg/µl), 1 µl of each forward and reverse primer (5 µM) and 5.84 µl of H₂O. The temperature profile was as follows: 95°C for 10 min; 35 cycles × (94°C/1 min, 45°C/1 min, 72°C/1 min); 72°C/5 min. Only one PCR replicate was run per sample. The success of PCR amplifications was checked by gel electrophoresis in 1% agarose and PCR products were then pooled together into a multiplex sample pool for each amplicon. MinElute PCR purification columns (Qiagen) were used to concentrate the pooled DNA and to remove fragments below 70 bp. Library preparation was performed with the NEXTflex PCR-free library preparation kit (BIOO Scientific) and the exact library concentration was measured in a qPCR machine (ThermoFisher), using the NEBNext Library Quant Kit (New England BioLabs). Finally, pools were sequenced along with 1% PhiX on an Illumina MiSeq platform using v3 chemistry (2 × 250 bp).

2.4.6. eDNA bioinformatic analyses

The Mjolnir v.1.2 pipeline (available from <https://github.com/uit-metabarcoding/MJOLNIR>) was used for bioinformatic processing of raw data. In short, the pipeline directed the following analyses for each primer set separately: The OBITools v1.01.22 software suite (Boyer et al., 2016) was used for the initial steps of the bioinformatic analyses. Paired-end reads were aligned using illumina paired-end and only sequences with alignment quality score > 40 were kept. Demultiplexing was done using the sample tags with ngsfilter, which also removed primer sequences. Aligned reads with length of 299–320 bp (CO1), and 140–190 bp (12S) and without ambiguous positions were selected using obigrep and then dereplicated with obiuniq. Chimeric sequences were removed using the uchime-denovo algorithm implemented in vsearch v1.10.1 (Rognes et al., 2016). Clustering of sequences into molecular operational taxonomic units (MOTUs) was performed using SWARM 2.0 (Mahé et al., 2015) with a d-value of 13 for CO1 (Bakker et al., 2019) and d-value of 1 for 12S following Mjolnir guidelines. Taxonomic assignment of the representative sequence of each MOTU was done with the ecotag algorithm (Boyer et al., 2016) using a local database of Leray or 12S fragment sequences (available from <https://github.com/uit-metabarcoding/DUFA>). Sequences for the MOTUs of interest (abundances > 0.5% of the total reads) were manually checked for a better match by BLAST search against the NCBI GenBank database, and best IDs were changed to reflect a higher percent match if one was found. Sequences assigned to contamination of terrestrial origin, and MOTUs that were present in the control samples with more than 10% of their total read abundance were removed. MOTUs with the same taxonomic assignment that resulted from intraspecific variation were merged. Prior to statistical analyses, non-bony fishes were removed from the final 12S list along with MOTUs of taxa not identified to genus or species level while non-metazoans were removed from the CO1 list along with MOTUs of taxa not identified to family, genus or species level. Extra steps were taken to explore the CO1 data; terrestrial organism traces were removed, and two datasets were generated, one with all species and one without those deemed to be planktonic only or in the top 5% of read abundance overall (*Obelia dichotoma*, *Membranipora membranacea*). Removing these provided a dataset that is more likely to represent trace DNA of animals residing at the Kelp Farm rather than whole organisms advected to the site that could hinder inferences.

eDNA sequence reads were first transformed to relative abundances to build a Bray-Curtis dissimilarity matrix, which was used to assess the variance in community composition using Permutational Multivariate Analyses of Variance (PERMANOVA). Samples were categorized as a function of Site (Kelp Forest Control, Kelp Farm, Pelagic Control), and the univariate effects of these factors on the community composition were tested using adonis function with 999 permutations. Alpha diversity was assessed using Shannon and Observed richness indices in the phyloseq package (McMurdie and Holmes 2013).

An indicator species analysis (Dufrêne and Legendre, 1997) was performed in R using the labdsv package (Roberts, 2016) to detect potential associations of certain eukaryotic phyla to each type of site (Kelp Farm or Controls) and dataset (12S or CO1). Those with Indval values > 0.5 (p-value < 0.05 in all cases) were identified as indicator phyla. The top six (for CO1) MOTU Species' and genus' that differed in sequence read abundance between sites (Kelp Farm and Controls) were identified and pairwise differences between sites were tested using Wilcoxon rank-sum tests. This was not performed for 12S due to low read abundance at the Kelp farm site. Numbers differed in accordance between variation for each dataset. For the CO1 dataset, these taxa were restricted to fauna with benthic adult life stages to test for the influence of fouling the Kelp Farm structures. Benthic or pelagic adult life stage was identified for all taxa using online databases (fishbase.se, marinespecies.org).

3 Results

3.1 Seafloor

3.1.1. ROV seafloor survey

The ROV seafloor survey at Storflua was conducted before the kelp farm was deployed and covered four areas under the planned kelp farm (**Figure 3**). The depth in the area was 53-59 m. The seabed was relatively flat, and the bottom substrate consisted mainly of sand and gravel, with elements of stones and shell sand (**Figure 9**). The full report is given in Appendix A.

Some kelp residues/pieces of kelp leaves were found on three of the dives. A funnel-shaped sponge and a possible fan-shaped sponge were observed, both growing on rocks, in addition to a sea feather (slender sea pen - *Virigularia mirabilis*). Some of the observed fauna includes starfish, brittle stars, bryozoans, sea squirts and troll lobsters. No vulnerable species or habitats were observed. However, as only a limited part of the seafloor below the kelp farm was surveyed, presence of vulnerable species or habitats cannot be ruled out.

The ROV survey provides a visual assessment of benthic habitats and conspicuous fauna within the areas surveyed. As with all imagery-based surveys, the absence of observations of red-listed species or threatened habitat types cannot be interpreted as proof of their absence from the wider site. The results therefore indicate that no red-listed species or threatened or near-threatened habitats were observed within the surveyed transects, but do not preclude their occurrence elsewhere within the farm footprint.

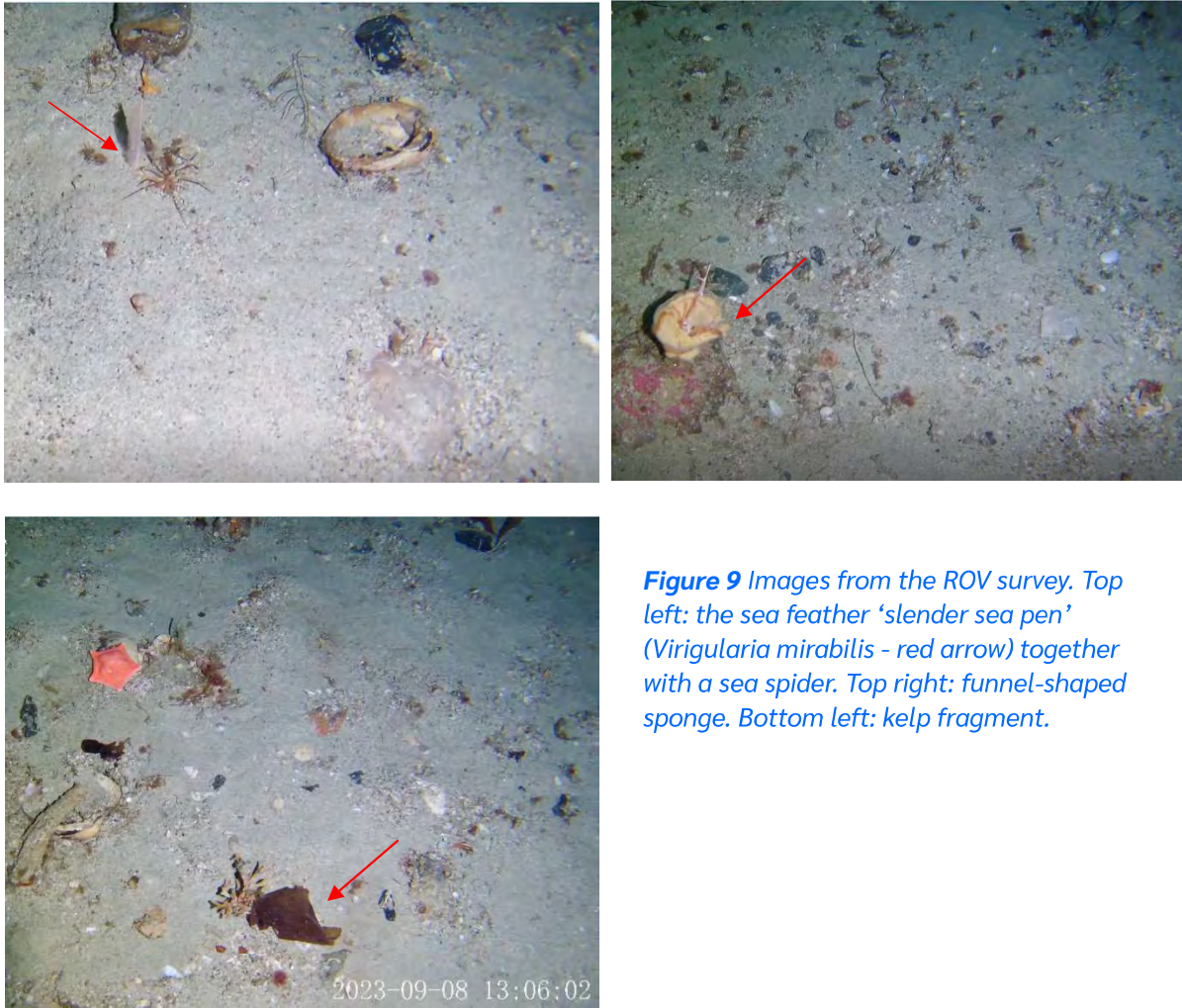


Figure 9 Images from the ROV survey. Top left: the sea feather ‘slender sea pen’ (*Virigularia mirabilis* - red arrow) together with a sea spider. Top right: funnel-shaped sponge. Bottom left: kelp fragment.

3.1.2. Sediment and benthic fauna

In 2023, a total of 321 taxa were identified from the 12 faunal samples. See Analysis Report in Appendix B for full list of species sampled and their abundances. The fauna was dominated by annelids (making up 80 % of the individuals and 57 % of the species), followed by mollusks (5 and 23 %) and crustaceans (7 and 13 %).

All stations acquired ‘very good’ quality status according to WFD classification system (**Table 6**). The species diversity (H' and ES100) and absolute species numbers (S) were generally high, exceeding the modelled reference value for the region (Borgersen et al. 2019) at all four stations for species numbers and at two of the stations for species diversity.

Table 6 Benthic fauna indices for the stations at Storflua in 2023, both the average of the grab samples' index values and normalized EQR (nEQR). S =average number of species per grab sample, S_{tot} =total number of species at the station, N =average number of individuals per grab sample, $NQI1$ =Norwegian Quality Index, H' =Shannon's diversity index, $ES100$ =Hurlbert's diversity index, $ISI2018$ =Indicator Species Index version 2018 and $NSI2018$ =Norwegian Sensitivity Index version 2018. Class limits and color code for condition classes are given in Table 4.

	S/S_{tot}	N	$NQI1$	H'	$ES100$	$ISI2018$	$NSI2018$	Average nEQR
Station id: 7								
Average grab value	95/155	449	0.81	5.71	47.7	8.36	28.5	
nEQR for average grab value			0.90	1.00	1.00	0.90	0.78	0.92
Station id: 2								
Average grab value	92/146	488	0.82	4.96	40.9	8.28	27.6	
nEQR for average grab value			0.91	0.94	0.96	0.89	0.75	0.89
Station id: 4								
Average grab value	97/167	453	0.84	5.5	44.7	8.81	29.5	
nEQR for average grab value			0.93	1.00	0.99	0.92	0.82	0.93
Station id: 14								
Average grab value	121/199	551	0.84	6.01	52.2	8.91	29.3	
nEQR for average grab value			0.93	1.00	1.00	0.93	0.81	0.93

In 2025, a total of 276 taxa were identified from the 11 faunal samples. See Analysis Report in Appendix C for full list of species sampled and their abundances. As in 2023, all stations in 2025 acquired ‘very good’ quality status according to WFD classification system (**Table 7**). The species diversity (H’ and ES100) and absolute species numbers (S) were high also in 2025, exceeding the modelled reference value for the region (Borgersen et al. 2019) at all four stations for species numbers and at two of the stations for species diversity.

Table 7 Benthic fauna indices for the stations at Storflua in 2025, both the average of the grab samples’ index values and normalized EQR (nEQR). S=average number of species per grab sample, S_{tot}=total number of species at the station, N=average number of individuals per grab sample, NQI1=Norwegian Quality Index, H’=Shannon’s diversity index, ES100=Hurlbert’s diversity index, ISI2018=Indicator Species Index version 2018 and NSI2018=Norwegian Sensitivity Index version 2018. Class limits and color code for condition classes are given in Table 4.

	S/S _{tot}	N	NQI1	H'	ES100	ISI2018	NSI2018	Average nEQR
Station id: 7								
Average grab value	88/162	318	0.83	5.54	47.8	8.79	28.3	
nEQR for average grab value			0.92	1.00	1.00	0.92	0.78	0.92
Station id: 2								
Average grab value	68/95*	318	0.80	4.58	35.9	8.08	27.8	
nEQR for average grab value			0.89	0.90	0.91	0.88	0.76	0.87
Station id: 4								
Average grab value	92/166	489	0.83	5.23	41.6	8.98	29.4	
nEQR for average grab value			0.92	0.97	0.96	0.93	0.81	0.92
Station id: 14								
Average grab value	85/149	364	0.81	5.53	45.9	8.21	28.4	
nEQR for average grab value			0.90	1.00	1.00	0.89	0.78	0.91

* Total number of species at station 2 from only two grab samples

Benthic fauna before kelp farm deployment (2023) and after two years of production (2025):

The nEQR value dictates the overall status class assessment of the benthic fauna at a site (**Table 4**). The nEQR value was the same in 2023 and 2025 at station 7 (closest to the kelp farm), and slightly lower at the other stations in 2025 compared to 2023 (**Figure 10**). However, the nEQR values were high at all stations both years, indicating ‘very good’ ecological status, and the difference between sampling years was small and within the range of variation expected in a natural environment.

The average number of species and individuals found in each grab sample was lower in 2025 at all sites except at site 4 (**Figure 10**).

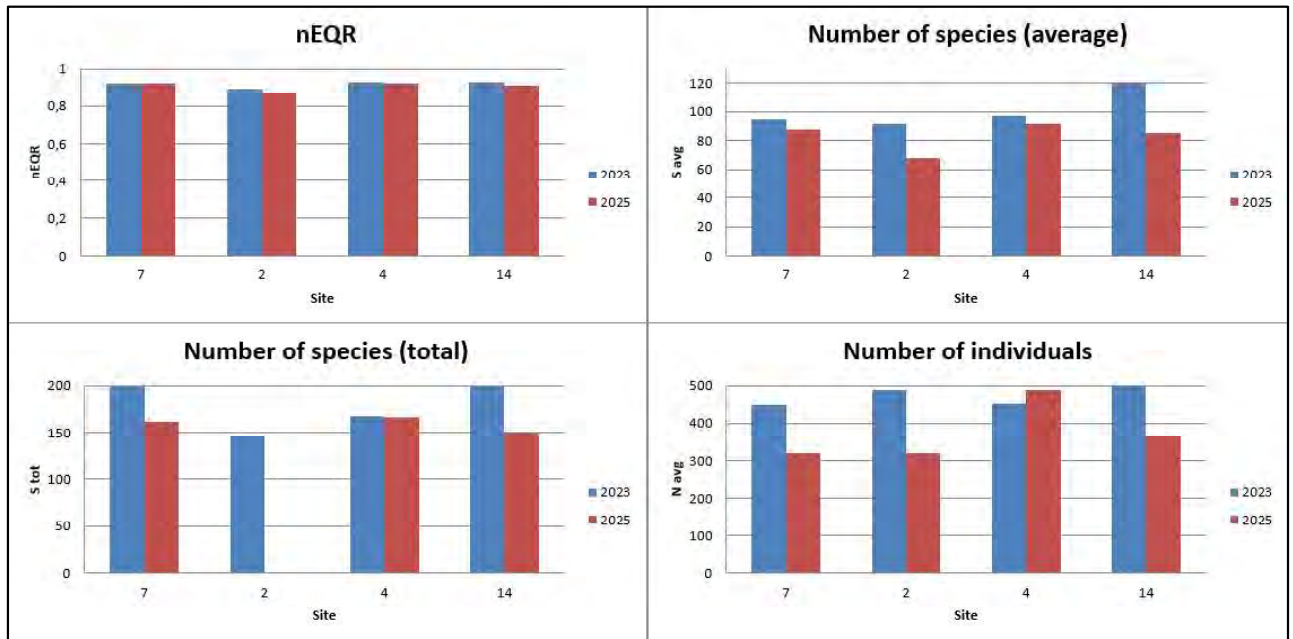


Figure 10 Benthic fauna parameters for the stations at Storflua in 2023 and 2025: normalized EQR-values (nEQR), average number of species per grab sample, total number of species at the station, and average number of individuals per grab sample. At site 2, only two grab samples were taken, and the total species number is not comparable to the others (and thus not shown).

A Non-metric Multidimensional Scaling (NMDS) plot is used to visualize the similarity or dissimilarity between samples based on species composition. Each point represents a sample, and the distance between points reflects how different the samples are: points that are close together have more similar species composition, while those farther apart have more dissimilar species composition. The axes are arbitrary and do not have specific meanings; only the relative distances between points are important.

The NMDS ordination indicated a difference in species composition between 2023 and 2025 samples (y-axis, Figure 11). On the x-axis, the samples from both years form a spatial gradient – site 2 is to the left and a bit away from the other sites, indicating that the species composition is different. Site 2 is the furthest away from the kelp farm, and the deepest at 80 m depth. In 2023 there was a more evident spatial gradient with samples from station 4 and 7 in the middle, and samples from station 14 to the right. In the 2025-data the samples from each station are to a lesser degree lumped together, indicating greater variation between replicate samples from the same station.

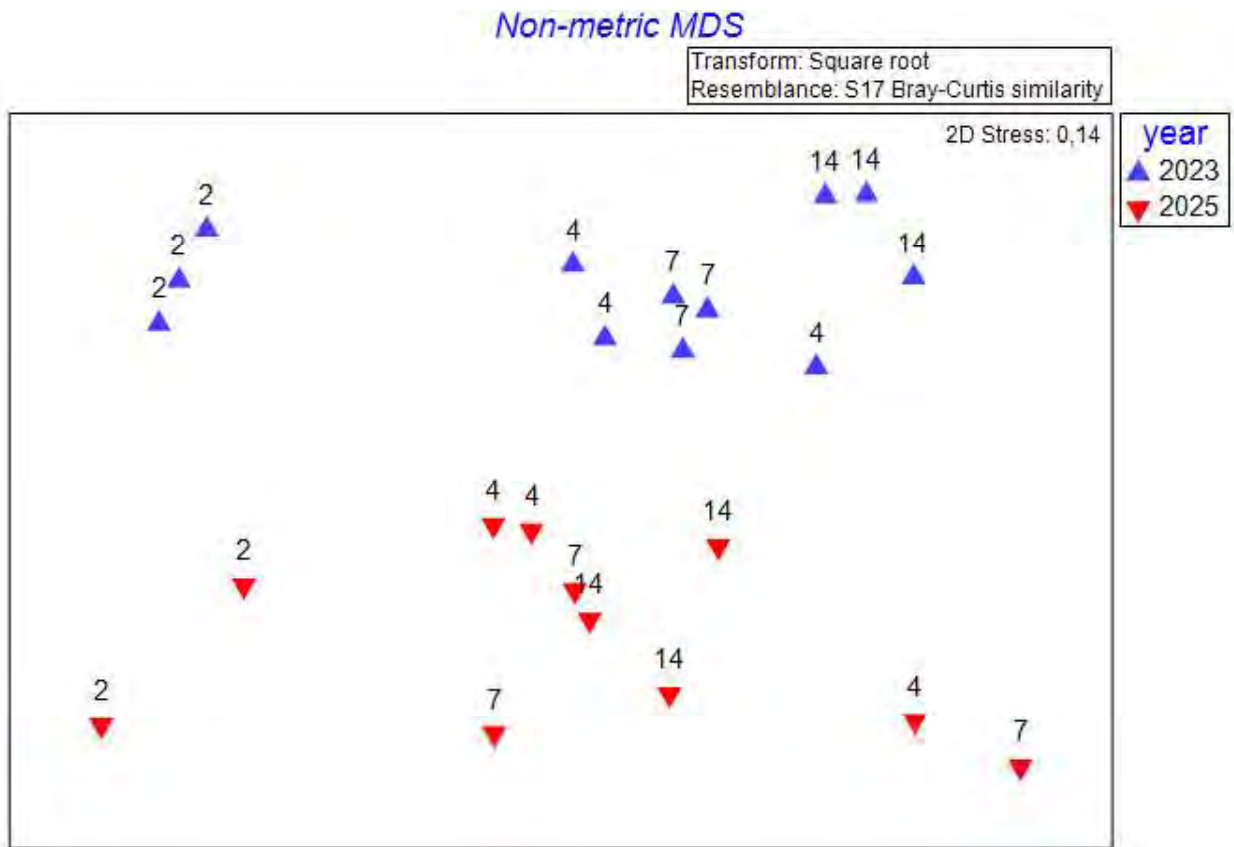


Figure 11 Nonmetric multidimensional scaling (NMDS) of macrofaunal community structure based on species abundances from grab samples from before kelp farm deployment (2023) and after two years of production (2025). Numbers in the plot indicate station number (see **Figure 5**). The ordination is based on Bray-Curtis similarities on root-transformed faunal data (NMDS stress = 0.14). Bray-Curtis is the standard distance measure for benthic ecology, and square-root transformation provides a balanced down-weighting of highly abundant species, since benthic datasets often include a few dominant taxa with very high counts and many rare taxa. Root transformation reduces the dominance of highly abundant species just enough to reveal underlying community patterns, while still preserving ecological structure and compatibility with Bray-Curtis.

TOC and grain distribution in sediment

An overview of all sediment parameters is given in **Table 8**. The full analysis report is given in Appendix D and E. All stations had very coarse-grained sediment, with a silt-clay fraction of only 4-8 %. All stations had low TOC-content in the sediments both years, ranging from 2.6-6.5 mg/g. Because the classification of TOC is standardized for theoretical 100% silt-clay fraction (see chapter 2.2.2), the normalized TOC-values (TOC63) are higher but corresponding to ‘good’ status for organic content in 2023 and ‘very good’ status in 2025 (all values very close to the ‘good’/‘very good’ status class boundary at 20 mg/g). The content of nitrogen in the sediments was also low, ranging from 0.11-0.64 mg/g in 2023, and slightly higher in 2025 (0.61-0.86 mg/g).

Table 8 Proportion of fine-grained sediments (silt-clay fraction) (% <63 μm), content of total organic carbon (TOC) and normalized TOC (TOC63), total nitrogen (TN) and the C/N ratio in the sediment. The color gives an indication of the status class of the organic content in the sediment and is set based on the class boundaries in **Table 5**. The classification of TOC in the sediment is not included in the final status classification of soft-bottom fauna.

Station id	Grain size (%<63 μm)		TOC mg/g		TOC63 normalized		Total nitrogen mg/g	
	2023	2025	2023	2025	2023	2025	2023	2025
7	4	6	4.4	2.5	21.7	19.4	0.39	0.70
1			6.5					
14	5	6	3.7	2.8	20.8	19.7	0.36	0.61
16			2.6					
4	5	7	2.9	3.1	20.0	19.8	0.11	0.84
2	7	8	5.1	3.3	21.8	19.9	0.64	0.86

3.2 Nutrient uptake by cultivated kelp

Macroalgae takes up nutrients (mainly nitrogen (N) and phosphorus (P)) from surrounding seawater and thereby reducing the seawater concentrations of these nutrients. If the macroalgae is harvested, the nutrients are permanently removed from the nutrient cycle. Cultivated kelp nutrient uptake may therefore potentially reduce nutrient load in eutrophic coastal areas and mitigate eutrophication effects. However, the uptake of nutrients may also cause competition with local microalgae and lead to reduced phytoplankton growth (Hasselström et al. 2018, Campbell et al. 2019). In the following we go through the scientific literature to evaluate the potential risk or benefit associated with kelp cultivation and nutrient uptake, both at Storflua specifically and for kelp cultivation in Norway generally.

3.2.1. Nutrients status in Frohavet

Frohavet is a dynamic and highly productive area. The North Atlantic Current (NAC) brings nutrient-rich Atlantic Water along the shelf break, below the Norwegian Coastal current (Fragoso et al. 2024). The varying bottom topography in Frohavet, in addition to strong tidal currents, leads to complex current conditions. The currents in combination with certain weather conditions regularly lead to mixing of deeper nutrient rich water masses with the surface waters, increasing the availability of nutrients to both micro- and macroalgae (Broch et al., 2019). Frohavet therefore has a high potential for seaweed cultivation (Broch et al. 2019). The rapidly changing weather conditions play a dominant role in spring bloom dynamics in this area (Fragoso et al. 2024).

The Norwegian national monitoring program "Ecosystem Monitoring in Coastal Water" (ØKOKYST) has one monitoring station located in Frohavet (VR61, ca. 35 km east of Storflua). The program samples water monthly for analysis of dissolved nutrients and chlorophyll a and provides ecological status class assessment according to The Norwegian Water Regulation (implementation of the EU Water Framework Directive). Monitoring results averaged over the last three years (2022-2024) indicated "very good" status for chlorophyll a (**Table 9**). However, with only one sampling a month, the phytoplankton bloom is easily missed, which was the case in 2023 and 2024 (Egge et al. 2024, Egge et al. 2025). The winter (Dec-Feb) concentrations of phosphate, total phosphorus and nitrate indicated 'good' status, whereas concentrations of ammonium and total nitrogen indicated 'very good' status (**Table 9**). All summer values indicated 'very good' status, except total phosphorus ('good' status).

The term ‘ecological status’ in marine monitoring implies the level of eutrophication in a water body. Chlorophyll a is used as a proxy for the amount of phytoplankton, and low levels indicate good status (no eutrophication), and high levels indicate bad status in the context of eutrophication. Low levels of dissolved nutrients also indicate good status and high levels bad status (Norwegian Environment Agency, 2025). Even though Frohavet is considered to have favorable levels of nutrients available for macro- and microalgae growth and kelp cultivation (Broch et al., 2019), the levels are considered low in the classification scheme and are giving no indication of eutrophication in the open water masses (Egge et al. 2025). ‘Good’ and ‘very good’ status for nutrient levels means the concentrations are in the range expected in pristine reference areas (‘very good’ status) or does not have negative impact on the ecosystem (‘good’ status).

Table 9 Concentrations of chlorophyll a (90 percentile for the growing season (March-September)) and dissolved nutrients (averaged values for the winter season (December-February) and summer season (June-August)). All values are based on data from 2022-2024, measured at VR61 in Frohavet. Color indicates ecological status: green=‘good’ status, blue=‘very good’ status. From Egge et al. (2025)

Parameter	Winter (Dec-Feb)	Summer (Jun-Aug)	Growing season (Mar-Sep)
Chlorophyll a (µg/L)			1.92
Phosphate (µg/L)	17.0	3.4	
Total P (µg/L)	22.7	13.8	
Nitrite + nitrate (µg/L)	102.8	1.5	
Ammonium (µg/L)	5.3	7.5	
Total N (µg/L)	170.7	108.4	

The nutrient concentrations measured at Storflua in September 2023 (prior to kelp farm deployment, **Table 10**) indicted nutrient status similar to the Økokyst VR61 monitoring station (**Table 9**). Ammonium at Storflua was similar to both winter and summer levels at VR61, whereas nitrite + nitrate at Storflua was much lower than winter at VR61, but higher than summer. Total nitrogen at Storflua was close to summer levels at VR61, but lower than winter. Phosphate and total phosphorus were similar to summer values at VR61, but lower than winter values. The nutrients concentrations at Storflua were only measured once and cannot as a single measurement be classified for status assessment. However, the concentrations are in the range of ‘good’ to ‘very good’ status.

Silicate was only measured at Storflua, with values increasing with depth, which may indicate upwelling or remineralization (**Table 10**). Also, nitrite + nitrate concentration increased with depth.

Table 10 Measurements of nutrients at different depths in the water column at Storflua 08.09.2023 (prior to kelp farm deployment)

Depth (m)	Ammonium (µg N/l)	Phosphate (µg P/l)	Nitrite + nitrate (µg N/l)	Silicate (µg SiO ₂ /l)	Total Phosphorus (µg P/l)	Total Nitrogen (µg N/l)
0	<5	5	6	49	11	110
5	<5	4	5	47	11	99
10	<5	4	8	45	12	99
20	<5	4	7	36	10	89
30	7	6	17	57	12	98
50	6	8	32	91	12	110

3.2.2. Macro- and microalgae seasonal cycle

Kelp species such as *Saccharina latissima* exhibit seasonal patterns in nutrient uptake and storage that reflect the interaction between environmental nutrient availability, light conditions, and growth demand (Broch & Slagstad 2012). During winter, nutrient concentrations in coastal waters are typically high due to vertical mixing and the absence of phytoplankton blooms. Although kelp growth is constrained by low light and low temperature, the kelp absorbs and store dissolved inorganic nitrogen (mainly nitrate and ammonium) and phosphorus, allowing the kelp to build internal nutrient reserves.

In spring, rising light availability and temperature stimulate rapid blade growth, using both external nutrients, which are still abundant in early spring, and the reserves accumulated during winter. By summer, stratification of the water column and competition with phytoplankton reduce nutrient concentrations in the water. Kelp growth slows, and the kelp becomes increasingly dependent on internal reserves to sustain metabolism. In autumn, storm-driven mixing replenishes nutrient concentrations in the upper water column. Kelp resumes active uptake of nitrate and phosphate, replenishing internal stores. Growth continues at moderate levels until decreasing light and temperature once again limit productivity during winter.

Microalgae nutrient uptake follows the same season cycle as macroalgae. During winter, limited daylight strongly restricts growth, but in early spring the increase of light and temperature initiate the spring bloom, dominated by diatoms. The phytoplankton rapidly assimilate large amounts of nutrients, which are often depleted within a few weeks. As stratification strengthens in late spring and early summer, nutrient inputs to the surface decline. The community shifts towards species adapted to low nutrient conditions, such as flagellates and small picoplankton, which rely on regenerated nitrogen forms like ammonium and urea. In summer, surface waters are typically nutrient-poor, and phytoplankton production depends mainly on recycling processes. Microalgae cannot store nutrients to the same extent as macroalgae and are mostly reliant on seawater nutrient availability. In autumn, storm mixing brings new nutrients into the upper layer, supporting a secondary, smaller bloom while light is still sufficient.

3.2.3. Cultivated kelp nutrient removal

The amount of nitrogen and phosphorus taken up and removed from the water masses by cultivated kelp depends on several factors, the most important being yield (cultivated biomass per area), tissue composition of nitrogen and phosphorus (different between species and also intraspecific variation), local nutrient availability (eutrophic vs. oligotrophic waters) and farming scale and harvest efficiency. Estimates of nutrients removal annually by cultivated kelp in scientific literature consequently varies a lot.

For cultivation of *S. latissima* in US and European waters, estimates of nitrogen removal has been reported to be in the range of 19-176 kg N ha⁻¹ year⁻¹ (Kim et al. 2015, Grebe et al. 2021, Seghetta et al. 2016), up to 576 N ha⁻¹ year⁻¹ (Holdt & Edwards 2014) (**Table 11**). The latter estimate seems closer to estimates from high intensity cultivation in China of 603 kg N removed ha⁻¹ year⁻¹ (Xiao et al. 2017) (**Table 11**). Phosphorus removal has been reported to be in the range of 6-43 kg Pha⁻¹ year⁻¹ in European waters (Kim et al. 2015, Seghetta et al. 2016), up to 76 kg N ha⁻¹ year⁻¹ in China (Xiao et al. 2017).

Table 11 Table of nutrient uptake (nitrogen and phosphorus) reported in scientific literature.

Uptake / removal	Geographical region	Species	References
576 kg N ha ⁻¹ year ⁻¹ *	Denmark / Ireland	<i>S.latissima</i>	Holdt & Edwards (2014)
38-139 kg N ha ⁻¹ year ⁻¹ 22-43 kg P ha ⁻¹ year ⁻¹ **	US	<i>S.latissima</i>	Kim et al. (2015)
~ 48 kg N ha ⁻¹ year ⁻¹ ~ 6 kg P ha ⁻¹ year ⁻¹ ***	Denmark	<i>S.latissima</i>	Seghetta et al. (2016)
19-176 kg N ha ⁻¹ year ⁻¹	US	<i>S.latissima</i>	Grebe et al. (2021)
603 kg N ha ⁻¹ year ⁻¹ 76 kg P ha ⁻¹ year ⁻¹	China	<i>Saccharina japonica</i> + <i>Gracilariopsis</i> spp.	Xiao et al. (2017)

* at yield of 120 t ww ha⁻¹ year⁻¹ (18 t dw ha⁻¹ year⁻¹ and a value of 15 % dry weight)

** in a hypothetical kelp farm system with 1.5 m spacing between longlines, at three sites differing in temperature, salinity and nutrients

***expressed as N and P-equivalents

At present, the Storflua kelp farm covers about 20 hectares and has a permit for growing 800 tonnes kelp (wet weight) per year (40 tonnes per hectare), corresponding to 80-20 tonnes dry weight (4-6 tonnes per hectare) assuming that dry weight is approximately 10-15 % of wet weight (Broch & Slagstad 2012). Assuming that macroalgae tissue typically contains 1-4 % N and 0.2-0.6 % P of dry weight (Grebe et al. 2021), every 1 tonne of dry weight seaweed harvested will remove about 20-40 kg of N and 2-6 kg of P permanently from the water column. Harvesting 800 t of kelp wet weight at Storflua would consequently theoretically remove 1600-4800 kg nitrogen and 160-720 kg phosphorus (per hectare: 80-240 kg N, 8-36 kg P).

3.2.4. Competition with microalgae

Both macro- and microalgae rely on nitrogen and phosphorus for photosynthesis and growth. As nitrogen is the main limiting factor for primary production in marine waters, negative ecological effects could occur if the nutrient uptake by cultivated macroalgae (**Table 11**) leads to nutrient limitation for primary production of microalgae, and possibly out-compete or change the local phytoplankton production or composition.

The KELPPRO project examined possible environmental effects of kelp farming on phytoplankton and the pelagic food web (Hancke et al. 2019). They argued that microalgae take up nutrients far more efficiently than kelp and consequently they are not negatively affected by competition for nutrients. Microalgae can grow near maximum rates even at very low nitrate levels, while kelp growth is strongly limited under the same conditions.

Measurements in and around kelp farms in Norway (nutrients, particulate matter, chlorophyll a) showed no differences compared to nearby reference sites, and no changes between inflowing and outflowing water (Hancke et al. 2021). Phytoplankton food quality for zooplankton was unaffected, implying no impact on higher trophic levels. The overall conclusion was that kelp farming does not negatively affect phytoplankton because kelp is outcompeted for nutrients, regardless of farm sizes. The conclusion applied to sugar kelp, and likely also to other large brown algae, but the authors emphasize that further studies are needed for other algal groups.

Experimental studies suggest that green macroalgae can outcompete microalgae. In a mesocosm experiment the green macroalgae *Ulva* caused phytoplankton to grow more slowly, probably caused by resource competition for inorganic nitrogen (Smith and Horne 1988). The same was found for the green macroalgae *Enteromorpha* and cyanobacterial mats (Fong et al. 1993) - at high nutrient loading the growth of phytoplankton was reduced by a factor of 10 in the presence of the algal mats. However, green algae such as *Ulva* and *Enteromorpha* have higher growth rate and faster nutrient uptake compared to brown algae, and can thrive opportunistically in nutrient-rich conditions. No mesocosm studies focusing directly on competition between brown algae and phytoplankton have been found.

Mesocosm experiments are performed within a confined space and cannot necessarily be extrapolated to the natural situation in an open ocean system. Field studies from China indicates that large-scale cultivation of the red algae *Gracilaria lemaneiformis* can lead to a decrease in nutrients (Xie et al. 2017, Yang et al. 2015), and a significant shift in the microbial community (Xie et al. 2017). Another field study from Venice Lagoon demonstrated that high production of nitrophile macroalgae (*Ulva*) led to reduced phytoplankton standing crop in most of the study area (Sfriso et al. 1992a and b). No field studies demonstrating the same effect on phytoplankton by cultivation of brown algae have been found.

3.2.5. Eutrophication mitigation

Kelp nutrient uptake might mitigate nutrient enrichment and eutrophication in coastal waters. This idea of seaweed cultivation as solution to the eutrophication problem is not new and was suggested already by Fei (2004) as eutrophication was becoming a serious problem in China's coastal waters. Integrated multi-trophic aquaculture (IMTA) is now an established concept, integrating the production of fed aquaculture species such as salmon with species that take up nutrients (e.g., shellfish, seaweeds). In the eutrophicated Oslofjord, Bellona is planning a pilot kelp farm as a measure towards reducing the nutrient load to the fjord ([Oslofjorden Tarepark](#)).

The potential benefit of the kelp nutrient uptake depends on many factors, where produced biomass and eutrophication level is the most important. Kelp cultivation at large scale can obviously remove a large quantity of nutrients, up to 600 kg N ha⁻¹ year⁻¹ in high intensity kelp cultivation areas such as China (see **Table 11** and references therein). For comparison, the total amount of nitrogen reaching the Oslofjord every year is 37 800 tonnes (Sample 2024). In an eutrophicated Danish fjord (Limfjorden), it would be necessary to use 79 % of the water surface area for kelp cultivation to counterbalance total yearly emission of N, and 33 % in the case of P emissions (Seghetta et al. 2016).

A fish farm producing 1,000 tons of Atlantic salmon in 1 year releases about 20-44 tons of nitrogen to the environment (Olsen et al. 2008, Grefsrud et al. 2021). Assuming a salmon farm releases 10 tons of nitrogen during the cultivation period (February-June), kelp cultivation must cover an area of about 80 ha (4 x the size of Storflua kelp farm) to remove all the released nitrogen (Broch & Slagstad 2012). There is also a seasonal mismatch between the rapid growth of kelp in spring and early summer and the increase in salmon biomass and feed use in late summer and early autumn, limiting the direct recycling of the nutrient input from salmon farming by kelp in Norwegian coastal waters (Handå et al. 2013).

3.3 Kelp farm as temporary habitat

3.3.1. Fish Community Composition

Traditional sampling using NORDIC gill-nets and hand collection revealed distinct differences in fish community composition between kelp farm and control sites (**Figure 12**). Across both May and June, fish diversity and abundance were generally lower at kelp farm sites where the lumpfish (juveniles, *Cyclopterus lumpus*) were the only species observed. Fish were more frequently captured in control habitats, particularly in the kelp forest control in June where typical benthic and benthic-pelagic fish were observed (e.g. Labrids, *Myxocephalus*), in addition to the pelagic component present at all sites (like saithe, *Pollachius virens*).

Camera deployments at the kelp farm recorded a total of 20, 202 images over 56 hours and 35 minutes, with two observations of fish (a lumpfish, **Figure 13**) recorded throughout one single day (9 May). Baited traps deployed in May resulted in no fish. Hand collections of lumpfish provided three juveniles during the June sampling event, and 10 juveniles at harvest of ca. 200 kg kelp (50 per tonne). In comparison, 36 lumpfish were collected from 40 tonne (0.9 per tonne) in 2025 at Austevoll. The presence of lumpfish appears to be ubiquitous among kelp farms in Norway and Sweden, but it remains challenging to assess the magnitude (**Table 12**).

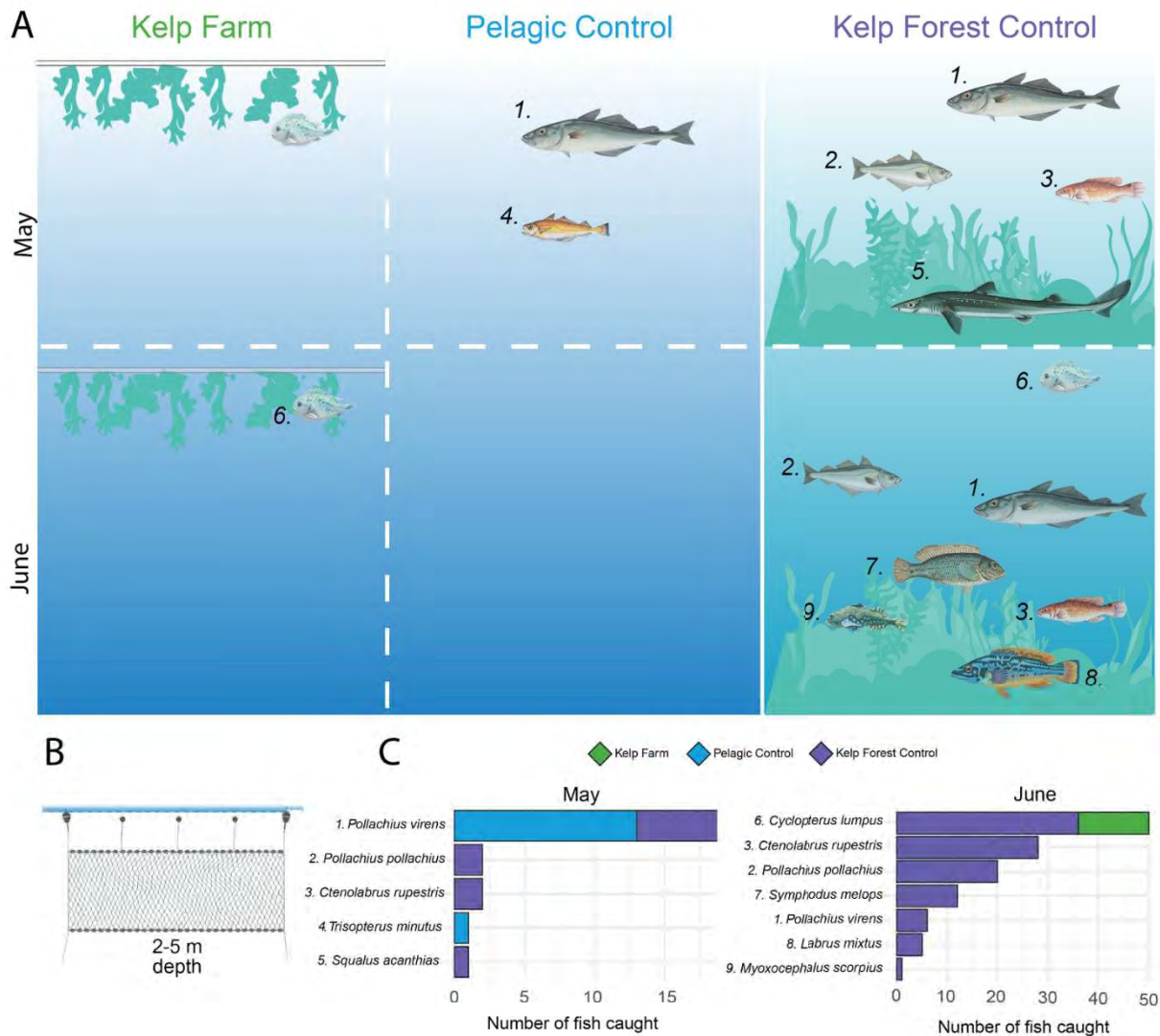


Figure 12 Traditionally observed fish community composition differences between the Kelp Farm and Control sites, surveyed using NORDIC gill-nets and hand collecting of 1. Lumpfish *Cyclopterus lumpus*. A) schematic of fish species diversity to compare Kelp Farm and Controls between May (top) and June (bottom) sites, species (1-9) are indicated in C. B) simplified schematic of the positioning of 9 NORDIC gill-nets deployed over four nights, in each period (May and June) containing panels of varying mesh size. C) Barplots of counts of fish caught across sites, where *Cyclopterus lumpus*, the lumpfish are not shown in May as it was captured by camera only.



Figure 13 Camera observation of fish at Storflua during the May sampling events; one juvenile lumpfish individual captured on 9 May. (B) juvenile lumpfish sampled during the June sampling period at Storflua. (C.) juvenile lumpfish sampled at harvest on 27 June at Storflua.

Table 12 Number of lumpfish recovered as samples from kelp farms in Norway and Sweden

Location	Sampling Date	Sampler	Number of lumpfish
Koster archipelago, Sweden	2017-05-01	Visch et al. 2020b	3
Risvær, Nordland, Norway	2021-04-03	Lofoten Blue Harvest	70
Misje, Øygarden, Vestland, Norway	2021-08-12	Arctic Seaweed	11
Stokksund, Trøndelag, Norway	2022-05-15	Tango seaweeds	48
Trollsøy/Flatøysundet, Vestland, Norway	2023-02-01	Lerøy Ocean Forest	6
Initian, Frøya, Trøndelag, Norway	2024-05-30	Seaweed Solutions	55
Trollsøy/Flatøysundet, Vestland, Norway	2025-04-29	Lerøy Ocean Forest	36
Storflua, Mausundvær, Trøndelag, Norway	2025-06-08	NIVA	3
Storflua, Mausundvær, Trøndelag, Norway	2025-06-25	Mausund Field Station	10

3.3.2. eDNA Community Composition

We analysed 31.1 million 12S and 21.2 million CO1 eDNA sequence reads, resulting in 27 and 93 MOTUs respectively after filtering. PERMANOVA indicated no significant overall differences in community composition by site for the 12S dataset ($F = 1.882$, $R^2 = 0.201$, $p = 0.093$) nor for the CO1 dataset ($F = 1.882$, $R^2 = 0.201$, $p = 0.100$), based on Bray–Curtis dissimilarity with 999 permutations.

12S Dataset

Indicator species analysis on 12S data identified *Pholis sp.* (IndVal = 0.833, $p = 0.010$) and *Gobiusculus flavescens* (IndVal = 0.816, $p = 0.015$) as indicators for the Kelp Forest control group, and *Pollachius virens* (IndVal = 0.881, $p = 0.049$) for the combined group Kelp Forest control + Pelagic control. Alpha diversity analyses showed significantly lower Shannon diversity and MOTU richness at the Kelp Farm and Pelagic control compared to the Kelp control ($p < 0.05$, 0.01 respectively, **Figure 14A**). The proportion of benthic to pelagic species was similar between the Kelp Farm and Pelagic control whereas the Kelp Forest control had a significantly greater proportion of benthic species ($p < 0.05$, **Figure 14B**). The DNA read abundance at the Kelp Farm was dominated by codfishes (*Pollachius sp.*, *Molva sp.* and *Gadid spp.*, **Figure 14C**) while the read abundance was significantly lower ($p < 0.001$) than both the Kelp Forest and Pelagic controls (**Figure 14D**).

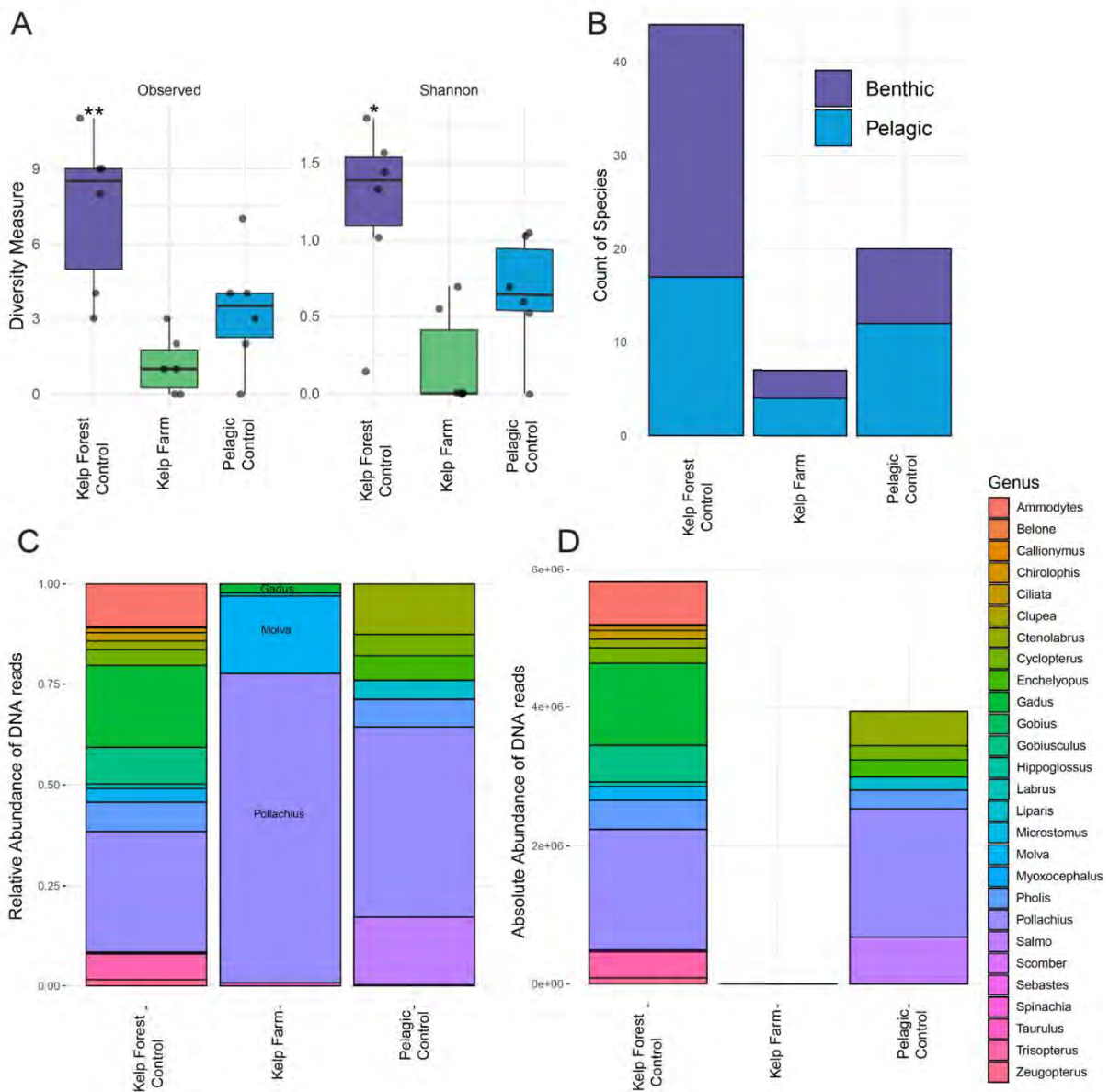


Figure 14 Environmental DNA (eDNA) 12S sequence diversity and relative abundance between the Kelp Farm and Control sites. A) Alpha diversity; MOTU richness and Shannon diversity between sites indicated by statistical significance ($p > 0.05$: no asterisk, $p < 0.05$ *, $p < 0.01$ **, $p < 0.001$ ***). B) Barplots of the counts of benthic (purple) and pelagic (blue) individuals observed at each site. C) Relative abundance of DNA reads between sites presented as a barplot and D) absolute abundance where each genus is represented by a unique color.

CO1 Dataset

For CO1 data, Saithe (*Pollachius virens*) was identified as an indicator species for the Kelp Forest control group (IndVal = 0.772, $p = 0.037$) and *Calanus finmarchicus* was an indicator for the combined group Kelp Forest control and Kelp Farm (IndVal = 0.816, $p = 0.032$). Alpha diversity analyses showed significantly lower Shannon diversity and MOTU richness at the Kelp Farm and Pelagic control compared to the Kelp control ($p < 0.01$, 0.01 respectively, **Figure 15A**). Lysanassidae was the only family/genus/species in increased abundance at the Kelp farm while *Peraphora sagamiensis* was the only family/genus/species with a significantly different abundance between the three sites, being in

significantly lower abundance at the Kelp Farm compared to the Kelp Forest and Pelagic controls ($p < 0.05$, **Figure 15B**). Similar to 12S, the proportion of benthic to pelagic species was similar between the Kelp Farm and Pelagic control but the Kelp Forest control had a significantly greater proportion of pelagic species ($p < 0.05$, **Figure 15C**).

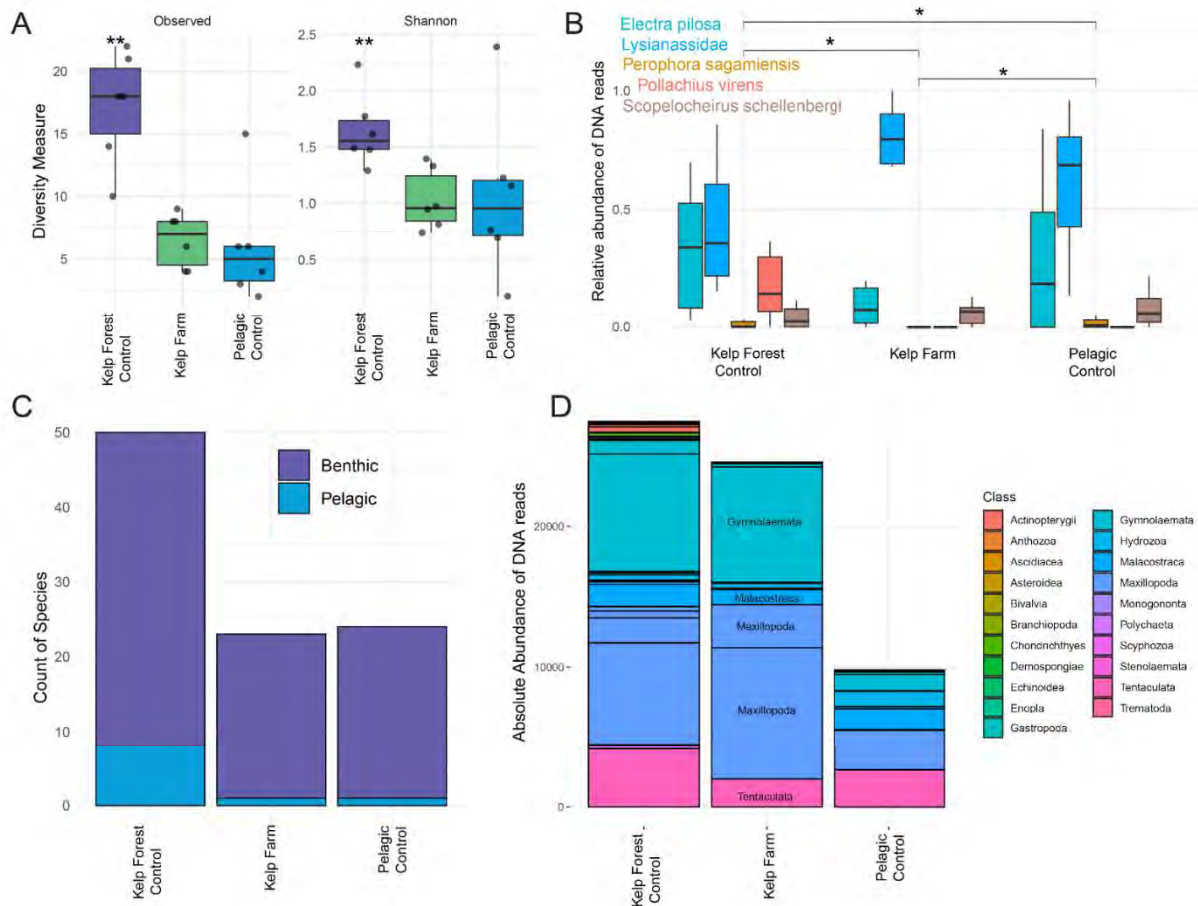


Figure 15 Environmental DNA (eDNA) 12S sequence diversity and relative abundance between the Kelp Farm and Control sites. A) Alpha diversity; MOTU richness and Shannon diversity between sites indicated by statistical significance ($p > 0.05$: no asterisk, $p < 0.05$ *, $p < 0.01$ ** , $p < 0.001$ ***). B) Relative abundance of sequence reads for select MOTU species showing differences between sites indicated by statistical significance ($p > 0.05$: no asterisk, $p < 0.05$ *, $p < 0.01$ ** , $p < 0.001$ ***). C) Barplots of the counts of benthic (purple) and pelagic (blue) individuals observed at each site. D) absolute abundance of DNA reads where each genus is represented by a unique color.

The composition of family/genus/species filtered to remove planktonic organisms was similar between all sites but in significantly lower abundance at the Pelagic control (**Figure 15D**). When planktonic and extremely high read abundant organisms are retained for analyses, the Kelp Farm is dominated by *Calanus finmarchicus*, *Membranipora membranacea* and *Oithona similis* (Figure 16). When only benthic organisms are retained that are more likely to represent trace DNA, the Kelp Farm is dominated by *Electra pilosa*, Lysianassidae and *Obelia geniculata*.

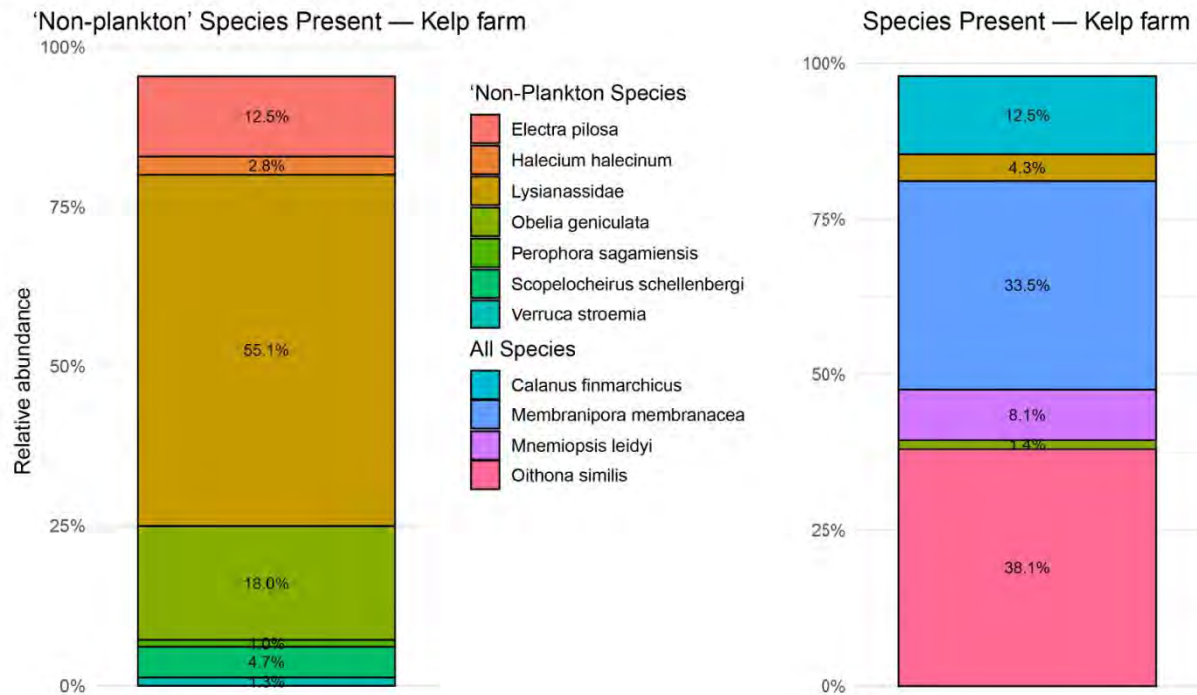


Figure 16 Proportions of relative abundance DNA reads for each family/genus/species represented with >1% relative abundance out of the total when dataset contains only benthic (non-plankton) organisms (left) or all (right).

3.3.3. Prey availability as epifauna and lumpfish stomach contents

Lumpfish sizes were mostly 20-40mm at Austevoll and Frøya, while 10-20mm at Storflua. These represent juvenile 0 group individuals. Those at Storflua were 16mm median, most likely spawned in spring. Whereas individuals from Austevoll and Frøya kelp farm sites likely also represent the autumn spawners.

A subset was studied for diet (Austevoll= 24, Frøya = 18, Storflua = 4). Numbers of diet taxa (prey, **Figure 17A, B**) do not properly represent biomass but in general copepods were a dominant prey item, of those that could be identified we mostly cyclopoida that are most likely pelagic like oithona sp. due to the time of sampling. Calanoida spp. further evidences pelagic prey and while are few in number were 10-20x the size of cyclopoida. Benthic foraging from the kelp and lines is also evidenced in harpacticoid copepods, and a range of amphipods, predominantly Jassa and Caprellidae. Small sizes of lumpfish (for Storflua) and decomposition of gut contents hindered identification of many amphipods and we cannot state with certainty that amphipods were foraged at the site and on the lines but it is likely considering other benthic prey observed including isopods and nematodes.

The composition of taxa observed in stomach contents of lumpfish at the kelp farms is highly similar to that observed at the kelp farm on kelp, ropes and buoys (predominantly Amphipods) that strengthens theories of lumpfish benefitting from the kelp farm secondary production.

See Appendix F for detailed results from the lump fish diet analysis.

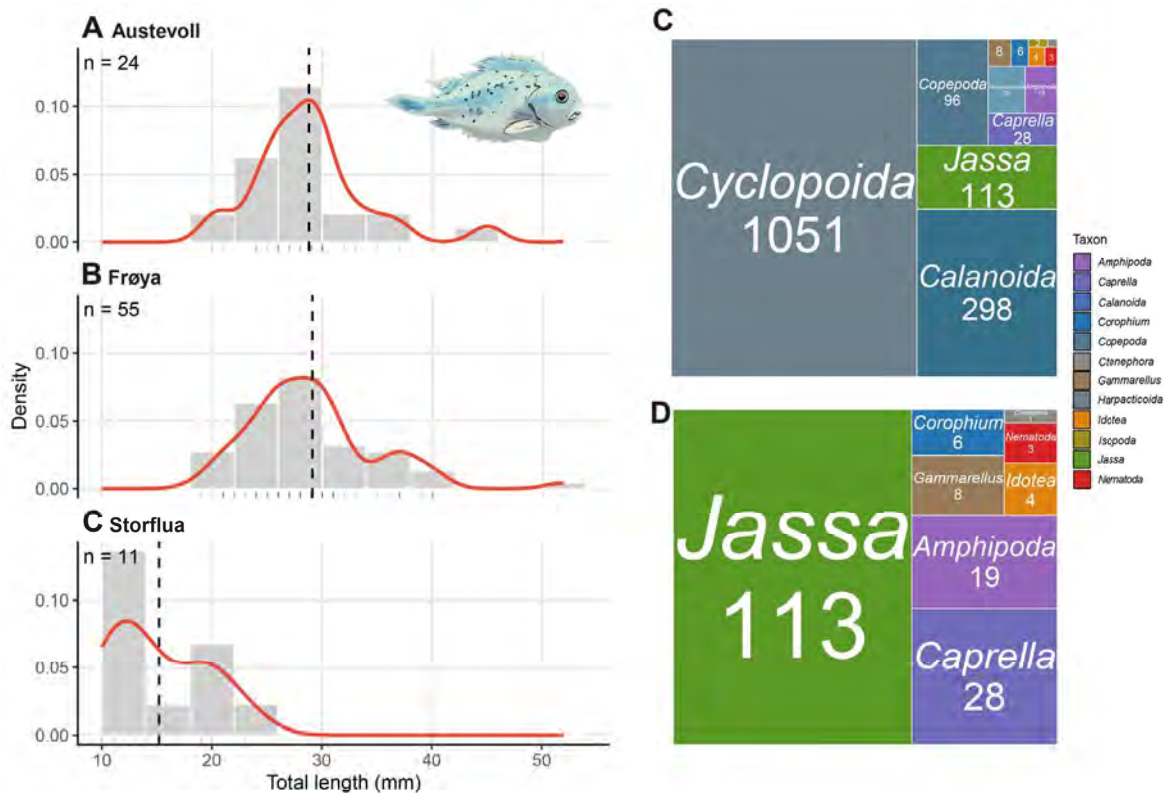


Figure 17 Analyses on lumpfish (*Cyclopterus lumpus*) size and diet at kelp farms sites. Histograms show size (Total length) distributions for all lumpfish ($n =$ numbers of individuals) gathered at three kelp farms, in Austevoll (A), Frøya (B) and Storflua (C). Red lines represent smoothed density (proxy for quantity) distributions across size bins. Dashed black lines represent median size for each site. Treemap overviews of the overall abundance of lumpfish diet taxa observed across all three (Austevoll, Frøya, Storflua) in 46 individuals with Copepoda included (A) and without Copepoda (B). Numbers refer to the number of individuals, as does the approximate size of each color block.

Epifauna present at the farm appear similar in composition to other sites in Norway analysed in Andrews et al. (2025) but results here are limited due to few samples taken. This can be observed in the relatively few invertebrate families retrieved overall (10, **Table 13**). Copepods (probably benthic copepods c.f Harpacticoids) were challenging to identify but appear the most dominant in number overall, followed by amphipods (Ischyroceridae and Caprellidae). The results indicate that diversity and abundance may be slightly greater on multi-year structures like structural ropes and multi-year kelp as in Andrews et al. (2025) but here differences are very small.

See Appendix G for detailed results from the invertebrate epifauna analyses.

Table 13 Summary of epifauna family richness at Storflua in May and June 2024 on various substrate types with the abundance of individuals in each family included in parentheses.

Substrate	Family Richness	Most abundant family	Second most abundant family	Third most abundant family
Overall	10	Copepoda (1825)	Ischyroceridae (399)	Caprellidae (88)
Structural Rope + Multi-Year Kelp	6	Copepoda (547)	Caprellidae (87)	Ischyroceridae (73)
Buoy	4	Ischyroceridae (250)	Copepoda (114)	Gammarellidae (1)
Kelp	4	Copepoda (1161)	Ischyroceridae (13)	Calliopiidae (3)
Structural Rope	4	Ischyroceridae (63)	Copepoda (3)	Idoteidae (2)

The Japanese ghost shrimp (*Caprella mutica*) was the only alien species present at the kelp farm (**Figure 16**). Its numbers were probably underestimated due to identification challenges for this taxa. Therefore the number of Caprellidae should be conservatively used to interpret the abundance of *Caprella mutica* with understanding that native Caprellids are likely also present. **Figure 18** details the genus' and species' present and where these are unavailable refers to the family (or class for Copepoda). Jassa amphipods were most abundant, followed by other amphipods in the family Ischyroceridae and Caprellids.

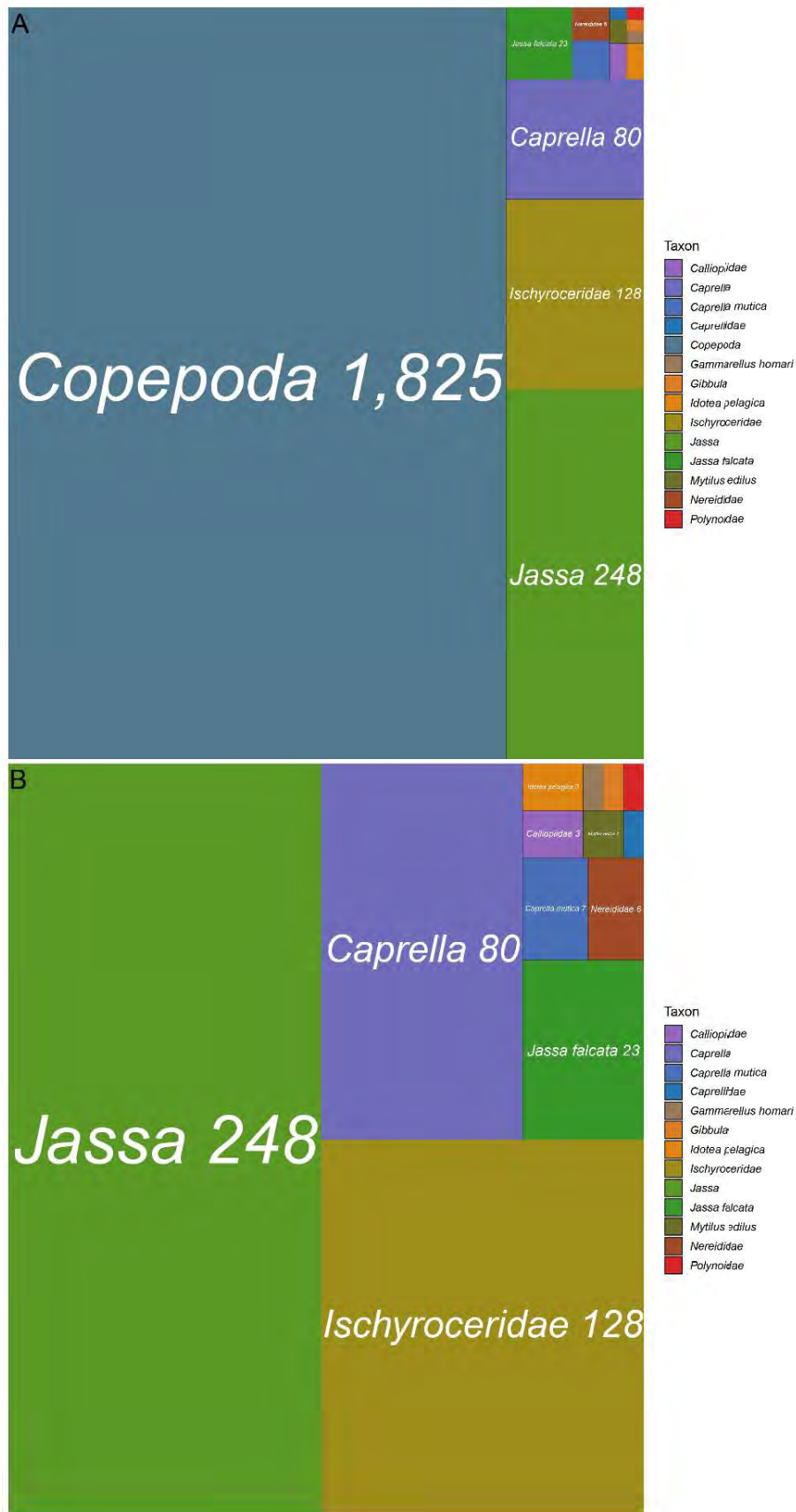


Figure 18 Treemap overview of the overall abundance of epifauna families, genus' and species' observed at Storflua in May and June 2025 with Copepoda included (A) and without Copepoda (B). Numbers refer to the number of individuals, as does the size of each color block.

4 Discussion

Introducing a farmed crop with associated artificial structures such as anchors, buoys and lines into an open water mass system will cause interactions with biological components within that system (fish and phytoplankton communities) as well as ecosystems nearby (local kelp forests and benthic fauna on the seafloor). However, environmental effects of macroalgae cultivation have been less investigated than those of for example finfish production, and there are fewer studies and data directed specifically at effects of macroalgae production, especially at large-scale cultivation outside of Asia. In this report we present field data from Storflua kelp farm in order to investigate whether this interaction causes an environmental effect and whether the effect is positive or negative.

Benthic fauna

Results from the baseline study of benthic fauna at Storflua gave ‘very good’ quality status according to WFD classification system, and the benthic biodiversity was very high at all sites. These results are as expected, since Storflua is in a region of Norway with high species diversity for benthic infauna (Borgersen et al. 2019). The coarse sediment type consisting mostly of sand and shell fragments supports species-rich benthic communities, and the high permeability of larger sediment grains and coarse shell sand can enhance water flow and oxygen penetration, which benefits most benthic species.

In the follow-up study conducted after two seasons of kelp cultivation at the site, the benthic fauna was still classified as ‘very good’, and the nEQR values were similar to the baseline study. This suggests that the benthic infauna was not negatively impacted by the moderate amounts of kelp detritus reaching the seafloor from the kelp production at Storflua. These results are in line with other studies of seaweed cultivation impact on benthic infauna, which all suggest little to no negative impact (Walls et al. 2017, Zhang et al 2009, Zhang et al 2020, Vishc et al 2020).

There was a reduction in the number of individuals and species in the follow-up survey, which is normally seen as a negative development. However, in this case we believe this reduction was due to reduced volume of sediment sampled compared to the baseline study (see chapter 2.2.2). Grab sample volume influences the number of individuals and species of benthic fauna because larger sample volumes capture more organisms and increase the likelihood of finding the rarer taxa. However, community indices used for ecological quality assessment (such as Shannon diversity, sensitivity indices etc.) are based on the relative proportions of species rather than absolute counts, so once a sample is large enough to represent the community structure, further increases in size do not substantially change these indices. Thus, the classification scheme is rather robust and not strongly influenced by sampling size.

Nutrient uptake

The removal of nutrients by kelp cultivation may cause competition with microalgae and/or mitigate eutrophication. These are two aspects of the same issue, as both describe the same process (nutrient uptake by kelp), but with different effects on ecosystem quality. Observed nutrient decrease in coastal waters by kelp cultivation is most often seen as a positive, since most studies focus on the mitigation aspect and very few focus on other ecological implications such as effects on phytoplankton.

Kelp can remove significant amounts of nutrients and contribute to eutrophication mitigation, particularly in semi-enclosed, nutrient-rich bays or fjords. However, the effect is minor compared to total nutrient loads in large water bodies like the Oslofjord. It can be locally beneficial (e.g., near fish farms), but not a stand-alone solution for large-scale nutrient pollution. Kelp cultivation may be most effective

as part of integrated systems (IMTA) or targeted mitigation strategies rather than as a large-scale, sole solution for eutrophication.

Mesocosm experiments and field studies show that competition from fast-growing green algae (*Ulva*, *Enteromorpha*) and red algae (*Gracilaria*) can suppress phytoplankton growth by outcompeting for nutrients, but there is no clear evidence for brown kelp, as no mesocosm or field studies have focused on competition effects with phytoplankton. Because brown algae have slower nutrient uptake, and microalgae generally outcompete kelp in nutrient uptake efficiency, it has been hypothesized that they will not be outcompeted by cultivated kelp. Although this claim seems plausible, there are very few studies done and thus little empirical evidence supporting or refuting this.

Kelp farm as temporary habitat

Through traditional sampling, we find that fish species diversity and abundance is lower at kelp farm sites compared to natural kelp forest control sites, instead it is more similar to pelagic control sites. The lumpfish was the only fish species observed at the Storflua kelp farm. This aligns with previous findings that kelp farms may not replicate the ecological complexity of natural blue forest habitats (Visch et al. 2020a; Christie et al. 2022).

Correspondingly, we found lower fish (12S) and invertebrate (CO1) diversity at the kelp farm and pelagic control compared to the kelp forest control site through eDNA sampling. 12S sequence MOTUs reveal no species were an indicator for the kelp farm or in significantly greater abundance there compared to the control sites. In comparison, the kelp forest had a much more balanced fish community where indicator species were present and a greater number of species were abundant. Significantly lower sequence read abundance at the kelp farm suggests a lack of habitat provision for fish. This differs with Andrews et al. (2025) who studied nearby kelp farms at Frøya and Austevoll and found no clear differences between control sites and kelp farms using eDNA (also see Schutt et al., 2023). The reason for this appears to be an even greater lack of fish at Storflua compared with other kelp farms in Norway.

We theorise limited fish attraction is driven by limited prey items i.e. the finding of significantly lower invertebrate richness in kelp farm samples than wild kelp samples as per Andrews et al. (2025), Bekkby et al., (2023) and Corrigan et al., (2024a). Instead, invertebrate (CO1) richness was more similar to the pelagic control suggesting that the abundance of invertebrates at the kelp farm is insufficient to drive significant increases in invertebrate DNA in the environmental conditions present.

It should be recognised that the Storflua site was very limited in extent, biomass of kelp and that its cultivation set up with lines deeper than that at Frøya and Austevoll (see Andrews et al. 2025) may provide poor shelter for fishes and insufficient prey. In addition, its location far from coast probably hinders the migration of many benthic fish species. Moreover, caution should be taken in the interpretation of the results due to them only representing a pre-harvest time without representing a late-summer or post-harvest period.

Andrews et al. (2025) shows that invertebrate richness is greater in supporting ropes and buoys that had remained over several years compared to farmed kelp. We did not test this but find this likely to be the same at Storflua. Literature points to these communities being likely driven by local species diversity that increases over time but is unlikely to represent those of natural kelp habitats even after prolonged periods of years (Eklöf et al., 2005).

In a Norwegian kelp forest, (Christie et al., 1998) found that it took more than 5 years for the species community associated with kelp to return after trawling, indicating the time needed for a kelp farm to function as a true kelp habitat. In the wild, the kelp-associated fauna increases in density and mobility

during the warmer seasons (Norderhaug et al., 2002; Christie et al., 2003). Our results indicate that similar effects in kelp farms cannot be expected with an early harvesting time. Supporting this, (Corrigan et al., 2024b) observed higher fish abundance in kelp and mussel (*Mytilus edulis*) farms compared to control sites in September in the UK.

Farm size, exposure and environmental conditions are other key factors influencing habitat provisioning and will differ geographically, due to differences in industry maturity, local regulations and climates. In our study, Storflua was a small-scale farm, cultivating ca. 10,000-20,000 tonnes kelp in the year of sampling that operated in relatively wave-exposed conditions, far from the coast. We cannot exclude the possibility that our results may have been different at larger scale farms. Given that fouling on sugar kelp is known to be impacted by exposure (Visch et al., 2020b), where it would be higher in more sheltered environments and higher on artificial substrates not seeded by kelp for cultivation (Walls et al., 2019), we find it likely that more sheltered farms in Norway would present increases in the degree of habitat provision for invertebrates and fish. The presence of *Caprella mutica*, an alien amphipod species, at kelp farms further supports the idea that artificial substrates can facilitate alien (non-native) species colonization, likely due to the reduced competition that provides opportunities compared to challenges of colonizing climax (mature) wild habitats (Ashton et al., 2007). While *Caprella mutica* appears common among kelp farms in Norway and can be found in wild kelp forest habitats (Andrews et al. 2025), its presence at Storflua can be considered a serious challenge to the Norwegian state and industries reaching several environmental targets related to limiting the spread of alien marine species.

Although current kelp farms may not significantly enhance the biodiversity of fishes and invertebrates herein or elsewhere in Norway (Andrews et al. 2025), this limited impact could be viewed positively in terms of minimizing ecological disruption. As noted by (WWF, 2025) a lack of effect may still align with sustainability goals. Currently we lack sufficient data to conclude and we remind the reader of the limited scope of both the monitoring work and farm scale herein. With this limited work we can say that Storflua appears to have had a limited impact on the attraction of fishes; that we perceive to be positive given that this does not significantly alter the ecological function of a pelagic habitat.

The presence of alien species is a potentially serious issue that requires action to define guidelines (like Wilding et al., 2021) that identify their impacts to limit their colonization and spread. In a previous work (Andrews et al. 2025), we conclude that the age of structures is likely to effect the invertebrate communities. This indicates that regular cleaning of structures may be effective in controlling marine alien species at kelp farms; although this was not tested herein. Actions such as these could be deemed as a nature positive action that if applied broadly enough to multiple industries and species, might aid the achievement of international biodiversity targets under the Kunming–Montreal Global Biodiversity Framework or national ones e.g. Norway’s ‘Ocean Management Plan’ (Meld. St. (2023-2024); www.regjeringen.no).

Policy should be developed surrounding the impacts of fish attraction (Methratta and Dardick, 2019), taking into account whether food provision occurs. Artificial habitats and additional efforts to increase biodiversity through placement of artificial reefs may result in unwanted and negative impacts, such as ecological-traps that hinder ecosystem restoration (Reubens et al., 2013; Methratta and Dardick, 2019; Rouse et al., 2019; Pardo et al., 2025). Concerns for biodiversity arise given that impacts of fish attraction are poorly understood and that local population and ecosystem vulnerability is not represented by vulnerability frameworks that occur at the species level e.g. IUCN red list (Bennun et al., 2024). Similar to fish aggregation effects of offshore energy structures, the attraction of fishes is not negative or positive per se (Coates et al., 2016). It depends on the actual benefits to populations in biomass increases as a result of secondary production (e.g. prey) and support of natural behaviours (Hasselström et al., 2018), requiring detailed scientific study of population structure, local dynamics,

natural niches and behaviours that exceeded the remit of this study before careful consideration by authorities on which effects are deemed to be positive or not. Both Andrews et al. (2025) and the current study show that the only relevant fish species present in Norwegian kelp farms that might benefit with increased productivity appears to be juvenile lumpfish. This appears to be because the current kelp farms are very small scale with few lines of kelp (shelter for fish) and performed in wave exposed conditions and over deep water far from the habitats of typical species found in kelp forests.

Lumpfish are a species of commercial interest in Norway but they are listed as least concern on the Norwegian Red List at the time of reporting (Artsdatabanken Rødlista). Together with evidence of stable population dynamics over the past decade <https://www.hi.no/en/hi/nettrapporter/rapport-fra-havforskningen-2025-70>, this information implies that there is limited ecological need or incentive want to artificially increase the numbers of lumpfish locally in Norway. This means that even if lumpfish numbers are increased by kelp farming in theory, this is unlikely to contribute to any nature restoration goals given their status. Further more, any local increase in their abundance attributed to kelp farms is not necessarily positive or a potential contributor to “nature positivity”. This will depend on their ecological role, quantity (extent of change) and stakeholders needs and targets.

Lumpfish appear to be a common component of kelp farms along the Norwegian Coast but there are large uncertainties on their quantity. The abundance of lumpfish is likely overestimated by extrapolating small quantities as collected and analysed herein (e.g. 50 per tonne based off 200 kg) and underestimated by estimating from harvests of 40 tonnes (e.g. that in Austevoll 2025) due to difficulty in locating lumpfish among the harvested kelp. However, this study can define their ability to benefit from prey items at the kelp farm. This information is vital to understand whether they benefit from the food provision at kelp farms. Results on lumpfish diet at kelp farms suggest they do benefit in food provision from the kelp and structures as habitats for epifauna. A large amount of pelagic prey was also observed but here the kelp farms also play roles in providing juvenile lumpfish with opportunities to access this prey while stationary and sheltered on structures. Any benefits to wild populations must consider the dispersal ability of lumpfish to migrate to nearby natural habitats during and after harvesting. Clearly those individuals removed during harvest are casualties that may indicate the abundance of lumpfish at kelp farms but are not beneficiaries in themselves, being removed from the system. Any ability to increase nature positive effects beyond the season or with various designs requires, like those tried in Japan to increase macroalgae fouling (Kodama et al. 2026), require their own dedicated study as detailed in the temporary habitat proposal.

5 Conclusion

The overall conclusion that we draw from the results of this study is that the Storflua kelp farm does not pose an overall significant environmental risk for the ecosystems investigated, however the presence of a marine alien species can be considered a serious concern.

The main findings from this study are:

- The ROV seafloor survey conducted before kelp cultivation started at Storflua did not observe any vulnerable species or habitats. However, as only a limited part of the seafloor below the planned kelp farm was surveyed, presence of vulnerable species or habitats cannot be ruled out.
- The ecological quality status of benthic fauna was ‘very good’ at Storflua before kelp cultivation started, and the status did not change after two years of kelp production at the site. There was a reduction in the number of individuals and species, but this was probably due to reduced sediment volume sampled in the follow-up study compared to the baseline study. Thus, there is no evidence that the kelp farm had any negative or positive impact on the benthic fauna in the area.
- This study provides one of the first empirical comparison of fish and invertebrate communities at kelp farms and natural habitats in Norway, suggesting that current kelp aquaculture, in wave exposed conditions, probably offers limited habitat provisioning. We interpret this positively however the marine alien species issue deserves attention because artificial structures are known to be an easier habitat to colonise than wild habitats. We caution that our findings are difficult to conclude on because the surveys conducted were limited and the scale of Storflua was small. Overall, we theorise biodiversity effects may be greater with larger farms with greater amounts of kelp for sheltering organisms and especially if they were operated closer to coasts. One good example of this is that despite our analyses of lumpfish diet suggesting potential food provision at the farm, their abundance was low and can be expected to be greater under more inshore operating conditions similar to those at Austevoll or Frøya.
- Potential ecological risk (competition with local microalgae) or benefit (eutrophication mitigation) from nutrient uptake by cultivated kelp were not investigated empirically in this study. Scientific literature indicates that nutrient uptake can be substantial in areas of high intensity kelp cultivation, but there is no evidence that this will lead to competition with phytoplankton (microalgae) and cause negative ecological effects. However, no mesocosm or field studies focusing specifically on competition between brown algae and phytoplankton were found, so the empirical knowledge base is weak. Nutrient removal from kelp cultivation can contribute to eutrophication mitigation, however the contribution is most likely minor in most cases and must be supplemented with other strategies on land.

The environmental impact of kelp cultivation is likely to be site-specific and dependent on scale of cultivation, hydrodynamics, and local nutrient regimes. **Our results from Storflua, which is a very exposed location, is therefore not necessarily generalizable to other locations for kelp cultivation in Norway, which tend to be in more sheltered areas.** In a risk assessment of macroalgae cultivation and environmental impact, Norderhaug et al. (2021) concluded that the risk associated with uptake of nutrients (competition with microalgae), shading effect and effect of particulate organic matter on the seafloor was small, because the potential effect is both local and reversible (Norderhaug et al. (2021)). The spread of alien species was considered the greatest threat to the environment, and the greatest knowledge gap related to the spread of species, including alien species, microorganisms and diseases, and genes. Future monitoring and research at Storflua should therefore focus on these aspects.

6 References

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7 Appendices

Appendix A: ROV seafloor survey full report

Appendix B: Analysis Report benthic fauna 2023

Appendix C: Analysis Report benthic fauna 2025

Appendix D: Analysis Report sediment 2023

Appendix E: Analysis Report sediment 2025

Appendix F: Lumpfish diet analyses

Appendix G: Invertebrate epifauna analyses

Notat

Til: Gunhild Borgersen, NIVA

Utført av: Charlotte Pedersen Ugelstad, Akvaplan-niva AS

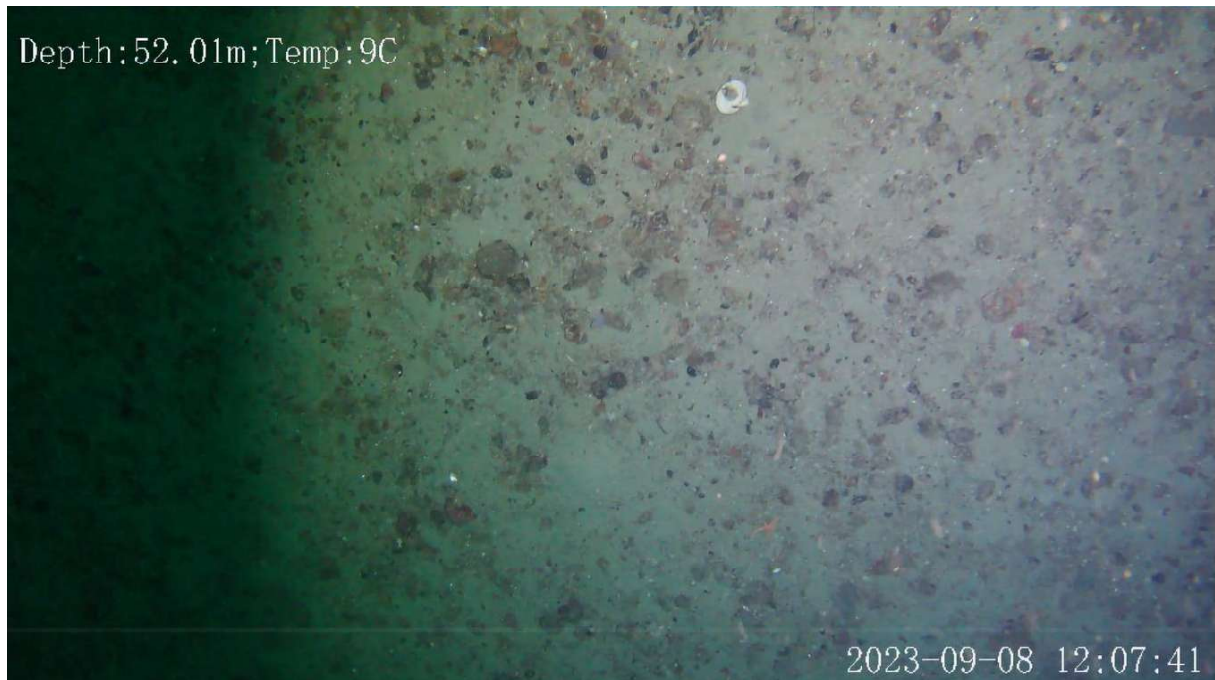
Sak: Beskrivelse av resultat fra visuell kartlegging utført av NIVA AS ved Storflua (Lokalitets id:45189) i Frøya kommune, Trøndelag fylke. (Ref: Akvaplan-niva 65929)

1. Resultat

Det ble totalt undersøkt 4 av 6 planlagte stasjoner ved inneværende undersøkelse. Dette grunnet problemer med kamera som gjorde at det ikke var mulig å få video fra de to siste stasjonene.

1.1. Dykk 1

Dypet varierte med mellom 52–55 m, og bunnen besto hovedsakelig av sand og grus, med innslag av skjellsand og større steiner (Figur 1). Det ble ikke registrert noen forvaltningsinteressante arter. Noe av den observerte faunaen inkluderer sjøstjerner, slangestjerne, bryozoa, sjøpung og en og annen trollhummer. For eksempel på observert bryozoa og sjøpung se Figur 2. Det ble også observert sletterugl på steiner og en rødalge (Figur 3).



Figur 1. Illustrasjonsbilde av bunntype sand og grus, med innslag av skjellsand og større steiner ved Dykk 1.



Figur 2. Illustrasjon av oransje forgreinet bryozoa og sjøpung ved Dykk 1.



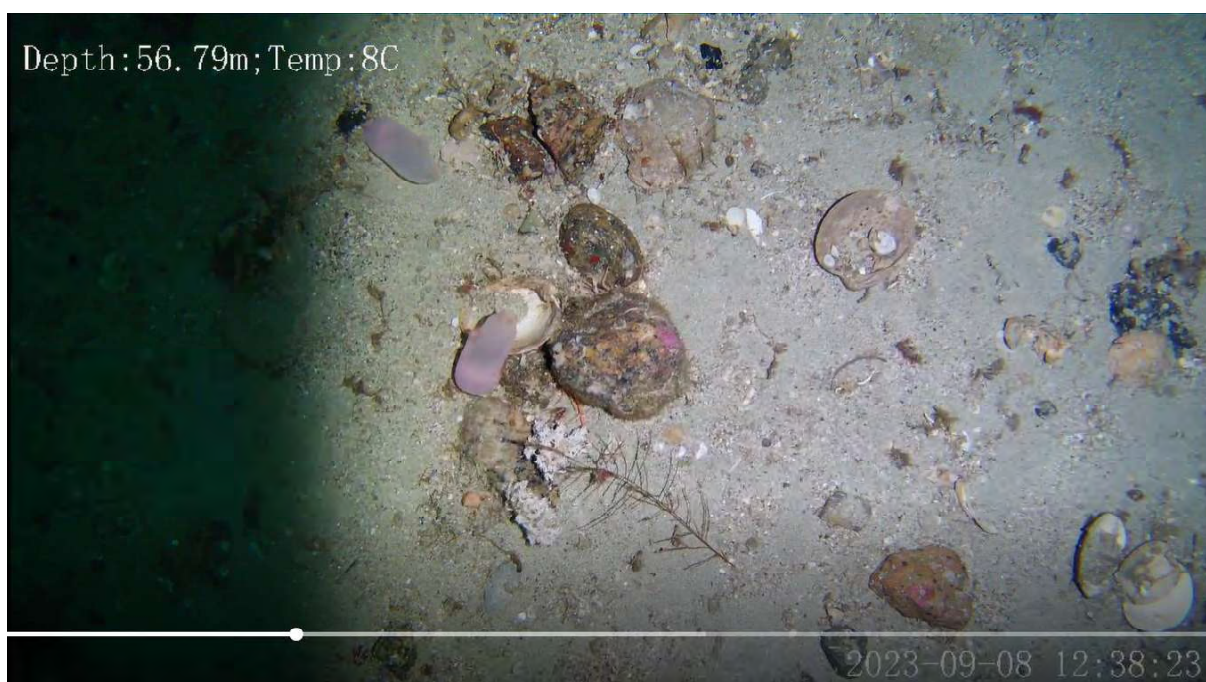
Figur 3. Rødalge ved Dykk 1.

1.2. Dykk 2

Dypet varierte mellom 54–58 m, og som ved Dykk 1 besto bunnen hovedsakelig av sand og grus, men med innslag av skjellsand og større steiner (Figur 4 og Figur 5). Det ble heller ikke registrert noen forvaltningsinteressante arter her, og observerte organismer var som ved Dykk 1. Det ble observert biter fra løsrevne tare-blader (Figur 6).



Figur 4. Illustrasjon av bunnsubstrat ved stasjon Dykk 2. Bunnen besto av blandingsbunn, med sand og grus med innslag av skjellsand og større steiner.



Figur 5. Sjøpung og hvit forgrenet bryozoa ved Dykk 2.



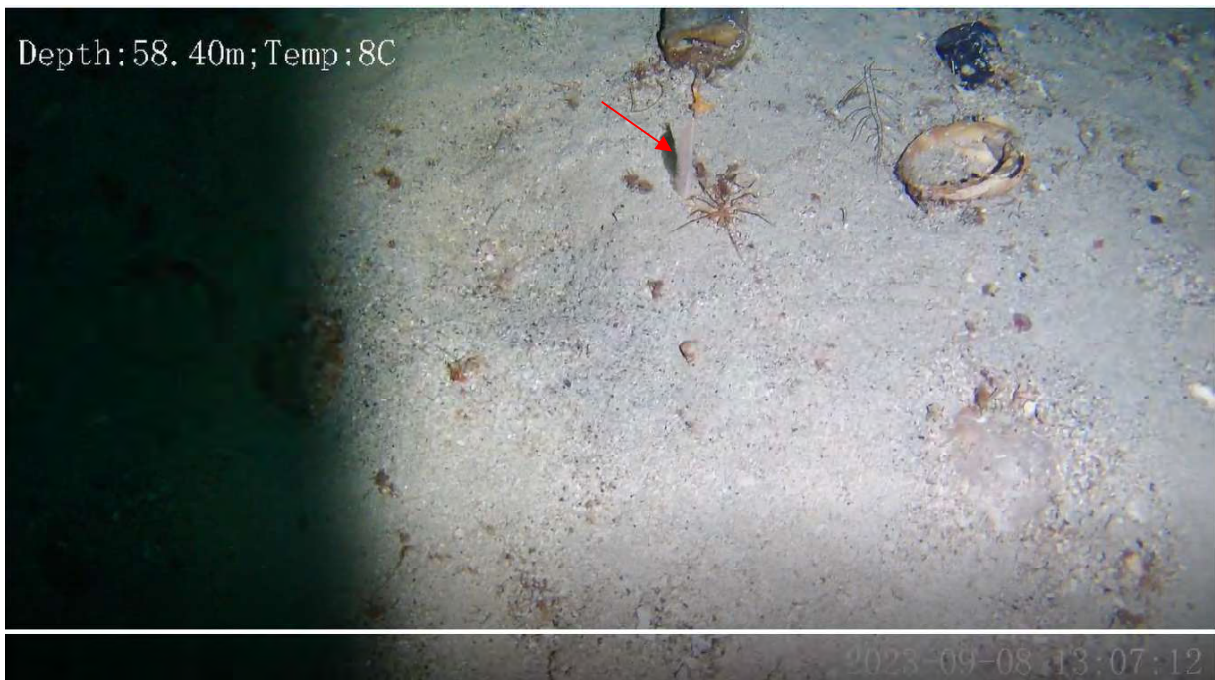
Figur 6. Avrevet tarebit (rød firkant) observert ved dykk 2.

1.3. Dykk 3

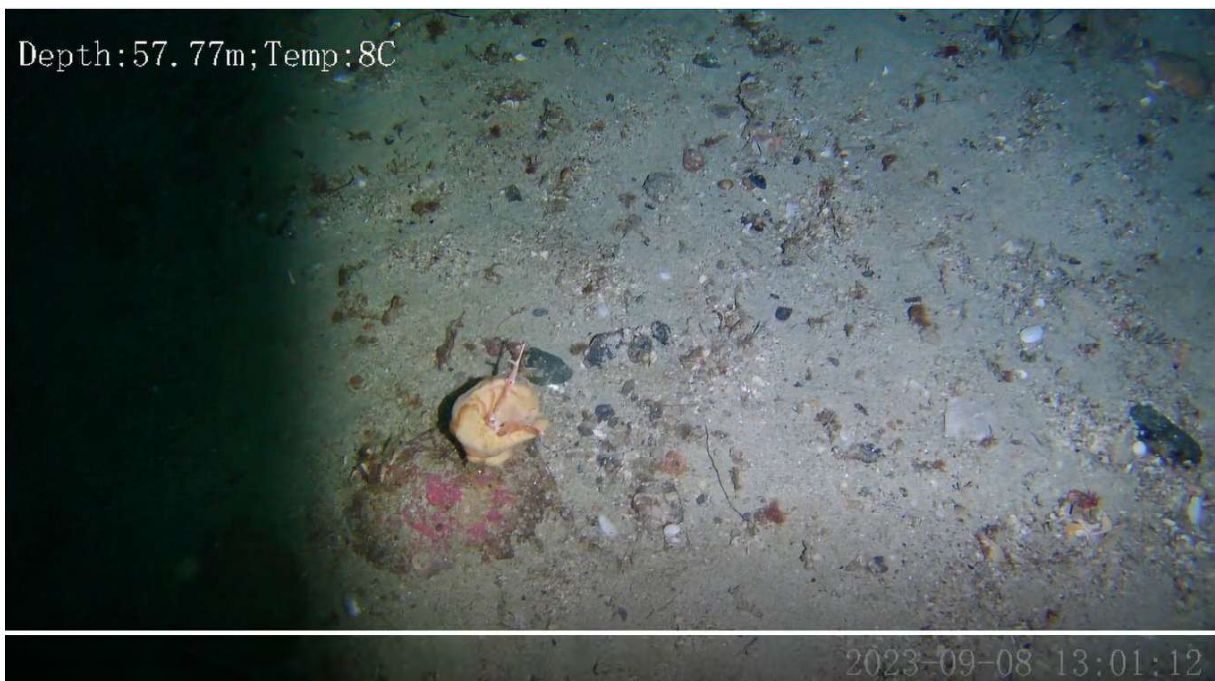
Dypet varierte fra 58–59 m og dominerende substrattyppe var sand og silt, med innslag av skjellsand (Figur 7). Områder med finere sediment var hyppigere her enn ved tidligere stasjoner (Dykk1 og Dykk 2). Det ble observert en sjøfjær av arten liten piperenser (*Virigularia mirabilis*) (Figur 8), samt en traktformet svamp (Figur 9) og en mulig viftesvamp på stein (Figur 10). Grunnet manglende nærbilde av den mulige viftesvampen på stein (Figur 10), er det uklart om dette er en viftesvamp eller en vifteformet bryozoa. Observerte fauna var ellers hovedsakelig som ved tidligere dykk. I tillegg ble det observert enkelte forekomster av tarerester/avrevne tarebladbit (Figur 11).



Figur 7. Illustrasjon av bunnsstrat og en rødalge observert på Dykk 3.



Figur 8. Liten piperenser (*Virigularia mirabilis*) (rød pil) sammen med havedderkopp ved Dykk 3.



Figur 9. Illustrasjon av traktformet svamp ved Dykk 3.



Figur 10. Illustrasjon av bryozoa (rød piler) og mulig viftesvamp (rød firkant) eventuelt en vifteformet bryozoa ved Stasjon Dykk 3.



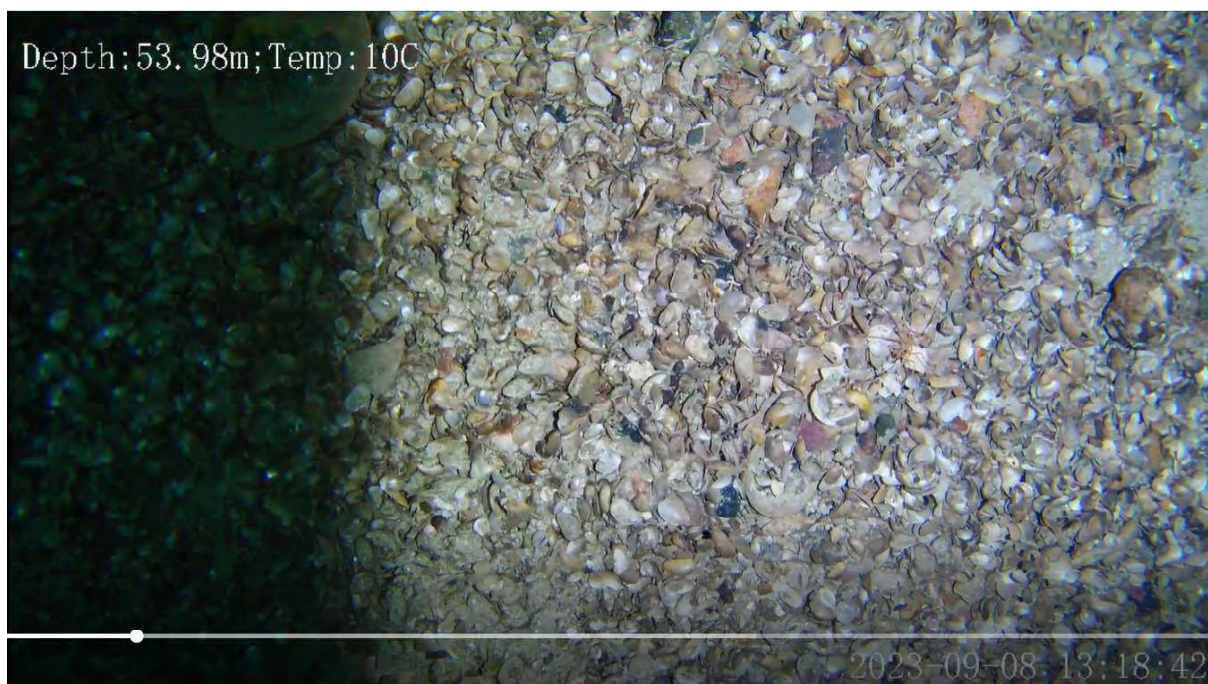
Figur 11. Bit av løsrevet tarebit (rød firkant) ved dykk 3.

1.4. Dykk 4

Dybden varierte mellom 54–55 m, og dominerende substrattypen var grus og stein, med innslag av sand og skjellsand (Figur 12). Ved denne stasjonen var det større forekomst av skjellsand enn ved tidligere stasjoner (Figur 13). Det ble ikke registrert noen sårbare arter og faunaen besto hovedsakelig av samme type dyr som ved tidligere dykk. Det ble observert slettrugl på enkelte steiner. I tillegg ble det observert enkelte forekomster av tarerester/avrevne tarebladbiten (Figur 12)



Figur 12. Illustrasjon av dominerende bunntype (grus og steiner, med innslag av skjellsand og sand), samt observert bit av tare (rød firkant) ved Dykk 4.



Figur 13. Illustrasjon av skjellsand ved Dykk 4.

2. Oppsummering og diskusjon

Den visuelle kartleggingen som ble gjennomført ved Storflua dekket et geografisk område på mellom 53–59 m dyp. Bunnen under det planlagte anlegget var relativt flatt og bunnssubstratet bestod hovedsakelig av sand og grus, med innslag av steiner og skjellsand.

Det ble gjort funn av enkelte tare rester/ biter av tareblader ved Dykk 2,3 og 4. Det er registrert tareskog i grunnområdene rundt anlegget (naturdatabase.no), og man kan derfor ikke konkludere, hvor tare restene stammer fra.

Det ble observert en traktformet svamp og en mulig vifteformet svamp ved dykk 3, begge voksende på stein. En observasjon av sjøfjæren liten piperenser (*Virigularia mirabilis*) ved dykk 3. Noe av den observerte faunaen inkluderer sjøstjerner, slangestjerne, bryozoer, sjøpung og trollhummer. På øvrige stasjoner ble det ikke observert noen sårbare arter eller naturtyper. Design på undersøkelse gjør imidlertid at man ikke kan utelukke tilstedeværelse av sårbare arter eller naturtyper, i tillegg til den kjente forekomsten av tareskog nevnt tidligere, i området rundt det planlagte toreanlegget.



ANALYSE- RAPPORT

Norsk institutt
for vannforskning

Økernveien 94
0579 Oslo
Tel: 22 18 51 00
Fax: 22 18 52 00

Analyserapport marin bløtbunnsfauna

Oppdragsgiver: NIVA

Kontaktperson oppdragsgiver: GBO

Prosjektnummer: 220098

Rapport ID: 010-2025

Versjon: 1

Versjonsendring:

Analyseperiode: 25.9.2023-6.11.24

Rapporteringsdato: 18.03.2025

Prøvemerkning (stasjons-id og grabbnummer)	Prøvens løpenummer (fra NIVAs database)	Prøvetakingsdato
Bløt nær G1	5994	20230907
Bløt nær G2	5995	20230907
Bløt nær G3	5996	20230907
Bløt2 G1	5997	20230908
Bløt2 G2	5998	20230908
Bløt2 G3	5999	20230908
Bløt4 G1	6000	20230908
Bløt4 G2	6001	20230908
Bløt4 G3	6002	20230908
SED7 G1	6003	20230907
SED7 G2	6004	20230907
SED7 G3	6005	20230907

Informasjon om prøven fra oppdragsgiver/prøvetaker: Bunnprøver fra 4 stasjoner ved taredyrkingsanlegget på Storflua i Frohavet

Analysemetode: Identifisering er i henhold til gjeldende versjon av ISO 16665 (Water quality - Guidelines for quantitative sampling and sample processing of marine soft-bottom macrofauna), NIVAs interne prosedyrer 16294 (Prosedyre M3 Bearbeidelse av bløtbunnsprøver), 16613 (Prosedyre M4 Artsidentifisering av bløtbunnsfauna) og 16620 (Prosedyre M10 Faglige vurderinger og fortolkninger).

Taksonomisk personell:

Grovsortering: Eli Johansen

Polychaeta: Gunhild Borgersen

Crustacea: Marijana Brkljadic

Echinodermata: Marijana Brkljadic

Mollusca: Rita Næss

Varia: Marijana Brkljadic

Databehandling:

Indeksberegning og beregning av nEQR: Gunhild Borgersen

Indekser og nEQR er beregnet etter: Klassifiseringsveileder datert: 28.1.2025

Kommentarer: Ingen kommentarer

Underleverandører: Det ble ikke benyttet underleverandører til dette analyseoppdraget

Vedlegg:

A Artslister

B Indekser og nEQR (normalized Ecological Quality Ratio)

Artsregistreringer og indekser er lagt inn i NIVAs bløtbunnsdatabase.

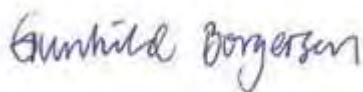
Artslisten og indekser leveres også til oppdragsgiver som excel-fil.

Referanser:

NS-EN ISO 16665:2013. Vannundersøkelse. Retningslinjer for kvantitativ prøvetaking og prøvebehandling av marin bløtbunnsfauna (ISO 16665:2014).

Direktoratsgruppa for vannforvaltning (28.01.2025). Veileder for klassifisering av miljøtilstand i kyst- og ferskvann. Vannportalen.

Godkjenning: Oslo / 24.3.2025



Rapport utarbeidet av: Gunhild Borgersen



Rapportgodkjenner: Marijana S. Brkljadic

Denne analyserapporten får kun kopieres i sin helhet og uten noen form for endringer. Analyseresultatet gjelder kun for den prøven som er testet.

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic)

Dokumentansvarlig

Gunhild Borgersen

Vedlegg A Artslister

Fullstendige artslister for bløtbunnsfauna.

G1=grabbprøve 1, G2=grabbprøve 2, G3=grabbprøve 3, G4=grabbprøve 4.

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt nær	ANTHOZOA		Anthozoa indet		1	
Bløt nær	ANTHOZOA	Cerianthidae	Cerianthidae indet	1		
Bløt nær	ANTHOZOA	Edwardsiidae	Edwardsia sp.		1	
Bløt nær	PLATYHELMINTHES		Platyhelminthes indet	1	1	
Bløt nær	NEMERTEA		Nemertea indet	9	2	4
Bløt nær	POLYCHAETA	Euphrosinidae	Euphrosine cirrata	1		
Bløt nær	POLYCHAETA	Polynoidae	Polynoidae indet	4	2	2
Bløt nær	POLYCHAETA	Phyllodocidae	Eteone longa/flava			1
Bløt nær	POLYCHAETA	Phyllodocidae	Eteone sp.	1		
Bløt nær	POLYCHAETA	Phyllodocidae	Eulalia mustela	1	3	5
Bløt nær	POLYCHAETA	Phyllodocidae	Eumida sanguinea		1	2
Bløt nær	POLYCHAETA	Phyllodocidae	Eumida cf. sanguinea	2		
Bløt nær	POLYCHAETA	Phyllodocidae	Hesionura elongata			1
Bløt nær	POLYCHAETA	Phyllodocidae	Mystides caeca		2	
Bløt nær	POLYCHAETA	Phyllodocidae	Paranaitis katoi			1
Bløt nær	POLYCHAETA	Phyllodocidae	Phyllodoce groenlandica		1	
Bløt nær	POLYCHAETA	Phyllodocidae	Phyllodoce rosea	1		1
Bløt nær	POLYCHAETA	Phyllodocidae	Phyllodocidae indet		1	
Bløt nær	POLYCHAETA	Pholoidae	Pholoe baltica	3	2	1
Bløt nær	POLYCHAETA	Hesionidae	Nereimyra punctata		5	3
Bløt nær	POLYCHAETA	Hesionidae	Psamathe cirrhata	3	7	3
Bløt nær	POLYCHAETA	Syllidae	Exogone verugera	9	4	5
Bløt nær	POLYCHAETA	Syllidae	Parexogone hebes			1
Bløt nær	POLYCHAETA	Syllidae	Sphaerosyllis hystrix	5	1	1
Bløt nær	POLYCHAETA	Syllidae	Syllidae indet	2	3	5
Bløt nær	POLYCHAETA	Syllidae	Trypanosyllis troll	1	1	2
Bløt nær	POLYCHAETA	Nereididae	Nereididae indet	1		
Bløt nær	POLYCHAETA	Nereididae	Nereis cf. zonata			2
Bløt nær	POLYCHAETA	Nephtyidae	Nephtys longosetosa	1	1	
Bløt nær	POLYCHAETA	Sphaerodoridae	Sphaerodoropsis philippi	1		
Bløt nær	POLYCHAETA	Glyceridae	Glycera lapidum	6	5	7
Bløt nær	POLYCHAETA	Eunicidae	Eunice pennata		8	
Bløt nær	POLYCHAETA	Eunicidae	Eunice sp.	1		
Bløt nær	POLYCHAETA	Lumbrineridae	Lumbrineris sp.	2	2	1
Bløt nær	POLYCHAETA	Dorvilleidae	Dorvillea sp.		2	
Bløt nær	POLYCHAETA	Dorvilleidae	Dorvilleidae indet		1	

Analyserapport marin bløtbunnsfauna

Sist godkjent dato

07.03.2025 (Marijana Stenrud Brkljadic)

Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt nær	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini			2
Bløt nær	POLYCHAETA	Apistobanchidae	Apistobanchus tullbergi			1
Bløt nær	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae	5	4	7
Bløt nær	POLYCHAETA	Paraonidae	Aricidea (Acmira) cf. cerrutii	4		
Bløt nær	POLYCHAETA	Paraonidae	Paradoneis Iyra	16	10	12
Bløt nær	POLYCHAETA	Poecilochaetidae	Poecilochaetus serpens			1
Bløt nær	POLYCHAETA	Spionidae	Aonides paucibranchiata	39	21	18
Bløt nær	POLYCHAETA	Spionidae	Dipolydora coeca		1	
Bløt nær	POLYCHAETA	Spionidae	Dipolydora quadrilobata			1
Bløt nær	POLYCHAETA	Spionidae	Malacoceros jirkovi			2
Bløt nær	POLYCHAETA	Spionidae	Prionospio cirrifera	8	7	7
Bløt nær	POLYCHAETA	Spionidae	Pseudopolydora nordica	4	27	16
Bløt nær	POLYCHAETA	Spionidae	Pseudopolydora pulchra	2	2	1
Bløt nær	POLYCHAETA	Spionidae	Spiophanes bombyx	4	4	6
Bløt nær	POLYCHAETA	Spionidae	Spiophanes kroyeri	25	21	60
Bløt nær	POLYCHAETA	Cirratulidae	Aphelochoeta sp.		3	
Bløt nær	POLYCHAETA	Cirratulidae	Chaetozone gibber	4	5	
Bløt nær	POLYCHAETA	Cirratulidae	Chaetozone pseudosetosa			1
Bløt nær	POLYCHAETA	Cirratulidae	Cirratulidae indet			1
Bløt nær	POLYCHAETA	Cirratulidae	Cirratulus cirratus			1
Bløt nær	POLYCHAETA	Cirratulidae	Macrochaeta sp.			1
Bløt nær	POLYCHAETA	Cirratulidae	Tharyx sp.	16	2	
Bløt nær	POLYCHAETA	Scalibregmidae	Scalibregma hansenii	2	3	7
Bløt nær	POLYCHAETA	Opheliidae	Ophelina cylindricaudata	1		
Bløt nær	POLYCHAETA	Capitellidae	Mediomastus fragilis	7	5	1
Bløt nær	POLYCHAETA	Capitellidae	Notomastus latericeus	14	13	17
Bløt nær	POLYCHAETA	Maldanidae	Euclymeninae indet	2		1
Bløt nær	POLYCHAETA	Maldanidae	Maldanidae indet		1	
Bløt nær	POLYCHAETA	Oweniidae	Galathowenia oculata	27	10	14
Bløt nær	POLYCHAETA	Oweniidae	Myriochele danielsseni	1	2	5
Bløt nær	POLYCHAETA	Oweniidae	Owenia sp.	20	16	17
Bløt nær	POLYCHAETA	Ampharetidae	Ampharete octocirrata	5	1	5
Bløt nær	POLYCHAETA	Ampharetidae	Ampharetidae indet			1
Bløt nær	POLYCHAETA	Ampharetidae	Amphicteis gunneri		2	
Bløt nær	POLYCHAETA	Ampharetidae	Amythasides macroglossus	7	15	5
Bløt nær	POLYCHAETA	Ampharetidae	Anobothrus gracilis	1	1	
Bløt nær	POLYCHAETA	Ampharetidae	Lysippe fragilis	3	1	4
Bløt nær	POLYCHAETA	Ampharetidae	Lysippe labiata	2	3	
Bløt nær	POLYCHAETA	Ampharetidae	Melinna elisabethae	2	1	
Bløt nær	POLYCHAETA	Ampharetidae	Samytha sexcirrata		1	1
Bløt nær	POLYCHAETA	Ampharetidae	Sosane sulcata	7	4	2

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic) Dokumentansvarlig Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt nær	POLYCHAETA	Ampharetidae	Sosane wireni	10	13	6
Bløt nær	POLYCHAETA	Terebellidae	Hauchiella tribullata	1		
Bløt nær	POLYCHAETA	Terebellidae	Neoamphitrite affinis	25	25	18
Bløt nær	POLYCHAETA	Terebellidae	Pista lornensis	5	5	8
Bløt nær	POLYCHAETA	Terebellidae	Polycirrus cf. medusa			1
Bløt nær	POLYCHAETA	Terebellidae	Polycirrus sp.	6	8	3
Bløt nær	POLYCHAETA	Terebellidae	Streblosoma intestinale	2	4	2
Bløt nær	POLYCHAETA	Terebellidae	Terebellidae indet			2
Bløt nær	POLYCHAETA	Trichobranchidae	Octobranchus floriceps			1
Bløt nær	POLYCHAETA	Trichobranchidae	Terebellides stroemii		3	1
Bløt nær	POLYCHAETA	Sabellidae	Chone sp.	21	20	27
Bløt nær	POLYCHAETA	Sabellidae	Euchone southerni	4	6	6
Bløt nær	POLYCHAETA	Sabellidae	Jasmineira caudata	14	4	6
Bløt nær	POLYCHAETA	Sabellidae	Sabella pavonina	1	1	2
Bløt nær	POLYCHAETA	Sabellidae	Sabellidae indet		1	
Bløt nær	POLYCHAETA	Serpulidae	Hydroides norvegica	6	8	4
Bløt nær	POLYCHAETA	Lacydoniidae	Lacydonia sp.	4	2	2
Bløt nær	OLIGOCHAETA		Oligochaeta indet	8	7	8
Bløt nær	PROSOBRANCHIA	Fissurellidae	Puncturella noachina			1
Bløt nær	PROSOBRANCHIA	Naticidae	Euspira montagui		3	
Bløt nær	PROSOBRANCHIA	Eulimidae	Melanella sp.	1		
Bløt nær	OPISTOBRANCHIA		Cephalaspidea indet	1		
Bløt nær	OPISTOBRANCHIA		Nudibranchia indet	1		1
Bløt nær	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus			9
Bløt nær	POLYPLACOPHORA	Ischnochitonidae	Stenosemus albus	1	2	1
Bløt nær	BIVALVIA	Nuculidae	Nucula tumidula			3
Bløt nær	BIVALVIA	Mytilidae	Modiolula phaseolina	1	3	9
Bløt nær	BIVALVIA	Arcidae	Asperarca nodulosa			1
Bløt nær	BIVALVIA	Limidae	Limatula gwyni	2		
Bløt nær	BIVALVIA	Pectinidae	Pseudamussium peslutrae	3	4	4
Bløt nær	BIVALVIA	Anomiidae	Pododesmus squama		1	
Bløt nær	BIVALVIA	Thyasiridae	Axinulus croulinensis		2	2
Bløt nær	BIVALVIA	Thyasiridae	Thyasira obsoleta	2		
Bløt nær	BIVALVIA	Thyasiridae	Thyasira sarsii		1	1
Bløt nær	BIVALVIA	Cardiidae	Papillicardium minimum	1	2	3
Bløt nær	BIVALVIA	Veneridae	Venus casina		1	
Bløt nær	BIVALVIA	Thraciidae	Thracia cf. phaseolina	1		1
Bløt nær	SCAPHOPODA	Dentaliidae	Antalis entalis	1		
Bløt nær	PYCNOGONIDA		Pycnogonida indet		1	
Bløt nær	CUMACEA	Lampropidae	Hemilamprops uniplicatus	1		
Bløt nær	ISOPODA	Gnathidae	Gnathia sp.		3	

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt nær	ISOPODA	Cirolanidae	Natatolana borealis		1	
Bløt nær	AMPHIPODA	Lysianassidae	Acidostoma obesum	1		
Bløt nær	AMPHIPODA	Lysianassidae	Scopelocheirus hopei	1	1	
Bløt nær	AMPHIPODA	Ampeliscidae	Ampelisca cf. aequicornis	3	6	1
Bløt nær	AMPHIPODA	Ampeliscidae	Ampelisca typica		1	
Bløt nær	AMPHIPODA	Ampeliscidae	Haploops setosa	28	7	6
Bløt nær	AMPHIPODA	Melitidae	Cheirocratus assimilis			1
Bløt nær	AMPHIPODA	Haustoriidae	Urothoe elegans	1	4	
Bløt nær	AMPHIPODA	Oedicerotidae	Deflexilodes sp.		1	
Bløt nær	AMPHIPODA	Oedicerotidae	Westwoodilla caecula		1	
Bløt nær	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	3	4	1
Bløt nær	AMPHIPODA	Liljeborgiidae	Cletodes sp.		1	
Bløt nær	AMPHIPODA	Atylidae	Nototropis vedlomensis	1		1
Bløt nær	AMPHIPODA	Isaeidae	Megamphopus cornutus	2		
Bløt nær	AMPHIPODA	Corophiidae	Medicorophium affine		2	
Bløt nær	AMPHIPODA	Podoceridae	Podoceridae indet			2
Bløt nær	DECAPODA	Galatheidae	Galathea sp.	2		4
Bløt nær	DECAPODA	Paguridae	Paguridae indet			1
Bløt nær	SIPUNCULIDA		Golfingiida indet	2	5	5
Bløt nær	SIPUNCULIDA		Phascolion (Phascolion) strombus strombus	2		
Bløt nær	PHORONIDA		Phoronida indet	2		
Bløt nær	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa			1
Bløt nær	OPHIUROIDEA		Ophiuroidea juvenil		1	2
Bløt nær	OPHIUROIDEA	Ophiactidae	Ophiactis sp.			1
Bløt nær	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata		3	
Bløt nær	OPHIUROIDEA	Amphiuridae	Amphipholis squamata		1	
Bløt nær	OPHIUROIDEA	Ophiuridae	Ophiocten affinis		1	
Bløt nær	OPHIUROIDEA	Ophiuridae	Ophiura albida		1	
Bløt nær	ECHINOIDEA		Spatangoida juvenil		1	
Bløt nær	ECHINOIDEA	Parechinidae	Echinus sp.	1	2	
Bløt nær	ECHINOIDEA	Loveniidae	Echinocardium sp.	4		2
Bløt nær	HOLOTHUROIDEA		Holothuroidea indet		1	
Bløt nær	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus		1	1
Bløt nær	HOLOTHUROIDEA	Sclerodactylidae	Thyone sp.		1	
Bløt nær	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet	1	8	3
Bløt nær	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii		5	2
Bløt nær	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria		6	2
Bløt nær	ASCIDIACEA	Molgulidae	Molgula sp.	4	4	4
Bløt2	PLATYHELMINTHES		Platyhelminthes indet			1
Bløt2	NEMERTEA		Nemertea indet	4	4	3

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	POLYCHAETA	Amphinomidae	Paramphinome jeffreysii		1	
Bløt2	POLYCHAETA	Aphroditidae	Aphrodita aculeata		1	
Bløt2	POLYCHAETA	Polynoidae	Polynoidae indet	1		
Bløt2	POLYCHAETA	Sigalionidae	Sthenelais boa		1	
Bløt2	POLYCHAETA	Phyllodocidae	Eulalia mustela		1	1
Bløt2	POLYCHAETA	Phyllodocidae	Mystides caeca	1	1	1
Bløt2	POLYCHAETA	Phyllodocidae	Notophyllum foliosum	1		
Bløt2	POLYCHAETA	Phyllodocidae	Sige fusigera	2	2	1
Bløt2	POLYCHAETA	Pholoidae	Pholoe assimilis	1		
Bløt2	POLYCHAETA	Pholoidae	Pholoe baltica	3	4	9
Bløt2	POLYCHAETA	Hesionidae	Nereimyra punctata	2	1	1
Bløt2	POLYCHAETA	Hesionidae	Oxydromus flexuosus		1	
Bløt2	POLYCHAETA	Syllidae	Exogone verugera	2	12	13
Bløt2	POLYCHAETA	Syllidae	Sphaerosyllis hystrix		1	
Bløt2	POLYCHAETA	Syllidae	Syllidae indet	4		1
Bløt2	POLYCHAETA	Syllidae	Syllis sp.		1	2
Bløt2	POLYCHAETA	Nephtyidae	Nephtys hombergii	2		
Bløt2	POLYCHAETA	Nephtyidae	Nephtys longosetosa		1	
Bløt2	POLYCHAETA	Glyceridae	Glycera lapidum		1	1
Bløt2	POLYCHAETA	Goniadidae	Goniada maculata	1	1	2
Bløt2	POLYCHAETA	Eunicidae	Eunice sp.	1		
Bløt2	POLYCHAETA	Lumbrineridae	Augeneria tentaculata			1
Bløt2	POLYCHAETA	Lumbrineridae	Lumbrineris sp.	4	3	1
Bløt2	POLYCHAETA	Apistobanchidae	Apistobanchus tullbergi		1	2
Bløt2	POLYCHAETA	Paraonidae	Aricidea (Aricidea) cf. albatrossae		1	
Bløt2	POLYCHAETA	Paraonidae	Aricidea (Aricidea) cf. wassi	2		3
Bløt2	POLYCHAETA	Paraonidae	Paradoneis lyra	5	10	3
Bløt2	POLYCHAETA	Poecilochaetidae	Poecilochaetus serpens	1	1	
Bløt2	POLYCHAETA	Spionidae	Aonides paucibranchiata	5	13	11
Bløt2	POLYCHAETA	Spionidae	Dipolydora coeca		1	
Bløt2	POLYCHAETA	Spionidae	Prionospio cirrifera	5	2	3
Bløt2	POLYCHAETA	Spionidae	Pseudopolydora nordica			3
Bløt2	POLYCHAETA	Spionidae	Pseudopolydora paucibranchiata	1		
Bløt2	POLYCHAETA	Spionidae	Spio sp.		1	
Bløt2	POLYCHAETA	Spionidae	Spiophanes kroyeri	207	31	165
Bløt2	POLYCHAETA	Spionidae	Spiophanes wigleyi		1	
Bløt2	POLYCHAETA	Cirratulidae	Aphelochaeta sp.	5		1
Bløt2	POLYCHAETA	Cirratulidae	Chaetozone monteverdii		1	
Bløt2	POLYCHAETA	Cirratulidae	Chaetozone pseudosetosa	2	1	3
Bløt2	POLYCHAETA	Cirratulidae	Tharyx sp.		9	4
Bløt2	POLYCHAETA	Scalibregmidae	Scalibregma hanseni			1

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	POLYCHAETA	Capitellidae	Mediomastus fragilis		1	
Bløt2	POLYCHAETA	Capitellidae	Notomastus latericeus	4	4	10
Bløt2	POLYCHAETA	Maldanidae	Euclymeninae indet	4		
Bløt2	POLYCHAETA	Maldanidae	Lumbriclymene cylindricauda		1	
Bløt2	POLYCHAETA	Maldanidae	Praxillella affinis		1	
Bløt2	POLYCHAETA	Oweniidae	Galathowenia oculata	28	32	23
Bløt2	POLYCHAETA	Oweniidae	Myriochele danielsseni	70	13	19
Bløt2	POLYCHAETA	Oweniidae	Owenia sp.	8	17	9
Bløt2	POLYCHAETA	Ampharetidae	Amage auricula	1		1
Bløt2	POLYCHAETA	Ampharetidae	Ampharete baltica	2		
Bløt2	POLYCHAETA	Ampharetidae	Ampharete lindstroemi	1	3	4
Bløt2	POLYCHAETA	Ampharetidae	Ampharete octocirrata	7	4	9
Bløt2	POLYCHAETA	Ampharetidae	Ampharetidae indet		2	
Bløt2	POLYCHAETA	Ampharetidae	Amphicteis gunneri	1		
Bløt2	POLYCHAETA	Ampharetidae	Amythasides macroglossus	31	17	17
Bløt2	POLYCHAETA	Ampharetidae	Eclysippe vanelli	5	7	7
Bløt2	POLYCHAETA	Ampharetidae	Lysippe fragilis	3	3	
Bløt2	POLYCHAETA	Ampharetidae	Samytha sexcirrata	1		7
Bløt2	POLYCHAETA	Ampharetidae	Sosane wahrbergi	2	1	11
Bløt2	POLYCHAETA	Ampharetidae	Sosane wireni	2	7	8
Bløt2	POLYCHAETA	Terebellidae	Eupolymnia nesidensis		2	
Bløt2	POLYCHAETA	Terebellidae	Neoamphitrite affinis	8		8
Bløt2	POLYCHAETA	Terebellidae	Nicolea venustula	3		
Bløt2	POLYCHAETA	Terebellidae	Paramphitrite birulai	4	3	2
Bløt2	POLYCHAETA	Terebellidae	Pista lornensis	2	5	7
Bløt2	POLYCHAETA	Terebellidae	Polycirrus plumosus	3	1	1
Bløt2	POLYCHAETA	Terebellidae	Polycirrus sp.	4	2	1
Bløt2	POLYCHAETA	Terebellidae	Streblosoma intestinale	1	3	
Bløt2	POLYCHAETA	Terebellidae	Terebellidae indet		1	20
Bløt2	POLYCHAETA	Trichobranhidae	Octobranthus floriceps		1	
Bløt2	POLYCHAETA	Trichobranhidae	Terebellides stroemii		5	4
Bløt2	POLYCHAETA	Trichobranhidae	Trichobranthus roseus	1	1	1
Bløt2	POLYCHAETA	Sabellidae	Chone sp.	29	12	17
Bløt2	POLYCHAETA	Sabellidae	Euchone sp.	9	7	13
Bløt2	POLYCHAETA	Sabellidae	Sabella pavonina	4	7	1
Bløt2	POLYCHAETA	Siboglinidae	Siboglinidae indet			1
Bløt2	PROSOBRANCHIA	Fissurellidae	Puncturella noachina	3		
Bløt2	PROSOBRANCHIA	Eulimidae	Haliella stenostoma			3
Bløt2	OPISTOBRANCHIA	Philinidae	Hermania sp.	2	2	1
Bløt2	OPISTOBRANCHIA	Scaphandridae	Cylichna alba	1		
Bløt2	OPISTOBRANCHIA	Scaphandridae	Cylichna cylindracea		1	1

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	CAUDOFOVEATA		Caudofoveata indet	3		
Bløt2	CAUDOFOVEATA		Solenogastres indet			2
Bløt2	BIVALVIA	Nuculanidae	Yoldiella philippiana	3	1	
Bløt2	BIVALVIA	Mytilidae	Dacrydium ockelmanni	1		
Bløt2	BIVALVIA	Mytilidae	Modiolula phaseolina	2		
Bløt2	BIVALVIA	Pectinidae	Pseudamussium peslutrae	1	3	2
Bløt2	BIVALVIA	Lucinidae	Lucinoma borealis			1
Bløt2	BIVALVIA	Lucinidae	Myrtea spinifera	2	1	4
Bløt2	BIVALVIA	Thyasiridae	Adontorhina similis	4	3	4
Bløt2	BIVALVIA	Thyasiridae	Axinulus croulinensis	11	5	7
Bløt2	BIVALVIA	Thyasiridae	Mendicula ferruginosa	4	2	2
Bløt2	BIVALVIA	Thyasiridae	Thyasira gouldi	2	1	5
Bløt2	BIVALVIA	Thyasiridae	Thyasira obsoleta	4	1	3
Bløt2	BIVALVIA	Thyasiridae	Thyasira sarsii			3
Bløt2	BIVALVIA	Montacutidae	Tellimya ferruginosa		1	2
Bløt2	BIVALVIA	Astartidae	Tridonta elliptica			1
Bløt2	BIVALVIA	Cardiidae	Papillicardium minimum		2	
Bløt2	BIVALVIA	Scrobiculariidae	Abra nitida	1		4
Bløt2	BIVALVIA	Veneridae	Timoclea ovata			1
Bløt2	BIVALVIA	Hiatellidae	Hiatella arctica	1		
Bløt2	BIVALVIA	Thraciidae	Thracia phaseolina	1	1	2
Bløt2	BIVALVIA	Cuspidariidae	Cardiomya costellata	2		1
Bløt2	SCAPHOPODA	Dentaliidae	Antalis entalis	1	1	1
Bløt2	CUMACEA	Pseudocumatidae	Pseudocuma sp.		1	
Bløt2	CUMACEA	Diastylidae	Diastylodes biplicatus	2	1	1
Bløt2	ISOPODA	Cirolanidae	Natanolana borealis		1	
Bløt2	AMPHIPODA	Lysianassidae	Hippomedon denticulatus			1
Bløt2	AMPHIPODA	Lysianassidae	Lysianassidae indet	2		
Bløt2	AMPHIPODA	Lysianassidae	Tmetonyx sp.	1	1	1
Bløt2	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis	5		
Bløt2	AMPHIPODA	Ampeliscidae	Ampelisca gibba			1
Bløt2	AMPHIPODA	Ampeliscidae	Ampelisca sp.	1		
Bløt2	AMPHIPODA	Ampeliscidae	Haploops setosa	1		1
Bløt2	AMPHIPODA	Haustoriidae	Urothoe elegans	2		1
Bløt2	AMPHIPODA	Oedicerotidae	Westwoodilla caecula		1	
Bløt2	AMPHIPODA	Phoxocephalidae	Harpinia sp.		1	1
Bløt2	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	2		1
Bløt2	AMPHIPODA	Aoridae	Microdeutopus sp.		1	
Bløt2	AMPHIPODA	Isaeidae	Isaeidae indet			1
Bløt2	AMPHIPODA	Corophiidae	Unciola planipes	1		
Bløt2	AMPHIPODA	Podoceridae	Dyopedos monacanthus		3	

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	AMPHIPODA	Caprellidae	Phtisica marina	1	2	2
Bløt2	DECAPODA	Galatheidae	Galathea sp.	4	1	5
Bløt2	SIPUNCULIDA		Golfingiida indet	1		
Bløt2	PHORONIDA		Phoronida indet			1
Bløt2	ASTEROIDEA		Asteroidea juvenil	1		1
Bløt2	OPHIUROIDEA		Ophiuroidea juvenil	2		2
Bløt2	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata	1		
Bløt2	OPHIUROIDEA	Ophiuridae	Ophiocten affinis	1		1
Bløt2	OPHIUROIDEA	Ophiuridae	Ophiura (Dictenophiura) carnea	3		
Bløt2	OPHIUROIDEA	Ophiuridae	Ophiuridae indet		1	
Bløt2	ECHINOIDEA		Camarodonta juvenil	1	2	2
Bløt2	ECHINOIDEA	Loveniidae	Echinocardium sp.	2	4	6
Bløt2	HOLOTHUROIDEA		Holothuroidea indet	2		
Bløt2	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus	2	1	
Bløt2	HOLOTHUROIDEA	Sclerodactylidae	Thyone sp.	6		
Bløt2	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet	4	4	
Bløt2	HOLOTHUROIDEA	Cucumariidae	Ocnus lacteus	1		
Bløt2	HOLOTHUROIDEA	Ypsilothuriidae	Echinocucumis hispida	1		
Bløt2	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	3	4	6
Bløt2	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria	3		1
Bløt2	ASCIDIACEA	Molgulidae	Molgula sp.	1	5	1
Bløt4	ANTHOZOA	Cerianthidae	Cerianthidae indet	1		
Bløt4	PLATYHELMINTHES		Platyhelminthes indet			1
Bløt4	NEMERTEA		Nemertea indet	4	1	3
Bløt4	POLYCHAETA	Aphroditidae	Aphrodita aculeata		1	
Bløt4	POLYCHAETA	Polynoidae	Harmothoe sp.	3	1	
Bløt4	POLYCHAETA	Polynoidae	Malmgrenia andreapolis	1		
Bløt4	POLYCHAETA	Polynoidae	Malmgrenia jungmani			5
Bløt4	POLYCHAETA	Polynoidae	Malmgrenia mcintoshii	1		
Bløt4	POLYCHAETA	Polynoidae	Polynoidae indet		1	1
Bløt4	POLYCHAETA	Phyllodocidae	Eteone longa/flava			1
Bløt4	POLYCHAETA	Phyllodocidae	Eulalia mustela	2	1	
Bløt4	POLYCHAETA	Phyllodocidae	Mystides caeca	2		
Bløt4	POLYCHAETA	Phyllodocidae	Pseudomystides spinachia			4
Bløt4	POLYCHAETA	Phyllodocidae	Sige fusigera	1	1	
Bløt4	POLYCHAETA	Pholoidae	Pholoe baltica	3	1	5
Bløt4	POLYCHAETA	Hesionidae	Psamathe cirrhata	2	4	1
Bløt4	POLYCHAETA	Syllidae	Exogone naidina		1	
Bløt4	POLYCHAETA	Syllidae	Exogone verugera	6	4	5
Bløt4	POLYCHAETA	Syllidae	Sphaerosyllis hystrix	2	1	
Bløt4	POLYCHAETA	Syllidae	Syllidae indet	3	1	3

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt4	POLYCHAETA	Syllidae	Trypanosyllis troll	1		
Bløt4	POLYCHAETA	Nereididae	Eunereis cf. longissima		2	
Bløt4	POLYCHAETA	Nereididae	Nereis zonata			1
Bløt4	POLYCHAETA	Glyceridae	Glycera lapidum	4	1	8
Bløt4	POLYCHAETA	Goniadidae	Goniada maculata	1		
Bløt4	POLYCHAETA	Eunicidae	Eunice pennata			6
Bløt4	POLYCHAETA	Eunicidae	Eunice cf. pennata	1		
Bløt4	POLYCHAETA	Eunicidae	Eunice sp.		1	
Bløt4	POLYCHAETA	Lumbrineridae	Lumbrineris sp.	6	2	6
Bløt4	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini			1
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae	3		
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Acmira) cf. catherinae		4	
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Acmira) cerrutii			1
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Aricidea) cf. wassi	2		
Bløt4	POLYCHAETA	Paraonidae	Paradoneis Iyra	6	4	3
Bløt4	POLYCHAETA	Spionidae	Aonides paucibranchiata	21	14	11
Bløt4	POLYCHAETA	Spionidae	Dipolydora coeca	1	2	
Bløt4	POLYCHAETA	Spionidae	Dipolydora quadrilobata			3
Bløt4	POLYCHAETA	Spionidae	Laonice bahusiensis	1		
Bløt4	POLYCHAETA	Spionidae	Laonice sp.			2
Bløt4	POLYCHAETA	Spionidae	Malacoceros jirkovi	2	1	
Bløt4	POLYCHAETA	Spionidae	Prionospio cirrifera	4	3	3
Bløt4	POLYCHAETA	Spionidae	Pseudopolydora nordica	3	2	1
Bløt4	POLYCHAETA	Spionidae	Pseudopolydora pulchra	4	1	
Bløt4	POLYCHAETA	Spionidae	Spiophanes bombyx	2	2	5
Bløt4	POLYCHAETA	Spionidae	Spiophanes kroyeri	33	25	12
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone monteverdii			1
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone pseudosetosa	2		
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone zetlandica	1		
Bløt4	POLYCHAETA	Cirratulidae	Cirratulidae indet			1
Bløt4	POLYCHAETA	Cirratulidae	Cirratulus cirratus		2	
Bløt4	POLYCHAETA	Cirratulidae	Macrochaeta sp.		1	
Bløt4	POLYCHAETA	Cirratulidae	Tharyx sp.	3	2	
Bløt4	POLYCHAETA	Scalibregmidae	Polyphysia crassa	1		
Bløt4	POLYCHAETA	Scalibregmidae	Scalibregma hanseni	3		3
Bløt4	POLYCHAETA	Opheliidae	Ophelina cylindricaudata	3		
Bløt4	POLYCHAETA	Capitellidae	Mediomastus fragilis	1		1
Bløt4	POLYCHAETA	Capitellidae	Notomastus latericeus	13	5	12
Bløt4	POLYCHAETA	Maldanidae	Euclymeninae indet		2	2
Bløt4	POLYCHAETA	Maldanidae	Maldanidae indet	1		1
Bløt4	POLYCHAETA	Oweniidae	Galathowenia oculata	33	11	24

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt4	POLYCHAETA	Oweniidae	Myriochele danielsseni	9	11	17
Bløt4	POLYCHAETA	Oweniidae	Owenia sp.	9	10	9
Bløt4	POLYCHAETA	Ampharetidae	Ampharete falcata			1
Bløt4	POLYCHAETA	Ampharetidae	Ampharete octocirrata	2	3	6
Bløt4	POLYCHAETA	Ampharetidae	Ampharete sp.	2		
Bløt4	POLYCHAETA	Ampharetidae	Ampharetidae indet	2	3	1
Bløt4	POLYCHAETA	Ampharetidae	Amphicteis gunneri			1
Bløt4	POLYCHAETA	Ampharetidae	Amythasides macroglossus	18	10	16
Bløt4	POLYCHAETA	Ampharetidae	Anobothrus laubieri			2
Bløt4	POLYCHAETA	Ampharetidae	Lysippe labiata	2	1	
Bløt4	POLYCHAETA	Ampharetidae	Melinna elisabethae			1
Bløt4	POLYCHAETA	Ampharetidae	Samytha sexcirrata	1		2
Bløt4	POLYCHAETA	Ampharetidae	Sosane sulcata	4	3	
Bløt4	POLYCHAETA	Ampharetidae	Sosane wireni	5	10	5
Bløt4	POLYCHAETA	Terebellidae	Hauchiella tribullata	3	2	3
Bløt4	POLYCHAETA	Terebellidae	Neoamphitrite affinis	17	14	17
Bløt4	POLYCHAETA	Terebellidae	Pista lornensis	20	11	5
Bløt4	POLYCHAETA	Terebellidae	Polycirrus medusa			7
Bløt4	POLYCHAETA	Terebellidae	Polycirrus sp.	1	5	
Bløt4	POLYCHAETA	Terebellidae	Streblosoma intestinale	2		1
Bløt4	POLYCHAETA	Terebellidae	Terebellidae indet		1	1
Bløt4	POLYCHAETA	Terebellidae	Thelepus cincinnatus			1
Bløt4	POLYCHAETA	Trichobranchidae	Octobranchus floriceps			1
Bløt4	POLYCHAETA	Trichobranchidae	Terebellides stroemii	1	1	
Bløt4	POLYCHAETA	Trichobranchidae	Trichobranchus roseus		1	3
Bløt4	POLYCHAETA	Sabellidae	Branchiomma bombyx			1
Bløt4	POLYCHAETA	Sabellidae	Chone sp.	40	27	51
Bløt4	POLYCHAETA	Sabellidae	Euchone southerni		5	
Bløt4	POLYCHAETA	Sabellidae	Euchone sp.	20	2	44
Bløt4	POLYCHAETA	Sabellidae	Fabricia stellaris	3	1	3
Bløt4	POLYCHAETA	Sabellidae	Jasmineira caudata	36	22	80
Bløt4	POLYCHAETA	Sabellidae	Myxocola infundibulum			1
Bløt4	POLYCHAETA	Sabellidae	Sabella pavonina	2	1	
Bløt4	POLYCHAETA	Sabellidae	Sabellidae indet	1		
Bløt4	POLYCHAETA	Lacydoniidae	Lacydonia sp.	1	3	3
Bløt4	OLIGOCHAETA		Oligochaeta indet	1	1	9
Bløt4	PROSOBRANCHIA	Fissurellidae	Puncturella noachina	1		2
Bløt4	PROSOBRANCHIA	Naticidae	Euspira montagui	2		1
Bløt4	PROSOBRANCHIA	Raphitomidae	Raphitoma sp.	1		
Bløt4	PROSOBRANCHIA	Turridae	Taranis moerchii		1	
Bløt4	OPISTHOBANCHIA		Cephalaspidea indet			1

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt4	OPISTOBRANCHIA		Nudibranchia indet	1	1	1
Bløt4	OPISTOBRANCHIA	Pyramidellidae	Odostomia sp.			1
Bløt4	OPISTOBRANCHIA	Retusidae	Retusa umbilicata	1		1
Bløt4	OPISTOBRANCHIA	Triviidae	Trivia arctica	1		
Bløt4	POLYPLACOPHORA		Polyplacophora indet	2		
Bløt4	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus	1	1	7
Bløt4	CAUDOFOVEATA		Solenogastres indet			2
Bløt4	BIVALVIA		Bivalvia indet	1		
Bløt4	BIVALVIA	Nuculidae	Nucula tumidula			1
Bløt4	BIVALVIA	Nuculanidae	Yoldiella philippiana		1	
Bløt4	BIVALVIA	Mytilidae	Dacrydium ockelmanni			1
Bløt4	BIVALVIA	Mytilidae	Modiolula phaseolina	1		2
Bløt4	BIVALVIA	Arcidae	Asperarca nodulosa			1
Bløt4	BIVALVIA	Limidae	Limaria loscombi			1
Bløt4	BIVALVIA	Limidae	Limatula gwyni	1	3	1
Bløt4	BIVALVIA	Pectinidae	Palliolium striatum	1		
Bløt4	BIVALVIA	Pectinidae	Pseudamussium peslutrae	3	1	6
Bløt4	BIVALVIA	Thyasiridae	Axinulus croulinensis	1		1
Bløt4	BIVALVIA	Thyasiridae	Thyasira gouldi	1	2	
Bløt4	BIVALVIA	Astartidae	Tridonta elliptica			1
Bløt4	BIVALVIA	Cardiidae	Papillicardium minimum	2		2
Bløt4	BIVALVIA	Veneridae	Timoclea ovata	1	1	
Bløt4	BIVALVIA	Veneridae	Venus casina			1
Bløt4	BIVALVIA	Thraciidae	Thracia cf. phaseolina	1		
Bløt4	BIVALVIA	Lyonsiidae	Lyonsia norwegica	1		
Bløt4	SCAPHOPODA	Dentaliidae	Antalis entalis			1
Bløt4	CUMACEA	Lampropidae	Hemilamprops cf. uniplicatus			1
Bløt4	ISOPODA	Gnathidae	Gnathia sp.			1
Bløt4	ISOPODA	Janiridae	Janira maculosa	2		2
Bløt4	AMPHIPODA	Lysianassidae	Orchomene sp.	1		
Bløt4	AMPHIPODA	Lysianassidae	Scopelocheirus hopei			1
Bløt4	AMPHIPODA	Tryphosidae	Tryphosidae indet		1	
Bløt4	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis		6	
Bløt4	AMPHIPODA	Ampeliscidae	Ampelisca gibba	1		
Bløt4	AMPHIPODA	Ampeliscidae	Ampelisca sp.	6		
Bløt4	AMPHIPODA	Ampeliscidae	Haploops setosa	38	2	20
Bløt4	AMPHIPODA	Amphilochidae	Amphilochus sp.	1		
Bløt4	AMPHIPODA	Cressidae	Cressa sp.			1
Bløt4	AMPHIPODA	Haustoriidae	Urothoe elegans	3	3	4
Bløt4	AMPHIPODA	Oedicerotidae	Deflexilodes sp.	2		2
Bløt4	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	2	2	3

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt4	AMPHIPODA	Atylidae	Nototropis vedlomensis			1
Bløt4	AMPHIPODA	Isaeidae	Isaeidae indet	2		
Bløt4	AMPHIPODA	Corophiidae	Medicorophium affine			2
Bløt4	AMPHIPODA	Corophiidae	Unciola planipes		2	
Bløt4	AMPHIPODA	Photidae	Gammaropsis sophiae		7	
Bløt4	DECAPODA	Galatheidae	Galathea sp.	1	1	
Bløt4	DECAPODA	Galatheidae	Munida sarsi		1	
Bløt4	SIPUNCULIDA		Golfingiida indet	1	2	7
Bløt4	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa			1
Bløt4	ASTEROIDEA		Asteroidea juvenil			1
Bløt4	OPHIUROIDEA		Ophiuroidea juvenil			1
Bløt4	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata	1	3	3
Bløt4	OPHIUROIDEA	Amphiuridae	Amphipholis squamata	1	1	4
Bløt4	OPHIUROIDEA	Ophiuridae	Ophiocten affinis			1
Bløt4	OPHIUROIDEA	Ophiuridae	Ophiura sarsii			1
Bløt4	ECHINOIDEA		Camarodonta juvenil		1	
Bløt4	ECHINOIDEA		Spatangoida juvenil	1	3	
Bløt4	ECHINOIDEA	Parechinidae	Echinus sp.	1		
Bløt4	HOLOTHUROIDEA		Holothuroidea indet		2	1
Bløt4	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus	1	2	
Bløt4	HOLOTHUROIDEA	Sclerodactylidae	Thyone sp.	1		3
Bløt4	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet	8		4
Bløt4	HOLOTHUROIDEA	Cucumariidae	Ocnus lacteus			1
Bløt4	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	2		3
Bløt4	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria	3	2	
Bløt4	ASCIDIACEA	Molgulidae	Molgula sp.	13	5	10
SED7	ANTHOZOA		Actinaria indet			1
SED7	ANTHOZOA	Cerianthidae	Cerianthidae indet	1		
SED7	PLATYHELMINTHES		Platyhelminthes indet		1	
SED7	NEMERTEA		Nemertea indet	1	5	7
SED7	POLYCHAETA	Polynoidae	Polynoidae indet	5	3	4
SED7	POLYCHAETA	Phyllodocidae	Eulalia bilineata	1		
SED7	POLYCHAETA	Phyllodocidae	Eulalia mustela	4		5
SED7	POLYCHAETA	Phyllodocidae	Eulalia viridis			1
SED7	POLYCHAETA	Phyllodocidae	Eumida sanguinea	4		3
SED7	POLYCHAETA	Phyllodocidae	Phyllodoce sp.			1
SED7	POLYCHAETA	Phyllodocidae	Protomystides exigua			2
SED7	POLYCHAETA	Phyllodocidae	Pseudomystides spinachia	1		1
SED7	POLYCHAETA	Phyllodocidae	Sige fusigera		1	
SED7	POLYCHAETA	Pholoidae	Pholoe baltica	6	1	2
SED7	POLYCHAETA	Hesionidae	Neogyptis rosea		1	

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	POLYCHAETA	Hesionidae	Nereimyra punctata	1		
SED7	POLYCHAETA	Hesionidae	Psamathe cirrhata	5	2	3
SED7	POLYCHAETA	Syllidae	Exogone verugera	1		
SED7	POLYCHAETA	Syllidae	Sphaerosyllis hystrix	6	3	4
SED7	POLYCHAETA	Syllidae	Syllidae indet	9	4	
SED7	POLYCHAETA	Syllidae	Syllis sp.			1
SED7	POLYCHAETA	Syllidae	Trypanosyllis troll	9	1	4
SED7	POLYCHAETA	Nereididae	Nereis sp.		1	
SED7	POLYCHAETA	Nereididae	Nereis zonata	2		2
SED7	POLYCHAETA	Sphaerodoridae	Sphaerodoridae indet	1		
SED7	POLYCHAETA	Glyceridae	Glycera lapidum	5	4	4
SED7	POLYCHAETA	Eunicidae	Eunice pennata	21	3	25
SED7	POLYCHAETA	Lumbrineridae	Lumbrineris sp.	4	4	3
SED7	POLYCHAETA	Arabellidae	Drilonereis sp.	1		1
SED7	POLYCHAETA	Dorvilleidae	Dorvillea sp.		1	
SED7	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini		5	
SED7	POLYCHAETA	Orbiniidae	Orbiniidae indet	1		
SED7	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae	6	2	9
SED7	POLYCHAETA	Paraonidae	Aricidea sp.	2		
SED7	POLYCHAETA	Paraonidae	Paradoneis lyra	10	6	11
SED7	POLYCHAETA	Poecilochaetidae	Poecilochaetus serpens		1	1
SED7	POLYCHAETA	Spionidae	Aonides paucibranchiata	8	19	11
SED7	POLYCHAETA	Spionidae	Dipolydora caulleryi	2		3
SED7	POLYCHAETA	Spionidae	Dipolydora coeca		2	
SED7	POLYCHAETA	Spionidae	Laonice bahusiensis		1	
SED7	POLYCHAETA	Spionidae	Malacoceros fuliginosus	1		2
SED7	POLYCHAETA	Spionidae	Prionospio cirrifera	15	7	9
SED7	POLYCHAETA	Spionidae	Pseudopolydora nordica	2		3
SED7	POLYCHAETA	Spionidae	Pseudopolydora pulchra		4	3
SED7	POLYCHAETA	Spionidae	Spio sp.	1	1	1
SED7	POLYCHAETA	Spionidae	Spiophanes bombyx	6	32	9
SED7	POLYCHAETA	Spionidae	Spiophanes kroyeri	54	14	54
SED7	POLYCHAETA	Chaetopteridae	Chaetopterus variopedatus	1		
SED7	POLYCHAETA	Cirratulidae	Caulleriella sp.	8	1	3
SED7	POLYCHAETA	Cirratulidae	Chaetozone gibber	3		
SED7	POLYCHAETA	Cirratulidae	Chaetozone monteverdii			1
SED7	POLYCHAETA	Cirratulidae	Chaetozone sp.		3	
SED7	POLYCHAETA	Cirratulidae	Cirratulidae indet	1	1	
SED7	POLYCHAETA	Cirratulidae	Cirratulus cirratus	1	2	3
SED7	POLYCHAETA	Cirratulidae	Dodecaceria concharum			1
SED7	POLYCHAETA	Cirratulidae	Macrochaeta clavicornis		1	

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	POLYCHAETA	Cirratulidae	Macrochaeta sp.	1		3
SED7	POLYCHAETA	Scalibregmidae	Axiokebuita minuta	8		7
SED7	POLYCHAETA	Scalibregmidae	Polyphysia crassa	1		1
SED7	POLYCHAETA	Scalibregmidae	Scalibregma hanseni	3	2	5
SED7	POLYCHAETA	Capitellidae	Mediomastus fragilis	5	19	3
SED7	POLYCHAETA	Capitellidae	Notomastus latericeus	21	19	12
SED7	POLYCHAETA	Maldanidae	Euclymene droebachiensis			1
SED7	POLYCHAETA	Maldanidae	Euclymeninae indet	5	2	3
SED7	POLYCHAETA	Maldanidae	Maldanidae indet	1		
SED7	POLYCHAETA	Maldanidae	Notoproctus sp.			1
SED7	POLYCHAETA	Maldanidae	Praxillella affinis			1
SED7	POLYCHAETA	Oweniidae	Galathowenia oculata	13	3	35
SED7	POLYCHAETA	Oweniidae	Myriochele danielsseni	12	3	10
SED7	POLYCHAETA	Oweniidae	Owenia sp.	5	9	10
SED7	POLYCHAETA	Ampharetidae	Ampharete octocirrata	6	2	
SED7	POLYCHAETA	Ampharetidae	Ampharetidae indet	3	1	1
SED7	POLYCHAETA	Ampharetidae	Amphicteis gunneri	1	1	2
SED7	POLYCHAETA	Ampharetidae	Amythasides macroglossus	1	1	11
SED7	POLYCHAETA	Ampharetidae	Anobothrus gracilis		1	
SED7	POLYCHAETA	Ampharetidae	Lysippe fragilis	2		1
SED7	POLYCHAETA	Ampharetidae	Melinna elisabethae			1
SED7	POLYCHAETA	Ampharetidae	Samytha sexcirrata	1	1	2
SED7	POLYCHAETA	Ampharetidae	Sosane sulcata		2	
SED7	POLYCHAETA	Ampharetidae	Sosane wireni	2	3	5
SED7	POLYCHAETA	Terebellidae	Amaeana trilobata			1
SED7	POLYCHAETA	Terebellidae	Eupolymnia nebulosa			3
SED7	POLYCHAETA	Terebellidae	Eupolymnia nesidensis			1
SED7	POLYCHAETA	Terebellidae	Hauchiella tribullata		3	
SED7	POLYCHAETA	Terebellidae	Neoamphitrite affinis	35	22	10
SED7	POLYCHAETA	Terebellidae	Pista lornensis	2	2	2
SED7	POLYCHAETA	Terebellidae	Polycirrus medusa	3		
SED7	POLYCHAETA	Terebellidae	Polycirrus sp.	1		3
SED7	POLYCHAETA	Terebellidae	Streblosoma intestinale	7		
SED7	POLYCHAETA	Terebellidae	Terebellidae indet		11	
SED7	POLYCHAETA	Terebellidae	Thelepus cincinnatus	1	1	3
SED7	POLYCHAETA	Trichobanchidae	Octobranthus floriceps	3		
SED7	POLYCHAETA	Trichobanchidae	Terebellides stroemii	3		2
SED7	POLYCHAETA	Trichobanchidae	Trichobanchidae indet			1
SED7	POLYCHAETA	Trichobanchidae	Trichobranthus glacialis			4
SED7	POLYCHAETA	Trichobanchidae	Trichobranthus roseus			1
SED7	POLYCHAETA	Sabellidae	Branchiomma bombyx	4		1

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	POLYCHAETA	Sabellidae	Chone sp.	23	26	13
SED7	POLYCHAETA	Sabellidae	Euchone southerni	31	13	10
SED7	POLYCHAETA	Sabellidae	Euchone sp.	1		
SED7	POLYCHAETA	Sabellidae	Fabricia stellaris		3	1
SED7	POLYCHAETA	Sabellidae	Jasmineira caudata	5	12	9
SED7	POLYCHAETA	Sabellidae	Laonome kroyeri			1
SED7	POLYCHAETA	Sabellidae	Sabella pavonina	5		3
SED7	POLYCHAETA	Sabellidae	Sabellidae indet			3
SED7	POLYCHAETA	Serpulidae	Hydroides norvegica	1	15	12
SED7	POLYCHAETA	Serpulidae	Placostegus tridentatus	3		
SED7	POLYCHAETA	Lacydoniidae	Lacydonia sp.	8	1	8
SED7	OLIGOCHAETA		Oligochaeta indet	4	14	2
SED7	PROSOBRANCHIA		Gastropoda indet		1	
SED7	PROSOBRANCHIA	Fissurellidae	Emarginula crassa	1		
SED7	PROSOBRANCHIA	Fissurellidae	Puncturella noachina	2		2
SED7	PROSOBRANCHIA	Lepetidae	Iothia fulva	1		
SED7	PROSOBRANCHIA	Trochidae	Calliostoma occidentale			1
SED7	PROSOBRANCHIA	Rissoidae	Alvania punctura			2
SED7	PROSOBRANCHIA	Rissoidae	Rissoidae indet	1		
SED7	PROSOBRANCHIA	Lamellaridae	Velutina velutina		3	
SED7	PROSOBRANCHIA	Naticidae	Euspira montagui	1	3	
SED7	PROSOBRANCHIA	Eulimidae	Eulima bilineata	3		
SED7	PROSOBRANCHIA	Buccinidae	Turrisipho sp.		1	
SED7	PROSOBRANCHIA	Nassariidae	Tritia sp.	3		
SED7	PROSOBRANCHIA	Turridae	Villiersiella attenuata			1
SED7	OPISTOBRANCHIA		Cephalaspidea indet		1	
SED7	OPISTOBRANCHIA		Nudibranchia indet	1	1	2
SED7	OPISTOBRANCHIA	Diaphanidae	Diaphana minuta	1		
SED7	OPISTOBRANCHIA	Retusidae	Retusa umbilicata	1	1	
SED7	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus	12	4	15
SED7	POLYPLACOPHORA	Ischnochitonidae	Stenosemus albus	7	1	4
SED7	BIVALVIA	Nuculidae	Nucula tumidula	1		
SED7	BIVALVIA	Mytilidae	Modiolula phaseolina	1	2	8
SED7	BIVALVIA	Arcidae	Bathyarca pectunculoides		1	
SED7	BIVALVIA	Limidae	Limaria loscombi	1		
SED7	BIVALVIA	Limidae	Limatula gwyni	2	4	5
SED7	BIVALVIA	Limidae	Limea crassa		1	
SED7	BIVALVIA	Pectinidae	Pseudamussium peslutrae	3	6	3
SED7	BIVALVIA	Lucinidae	Lucinoma borealis	1		
SED7	BIVALVIA	Thyasiridae	Axinulus croulinensis	3		
SED7	BIVALVIA	Thyasiridae	Thyasira gouldi	2		3

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Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic) Dokumentansvarlig Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	BIVALVIA	Thyasiridae	Thyasira obsoleta	1		3
SED7	BIVALVIA	Thyasiridae	Thyasiridae indet	1		
SED7	BIVALVIA	Astartidae	Tridonta elliptica		1	1
SED7	BIVALVIA	Cardiidae	Papillicardium minimum	4	1	1
SED7	BIVALVIA	Veneridae	Timoclea ovata		1	
SED7	BIVALVIA	Veneridae	Venerupis corrugata	1		
SED7	BIVALVIA	Veneridae	Venus casina		1	
SED7	BIVALVIA	Hiatellidae	Hiatella arctica	1	1	1
SED7	BIVALVIA	Thraciidae	Thracia cf. phaseolina	1	1	3
SED7	BIVALVIA	Lyonsiidae	Lyonsia norwegica	2	1	2
SED7	SCAPHOPODA	Dentaliidae	Antalis entalis			1
SED7	PYCNOGONIDA		Pycnogonida indet	1		3
SED7	ISOPODA	Gnathidae	Gnathia sp.	1		3
SED7	ISOPODA	Arcturidae	Astacilla dilatata	1		
SED7	ISOPODA	Cirolanidae	Natanolana borealis		1	1
SED7	ISOPODA	Janiridae	Janira maculosa	2	1	
SED7	AMPHIPODA	Lysianassidae	Lysianassidae indet	2	2	
SED7	AMPHIPODA	Lysianassidae	Orchomene serratus	9	3	2
SED7	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis	21	7	
SED7	AMPHIPODA	Ampeliscidae	Ampelisca sp.			1
SED7	AMPHIPODA	Ampeliscidae	Ampelisca cf. spinipes		1	
SED7	AMPHIPODA	Ampeliscidae	Ampeliscidae indet	1		
SED7	AMPHIPODA	Ampeliscidae	Haploops setosa	6	10	33
SED7	AMPHIPODA	Haustoriidae	Urothoe elegans	9	1	5
SED7	AMPHIPODA	Oedicerotidae	Deflexilodes subnudus	1		3
SED7	AMPHIPODA	Phoxocephalidae	Harpinia crenulata		1	
SED7	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	2	3	3
SED7	AMPHIPODA	Liljeborgiidae	Cletodes sp.			1
SED7	AMPHIPODA	Liljeborgiidae	Liljeborgia kinahani	1		2
SED7	AMPHIPODA	Eusiridae	Eusirus longipes	1		
SED7	AMPHIPODA	Isaeidae	Megamphopus cornutus	3		1
SED7	DECAPODA		Caridea indet			1
SED7	DECAPODA	Hippolytidae	Caridion steveni	1		
SED7	DECAPODA	Hippolytidae	Eualus sp.	3		
SED7	DECAPODA	Galatheidae	Galathea intermedia	3		
SED7	DECAPODA	Galatheidae	Galathea sp.	3	1	4
SED7	DECAPODA	Paguridae	Paguridae indet			2
SED7	DECAPODA	Atelecyclidae	Atelecyclus rotundatus			1
SED7	SIPUNCULIDA		Golfingiida indet	10	7	14
SED7	SIPUNCULIDA		Nephasoma sp.		1	1
SED7	SIPUNCULIDA		Onchnesoma steenstrupii steenstrupii			1

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	SIPUNCULIDA		Phascolion (Phascolion) strombus strombus		1	
SED7	PHORONIDA		Phoronida indet	4	18	8
SED7	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa	5	1	3
SED7	OPHIUROIDEA		Ophiuroidea juvenil		1	1
SED7	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata	11	1	6
SED7	OPHIUROIDEA	Amphiuridae	Amphipholis squamata	5	1	1
SED7	OPHIUROIDEA	Ophiuridae	Ophiocten affinis			1
SED7	ECHINOIDEA		Spatangoida juvenil	1	1	2
SED7	ECHINOIDEA	Loveniidae	Echinocardium sp.	2		
SED7	HOLOTHUROIDEA		Holothuroidea indet	1		
SED7	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus		1	
SED7	HOLOTHUROIDEA	Sclerodactylidae	Thyone sp.	1		
SED7	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet		2	1
SED7	HOLOTHUROIDEA	Cucumariidae	Ocnus lacteus			1
SED7	HOLOTHUROIDEA	Cucumariidae	Panningia hyndmani		1	
SED7	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii		2	5
SED7	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria	4		1
SED7	HOLOTHUROIDEA	Phylloporidae	Neopentadactyla mixta		1	
SED7	ASCIDIACEA		Ascidia virginea	1		
SED7	ASCIDIACEA	Molgulidae	Molgula sp.	6	6	11

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic)

Dokumentansvarlig

Gunhild Borgersen

Vedlegg B Indekser og nEQR (normalized Ecological Quality Ratio)

Bløtbunnsindekser per grabbprøve: S=antall arter, N=antall individer, NQI1=Norwegian Quality Index, H'=Shannons diversitetsindeks, ES100=Hurlberts diversitetsindeks, ISI2018=Indicator Species Index versjon 2018 og NSI2018=Norwegian Sensitivity Index versjon 2018. AMBI, som inngår i NQI1, er beregnet på grunnlag av AMBI versjon: Oktober 2024

Dato	NR	Stasjon	Grabb	Prøvens areal (m ²)	S	N	NQI1	H'	ES100	ISI2018	NSI2018
20230907	5994	Bløt nær	G1	0,1	88	465	0,79	5,56	44,4	8,73	28,6
20230907	5995	Bløt nær	G2	0,1	102	443	0,82	5,94	51,5	8,14	28,8
20230907	5996	Bløt nær	G3	0,1	95	439	0,81	5,62	47,2	8,22	27,9
20230908	5997	Bløt2	G1	0,1	97	606	0,81	4,51	36,6	8,75	27,5
20230908	5998	Bløt2	G2	0,1	89	332	0,85	5,56	46,5	7,85	28,3
20230908	5999	Bløt2	G3	0,1	89	525	0,82	4,82	39,6	8,24	27,0
20230908	6000	Bløt4	G1	0,1	105	505	0,85	5,54	44,0	8,90	29,5
20230908	6001	Bløt4	G2	0,1	81	310	0,84	5,52	46,0	8,91	29,3
20230908	6002	Bløt4	G3	0,1	105	543	0,85	5,43	44,1	8,63	29,8
20230907	6003	SED7	G1	0,1	131	622	0,86	6,13	54,0	9,47	29,9
20230907	6004	SED7	G2	0,1	106	442	0,82	5,81	48,5	8,43	28,6
20230907	6005	SED7	G3	0,1	126	588	0,85	6,10	54,0	8,82	29,2

Gjennomsnittsverdier av de ulike indeksene for hver stasjon. AMBI, som inngår i NQI1, er beregnet på grunnlag av AMBI versjon: Oktober 2024

Stasjon	Dato	S	N	NQI1	H'	ES100	ISI2018	NSI2018
Bløt nær	20230907	95	449	0,81	5,71	47,7	8,36	28,5
Bløt2	20230908	92	488	0,82	4,96	40,9	8,28	27,6
Bløt4	20230908	97	453	0,84	5,50	44,7	8,81	29,5
SED7	20230907	121	551	0,84	6,01	52,2	8,91	29,3

nEQR (normalized Ecological Quality Ratio) for gjennomsnittsverdier av de ulike indeksene

Vanntype	Stasjon	Dato	NQI1 nEQR	H nEQR	ES100 nEQR	ISI2018 nEQR	NSI2018 nEQR
H1	Bløt nær	20230907	0,90	1,00*	1,00*	0,90	0,78
H1	Bløt2	20230908	0,91	0,94	0,96	0,89	0,75
H1	Bløt4	20230908	0,93	1,00*	0,99	0,92	0,82
H1	SED7	20230907	0,93	1,00*	1,00*	0,93	0,81

* Indeksverdien er over referanseverdien, og nEQR er satt til 1,00



ANALYSE- RAPPORT

**Norsk institutt
for vannforskning**

Økernveien 94
0579 Oslo
Tel: 22 18 51 00
Fax: 22 18 52 00

Analyserapport marin bløtbunnsfauna

Oppdragsgiver: NIVA

Kontaktperson oppdragsgiver: Gunhild Borgersen

Prosjektnummer: 220098

Rapport ID: 011-2025

Versjon: 1

Versjonsendring:

Analyseperiode:

Rapporteringsdato: 15.09.2025

Prøvermerking (stasjons-id og grabbnummer)	Prøvens løpenummer (fra NIVAs database)	Prøvetakingsdato	Prøve mottatt dato
Bløt2 G1*	6168	20250509	20250513
Bløt2 G2*	6169	20250509	20250513
Bløt4 G1*	6170	20250509	20250513
Bløt4 G2*	6171	20250509	20250513
Bløt4 G3*	6172	20250509	20250513
BløtNær G1	6173	20250509	20250513
BløtNær G2	6174	20250509	20250513
BløtNær G3*	6175	20250509	20250513
SED7 G1*	6176	20250509	20250513
SED7 G2	6177	20250509	20250513
SED7 G3	6178	20250509	20250513

* hadde innhold av materiale under grensen på 5 L.

Informasjon om prøven fra oppdragsgiver/prøvetaker: Bunnprøver fra 4 stasjoner ved tare dyrkingsanlegget på Storflua i Frohavet. På stasjon BLØT2 ble det kun tatt to replikate grabber. Sedimentet var grovt og hardt, og det var ikke nok materiale i grabben for å godkjennes. Båtenes teinehaler hadde ikke nok kraft til at ekstra vekter kunne brukes, noe som kanskje vil gi bedre resultater.

Analysemetode: Identifisering er i henhold til gjeldende versjon av ISO 16665 (Water quality - Guidelines for quantitative sampling and sample processing of marine soft-bottom macrofauna), NIVAs interne prosedyrer 16294 (Prosedyre M3 Bearbeidelse av bløtbunnsprøver), 16613 (Prosedyre

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljadic)

Dokumentansvarlig

Gunhild Borgersen

M4 Artsidentifisering av bløtbunnsfauna) og 16620 (Prosedyre M10 Faglige vurderinger og fortolkninger).

Taksonomisk personell:

Grovsortering: Rita Næss, Marijana Brkljadic

Polychaeta: Gunhild Borgersen, Rita Næss

Crustacea: Marijana Brkljadic

Echinodermata: Rita Næss, Marijana Brkljadic

Mollusca: Rita Næss

Varia: Rita Næss, Marijana Brkljadic

Databehandling:

Indeksberegning og beregning av nEQR: Gunhild Borgersen

Indekser og nEQR er beregnet etter: Klassifiseringsveileder, siste endring: 06.10.2025

Kommentarer: Flere av grabbprøvene hadde innhold av materialet under grensen på 5 L (se tabell forrige side). De ble likevel beholdt fordi det var utfordrende å få mer materiale grunnet den grove sedimenttypen på lokaliteten. På stasjon Bløt4 G1 ble en delprøve på ¼ sortert.

Underleverandører: Mausund feltstasjon bisto med fartøy.

Vedlegg:

A Artslister

B Indekser og nEQR (normalized Ecological Quality Ratio)

Artsregistreringer og indekser er lagt inn i NIVAs bløtbunnsdatabase.

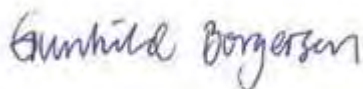
Artslisten og indekser leveres også til oppdragsgiver som excel-fil.

Referanser:

NS-EN ISO 16665:2013. Vannundersøkelse. Retningslinjer for kvantitativ prøvetaking og prøvebehandling av marin bløtbunnsfauna (ISO 16665:2014).

Miljødirektoratet (2025, 22.11): Veileder for klassifisering av miljøtilstand i kyst- og ferskvann. [Veileder for klassifisering av miljøtilstand i kyst- og ferskvann](#)

Godkjenning: Oslo, 23.11.2025



Rapport utarbeidet av: Gunhild Borgersen



Rapportgodkjenner: Marijana Brkljadic

Denne analyserapporten får kun kopieres i sin helhet og uten noen form for endringer. Analyseresultatet gjelder kun for den prøven som er testet.

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic)

Dokumentansvarlig

Gunhild Borgersen

Vedlegg A Artslister

Fullstendige artslister for bløtbunnsfauna.

G1=grabbprøve 1, G2=grabbprøve 2, G3=grabbprøve 3.

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	NEMERTEA		Nemertea indet	1	2	
Bløt2	POLYCHAETA	Amphinomidae	Paramphinome jeffreysii		1	
Bløt2	POLYCHAETA	Aphroditidae	Aphrodita aculeata		1	
Bløt2	POLYCHAETA	Polynoidae	Malmgrenia ljunghmani		1	
Bløt2	POLYCHAETA	Phyllodocidae	Eulalia mustela		1	
Bløt2	POLYCHAETA	Phyllodocidae	Eumida bahusiensis	1		
Bløt2	POLYCHAETA	Phyllodocidae	Phyllodoce rosea		1	
Bløt2	POLYCHAETA	Phyllodocidae	Sige fusigera	3	1	
Bløt2	POLYCHAETA	Pholoidae	Pholoe baltica	7	5	
Bløt2	POLYCHAETA	Syllidae	Exogone naidina		1	
Bløt2	POLYCHAETA	Syllidae	Exogone verugera	8	2	
Bløt2	POLYCHAETA	Nephtyidae	Nephtys hombergii		3	
Bløt2	POLYCHAETA	Nephtyidae	Nephtys paradoxa	1		
Bløt2	POLYCHAETA	Sphaerodoridae	Sphaerodorum gracilis	1		
Bløt2	POLYCHAETA	Glyceridae	Glycera lapidum	1	4	
Bløt2	POLYCHAETA	Lumbrineridae	Lumbrineris cf. aniana		1	
Bløt2	POLYCHAETA	Paraonidae	Aricidea (Aricidea) cf. wassi	1		
Bløt2	POLYCHAETA	Paraonidae	Paradoneis lyra	2	6	
Bløt2	POLYCHAETA	Poecilochaetidae	Poecilochaetus serpens		1	
Bløt2	POLYCHAETA	Spionidae	Aonides paucibranchiata	4	5	
Bløt2	POLYCHAETA	Spionidae	Laonice sarsi	1		
Bløt2	POLYCHAETA	Spionidae	Prionospio cirrifera	6	2	
Bløt2	POLYCHAETA	Spionidae	Prionospio multisetosa	1		
Bløt2	POLYCHAETA	Spionidae	Spiophanes kroyeri	64	54	
Bløt2	POLYCHAETA	Cirratulidae	Aphelochaeta sp.	1		
Bløt2	POLYCHAETA	Cirratulidae	Tharyx killariensis	4	2	
Bløt2	POLYCHAETA	Capitellidae	Notomastus latericeus	5	3	
Bløt2	POLYCHAETA	Maldanidae	Euclymeninae indet		2	
Bløt2	POLYCHAETA	Oweniidae	Galathowenia oculata	42	40	
Bløt2	POLYCHAETA	Oweniidae	Myriochele danielsseni	37	69	
Bløt2	POLYCHAETA	Oweniidae	Owenia sp.	5	6	
Bløt2	POLYCHAETA	Pectinariidae	Amphictene auricoma	1	2	
Bløt2	POLYCHAETA	Ampharetidae	Ampharete octocirrata	9	2	
Bløt2	POLYCHAETA	Ampharetidae	Ampharetidae indet		8	
Bløt2	POLYCHAETA	Ampharetidae	Amythasides macroglossus	5	13	
Bløt2	POLYCHAETA	Ampharetidae	Eclysippe vanelli	1	6	
Bløt2	POLYCHAETA	Ampharetidae	Lysippe fragilis	2	1	
Bløt2	POLYCHAETA	Ampharetidae	Lysippe labiata		1	

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Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	POLYCHAETA	Ampharetidae	Sosane wireni	2	5	
Bløt2	POLYCHAETA	Terebellidae	Eupolymnia nesidensis	1	10	
Bløt2	POLYCHAETA	Terebellidae	Hauchiella tribullata	1	1	
Bløt2	POLYCHAETA	Terebellidae	Nicolea venustula	1		
Bløt2	POLYCHAETA	Terebellidae	Paramphitrite birulai	1		
Bløt2	POLYCHAETA	Terebellidae	Pista lornensis	3	8	
Bløt2	POLYCHAETA	Terebellidae	Polycirrus medusa	1	2	
Bløt2	POLYCHAETA	Terebellidae	Polycirrus norvegicus	2		
Bløt2	POLYCHAETA	Terebellidae	Streblosoma intestinale		3	
Bløt2	POLYCHAETA	Trichobranchidae	Terebellides stroemii	1		
Bløt2	POLYCHAETA	Trichobranchidae	Trichobranchus roseus	1		
Bløt2	POLYCHAETA	Sabellidae	Chone sp.	3	4	
Bløt2	POLYCHAETA	Sabellidae	Euchone sp.	3	2	
Bløt2	POLYCHAETA	Sabellidae	Jasmineira caudata		1	
Bløt2	PROSOBRANCHIA	Naticidae	Euspira montagui	1		
Bløt2	PROSOBRANCHIA	Cerithiellidae	Cerithiella metula	1		
Bløt2	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus	1	2	
Bløt2	CAUDOFOVEATA		Caudofoveata indet		1	
Bløt2	BIVALVIA	Nuculanidae	Yoldiella philippiana		3	
Bløt2	BIVALVIA	Mytilidae	Modiolula phaseolina	1	1	
Bløt2	BIVALVIA	Arcidae	Batharca pectunculoides	1	1	
Bløt2	BIVALVIA	Limidae	Limatula gwyni		2	
Bløt2	BIVALVIA	Lucinidae	Myrtea spinifera	1	2	
Bløt2	BIVALVIA	Thyasiridae	Axinulus croulinensis	4	8	
Bløt2	BIVALVIA	Thyasiridae	Mendicula ferruginosa	7	2	
Bløt2	BIVALVIA	Thyasiridae	Thyasira obsoleta		2	
Bløt2	BIVALVIA	Thyasiridae	Thyasira sarsii	1	4	
Bløt2	BIVALVIA	Astartidae	Astarte sulcata	1		
Bløt2	BIVALVIA	Cardiidae	Papillicardium minimum		1	
Bløt2	SCAPHOPODA	Dentaliidae	Antalis entalis	2	1	
Bløt2	PYCNOGONIDA		Pycnogonida indet		1	
Bløt2	TANAIDACEA	Apseudidae	Apseudes spinosus	1		
Bløt2	ISOPODA	Gnathidae	Gnathia sp.		1	
Bløt2	AMPHIPODA	Lysianassidae	Scopelocheirus hopei		1	
Bløt2	AMPHIPODA	Lysianassidae	Tmetonyx sp.		2	
Bløt2	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis		3	
Bløt2	AMPHIPODA	Ampeliscidae	Ampelisca sp.		6	
Bløt2	AMPHIPODA	Ampeliscidae	Haploops setosa	1	13	
Bløt2	AMPHIPODA	Oedicerotidae	Westwoodilla caecula	1		
Bløt2	AMPHIPODA	Phoxocephalidae	Harpinia sp.		1	
Bløt2	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus		4	
Bløt2	AMPHIPODA	Aoridae	Aoridae indet		1	
Bløt2	DECAPODA	Paguridae	Paguridae indet	1		

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic)

Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
Bløt2	SIPUNCULIDA		Golfingiidae indet		1	
Bløt2	SIPUNCULIDA		Phascolion (Phascolion) strombus strombus		2	
Bløt2	PHORONIDA		Phoronis muelleri	1		
Bløt2	OPHIUROIDEA		Ophiuroidea juvenil		1	
Bløt2	OPHIUROIDEA	Amphiuridae	Amphiura chiajei	1	1	
Bløt2	OPHIUROIDEA	Ophiuridae	Ophiura sarsii	1		
Bløt2	OPHIUROIDEA	Ophiuridae	Ophiuridae indet		1	
Bløt2	ECHINOIDEA		Camarodonta juvenil		1	
Bløt2	ECHINOIDEA	Loveniidae	Echinocardium sp.	1	1	
Bløt2	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus	1	1	
Bløt2	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet		1	
Bløt2	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	6	3	
Bløt2	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria	2	4	
Bløt2	ASCIDIACEA	Molgulidae	Molgula sp.		1	
Bløt4	NEMERTEA		Nemertea indet	1	2	4
Bløt4	POLYCHAETA	Euphrosinidae	Euphrosine cirrata		1	
Bløt4	POLYCHAETA	Polynoidae	Harmothoe cf. fragilis		1	
Bløt4	POLYCHAETA	Polynoidae	Malmgrenia mcintoshi	1		
Bløt4	POLYCHAETA	Phyllodocidae	Eteone longa/flava		1	
Bløt4	POLYCHAETA	Phyllodocidae	Eulalia bilineata		1	
Bløt4	POLYCHAETA	Phyllodocidae	Eulalia tjalfiensis			1
Bløt4	POLYCHAETA	Phyllodocidae	Eulalia cf. tjalfiensis	1		
Bløt4	POLYCHAETA	Phyllodocidae	Mystides caeca	1		
Bløt4	POLYCHAETA	Phyllodocidae	Notophyllum foliosum		1	
Bløt4	POLYCHAETA	Phyllodocidae	Phyllodocidae indet			1
Bløt4	POLYCHAETA	Phyllodocidae	Pseudomystides limbata			1
Bløt4	POLYCHAETA	Phyllodocidae	Pseudomystides spinachia	1		
Bløt4	POLYCHAETA	Phyllodocidae	Sige fusigera	1		2
Bløt4	POLYCHAETA	Pholoidae	Pholoe baltica	1	7	5
Bløt4	POLYCHAETA	Hesionidae	Nereimyra punctata		1	
Bløt4	POLYCHAETA	Hesionidae	Psamathe cirrhata	1	2	2
Bløt4	POLYCHAETA	Pilargidae	Glyphohesione klatti	1		
Bløt4	POLYCHAETA	Syllidae	Exogone verugera	6		3
Bløt4	POLYCHAETA	Syllidae	Odontosyllis fasciata		1	
Bløt4	POLYCHAETA	Syllidae	Parexogone hebes	3		1
Bløt4	POLYCHAETA	Syllidae	Sphaerosyllis taylori	1	1	
Bløt4	POLYCHAETA	Syllidae	Syllidae indet	2	3	
Bløt4	POLYCHAETA	Nereididae	Nereis zonata		2	
Bløt4	POLYCHAETA	Glyceridae	Glycera lapidum	7	4	7
Bløt4	POLYCHAETA	Eunicidae	Eunice pennata		11	1
Bløt4	POLYCHAETA	Eunicidae	Eunice sp.		1	
Bløt4	POLYCHAETA	Lumbrineridae	Lumbrineris cf. aniara	8	5	5

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Bløt4	POLYCHAETA	Dorvilleidae	Dorvillea sp.		1	
Bløt4	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini	1		1
Bløt4	POLYCHAETA	Orbiniidae	Phylo norvegica		1	
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae	6		4
Bløt4	POLYCHAETA	Paraonidae	Aricidea (Acmira) cf. catherinae		1	
Bløt4	POLYCHAETA	Paraonidae	Aricidea sp.			1
Bløt4	POLYCHAETA	Paraonidae	Paradoneis lyra	8	8	9
Bløt4	POLYCHAETA	Spionidae	Aonides paucibranchiata	36		22
Bløt4	POLYCHAETA	Spionidae	Dipolydora caulleryi	1		
Bløt4	POLYCHAETA	Spionidae	Dipolydora coeca	2		
Bløt4	POLYCHAETA	Spionidae	Laonice bahusiensis		1	
Bløt4	POLYCHAETA	Spionidae	Malacoceros jirkovi	2		1
Bløt4	POLYCHAETA	Spionidae	Polydora sp.		1	
Bløt4	POLYCHAETA	Spionidae	Prionospio cirrifera	6	4	10
Bløt4	POLYCHAETA	Spionidae	Pseudopolydora nordica	1		1
Bløt4	POLYCHAETA	Spionidae	Pseudopolydora pulchra	2		
Bløt4	POLYCHAETA	Spionidae	Scolelepis korsuni	1		
Bløt4	POLYCHAETA	Spionidae	Spiophanes bombyx	3		1
Bløt4	POLYCHAETA	Spionidae	Spiophanes kroyeri	28	13	28
Bløt4	POLYCHAETA	Cirratulidae	Aphelochaeta sp.	3	2	
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone monteverdii		1	
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone sp.	4		
Bløt4	POLYCHAETA	Cirratulidae	Chaetozone zetlandica	1	2	1
Bløt4	POLYCHAETA	Cirratulidae	Macrochaeta sp.	1		2
Bløt4	POLYCHAETA	Cirratulidae	Tharyx killariensis		2	
Bløt4	POLYCHAETA	Cirratulidae	Tharyx sp.			1
Bløt4	POLYCHAETA	Scalibregmidae	Axiokebuita minuta		2	1
Bløt4	POLYCHAETA	Scalibregmidae	Polyphysia crassa		1	
Bløt4	POLYCHAETA	Scalibregmidae	Pseudoscalibregma parvum			1
Bløt4	POLYCHAETA	Scalibregmidae	Scalibregma hanseni	3	3	3
Bløt4	POLYCHAETA	Capitellidae	Mediomastus fragilis		2	
Bløt4	POLYCHAETA	Capitellidae	Notomastus latericeus	29	10	11
Bløt4	POLYCHAETA	Maldanidae	Euclymeninae indet	1	1	1
Bløt4	POLYCHAETA	Maldanidae	Notoproctus sp.		2	
Bløt4	POLYCHAETA	Oweniidae	Galathowenia oculata	26	33	34
Bløt4	POLYCHAETA	Oweniidae	Myriochele danielsseni	5	20	4
Bløt4	POLYCHAETA	Oweniidae	Owenia sp.	2	6	5
Bløt4	POLYCHAETA	Pectinariidae	Amphictene auricoma		1	
Bløt4	POLYCHAETA	Ampharetidae	Ampharete lindstroemi		2	1
Bløt4	POLYCHAETA	Ampharetidae	Ampharete octocirrata	2	4	5
Bløt4	POLYCHAETA	Ampharetidae	Ampharetidae indet	6		4
Bløt4	POLYCHAETA	Ampharetidae	Amphicteis gunneri		1	2
Bløt4	POLYCHAETA	Ampharetidae	Amythasides macroglossus	7	7	24

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Bløt4	POLYCHAETA	Ampharetidae	Eclysippe vanelli			4
Bløt4	POLYCHAETA	Ampharetidae	Lysippe fragilis	4		4
Bløt4	POLYCHAETA	Ampharetidae	Lysippe labiata		1	2
Bløt4	POLYCHAETA	Ampharetidae	Sosane sulcata		2	1
Bløt4	POLYCHAETA	Ampharetidae	Sosane wireni	5	5	18
Bløt4	POLYCHAETA	Terebellidae	Eupolymnia nebulosa		2	
Bløt4	POLYCHAETA	Terebellidae	Eupolymnia nesidensis	10		13
Bløt4	POLYCHAETA	Terebellidae	Neoamphitrite affinis		5	
Bløt4	POLYCHAETA	Terebellidae	Pista lornensis	5	1	7
Bløt4	POLYCHAETA	Terebellidae	Polycirrus norvegicus		3	
Bløt4	POLYCHAETA	Terebellidae	Polycirrus sp.	7		1
Bløt4	POLYCHAETA	Trichobranchidae	Octobranchus floriceps	2	4	
Bløt4	POLYCHAETA	Trichobranchidae	Terebellides stroemii	1	7	1
Bløt4	POLYCHAETA	Trichobranchidae	Trichobranchus roseus	1	1	
Bløt4	POLYCHAETA	Sabellidae	Branchiomma bombyx	4	7	
Bløt4	POLYCHAETA	Sabellidae	Chone duneri			1
Bløt4	POLYCHAETA	Sabellidae	Chone sp.	45		41
Bløt4	POLYCHAETA	Sabellidae	Euchone sp.	14	16	22
Bløt4	POLYCHAETA	Sabellidae	Fabricia stellaris		3	
Bløt4	POLYCHAETA	Sabellidae	Jasmineira caudata	43	71	141
Bløt4	POLYCHAETA	Sabellidae	Myxicola infundibulum			1
Bløt4	POLYCHAETA	Serpulidae	Placostegus tridentatus	1		
Bløt4	POLYCHAETA	Serpulidae	Spirobranchus triqueter		2	
Bløt4	POLYCHAETA	Lacydoniidae	Lacydonia miranda	1	1	
Bløt4	POLYCHAETA	Lacydoniidae	Lacydonia sp.			1
Bløt4	OLIGOCHAETA		Oligochaeta indet	5	11	3
Bløt4	PROSOBRANCHIA	Fissurellidae	Emarginula crassa		6	
Bløt4	PROSOBRANCHIA	Lepetidae	Lepeta caeca		1	
Bløt4	PROSOBRANCHIA	Rissoidae	Alvania sp.			1
Bløt4	PROSOBRANCHIA	Naticidae	Euspira montagui		1	
Bløt4	PROSOBRANCHIA	Cerithiellidae	Cerithiella metula		1	
Bløt4	PROSOBRANCHIA	Eulimidae	Haliella stenostoma		1	1
Bløt4	OPISTHOBANCHIA		Nudibranchia indet		1	
Bløt4	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus		17	
Bløt4	POLYPLACOPHORA	Ischnochitonidae	Stenosemus albus	1	3	
Bløt4	BIVALVIA	Nuculidae	Nucula nucleus		1	
Bløt4	BIVALVIA	Mytilidae	Modiolula phaseolina		3	1
Bløt4	BIVALVIA	Arcidae	Batharca pectunculoides		3	1
Bløt4	BIVALVIA	Limidae	Limatula gwyni	1	2	
Bløt4	BIVALVIA	Limidae	Limea crassa		2	
Bløt4	BIVALVIA	Pectinidae	Similipecten similis	5	4	1
Bløt4	BIVALVIA	Lucinidae	Lucinoma borealis			1
Bløt4	BIVALVIA	Thyasiridae	Axinulus croulinensis	2	2	2

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Bløt4	BIVALVIA	Thyasiridae	Thyasira obsoleta	1		1
Bløt4	BIVALVIA	Thyasiridae	Thyasira sarsii	2	1	4
Bløt4	BIVALVIA	Lasaeidae	Kurtiella bidentata			2
Bløt4	BIVALVIA	Lasaeidae	Tellimya tenella		1	
Bløt4	BIVALVIA	Montacutidae	Tellimya ferruginosa	1	1	
Bløt4	BIVALVIA	Astartidae	Astarte sulcata		3	
Bløt4	BIVALVIA	Astartidae	Tridonta elliptica	1		
Bløt4	BIVALVIA	Cardiidae	Papillicardium minimum		3	
Bløt4	BIVALVIA	Psammobiidae	Gari fervensis			1
Bløt4	BIVALVIA	Arctidae	Arctica islandica	1		
Bløt4	BIVALVIA	Veneridae	Timoclea ovata		1	
Bløt4	BIVALVIA	Hiatellidae	Hiatella arctica	1		
Bløt4	BIVALVIA	Thraciidae	Thracia sp.			1
Bløt4	BIVALVIA	Lyonsiidae	Lyonsia norvegica	1	1	2
Bløt4	BIVALVIA	Cuspidariidae	Tropidomya abbreviata	1		
Bløt4	SCAPHOPODA	Dentaliidae	Antalis entalis			2
Bløt4	CUMACEA	Lampropidae	Hemilamprops uniplicatus	1		
Bløt4	ISOPODA	Gnathidae	Gnathia sp.	1		2
Bløt4	ISOPODA	Arcturidae	Astacilla longicornis			1
Bløt4	ISOPODA	Cirolanidae	Natatolana borealis	1		
Bløt4	ISOPODA	Parasellidae	Munnopsidae indet		1	
Bløt4	ISOPODA	Janiridae	Janira maculosa		2	
Bløt4	ISOPODA	Munnopsidae	Echinozone coronata		1	
Bløt4	AMPHIPODA	Lysianassidae	Orchomene sp.		3	
Bløt4	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis	15	13	4
Bløt4	AMPHIPODA	Ampeliscidae	Ampelisca sp.			1
Bløt4	AMPHIPODA	Ampeliscidae	Haploops setosa	24	9	28
Bløt4	AMPHIPODA	Haustoriidae	Urothoe elegans	4	2	4
Bløt4	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus		3	1
Bløt4	AMPHIPODA	Atylidae	Nototropis vedlomensis	1	1	
Bløt4	AMPHIPODA	Isaeidae	Megamphopus cornutus	2		
Bløt4	AMPHIPODA	Corophiidae	Medicorophium affine	2		2
Bløt4	AMPHIPODA	Corophiidae	Unciola planipes	1		
Bløt4	AMPHIPODA	Photidae	Gammaropsis sophiae			2
Bløt4	DECAPODA	Galatheidae	Munida sarsi		3	
Bløt4	DECAPODA	Paguridae	Paguridae indet		1	
Bløt4	SIPUNCULIDA		Golfingiidae indet		5	1
Bløt4	SIPUNCULIDA		Phascalion (Phascalion) strombus strombus			2
Bløt4	SIPUNCULIDA		Thysanocardia procera		1	
Bløt4	BRACHIOPODA		Novocrania anomala		5	
Bløt4	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa		4	
Bløt4	OPHIUROIDEA		Ophiuroidea juvenil		4	1

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Bløt4	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata		5	
Bløt4	OPHIUROIDEA	Amphiuridae	Amphipholis squamata		4	3
Bløt4	ECHINOIDEA		Camarodonta juvenil		1	
Bløt4	ECHINOIDEA		Spatangoida juvenil		1	
Bløt4	ECHINOIDEA	Loveniidae	Echinocardium sp.	5		2
Bløt4	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus	3	1	
Bløt4	HOLOTHUROIDEA	Sclerodactylidae	Thyone fusus		2	
Bløt4	HOLOTHUROIDEA	Cucumariidae	Cucumariidae indet			1
Bløt4	HOLOTHUROIDEA	Cucumariidae	Ocnus lacteus	1	1	
Bløt4	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	3	1	8
Bløt4	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria		1	2
Bløt4	ASCIDIACEA	Molgulidae	Molgula sp.	2		2
BløtNær	ANTHOZOA	Edwardsiidae	Edwardsia sp.	1		
BløtNær	PLATYHELMINTHES		Platyhelminthes indet		1	
BløtNær	NEMERTEA		Nemertea indet	2	2	3
BløtNær	POLYCHAETA	Euprosinidae	Euprosine cirrata		1	
BløtNær	POLYCHAETA	Aphroditidae	Laetmonice filicornis	1		
BløtNær	POLYCHAETA	Polynoidae	Harmothoe cf. fragilis		1	
BløtNær	POLYCHAETA	Polynoidae	Harmothoe sp.	1		
BløtNær	POLYCHAETA	Phyllodocidae	Eumida sanguinea	1		
BløtNær	POLYCHAETA	Phyllodocidae	Nereiphylla lutea	1		
BløtNær	POLYCHAETA	Phyllodocidae	Phyllodoce groenlandica	1		
BløtNær	POLYCHAETA	Phyllodocidae	Protomystides exigua	1		
BløtNær	POLYCHAETA	Phyllodocidae	Pseudomystides spinachia			1
BløtNær	POLYCHAETA	Phyllodocidae	Sige fusigera		1	
BløtNær	POLYCHAETA	Pholoidae	Pholoe baltica	3	17	2
BløtNær	POLYCHAETA	Hesionidae	Psamathe cirrhata	4	10	1
BløtNær	POLYCHAETA	Syllidae	Exogone verugera	3	2	2
BløtNær	POLYCHAETA	Syllidae	Parexogone hebes			1
BløtNær	POLYCHAETA	Syllidae	Sphaerosyllis taylori	2	2	
BløtNær	POLYCHAETA	Syllidae	Syllidae indet			3
BløtNær	POLYCHAETA	Syllidae	Trypanosyllis troll		3	
BløtNær	POLYCHAETA	Nereididae	Nereis zonata		1	
BløtNær	POLYCHAETA	Sphaerodoridae	Sphaerodoropsis philippi		1	
BløtNær	POLYCHAETA	Glyceridae	Glycera alba	1		
BløtNær	POLYCHAETA	Glyceridae	Glycera lapidum	5	6	4
BløtNær	POLYCHAETA	Goniadidae	Goniada maculata			1
BløtNær	POLYCHAETA	Onuphidae	Hyalinoecia tubicola	2		
BløtNær	POLYCHAETA	Onuphidae	Nothria conchylega		2	
BløtNær	POLYCHAETA	Eunicidae	Eunice pennata	3	5	
BløtNær	POLYCHAETA	Lumbrineridae	Lumbrineris cf. aniara	3	3	3
BløtNær	POLYCHAETA	Dorvilleidae	Dorvillea sp.		1	
BløtNær	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini	1		

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BløtNær	POLYCHAETA	Orbiniidae	Phylo norvegica		2	
BløtNær	POLYCHAETA	Apistobranchidae	Apistobranchus tullbergi		1	
BløtNær	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae			4
BløtNær	POLYCHAETA	Paraonidae	Aricidea (Acmira) cf. catherinae	2		
BløtNær	POLYCHAETA	Paraonidae	Aricidea (Acmira) cerrutii			3
BløtNær	POLYCHAETA	Paraonidae	Paradoneis Iyra	22	4	7
BløtNær	POLYCHAETA	Spionidae	Aonides paucibranchiata	11	3	24
BløtNær	POLYCHAETA	Spionidae	Prionospio cirrifera	8	5	3
BløtNær	POLYCHAETA	Spionidae	Pseudopolydora nordica	1	1	6
BløtNær	POLYCHAETA	Spionidae	Pseudopolydora pulchra			1
BløtNær	POLYCHAETA	Spionidae	Spiophanes bombyx	1	1	1
BløtNær	POLYCHAETA	Spionidae	Spiophanes kroyeri	64	5	12
BløtNær	POLYCHAETA	Chaetopteridae	Chaetopterus variopedatus		1	
BløtNær	POLYCHAETA	Cirratulidae	Aphelochaeta sp.	3	1	
BløtNær	POLYCHAETA	Cirratulidae	Cauleriella sp.			1
BløtNær	POLYCHAETA	Cirratulidae	Chaetozone zetlandica	4	2	3
BløtNær	POLYCHAETA	Cirratulidae	Cirratulus cirratus		2	
BløtNær	POLYCHAETA	Cirratulidae	Dodecaceria concharum		1	
BløtNær	POLYCHAETA	Cirratulidae	Tharyx killariensis		3	1
BløtNær	POLYCHAETA	Cirratulidae	Tharyx sp.	2		
BløtNær	POLYCHAETA	Scalibregmidae	Axiokebuita minuta		23	
BløtNær	POLYCHAETA	Scalibregmidae	Polyphysia crassa		2	
BløtNær	POLYCHAETA	Scalibregmidae	Pseudoscalibregma parvum			1
BløtNær	POLYCHAETA	Scalibregmidae	Scalibregma hanseni	1	3	1
BløtNær	POLYCHAETA	Opheliidae	Ophelina cylindricaudata			1
BløtNær	POLYCHAETA	Capitellidae	Mediomastus fragilis	1		6
BløtNær	POLYCHAETA	Capitellidae	Notomastus latericeus	11	14	12
BløtNær	POLYCHAETA	Maldanidae	Nicomache sp.		1	
BløtNær	POLYCHAETA	Maldanidae	Praxillella affinis	1	2	
BløtNær	POLYCHAETA	Oweniidae	Galathowenia oculata	48	11	9
BløtNær	POLYCHAETA	Oweniidae	Myriochele danielsseni	7	8	1
BløtNær	POLYCHAETA	Oweniidae	Owenia sp.	10	11	14
BløtNær	POLYCHAETA	Pectinariidae	Pectinaria belgica		1	
BløtNær	POLYCHAETA	Ampharetidae	Ampharete lindstroemi	4		
BløtNær	POLYCHAETA	Ampharetidae	Ampharete octocirrata	7	2	2
BløtNær	POLYCHAETA	Ampharetidae	Ampharetidae indet			1
BløtNær	POLYCHAETA	Ampharetidae	Amphicteis gunneri	1		
BløtNær	POLYCHAETA	Ampharetidae	Amythasides macroglossus	4	2	1
BløtNær	POLYCHAETA	Ampharetidae	Lysippe fragilis	2		1
BløtNær	POLYCHAETA	Ampharetidae	Melinna elisabethae	1	1	
BløtNær	POLYCHAETA	Ampharetidae	Samytha sexcirrata	3		2
BløtNær	POLYCHAETA	Ampharetidae	Sosane sulcata	2	1	3
BløtNær	POLYCHAETA	Ampharetidae	Sosane wireni	19	1	2

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BløtNær	POLYCHAETA	Terebellidae	Eupolymnia nesidensis			5
BløtNær	POLYCHAETA	Terebellidae	Hauchiella tribullata	1		1
BløtNær	POLYCHAETA	Terebellidae	Neoamphitrite affinis	6	3	
BløtNær	POLYCHAETA	Terebellidae	Paramphitrite birulai			5
BløtNær	POLYCHAETA	Terebellidae	Pista lornensis	8		8
BløtNær	POLYCHAETA	Terebellidae	Polycirrus medusa	1		
BløtNær	POLYCHAETA	Terebellidae	Polycirrus norvegicus		2	1
BløtNær	POLYCHAETA	Terebellidae	Polycirrus sp.	2		1
BløtNær	POLYCHAETA	Terebellidae	Streblosoma intestinale	5		3
BløtNær	POLYCHAETA	Trichobranchidae	Octobranchus floriceps		1	1
BløtNær	POLYCHAETA	Trichobranchidae	Terebellides stroemii	3	3	
BløtNær	POLYCHAETA	Trichobranchidae	Trichobranchus roseus	2		
BløtNær	POLYCHAETA	Sabellidae	Branchiomma bombyx		2	
BløtNær	POLYCHAETA	Sabellidae	Chone duneri			1
BløtNær	POLYCHAETA	Sabellidae	Chone sp.	12		5
BløtNær	POLYCHAETA	Sabellidae	Euchone sp.	3	8	
BløtNær	POLYCHAETA	Sabellidae	Jasmineira caudata	2	16	2
BløtNær	POLYCHAETA	Sabellidae	Myxicola infundibulum		1	
BløtNær	POLYCHAETA	Serpulidae	Hydroides norvegica	2		
BløtNær	POLYCHAETA	Serpulidae	Spirorbis (Spirorbis) tridentatus		1	
BløtNær	OLIGOCHAETA		Oligochaeta indet	5	4	1
BløtNær	PROSOBRANCHIA	Fissurellidae	Puncturella noachina		3	
BløtNær	PROSOBRANCHIA	Lepetidae	Iothia fulva		1	
BløtNær	PROSOBRANCHIA	Cerithiellidae	Cerithiella metula		1	
BløtNær	PROSOBRANCHIA	Eulimidae	Melanella sp.		1	
BløtNær	PROSOBRANCHIA	Eulimidae	Vitreolina philippi		1	
BløtNær	PROSOBRANCHIA	Buccinidae	Buccinum undatum		2	
BløtNær	OPISTOBRANCHIA		Nudibranchia indet		1	
BløtNær	OPISTOBRANCHIA	Scaphandridae	Cylichna alba	1		
BløtNær	OPISTOBRANCHIA	Triviidae	Trivia arctica		1	
BløtNær	HETEROBRANCHIA	Dorididae	Archidoris pseudoargus		1	
BløtNær	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus	2	23	1
BløtNær	POLYPLACOPHORA	Ischnochitonidae	Stenosemus albus	1	4	
BløtNær	POLYPLACOPHORA	Acanthochitonidae	Acanthochitona crinita		5	
BløtNær	CAUDOFOVEATA		Caudofoveata indet	1		
BløtNær	BIVALVIA	Mytilidae	Crenella decussata		1	
BløtNær	BIVALVIA	Mytilidae	Modiolula phaseolina		6	
BløtNær	BIVALVIA	Arcidae	Asperarca nodulosa		2	
BløtNær	BIVALVIA	Limidae	Limaria loscombi		2	
BløtNær	BIVALVIA	Limidae	Limatula gwyni	3	2	1
BløtNær	BIVALVIA	Limidae	Limea crassa		1	
BløtNær	BIVALVIA	Pectinidae	Palliolium striatum	1	1	
BløtNær	BIVALVIA	Pectinidae	Pseudamussium peslutrae		1	

Analyserapport marin bløtbunnsfauna

Sist godkjent dato 07.03.2025 (Marijana Stenrud Brkljacic)

Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
BløtNær	BIVALVIA	Lucinidae	Myrtea spinifera		1	
BløtNær	BIVALVIA	Thyasiridae	Axinulus croulinensis	1		2
BløtNær	BIVALVIA	Thyasiridae	Mendicula ferruginosa		1	1
BløtNær	BIVALVIA	Thyasiridae	Thyasira sarsii	7	3	2
BløtNær	BIVALVIA	Lasaeidae	Tellimya tenella			1
BløtNær	BIVALVIA	Astartidae	Astarte sulcata		2	
BløtNær	BIVALVIA	Cardiidae	Papillicardium minimum	1	1	
BløtNær	BIVALVIA	Mactridae	Spisula elliptica			1
BløtNær	BIVALVIA	Arcticidae	Arctica islandica	2		
BløtNær	BIVALVIA	Veneridae	Timoclea ovata	2	6	
BløtNær	BIVALVIA	Veneridae	Venus casina		1	
BløtNær	BIVALVIA	Hiatellidae	Hiatella rugosa	1		
BløtNær	BIVALVIA	Thraciidae	Thracia sp.	1	1	2
BløtNær	BIVALVIA	Lyonsiidae	Lyonsia norvegica	1		
BløtNær	BIVALVIA	Cuspidariidae	Cardiomya costellata			2
BløtNær	ISOPODA	Gnathidae	Gnathia sp.	1		1
BløtNær	ISOPODA	Janiridae	Janira maculosa		1	
BløtNær	AMPHIPODA	Lysianassidae	Hippomedon denticulatus			1
BløtNær	AMPHIPODA	Lysianassidae	Lysianassidae indet		2	
BløtNær	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis	3		
BløtNær	AMPHIPODA	Ampeliscidae	Ampelisca cf. aequicornis		2	1
BløtNær	AMPHIPODA	Ampeliscidae	Ampelisca sp.	1		
BløtNær	AMPHIPODA	Ampeliscidae	Haploops setosa	9	8	1
BløtNær	AMPHIPODA	Amphilochoidea	Amphilocheus manudens		2	
BløtNær	AMPHIPODA	Haustoriidae	Urothoe elegans	3		3
BløtNær	AMPHIPODA	Oedicerotidae	Deflexilodes sp.		1	
BløtNær	AMPHIPODA	Phoxocephalidae	Harpinia sp.	1		
BløtNær	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	1	2	2
BløtNær	AMPHIPODA	Liljeborgiidae	Cletodes sp.		1	
BløtNær	AMPHIPODA	Liljeborgiidae	Liljeborgia kinahani		2	
BløtNær	AMPHIPODA	Atylidae	Nototropis vedlomensis	1	1	
BløtNær	AMPHIPODA	Isaeidae	Megamphopus cornutus			1
BløtNær	AMPHIPODA	Photidae	Gammaropsis sophiae	1		
BløtNær	DECAPODA	Galatheidae	Galathea intermedia		1	
BløtNær	DECAPODA	Paguridae	Paguridae indet		5	
BløtNær	SIPUNCULIDA		Golfingiidae indet		2	
BløtNær	SIPUNCULIDA		Phascolion (Phascolion) strombus strombus	1	1	1
BløtNær	BRACHIOPODA		Novocrania anomala	4	21	
BløtNær	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa		1	
BløtNær	OPHIUROIDEA		Ophiuroidea juvenil		1	
BløtNær	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata		4	
BløtNær	OPHIUROIDEA	Ophiuridae	Ophiura albida		1	

Analyserapport marin bløtbunnsfauna

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Dokumentansvarlig

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STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
BløtNær	ECHINOIDEA	Loveniidae	Echinocardium sp.	1		3
BløtNær	HOLOTHUROIDEA	Sclerodactylidae	Thyone fusus	1	2	
BløtNær	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	4	1	3
BløtNær	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria	1	2	
BløtNær	ASCIDIACEA	Molgulidae	Molgula sp.	2	1	1
SED7	NEMERTEA		Nemertea indet	3	3	2
SED7	POLYCHAETA	Polynoidae	Harmothoe sp.		1	
SED7	POLYCHAETA	Polynoidae	Malmgrenia ljunmani			1
SED7	POLYCHAETA	Phyllodocidae	Eteone longa/flava	1		
SED7	POLYCHAETA	Phyllodocidae	Eulalia mustela			4
SED7	POLYCHAETA	Phyllodocidae	Eumida sanguinea			1
SED7	POLYCHAETA	Phyllodocidae	Mystides caeca		1	
SED7	POLYCHAETA	Phyllodocidae	Phyllodoce groenlandica		2	
SED7	POLYCHAETA	Phyllodocidae	Phyllodoce rosea	1		
SED7	POLYCHAETA	Pholoidae	Pholoe baltica	3	6	6
SED7	POLYCHAETA	Hesionidae	Nereimyra punctata	3		1
SED7	POLYCHAETA	Hesionidae	Psamathe cirrhata	2		6
SED7	POLYCHAETA	Syllidae	Exogone verugera	8	3	3
SED7	POLYCHAETA	Syllidae	Parexogone hebes			1
SED7	POLYCHAETA	Syllidae	Parexogone hebes		1	
SED7	POLYCHAETA	Syllidae	Sphaerosyllis taylori			1
SED7	POLYCHAETA	Syllidae	Syllidae indet	1	2	2
SED7	POLYCHAETA	Syllidae	Trypanosyllis troll		1	4
SED7	POLYCHAETA	Nereididae	Nereididae indet			1
SED7	POLYCHAETA	Nephtyidae	Nephtys hombergii			1
SED7	POLYCHAETA	Nephtyidae	Nephtys longosetosa		1	
SED7	POLYCHAETA	Glyceridae	Glycera lapidum	2	4	4
SED7	POLYCHAETA	Eunicidae	Eunice pennata		3	5
SED7	POLYCHAETA	Eunicidae	Eunice sp.	3		2
SED7	POLYCHAETA	Lumbrineridae	Lumbrineris aniara			4
SED7	POLYCHAETA	Lumbrineridae	Lumbrineris cf. aniara	2	4	
SED7	POLYCHAETA	Dorvilleidae	Dorvillea sp.	1		
SED7	POLYCHAETA	Dorvilleidae	Protodorvillea kefersteini			4
SED7	POLYCHAETA	Paraonidae	Aricidea (Acmira) catherinae			6
SED7	POLYCHAETA	Paraonidae	Aricidea (Acmira) cf. catherinae	7	3	
SED7	POLYCHAETA	Paraonidae	Aricidea (Aricidea) cf. wassi	1		
SED7	POLYCHAETA	Paraonidae	Paradoneis lyra	12	10	19
SED7	POLYCHAETA	Spionidae	Aonides paucibranchiata	25	26	20
SED7	POLYCHAETA	Spionidae	Laonice bahusiensis			1
SED7	POLYCHAETA	Spionidae	Prionospio cirrifera	3	5	15
SED7	POLYCHAETA	Spionidae	Pseudopolydora nordica			1
SED7	POLYCHAETA	Spionidae	Scolecopsis sp.			1
SED7	POLYCHAETA	Spionidae	Spio sp.			1

Analyserapport marin bløtbunnsfauna

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Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	POLYCHAETA	Spionidae	Spiophanes bombyx	11	3	6
SED7	POLYCHAETA	Spionidae	Spiophanes kroyeri	24	33	39
SED7	POLYCHAETA	Chaetopteridae	Chaetopterus variopedatus		1	
SED7	POLYCHAETA	Cirratulidae	Aphelochaeta sp.	1		2
SED7	POLYCHAETA	Cirratulidae	Cauleriella sp.	4		4
SED7	POLYCHAETA	Cirratulidae	Chaetozone sp.	2	1	
SED7	POLYCHAETA	Cirratulidae	Chaetozone zetlandica	1	3	1
SED7	POLYCHAETA	Cirratulidae	Cirratulus cirratus	2	1	
SED7	POLYCHAETA	Cirratulidae	Macrochaeta sp.			2
SED7	POLYCHAETA	Cirratulidae	Tharyx killariensis			1
SED7	POLYCHAETA	Cirratulidae	Tharyx sp.		3	
SED7	POLYCHAETA	Scalibregmidae	Axiokebuita minuta			1
SED7	POLYCHAETA	Scalibregmidae	Pseudoscalibregma parvum			3
SED7	POLYCHAETA	Scalibregmidae	Scalibregma hanseni	1	2	1
SED7	POLYCHAETA	Scalibregmidae	Scalibregma inflatum	1	1	
SED7	POLYCHAETA	Capitellidae	Mediomastus fragilis	1	3	6
SED7	POLYCHAETA	Capitellidae	Notomastus latericeus	14	17	15
SED7	POLYCHAETA	Maldanidae	Euclymene droebachiensis			1
SED7	POLYCHAETA	Maldanidae	Nicomache sp.		1	
SED7	POLYCHAETA	Maldanidae	Praxillella affinis		1	
SED7	POLYCHAETA	Oweniidae	Galathowenia oculata	13	31	19
SED7	POLYCHAETA	Oweniidae	Myriochele danielsseni	6	5	16
SED7	POLYCHAETA	Oweniidae	Owenia sp.	12	6	13
SED7	POLYCHAETA	Pectinariidae	Lagis koreni		1	
SED7	POLYCHAETA	Ampharetidae	Ampharete lindstroemi		3	1
SED7	POLYCHAETA	Ampharetidae	Ampharete octocirrata	3	2	1
SED7	POLYCHAETA	Ampharetidae	Amphicteis gunneri	1	3	
SED7	POLYCHAETA	Ampharetidae	Amythasides macroglossus	1	3	
SED7	POLYCHAETA	Ampharetidae	Lysippe fragilis	2		2
SED7	POLYCHAETA	Ampharetidae	Lysippe labiata			1
SED7	POLYCHAETA	Ampharetidae	Melinna elisabethae		3	
SED7	POLYCHAETA	Ampharetidae	Samytha sexcirrata		3	1
SED7	POLYCHAETA	Ampharetidae	Sosane sulcata	1	1	
SED7	POLYCHAETA	Ampharetidae	Sosane wireni	5	4	4
SED7	POLYCHAETA	Terebellidae	Eupolymnia nebulosa	3		
SED7	POLYCHAETA	Terebellidae	Eupolymnia nesidensis			9
SED7	POLYCHAETA	Terebellidae	Hauchiella tribullata			2
SED7	POLYCHAETA	Terebellidae	Neoamphitrite affinis	2	17	
SED7	POLYCHAETA	Terebellidae	Pista lornensis	4	9	5
SED7	POLYCHAETA	Terebellidae	Polycirrus medusa	2		
SED7	POLYCHAETA	Terebellidae	Polycirrus norvegicus	3		
SED7	POLYCHAETA	Terebellidae	Polycirrus sp.			7
SED7	POLYCHAETA	Terebellidae	Streblosoma intestinale	1		1

Analyserapport marin bløtbunnsfauna

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Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	POLYCHAETA	Trichobranchidae	Terebellides stroemii		1	1
SED7	POLYCHAETA	Sabellidae	Branchiomma bombyx	2		
SED7	POLYCHAETA	Sabellidae	Chone sp.	2	3	14
SED7	POLYCHAETA	Sabellidae	Euchone sp.	5	8	11
SED7	POLYCHAETA	Sabellidae	Fabricia stellaris	1		
SED7	POLYCHAETA	Sabellidae	Jasmineira caudata	3	8	15
SED7	POLYCHAETA	Sabellidae	Potamilla neglecta			2
SED7	POLYCHAETA	Sabellidae	Sabella pavonina	3		
SED7	POLYCHAETA	Serpulidae	Circeis spirillum	1		
SED7	POLYCHAETA	Serpulidae	Hydroides norvegica			1
SED7	POLYCHAETA	Serpulidae	Placostegus tridentatus	1		
SED7	POLYCHAETA	Lacydoniidae	Lacydonia miranda	1		4
SED7	OLIGOCHAETA		Oligochaeta indet	2		21
SED7	PROSOBRANCHIA	Naticidae	Euspira montagui		1	
SED7	PROSOBRANCHIA	Turridae	Cyrrillia linearis		1	
SED7	OPISTOBRANCHIA		Nudibranchia indet			1
SED7	OPISTOBRANCHIA	Diaphanidae	Diaphana minuta	1		
SED7	POLYPLACOPHORA		Polyplacophora indet			1
SED7	POLYPLACOPHORA	Lepidopleuridae	Leptochiton asellus	1	2	11
SED7	POLYPLACOPHORA	Ischnochitonidae	Stenosemus albus	2		2
SED7	BIVALVIA	Nuculidae	Nucula nucleus	1		
SED7	BIVALVIA	Mytilidae	Modiolula phaseolina		3	4
SED7	BIVALVIA	Limidae	Limatula gwyni	6	18	12
SED7	BIVALVIA	Pectinidae	Palliolum striatum		2	
SED7	BIVALVIA	Pectinidae	Similipecten similis			5
SED7	BIVALVIA	Lucinidae	Lucinoma borealis		1	
SED7	BIVALVIA	Thyasiridae	Axinulus croulinensis		3	5
SED7	BIVALVIA	Thyasiridae	Thyasira obsoleta		2	
SED7	BIVALVIA	Thyasiridae	Thyasira sarsii	1	3	2
SED7	BIVALVIA	Cardiidae	Papillicardium minimum	2	1	3
SED7	BIVALVIA	Hiatellidae	Hiatella arctica	1		
SED7	BIVALVIA	Thraciidae	Thracia sp.	1	1	1
SED7	BIVALVIA	Lyonsiidae	Lyonsia norvegica			1
SED7	BIVALVIA	Cuspidariidae	Cardiomya costellata		1	1
SED7	SCAPHOPODA		Scaphopoda indet			1
SED7	SCAPHOPODA	Dentaliidae	Antalis entalis	1	1	1
SED7	PYCNOGONIDA		Pycnogonida indet	1		
SED7	ISOPODA	Cirolanidae	Natatulana borealis	1		1
SED7	ISOPODA	Janiridae	Janira maculosa			1
SED7	AMPHIPODA	Ampeliscidae	Ampelisca aequicornis		10	1
SED7	AMPHIPODA	Ampeliscidae	Haploops setosa	3	39	8
SED7	AMPHIPODA	Melitidae	Cheirocratus sp.		1	
SED7	AMPHIPODA	Haustoriidae	Urothoe elegans			5

Analyserapport marin bløtbunnsfauna

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Dokumentansvarlig

Gunhild Borgersen

STASJON	GRUPPENAVN	FAMILIENAVN	ARTSNAVN	G1	G2	G3
SED7	AMPHIPODA	Oedicerotidae	Deflexilodes sp.			2
SED7	AMPHIPODA	Phoxocephalidae	Harpinia crenulata			1
SED7	AMPHIPODA	Phoxocephalidae	Paraphoxus oculatus	2	1	6
SED7	AMPHIPODA	Atylidae	Nototropis vedlomensis	1		
SED7	AMPHIPODA	Isaeidae	Megamphopus cornutus		2	
SED7	AMPHIPODA	Photidae	Gammaropsis sp.		1	
SED7	DECAPODA	Paguridae	Paguridae indet			2
SED7	SIPUNCULIDA		Golfingiidae indet	2	3	6
SED7	SIPUNCULIDA		Nephasoma sp.			1
SED7	SIPUNCULIDA		Thysanocardia procera		1	
SED7	PHORONIDA		Phoronida indet			1
SED7	PHORONIDA		Phoronis muelleri		2	
SED7	BRACHIOPODA		Novocrania anomala	2		1
SED7	BRACHIOPODA	Cancellothyrididae	Terebratulina retusa			2
SED7	ASTEROIDEA		Asteroidea juvenil			1
SED7	OPHIUROIDEA		Ophiuroidea juvenil	1		
SED7	OPHIUROIDEA	Ophiactidae	Ophiopholis aculeata	4		7
SED7	OPHIUROIDEA	Amphiuridae	Amphipholis squamata			1
SED7	ECHINOIDEA		Camarodonta juvenil		1	1
SED7	ECHINOIDEA		Spatangoida juvenil			2
SED7	ECHINOIDEA	Loveniidae	Echinocardium sp.	1		
SED7	HOLOTHUROIDEA	Sclerodactylidae	Pseudothyone raphanus		3	2
SED7	HOLOTHUROIDEA	Sclerodactylidae	Thyone fusus		1	
SED7	HOLOTHUROIDEA	Sclerodactylidae	Thyone sp.			1
SED7	HOLOTHUROIDEA	Cucumariidae	Panningia hyndmani	1		
SED7	HOLOTHUROIDEA	Synaptidae	Labidoplax buskii	4	1	1
SED7	HOLOTHUROIDEA	Synaptidae	Leptosynapta decaria		2	4
SED7	ASCIDIACEA	Molgulidae	Molgula sp.	2	2	3

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Vedlegg B Indekser og nEQR (normalized Ecological Quality Ratio)

Bløtbunnsindekser per grabbprøve: S=antall arter, N=antall individer, NQI1=Norwegian Quality Index, H'=Shannons diversitetsindeks, ES100=Hurlberts diversitetsindeks, ISI2018=Indicator Species Index versjon 2018 og NSI2018=Norwegian Sensitivity Index versjon 2018. AMBI, som inngår i NQI1, er beregnet på grunnlag av AMBI versjon: Oktober 2024

Dato	NR	Stasjon	Grabb	Prøvens areal (m ²)	S	N	NQI1	H'	ES100	ISI2018	NSI2018
20250509	6168	Bløt2	G1	0,1	60	272	0,78	4,35	33,5	7,55	27,0
20250509	6169	Bløt2	G2	0,1	75	364	0,81	4,82	38,3	8,61	28,6
20250509	6170	Bløt4	G1	0,1	83	455	0,80	5,22	39,7	8,89	29,7
20250509	6171	Bløt4	G2	0,1	108	453	0,86	5,69	49,4	9,35	28,8
20250509	6172	Bløt4	G3	0,1	86	560	0,82	4,79	35,8	8,69	29,6
20250509	6173	BløtNær	G1	0,1	87	388	0,81	5,25	43,4	8,79	27,4
20250509	6174	BløtNær	G2	0,1	107	356	0,88	5,95	53,0	8,59	28,9
20250509	6175	BløtNær	G3	0,1	69	209	0,81	5,42	47,0	8,99	28,6
20250509	6176	SED7	G1	0,1	76	262	0,81	5,48	46,8	7,54	28,2
20250509	6177	SED7	G2	0,1	77	367	0,81	5,26	41,7	7,92	28,9
20250509	6178	SED7	G3	0,1	101	462	0,82	5,83	49,2	9,18	28,1

Gjennomsnittsverdier av de ulike indeksene for hver stasjon. AMBI, som inngår i NQI1, er beregnet på grunnlag av AMBI versjon: Oktober 2024

Stasjon	Dato	S	N	NQI1	H'	ES100	ISI2018	NSI2018
Bløt2	20250509	68	318	0,8	4,58	35,9	8,08	27,8
Bløt4	20250509	92	489	0,83	5,23	41,6	8,98	29,4
BløtNær	20250509	88	318	0,83	5,54	47,8	8,79	28,3
SED7	20250509	85	364	0,81	5,53	45,9	8,21	28,4

nEQR (normalized Ecological Quality Ratio) for gjennomsnittsverdier av de ulike indeksene

Vanntype	Stasjon	Dato	NQI1 nEQR	H nEQR	ES100 nEQR	ISI2018 nEQR	NSI2018 nEQR
H1	Bløt2	20250509	0,89	0,90	0,91	0,88	0,76
H1	Bløt4	20250509	0,92	0,97	0,96	0,93	0,81
H1	BløtNær	20250509	0,92	1,00	1,00	0,92	0,78
H1	SED7	20250509	0,9	1,00	1,00	0,89	0,78



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ANALYSERAPPORT

RapportID: 18680

Kunde: Gunhild Borgersen
Prosjektnummer: O 220098;BENTHI - Seaweed Carbon Solutions JIP

Analyseoppdrag: 1416-12966
Versjon: 1
Dato: 17.01.2024

Prøvenr.: NR-2023-12614
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 02.01.2024 - 02.01.2024

Prøvemerking: Id 1 Bløt1/Vann1/eDNA2-TOC 0-2
Stasjon : Id 1 Bløt1/Vann1/eDNA2
KjerneID/Replikant : A
Prøvetakingsdyp : 60,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	6,5	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:
Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12615
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 20.12.2023 - 20.12.2023

Prøvemerking: Id 14 SED7-Korn 0-5
Stasjon : Id 14 SED7
KjerneID/Replikant : A
Prøvetakingsdyp : 52,00 m Snitt: 0,00-5,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
KORNFORDELING					
* <63 µm	Intern metode (INTERN_NIVA)	5	% t.v.		

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Prøvenr.: NR-2023-12616 **Prøvemerkning:** Id 14 SED7-TOC TN 0-1
Prøvetype: SEDIMENT Stasjon : Id 14 SED7
Prøvetakningsdato: 07.09.2023 KjerneID/Replikant : A
Prøve mottatt dato: 28.11.2023 Prøvetakingsdyp : 52,00 m Snitt: 0,00-1,00 cm
Analyseperiode: 02.01.2024 - 02.01.2024 Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
PAKKE SM APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	3,8	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,36	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) C/N-forhold	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	10,6	t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12617 **Prøvemerkning:** Id 14 SED7-TOC 0-2
Prøvetype: SEDIMENT Stasjon : Id 14 SED7
Prøvetakningsdato: 07.09.2023 KjerneID/Replikant : A
Prøve mottatt dato: 28.11.2023 Prøvetakingsdyp : 52,00 m Snitt: 0,00-2,00 cm
Analyseperiode: 02.01.2024 - 02.01.2024 Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	3,6	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12618 **Prøvemerkning:** Id 16 SED9-TOC 0-2
Prøvetype: SEDIMENT Stasjon : Id 16 SED9
Prøvetakningsdato: 07.09.2023 KjerneID/Replikant : A
Prøve mottatt dato: 28.11.2023 Prøvetakingsdyp : 60,00 m Snitt: 0,00-2,00 cm
Analyseperiode: 02.01.2024 - 02.01.2024 Prøvetakingsmetode: Grab sampler

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerkning, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	2,6	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12619
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 20.12.2023 - 20.12.2023

Prøve­merking: Id 4 Bløt4-Korn 0-5
Stasjon : Id 4 Bløt4
KjerneID/Replikat : A
Prøvetakingsdyp : 66,00 m Snitt: 0,00-5,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
KORNFORDELING					
* <63 µm	Intern metode (INTERN_NIVA)	5	% t.v.		

Prøvenr.: NR-2023-12620
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 02.01.2024 - 02.01.2024

Prøve­merking: Id 4 Bløt4-TOC TN 0-1
Stasjon : Id 4 Bløt4
KjerneID/Replikat : A
Prøvetakingsdyp : 66,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
PAKKE SM APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	2,9	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,11	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) C/N-forhold	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	26,5	t.v.		AKVAPLAN_NIVA

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøve­merking, er oppgitt av oppdrags­giver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Utførende laboratorium / Underleverandør:

Akvi) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12621
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 02.01.2024 - 02.01.2024

Prøvemerking: Id 4 Bløt4-TOC 0-2
Stasjon : Id 4 Bløt4
KjerneID/Replikat : A
Prøvetakingsdyp : 66,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akvi) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	2,9	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akvi) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2023-12622
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 20.12.2023 - 20.12.2023

Prøvemerking: Id 2 Bløt2-Korn 0-5
Stasjon : Id 2 Bløt2
KjerneID/Replikat : A
Prøvetakingsdyp : 80,00 m Snitt: 0,00-5,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
KORNFORDELING					
* <63 µm	Intern metode (INTERN_NIVA)	7	% t.v.		

Prøvenr.: NR-2023-12623
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 02.01.2024 - 02.01.2024

Prøvemerking: Id 2 Bløt2-TOC TN 0-1
Stasjon : Id 2 Bløt2
KjerneID/Replikat : A
Prøvetakingsdyp : 80,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
PAKKE SM APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	5,2	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,64	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) C/N-forhold	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	8,2	t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.:	NR-2023-12624	Prøvermerking:	Id 2 Bløt2-TOC 0-2
Prøvetype:	SEDIMENT	Stasjon	: Id 2 Bløt2
Prøvetakningsdato:	08.09.2023	KjerneID/Replikant	: A
Prøve mottatt dato:	28.11.2023	Prøvetakingsdyp	: 80,00 m Snitt: 0,00-2,00 cm
Analyseperiode:	02.01.2024 - 02.01.2024	Prøvetakingsmetode:	Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	4,9	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.:	NR-2023-12625	Prøvermerking:	Id 1 Bløt1/Vann1/eDNA2-tørstoff
Prøvetype:	SEDIMENT	Stasjon	: Id 1 Bløt1/Vann1/eDNA2
Prøvetakningsdato:	07.09.2023	KjerneID/Replikant	: A
Prøve mottatt dato:	28.11.2023	Prøvetakingsdyp	: 0,00 m Snitt: 0,00-2,00 cm
Analyseperiode:	04.12.2023 - 04.12.2023	Prøvetakingsmetode:	Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
TTS TGR					
* Tørstoff %	Mod. NS 4764:1980 (B3)	65,9	%		

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvermerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Prøvenr.: NR-2023-12626
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 04.12.2023 - 04.12.2023

Prøvemerking: Id 14 SED7-tørrstoff
Stasjon : Id 14 SED7
KjerneID/Replikat : A
Prøvetakingsdyp : 52,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
TTS TGR * Tørrstoff %	Mod. NS 4764:1980 (B3)	66,0	%		

Prøvenr.: NR-2023-12627
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 04.12.2023 - 04.12.2023

Prøvemerking: Id 16 SED9-tørrstoff
Stasjon : Id 16 SED9
KjerneID/Replikat : A
Prøvetakingsdyp : 60,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
TTS TGR * Tørrstoff %	Mod. NS 4764:1980 (B3)	70,2	%		

Prøvenr.: NR-2023-12628
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 04.12.2023 - 04.12.2023

Prøvemerking: Id 4 Blot4-tørrstoff
Stasjon : Id 4 Blot4
KjerneID/Replikat : A
Prøvetakingsdyp : 66,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
TTS TGR * Tørrstoff %	Mod. NS 4764:1980 (B3)	70,0	%		

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Prøvenr.: NR-2023-12629
Prøvetype: SEDIMENT
Prøvetakningsdato: 08.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 04.12.2023 - 04.12.2023

Prøvemerking: Id 2 Bløt2-tørrstoff
Stasjon : Id 2 Bløt2
KjerneID/Replikat : A
Prøvetakingsdyp : 80,00 m Snitt: 0,00-2,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
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TTS TGR

* Tørrstoff %	Mod. NS 4764:1980 (B3)	62,3	%		
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Prøvenr.: NR-2023-13084
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 20.12.2023 - 20.12.2023

Prøvemerking: Id 7 Bløt nær - Korn 0-5
Stasjon : Id 7 Bløt nær
KjerneID/Replikat : A
Prøvetakingsdyp : 53,00 m Snitt: 0,00-5,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
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KORNFORDELING

* <63 µm	Intern metode (INTERN_NIVA)	4	% t.v.		
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Prøvenr.: NR-2023-13085
Prøvetype: SEDIMENT
Prøvetakningsdato: 07.09.2023
Prøve mottatt dato: 28.11.2023
Analyseperiode: 02.01.2024 - 02.01.2024

Prøvemerking: Id 7 Bløt nær - TOC TN 0-1
Stasjon : Id 7 Bløt nær
KjerneID/Replikat : A
Prøvetakingsdyp : 53,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Grab sampler

Kommentar:

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
PAKKE SM APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	4,7	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,39	mg/g TS t.v.		AKVAPLAN_NIVA
Akv) C/N-forhold	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	12,1	t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.:	NR-2023-13086	Prøvermerking:	Id 7 Bløt nær - TOC 0-2
Prøvetype:	SEDIMENT	Stasjon	: Id 7 Bløt nær
Prøvetakningsdato:	07.09.2023	KjerneID/Replikant	: A
Prøve mottatt dato:	28.11.2023	Prøvetakingsdyp	: 53,00 m Snitt: 0,00-2,00 cm
Analyseperiode:	02.01.2024 - 02.01.2024	Prøvetakingsmetode:	Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
NITROGEN KARBON APN					
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC/TC) og NS-EN 16168:2012 (Tot N)	4,1	mg/g TS t.v.		AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.:	NR-2023-13087	Prøvermerking:	Id 7 Bløt nær - tørrstoff
Prøvetype:	SEDIMENT	Stasjon	: Id 7 Bløt nær
Prøvetakningsdato:	07.09.2023	KjerneID/Replikant	: A
Prøve mottatt dato:	28.11.2023	Prøvetakingsdyp	: 53,00 m Snitt: 0,00-2,00 cm
Analyseperiode:	04.12.2023 - 04.12.2023	Prøvetakingsmetode:	Grab sampler

Kommentar:

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	Underlev.
TTS TGR					
* Tørrstoff %	Mod. NS 4764:1980 (B3)	63,4	%		

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor k=2),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvermerking, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.



Norsk institutt for vannforskning

Veronica Eftevåg

Overingeniør

Rapporten er elektronisk signert

Tegnforklaring:

* : Ikke akkreditert, >: Større enn, <: Mindre enn, MU: Måleusikkerhet (dekningsfaktor $k=2$),

LOQ: Kvantifiseringsgrense, t.v. (TS): tørrvekt, v.v.: våtvekt.

Mod: Intern metode basert på angitt standard. Ytterligere informasjon om benyttet metode, MU, LOQ eller utførende laboratorie kan fås ved henvendelse til laboratoriet. All informasjon angående prøvetaking, inkludert prøvemerkning, er oppgitt av oppdragsgiver. Analyserapporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.



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ANALYSERAPPORT

RapportID: 20938

Kunde: Gunhild Borgersen
Prosjektnummer: O 220098;BENTHI - Seaweed Carbon Solutions JIP

Analyseoppdrag: 1416-14957
Versjon: 1
Dato: 13.10.2025

Prøvenr.: NR-2025-09876
Prøvetype: SEDIMENT
Prøvetakningsdato: 09.05.2025
Prøve mottatt dato: 15.08.2025 13:39:23
Analyseperiode: 15.08.2025 - 13.10.2025

Prøvermerking: Id 14 SED7
Stasjon : SED7 Id 14
KjerneID/Replikant : A
Prøvetakingsdyp : 52,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
PAKKE SM APN						
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	2,8	mg/g TS t.v.			AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,61	mg/g TS t.v.			AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2025-09877
Prøvetype: SEDIMENT
Prøvetakningsdato: 09.05.2025
Prøve mottatt dato: 15.08.2025 13:39:23
Analyseperiode: 15.08.2025 - 13.10.2025

Prøvermerking: Id 4 Bløt4
Stasjon : Bløt4 Id 4
KjerneID/Replikant : A
Prøvetakingsdyp : 70,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
PAKKE SM APN						
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	3,1	mg/g TS t.v.			AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,84	mg/g TS t.v.			AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Tegnforklaring:

* : Ikke akkreditert, >: større enn, <: mindre enn, MU: måleusikkerhet (dekningsfaktor k=2), LOQ: kvantifiseringsgrense, t.v./TS: tørrvekt/tørrstoff, v.v.: våtvekt, na: ikke analysert, nq: ikke kvantifisert. Mod: intern metode basert på angitt standard. Ytterligere informasjon kan fås ved henvendelse til laboratoriet.

Analysereporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Prøvenr.: NR-2025-09878
Prøvetype: SEDIMENT
Prøvetakningsdato: 09.05.2025
Prøve mottatt dato: 15.08.2025 13:39:23
Analyseperiode: 15.08.2025 - 13.10.2025

Prøvemerking: Id 7 Bløt nær
Stasjon : Bløtnær Id 7
KjerneID/Replikant : A
Prøvetakingsdyp : 53,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
PAKKE SM APN						
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	2,5	mg/g TS t.v.			AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,70	mg/g TS t.v.			AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2025-09879
Prøvetype: SEDIMENT
Prøvetakningsdato: 09.05.2025
Prøve mottatt dato: 15.08.2025 13:39:23
Analyseperiode: 15.08.2025 - 13.10.2025

Prøvemerking: Id 2 Bløt2
Stasjon : Bløt2 Id 2
KjerneID/Replikant : A
Prøvetakingsdyp : 80,00 m Snitt: 0,00-1,00 cm
Prøvetakingsmetode: Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
PAKKE SM APN						
Akv) Totalt organisk karbon	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	3,3	mg/g TS t.v.			AKVAPLAN_NIVA
Akv) Total nitrogen	DIN 19539:2016 (TOC) og NS-EN 16168:2012 (Tot N)	0,86	mg/g TS t.v.			AKVAPLAN_NIVA

Utførende laboratorium / Underleverandør:

Akv) Akvaplan-Niva AS, ISO/IEC 17025:2017 Norsk Akkreditering TEST 079

Prøvenr.: NR-2025-09880
Prøvetype: SEDIMENT
Prøvetakningsdato: 09.05.2025
Prøve mottatt dato: 15.08.2025 13:39:23
Analyseperiode: 15.08.2025 - 09.10.2025

Prøvemerking: Id 14 SED7
Stasjon : SED7 Id 14
KjerneID/Replikant : A
Prøvetakingsdyp : 52,00 m Snitt: 0,00-5,00 cm
Prøvetakingsmetode: Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
KORNFORDELING						
* <63 µm	Intern metode (INTERN_NIVA)	6	% t.v.			

Tegnforklaring:

* : Ikke akkreditert, >: større enn, <: mindre enn, MU: måleusikkerhet (dekningsfaktor k=2), LOQ: kvantifiseringsgrense, t.v./TS: tørrvekt/tørrstoff, v.v.: våtvekt, na: ikke analysert, nq: ikke kvantifisert. Mod: intern metode basert på angitt standard.

Ytterligere informasjon kan fås ved henvendelse til laboratoriet.

Analysereporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Prøvenr.:	NR-2025-09881	Prøvemerkning:	Id 4 Bløt4
Prøvetype:	SEDIMENT	Stasjon	: Bløt4 Id 4
Prøvetakningsdato:	09.05.2025	KjerneID/Replikat	: A
Prøve mottatt dato:	15.08.2025 13:39:23	Prøvetakingsdyp	: 70,00 m Snitt: 0,00-5,00 cm
Analyseperiode:	15.08.2025 - 09.10.2025	Prøvetakingsmetode:	Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
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KORNFORDELING

* <63 µm	Intern metode (INTERN_NIVA)	7	% t.v.			
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Prøvenr.:	NR-2025-09882	Prøvemerkning:	Id 7 Bløt nær
Prøvetype:	SEDIMENT	Stasjon	: Bløtnær Id 7
Prøvetakningsdato:	09.05.2025	KjerneID/Replikat	: A
Prøve mottatt dato:	15.08.2025 13:39:23	Prøvetakingsdyp	: 53,00 m Snitt: 0,00-5,00 cm
Analyseperiode:	15.08.2025 - 09.10.2025	Prøvetakingsmetode:	Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
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KORNFORDELING

* <63 µm	Intern metode (INTERN_NIVA)	6	% t.v.			
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Prøvenr.:	NR-2025-09883	Prøvemerkning:	Id 2 Bløt2
Prøvetype:	SEDIMENT	Stasjon	: Bløt2 Id 2
Prøvetakningsdato:	09.05.2025	KjerneID/Replikat	: A
Prøve mottatt dato:	15.08.2025 13:39:23	Prøvetakingsdyp	: 80,00 m Snitt: 0,00-5,00 cm
Analyseperiode:	15.08.2025 - 09.10.2025	Prøvetakingsmetode:	Van Veen grab

Analyse / Parameter	Standard (NIVA metodekode)	Resultat	Enhet	LOQ	MU	Underlev.
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KORNFORDELING

* <63 µm	Intern metode (INTERN_NIVA)	8	% t.v.			
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Tegnforklaring:

* : Ikke akkreditert, >: større enn, <: mindre enn, MU: måleusikkerhet (dekningsfaktor k=2), LOQ: kvantifiseringsgrense, t.v./TS: tørrvekt/tørrstoff, v.v.: våtvekt, na: ikke analysert, nq: ikke kvantifisert. Mod: intern metode basert på angitt standard.

Ytterligere informasjon kan fås ved henvendelse til laboratoriet.

Analysereportoren må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.



Norsk institutt for vannforskning
Tina Bryntesen

Rapporten er elektronisk signert

Tegnforklaring:

* : Ikke akkreditert, >: større enn, <: mindre enn, MU: måleusikkerhet (dekningsfaktor $k=2$), LOQ: kvantifiseringsgrense, t.v./TS: tørrvekt/tørrestoff, v.v.: våtvekt, na: ikke analysert, nq: ikke kvantifisert. Mod: intern metode basert på angitt standard.

Ytterligere informasjon kan fås ved henvendelse til laboratoriet.

Analysereporten må kun gjengis i sin helhet og uten noen form for endringer. Analyseresultatet gjelder prøven slik den ble mottatt.

Appendix G invertebrate epifauna analyses

Location	Substrate	Sample	Date	Class	Family	Genus	Species	Count
Storflua	Structural Rope	6	07/05/2025	Copepoda	Copepoda			1
Storflua	Structural Rope	6	07/05/2025	Amphipoda	Ischyroceridae			1
Storflua	Structural Rope	6	07/05/2025	Amphipoda	Ischyroceridae	Jassa		4
Storflua	Structural Rope	6	07/05/2025	Mytilida	Mytilidae	Mytilus	Mytilus edilus	1
Storflua	Structural Rope	03-May	07/05/2025	Copepoda	Copepoda			1
Storflua	Structural Rope	03-May	07/05/2025	Amphipoda	Ischyroceridae			2
Storflua	Structural Rope	03-May	07/05/2025	Amphipoda	Ischyroceridae	Jassa		7
Storflua	Structural Rope	03-May	07/05/2025	Mytilida	Mytilidae	Mytilus	Mytilus edilus	1
Storflua	Structural Rope	03-May	07/05/2025	Isopoda	Idoteidae	Idotea	Idotea pelagica	1
Storflua	Structural Rope	2	10/05/2025	Copepoda	Copepoda			1
Storflua	Structural Rope	2	10/05/2025	Amphipoda	Ischyroceridae			1
Storflua	Structural Rope	2	10/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	2
Storflua	Structural Rope	2	10/05/2025	Isopoda	Idoteidae	Idotea	Idotea pelagica	1
Storflua	Buoy	04-Jan	10/05/2025	Copepoda	Copepoda			31
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae			30
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae	Jassa		33
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	1
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda				2
Storflua	Buoy	11-Apr	07/05/2025	Copepoda	Copepoda			42
Storflua	Buoy	11-Apr	07/05/2025	Amphipoda	Ischyroceridae			10
Storflua	Buoy	11-Apr	07/05/2025	Amphipoda	Ischyroceridae	Jassa		37
Storflua	Buoy	11-Apr	07/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	1
Storflua	Buoy	11-Apr	07/05/2025	Amphipoda	Gammarellidae	Gammarellus	Gammarellus homari	1
Storflua	Buoy	11-Apr	07/05/2025	Amphipoda				2
Storflua	Buoy	05-Mar	10/05/2025	Copepoda	Copepoda			10
Storflua	Buoy	05-	10/05/2025	Amphipoda	Ischyroceridae	Jassa		25

Location	Substrate	Sample	Date	Class	Family	Genus	Species	Count
		Mar	5					
Storflua	Buoy	05-Mar	10/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	3
Storflua	Buoy	05-Mar	10/05/2025	Amphipoda				1
Storflua	Buoy	04-Jan	10/05/2025	Copepoda	Copepoda			30
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae			34
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae	Jassa		37
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	1
Storflua	Buoy	04-Jan	10/05/2025	Amphipoda				1
Storflua	Buoy	03-May	07/05/2025	Copepoda	Copepoda			1
Storflua	Buoy	03-May	07/05/2025	Amphipoda	Ischyroceridae			4
Storflua	Buoy	03-May	07/05/2025	Amphipoda	Ischyroceridae	Jassa		27
Storflua	Buoy	03-May	07/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	7
Storflua	Buoy	03-May	07/05/2025	Isopoda	Idoteidae	Idotea	Idotea pelagica	1
Storflua	Structural Rope	03-May	07/05/2025	Amphipoda	Ischyroceridae			2
Storflua	Structural Rope	03-May	07/05/2025	Amphipoda	Ischyroceridae	Jassa		40
Storflua	Structural Rope	03-May	07/05/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	4
Storflua	Kelp	1	28/05/2025	Copepoda	Copepoda			374
Storflua	Kelp	1	28/05/2025	Amphipoda	Ischyroceridae			1
Storflua	Kelp	1	28/05/2025	Amphipoda	Ischyroceridae	Jassa		5
Storflua	Kelp	1	28/05/2025	Amphipoda	Calliopiidae			3
Storflua	Kelp	1	28/05/2025	Amphipoda	Caprellidae			1
Storflua	Kelp	1	28/05/2025	Amphipoda				4
Storflua	Kelp	3	28/05/2025	Copepoda	Copepoda			332
Storflua	Kelp	3	28/05/2025	Amphipoda	Ischyroceridae			2
Storflua	Kelp	3	28/05/2025	Amphipoda	Ischyroceridae	Jassa		5
Storflua	Kelp	3	28/05/2025	Amphipoda				10
Storflua	Kelp	2	28/05/2025	Copepoda	Copepoda			455
Storflua	Kelp	2	28/05/2025	Amphipoda				1

Location	Substrate	Sample	Date	Class	Family	Genus	Species	Count
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Copepoda	Copepoda			20
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Caprellidae	Caprella sp		53
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Caprellidae	Caprella sp	Caprellamutica	7
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Copepoda	Copepoda			20
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Ischyroceridae	Jassa		19
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Ischyroceridae	Jassa	Jassa falcata	4
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda				3
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Copepoda	Copepoda			20
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Ischyroceridae			1
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Amphipoda	Caprellidae	Caprella sp		1
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Phyllodocida	Polynoidae			1
Storflua	Structure I Rope + Multi-Year Kelp	1	08/06/2025	Phyllodocida	Nereididae			6
Storflua	Structure I Rope + Multi-Year Kelp	2	08/06/2025	Copepoda	Copepoda			20
Storflua	Structure I Rope + Multi-Year Kelp	2	08/06/2025	Amphipoda	Caprellidae	Caprella sp		22

Location	Substrate	Sample	Date	Class	Family	Genus	Species	Count
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Amphipoda				1
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Copepoda	Copepoda			20
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Amphipoda	Ischyroceridae			20
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Amphipoda	Ischyroceridae	Jassa		8
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Amphipoda				2
Storflua	Structural Rope + Multi-Year Kelp	2	08/06/2025	Trochida	Trochidae	Gibbula sp		1
Storflua	Structural Rope + Multi-Year Kelp	3	08/06/2025	Copepoda	Copepoda			447
Storflua	Structural Rope + Multi-Year Kelp	3	08/06/2025	Amphipoda	Ischyroceridae			20
Storflua	Structural Rope + Multi-Year Kelp	3	08/06/2025	Amphipoda	Ischyroceridae	Jassa		1
Storflua	Structural Rope + Multi-Year Kelp	3	08/06/2025	Amphipoda	Caprellidae	Caprella sp		4
Storflua	Structural Rope + Multi-Year Kelp	3	08/06/2025	Amphipoda				2



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SINTEF

Technical Report

JIP Seaweed Carbon Solutions: Kelp carbon deposition in deep ocean (WP6) – FINAL REPORT

Author(s):

Luiza Neves, Jorunn Skjermo, Kristin Sagosen Smeby, Ole Jacob Broch

Report No: 2025:01113 - Unrestricted

Client(s):

DNV, Equinor, Aker BP, Ocean Rainforest, Wintershall DEA

Report

JIP Seaweed Carbon Solutions

Kelp carbon deposition in deep ocean (WP6) – FINAL REPORT

KEYWORDS

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 CO2
 Marine biomass
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 Aquaculture

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3

DATE

2025-10-29

AUTHOR(S)

Luiza Neves, Jorunn Skjermo, Kristin Sagosen Smeby, Ole Jacob Broch

CLIENT(S)

DNV, Equinor, Aker BP, Ocean Rainforest, Wintershall
 DEA

CLIENT'S REFERENCE

Ellen Skarsgård, Hanne Greiff, Axel
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 Shultz

PROJECT NO.

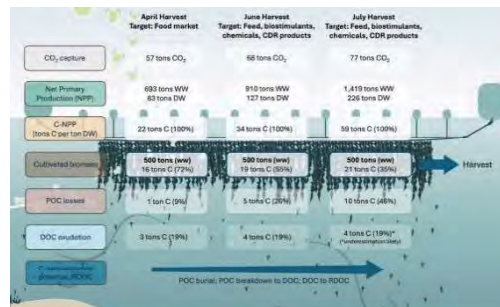
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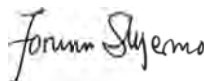
145

SUMMARY

This report is a summary of the scientific paper by Luiza Neves et al, 2025, published as part of L. Neves PhD. The work has been financed by an institute PhD scholarship provided by SINTEF Ocean and by WP6 in the SCS JIP.

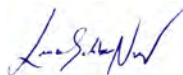


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 Jorunn Skjermo



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 Luiza Neves



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APPROVED BY
 Silje Forbord



Silje Forbord (Jan 23, 2026 11:06:33 GMT+1)

SIGNATURE

Document history

VERSION	DATE	VERSION DESCRIPTION
1	2025-03-31	First draft of WP6-report
2	2025-10-24	Second draft checked by L Neves
3	2025-10-29	Final

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1 Main findings and conclusions

- New data is provided for dissolved organic carbon (DOC) release from cultivated *Saccharina latissima*.
- Losses of particular organic carbon (POC) and DOC from seaweed farms have been assessed for autumn and winter out-plantings in two cultivation seasons.
- Optimal harvest strategies for maximising carbon capture are suggested, indicating harvest in June or July for highest CDR potential and April for food grade kelp.
- **A kelp farm producing 500 tons wet weight for harvest in June or July may capture 68 or 77 tons CO₂ depending on harvest time (136 or 154 kg CO₂ per ton WW).**
 - At harvest the biomass contains 19-21 tons C (72-35% of the C-NPP)
 - At harvest the loss to the sea is 9-14 tons C, corresponding to 33-51 tons CO₂
- By prolonging the cultivation season to June or July 45-65% of the captured CO₂ is lost passively to the sea as POC and DOC, contributing to natural carbon sequestration processes.
- From April to July the POC loss increases heavily (from 9 to 46% of the C-NPP).
- DOC loss from the farm was calculated at 19% of the C-NPP for kelp in April (unfouled), however more seasonal studies are needed to better understand continuous DOC losses throughout the season.
- Both POC and DOC may be broken down and converted to recalcitrant dissolved organic carbon (RDOC), contributing to long-term sequestration, yet more studies are needed to assess its permanence in the marine ecosystem.
- Future research should focus on quantifying the contribution of macroalgae farming to natural carbon capture, utilization and storage (CCUS) processes and optimizing farming practices to enhance carbon capture efficiency.

2 Abstract

This report is a short summary of the full article:

Neves, L., Smeby, K., Broch, O.J., Johnsen, G., Ardelan, M., Skjermo, J. (2025). Particulate and dissolved organic carbon losses in high latitude seaweed farms, *Science of the Total Environment*, 982. <https://doi.org/10.1016/j.scitotenv.2025.179677>

The role of macroalgae as natural CO₂ sinks has long been recognized, and interest for climate mitigating solutions from seaweed cultivation is quickly rising. Erosion of biomass provides a natural avenue for carbon sequestration at sea, yet data is still lacking for important European cultivars, particularly combining the “passive” particulate and dissolved organic carbon losses from seaweed farms. Active deposition of cultivated biomass at deepwater seafloor, i.e., intentionally placing kelp biomass at the seafloor below 1000 metres depth for long term storage (>1000 years) of the carbon, is also proposed as a solution for Carbon Dioxide Removal (CDR) and the concept and possible ideas for testing and knowledge building have been discussed in the JIP SCS project. However, due to large uncertainties regarding direct effects of the deposited kelp biomass on the deep-sea environment the project decided to focus only on the passive deposition of seaweed carbon.

In the study presented in this report, data is given on carbon uptake, lamina growth and erosion over two consecutive seasons, in 2021-22 and 2022-23, for the kelp *Saccharina latissima* deployed in autumn (October) and winter (January) in Hitra, Norway. A short-term carbon exudation experiment was performed with kelp from the farm in 2023.

By April, the typical harvest time for food applications, average losses to particulate (POC) and dissolved organic carbon (DOC) pools were equivalent to 12% and 27% of the cultivated biomass, or 9% and 19% of the net primary production (NPP) of the farm. By June and July, 45% and 65% of NPP were attributed to POC and DOC losses, respectively. DOC exudation rates reached 4.1-7.6 mg C g⁻¹ h⁻¹ after 4h incubation, reducing to 24h. On average, 29% and 12% of the carbon fixed by *S. latissima* was released as DOC from autumn and winter deployments, respectively, before the progression of bryozoan biofouling. POC and DOC losses provide a continuous source for carbon deposition, burial or further breakdown into RDOC, crucial for environmental impact assessments and carbon accounting methodologies. The study provides valuable data for future research aimed at evaluating various aspects of macroalgae cultivation and its contribution to global carbon mitigation efforts.

3 Introduction

An increasing number of studies support the role of cultivated macroalgae in carbon sequestration, in parallel to multiple social and ecosystem benefits (Krause-Jensen & Duarte, 2016; Froehlich et al., 2019; Gao et al., 2022; Rose & Hemery, 2023; Fricke et al., 2024). Seaweed cultivation may contribute to lowering carbon emissions by replacing products of higher carbon footprints (DeAngelo et al., 2022; Troell et al., 2022), producing carbon dioxide removal (CDR) products where the carbon does not return to the atmosphere after use for hundreds or thousands of years, such as biochar (Bird et al., 2012; Roberts et al., 2015), through co-utilization of energy streams and re-utilization of seaweed waste in biorefineries for additional valuable products (Liu et al., 2024), in reforestation to recover lost or severely impacted kelp forests, or afforestation to create new forest areas (Chung et al., 2013; Eger et al., 2022; Ross et al., 2022).

Seaweed farms may function as “hanging forests”, creating habitat for a diverse assemblage of organisms (Bekkby et al., 2009; Corrigan et al., 2024) whilst increasing carbon capture by the oceans through photosynthesis and helping to counteract ocean acidification locally by increasing seawater pH (Duarte, 2017; Xiao et al., 2021; Young et al., 2022; Edworthy et al., 2023). Seaweed cultivation can therefore help in

mitigation and adaptation to climate change, while helping to achieve many of the United Nations Sustainable Development Goals (Duarte et al., 2017, 2021; Spillias et al., 2022). Particularly at large scales, seaweed farming may also bring negative impacts which should be monitored holistically (Campbell et al., 2019). Loss of organic matter from cultivation facilities should be monitored for any negative ecological impact, as well as contributions to long-term carbon sequestration (Hancke et al., 2021).

Both particulate (POC) and dissolved organic carbon (DOC) may be broken down and converted by bacteria into long-lasting, recalcitrant dissolved organic carbon (RDOC), able to accumulate and become sequestered in the water column (Jiao et al., 2010; Hansell, 2013), in sediments under farms (Duarte et al., 2025) or in the deep sea (Filbee-Dexter et al., 2018; Ortega et al., 2019; Queirós et al., 2019; Gao et al., 2021; Li et al., 2022). Though the 1000 m depth horizon is commonly used, carbon aggregates that sink below the ocean mixed layer can persist for thousands of years away from atmospheric exchange (Jiao et al., 2010; Ogawa et al., 2001; Santos et al., 2021). Methods for measuring carbon uptake in macroalgae are well established, however, the magnitude of biomass losses from seaweed farms has only been documented in a few studies (Zhang et al., 2012; Fieler et al., 2021; Dolliver & O'Connor, 2022; Canvin et al., 2024), and data on DOC losses is largely lacking (Wada et al., 2007; Pessarrodona et al., 2023).

This study combines data on growth, carbon tissue storage and losses to both POC and DOC pools within the same time-period for two deployment times of cultivated *Saccharina latissima*, an important European cultivar, at a coastal site in mid-Norway. We emphasize the under-reported “unseen” portion of erosion from the cultivated kelp and provide new data for DOC release by cultivated *S. latissima*.

The present work strives to develop further standardized methodologies for measuring carbon uptake and losses at seaweed farms, contributing to environmental impact assessments and expanding the field of research on seaweed-derived DOC and carbon accounting, to better inform blue carbon sequestration calculations from seaweed farming (passive process).

4 Objective

A possible low-cost solution to the storage problem is to deposit freshly harvested, fully grown seaweed in deep-sea trenches outside the continental shelf. Initially, the project planned to study the technological challenges regarding sinking as a solution, and what technologies needed to be developed and tested *in situ* as well as measures to reduce possible risk for harmful effects on the ecosystem. Due to highly unknown effects on the deep-sea ecosystems, active sinking of kelp biomass was precluded from the project, and the focus shifted to quantification of only the passive CDR. The work package thus includes evaluation of the fate of seaweed released and deposited naturally during farming (DOC, POC, DIC).

Sub-goal: To quantify the carbon sequestration potential from large kelp farming.

This report is based on the first published paper aiming at quantifying POC and DOC losses and their impacts on carbon sequestration. To further this research, two additional papers are being written (also supported by JIP Seaweed Carbon Solutions project) to study the composition of DOC and its level of recalcitrance (biodegradability), both in lab studies and at a seaweed farm at sea. Due to its low biodegradability, recalcitrant DOC (RDOC) is a strong contributor to passive CDR, and so far not quantified or studied for *S. latissima*.

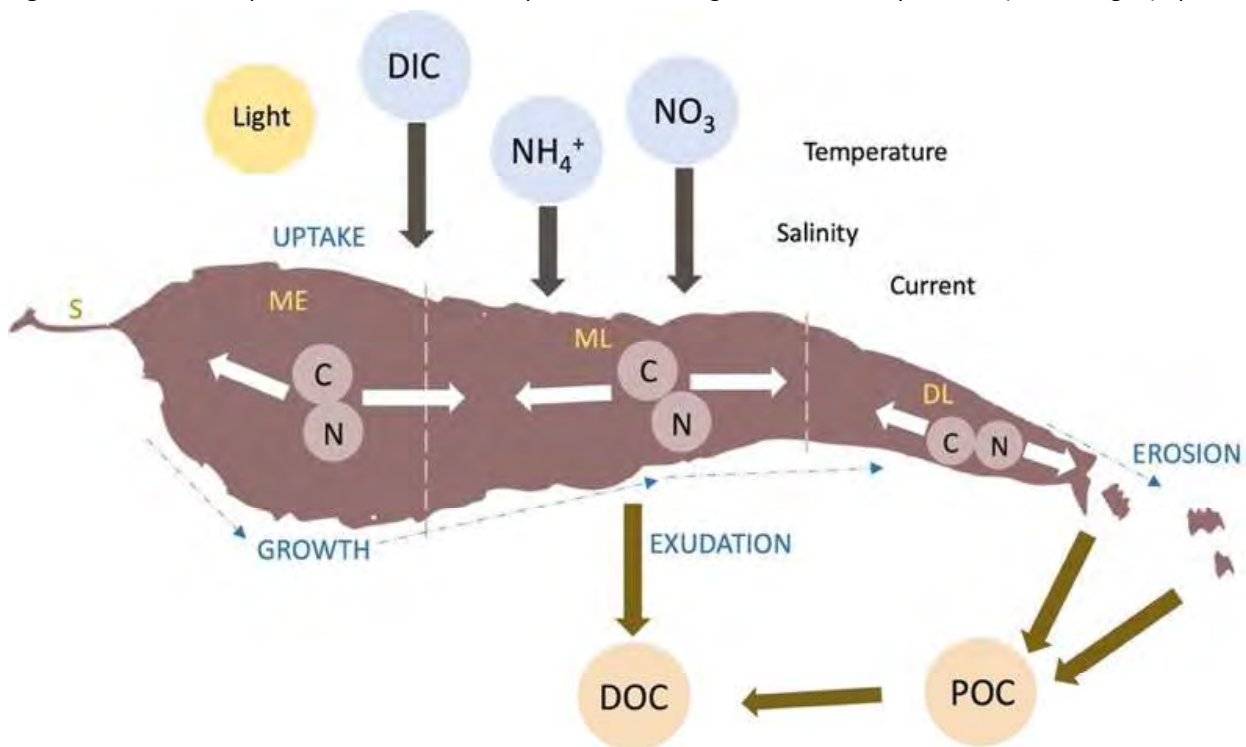
5 Methods

For detailed description of the materials and methods used in this study, see Neves et al., 2025. Below follows summarised description of the experiments.

5.1 Carbon uptake in cultivated *S. latissima*

The main processes that were investigated in this study are explained in Fig.1. The experimental study was conducted in Skarvøya, Hitra, on the west coast of mid-Norway (63° 39'0" N, 8° 38'57") during two cultivation seasons in 2022 and 2023. The site is sheltered to wave exposure by the surrounding islets, but tidal forcing allows for well mixed water layers, with no pronounced thermocline or halocline seen throughout the two years. The average current velocity is 10.5 cm/s and the maximum depth under the cultivation rig is ca. 25 m. Kelp samples were collected monthly during March to August in 2022 and May to August 2023, for two deployment times, autumn (October) and winter (January), and analysed for dry weight (DW), carbon (C) and nitrogen (N) content.

Figure 1. Schematic representation of the main processes investigated in this study: carbon (and nitrogen) uptake and



storage in stipe (S), meristem (ME), mid lamina (ML) and distal lamina (DL); kelp length growth, erosion (POC losses) and exudation (DOC losses). Modified from Broch et al., 2019. (Neves et al., 2025. *Science of the Total Environment*).

5.2 Seaweed growth and losses to POC pool

Lamina growth and erosion were studied on 100 tagged *S. latissima* individuals each season. For each autumn and winter deployment, 10 individuals were tagged within one meter on 5 replicate horizontally-seeded ropes and measured monthly (except twice in July 2023). Using a modified version of the hole-punching method from Parke (1948) the first hole was punched 10 cm from the base of meristem in March 2022 and May 2023. Dislodgement was considered when the full kelp sporophyte was lost between monitoring dates. If breakage occurred at the stipe, stipe-lamina intersection or inside the meristematic tissue, the kelp was considered fully lost. If a full kelp was lost during sampling due to handling, data from

the present sampling was recorded and the dislodgement loss was registered in the following month. Dislodgement of individuals were quantified between each monitoring date and for the whole experimental period. Weighted averages are used to ensure that occasional dislodgement events are not given more importance than smaller yet constant erosion. Densities from 2023 were used for both years, as data was not available for 2022.

5.3 Initial (24h) losses to DOC pool

To measure losses to the dissolved organic carbon (DOC) pool, a short incubation test was done in parallel with kelp from the same deployment groups. The experiment was performed in April and July 2023 in the same manner, accounting for any effect of kelp size/age and biofouling state on the initial DOC concentrations released into the seawater. Twelve 20 L incubation containers were filled with natural seawater from the research site in Skarvøya, Hitra, through a hose attached to a portable pump onboard a vessel and filtered through a 200 μm plankton mesh to remove larger phytoplankton and debris. Individual kelps were carefully inserted and three containers were kept without kelp as a reference treatment. Lengths, widths and a visual biofouling assessment were taken for all experimental kelp individuals. All incubation containers were brought to the pier for greater ease of sampling and kept submerged at 1m depth for a 24-hour period.

DOC released by the kelp and POC_z, the particulate organic carbon retained on the GF/F filter were sampled after 4 and 24 hours in each incubation treatment. Water was filtered through pre-combusted, $\varnothing 25$ mm, 0.7 μm GF/F Whatman filters, placed in pre-cleaned plastic filter holders attached to 100 ml glass syringes. DOC samples were collected in triplicates into 40 ml glass vials and immediately acidified with 6M HCl to pH<2. DOC vials were pre-combusted at 450°C for 8 hours and pre-labelled. All non-combustible glassware were pre-washed in 0.1M HCl acid baths for 8 hours or sterilized with an autoclave. Filter holders were washed in 1M HCl for 2 hours. Vial caps were washed in 1M HCl for 2 hours, followed by soaking in methanol for 8 hours, then drying at 60°C for 1-2 hours. All acidified water samples were kept frozen at -20°C and dark, until analysis at GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany.

6 Carbon losses and sequestration potential

Carbon that is taken up through photosynthesis and assimilated into seaweed biomass is stored for various timescales but not sequestered, as it can return to the atmosphere once degraded and remineralized, or after the utilization of seaweed-derived products (Hasselström & Thomas, 2022; Hurd et al., 2022; Troell et al., 2022). Changes in length show the magnitude of growth versus erosion throughout the year (fig. 2). Raw data from 50 kelp individuals per deployment group are used for maximum data resolution. Calculations of length increments between holes (ΔL_i) and length loss (LL_i) allow insight into an unseen portion of additional erosion, which cannot be recorded through direct measurements on-site (fig. 2). Continuous pulses of erosion occur as early as April in 2022 (sampling in 2023 only began in May) (fig. 2a, c) and mostly from the distal tissue in 48.0-88.0% of individuals, apart from August. Section losses show breakage from the mid-lamina is less common but can occur throughout the season with up to 16.0% of individuals exhibiting this, and up to 4.3% of individuals showed breakage at the meristem area not yet qualifying as dislodgement. The high amounts of dislodgement in August 2022 are partly due to lack of data in July 2022 (fig. 2a, c). Data from 2023 shows progressive erosion and dislodgement between early July (Jul 1) and August, worsening from mid-July (Jul 2) (fig. 2b, d). In August the greatest loss is whole lamina loss, i.e. dislodgement.

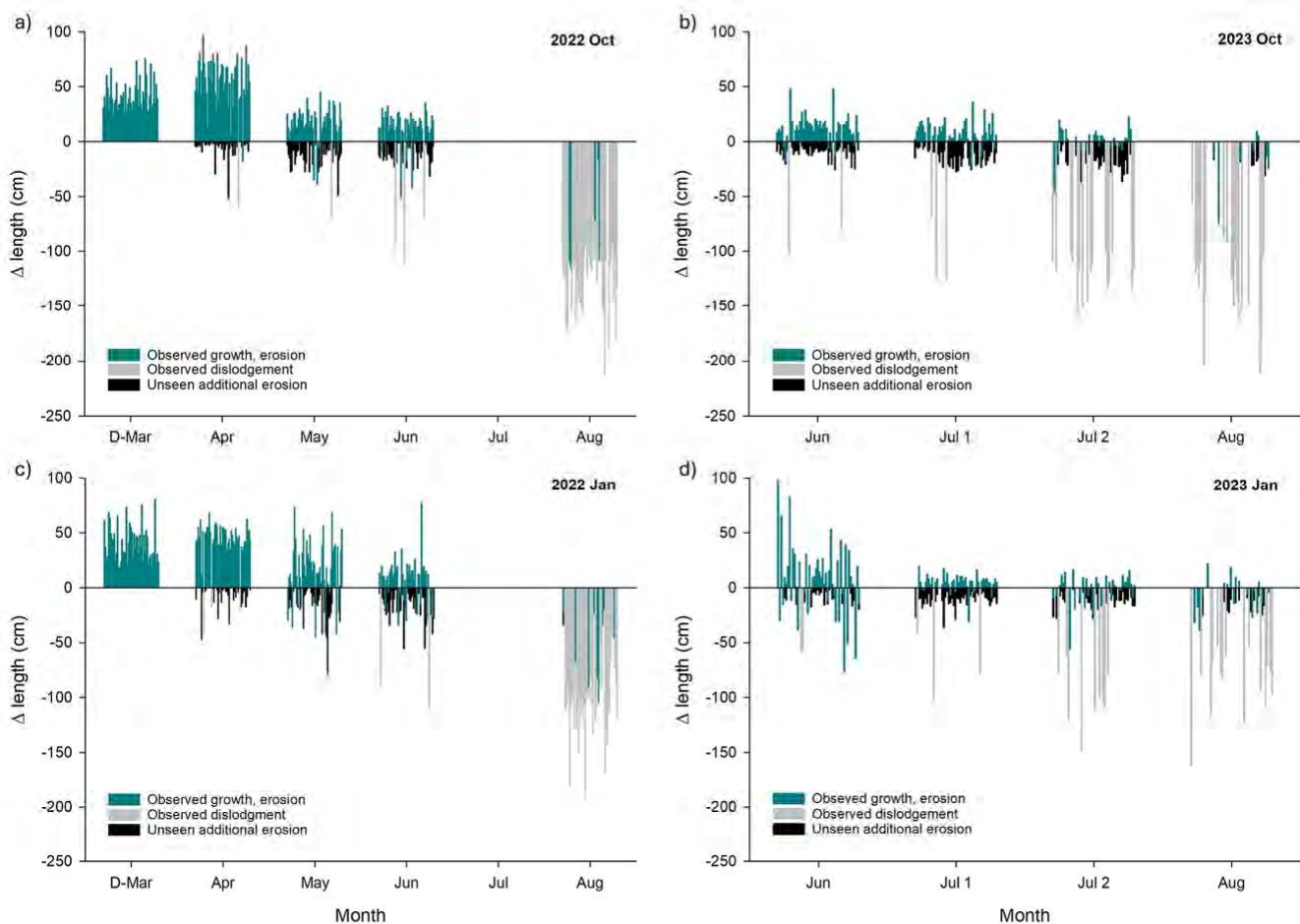


Figure 2. Kelp laminar growth and losses to the POC pool, separated into 3 categories: observed (measured) changes in length, observed (measured) dislodgement, and the unseen losses due to erosion. Data from October (a-b) and January (c-d) deployments during 2022 (a, c) and 2023 (b, d). (Neves et al., 2025. *Science of the Total Environment*).

Some CDR products, such as biochar, may bind carbon into stable and recalcitrant form for hundreds of years (Bird et al., 2012; Roberts et al., 2015). During the grow-out phase in seaweed farms, before harvest, carbon is continuously being eroded and exuded entering both the particulate and dissolved organic pools, as demonstrated in this study. The concept exemplified in fig. 3 is based on data averaged for all deployment groups, excluding cropping, meaning values represent a one-time event depending on harvest time.

A 500-ton kelp biomass (wet weight) production may capture between 57 and 77 tons CO₂ depending on harvest time (114 to 154 kg CO₂ per ton WW), equivalent to 16, 19 or 21 tons C, which is the net fixed carbon, C-NPP. Autumn deployments will contribute to greater quantities of biomass-fixed carbon, as well as losses to POC and DOC, compared to winter deployments (fig. A8). As we lack seasonal data for DOC losses, a uniform averaged rate of release is used in fig. 3. For each ton of kelp harvested in April, June and July, 8, 18 and 28 kg C has been lost to the environment, respectively. This means that 25%, 47% and 67% of biomass carbon, respectively, enters the organic carbon pool, whilst 75%, 53% and 33% of biomass carbon is stored temporarily in products (unless used in CDR products).

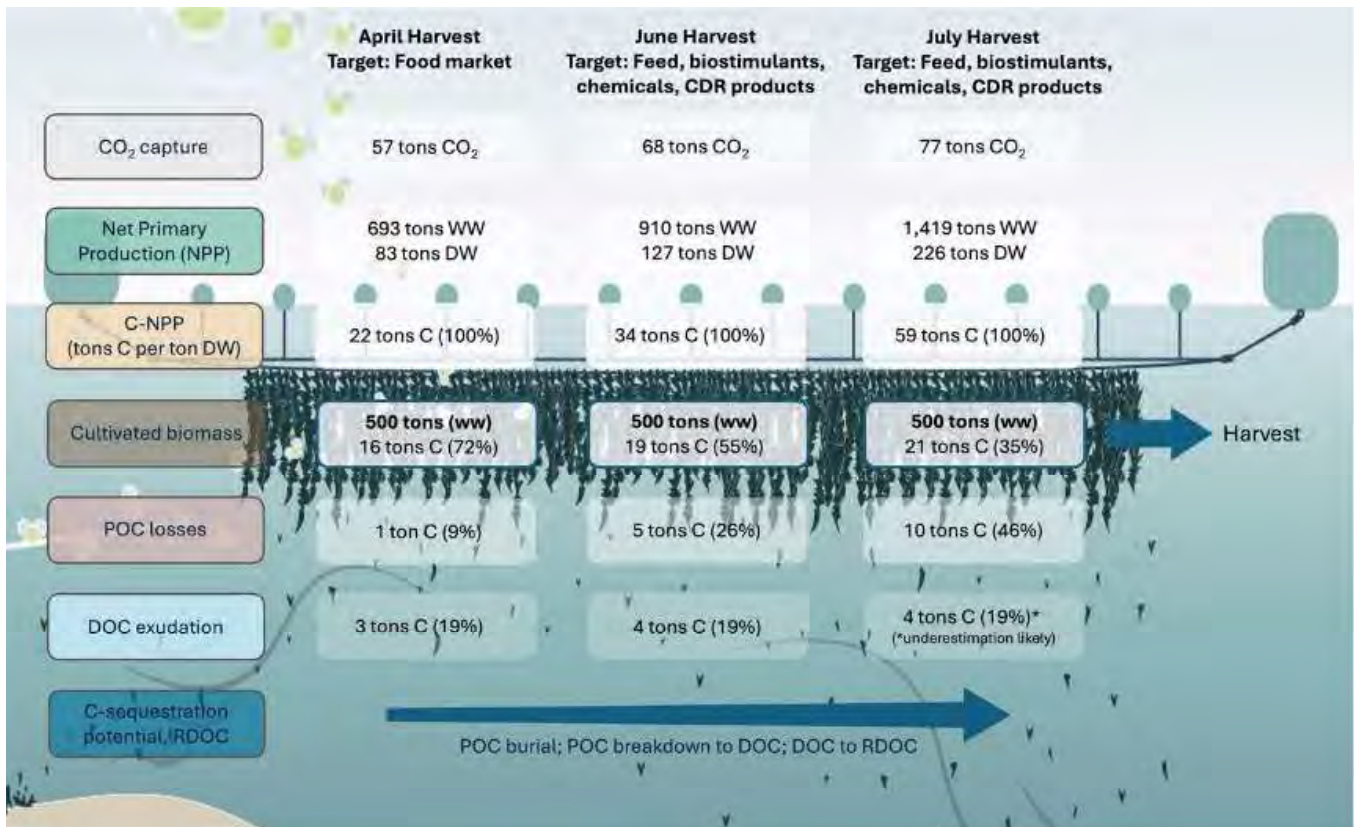


Figure 3 – Particulate and dissolved organic carbon losses in high latitude seaweed farms with 500 tons production capacity. Values are averages for 2022-2023 relative to C-NPP (%) and biomass volumes, for different harvest times targeting different markets. X tons C in cultivated biomass is the carbon remaining in kelp tissue after losses are accounted for in one cultivation cycle. Calculated based on dry matter and carbon content data for *S. latissima*. Background illustration courtesy of Aurora Nilsen, SINTEF Ocean. (Neves et al., 2025. *Science of the Total Environment*).

By June, 55% of C-NPP is kelp carbon remaining at the farm, whilst total losses account for 45% of C-NPP, consisting of 59% POC and 41% DOC. By contrast, an estimated 43% of C-NPP in wild kelp forests (predominantly *Laminaria hyperborea*) is exported from the algae bed, comprising 48% POC and 52% DOC (Krause-Jensen & Duarte, 2016). This suggests that rates of losses from a seaweed farm by mid-June may be comparable to losses estimated for natural kelp beds, although the overall level of primary production is still substantially higher in kelp forests given its greater areal extent compared to present cultivation scales in Europe. Site-specific environmental factors and hydrology will also contribute to differences in carbon dynamics and export between the two.

When located in depositional environments, organic carbon burial rates attributable to seaweed farming averaged $1.06 \pm 0.74 \text{ CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ in a study involving 20 farms around the world of different sizes and ages (Duarte et al., 2025). When organic carbon is exported, connecting source and sink is much harder, yet an estimated 4 to 9% of the POC exported annually from wild macroalgae in coastal zones was sequestered in deep coastal sediments ca. 13 km away (Queirós et al., 2019). Krause-Jensen and Duarte (2016) estimate an export of POC and DOC to the deep sea of 2% and 8% of C-NPP, respectively. POC may also be broken down to DOC, and a very small fraction of 0.3-1.2% may additionally be converted from POC to RDOC (Feng et al., 2022; Zhang et al., 2023). Additionally, studies with *Sargassum* and *S. japonica* revealed that 5 to 78% of seaweed-produced DOC was refractory (RDOC) (Watanabe et al., 2020; Gao et al., 2021; Li et al., 2022; Zhang

et al., 2022), but data is still lacking for European species. Further research on the composition and degradation of DOC released from cultivated *S. latissima* could help determine its fate and production of RDOC. Techniques such as molecular tracing, eDNA (Ortega et al., 2019; Queirós et al., 2019), autonomous monitoring technologies such as Underwater Hyperspectral Imaging (UHI) to monitor kelp fragment deposition on the seafloor (Summers et al., 2022), modelling and carbon accounting (Siegel et al., 2021; Hurd et al., 2022) are promising tools to monitor the fate of eroded material.

Although carbon sequestration potential may be higher from the latest harvest times, the ecological impact arising from losses over 60-70% of C-NPP must be considered and monitored (Hancke et al., 2021). Dispersal versus accumulation rates and subsequent degradation processes must be better understood for sites with specific characteristics and associated benthic, pelagic and micro-organisms. Furthermore, bryozoans are calcifying organisms, and their calcification process releases CO₂, offsetting some of the sequestered carbon. This should also be considered in the overall CO₂ budget.

With scaling-up of seaweed cultivation in sight, opportunities for carbon mitigation and sequestration are more substantial, however, technological and material innovation along with emission reductions are still needed in the full value chain to meet sustainability targets for the industry (Hasselström & Thomas, 2022). Diversification of markets and robust product portfolios beyond the food market are necessary to drive higher demands for biomass and profitability that allows farming companies to survive and grow.

Carbon sequestration from erosion of biomass during the grow-out stage and DOC losses results in a passive co-benefit for seaweed farmers (Canvin et al., 2024), regardless of their main target market. In addition, multi-purpose cultivation may also help promote carbon sequestration opportunities without substituting important uses of the biomass such as food and feed. Harvest timings and strategies may be adjusted to fulfil multiple objectives, opening the harvest window by up to 1-2 months. Strategies such as cropping/coppicing have allowed survivability of cultivated kelp into a second and third year (Bak et al., 2018; Boderskov et al., 2023), but even when this is not possible, it can help increase yields for different applications within one cultivation cycle, including CDR products. Diversification within farms, between sites and regions may together contribute to a national portfolio of climate mitigation solutions from seaweed farming.

7 Conclusions

Macroalgae farming can contribute to natural carbon sequestration processes during the grow-out phase at sea through the erosional production of particulate (POC) and dissolved organic carbon (DOC). Both POC and DOC may be broken down and converted to recalcitrant dissolved organic carbon (RDOC), contributing to long-term sequestration, yet further research is needed to assess its permanence in the marine ecosystem. New data is provided for DOC release from cultivated *Saccharina latissima*, with 29% of fixed carbon being released from October-deployed kelp and 12% from January-deployed kelp, before the progression of bryozoan biofouling. The effect from bryozoan biofouling on DOC release needs further study, along with more seasonal DOC release data.

POC and DOC losses depend on seedlings deployment and biomass harvest times. For each ton of kelp harvested in April, June and July, 8, 18 and 28 kg C has been lost to the environment, respectively. These findings encourage further investigation into the dynamics and characterization of POC and DOC in marine environments, to assess their contribution to marine biogeochemical cycles and long-term impacts on carbon sequestration.

Future research should focus on quantifying the contribution of macroalgae farming to natural carbon capture, utilization and storage (CCUS) processes and optimizing farming practices to enhance carbon capture efficiency. A multi-purpose approach to macroalgae farming is recommended to make use of opportunities in multiple target markets, where techniques such as partial harvesting or coppicing may be applied.

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SINTEF

JIP Seaweed Carbon Solutions

**Pre-processing and storage of seaweed (WP7):
FINAL REPORT**

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Report

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SUMMARY

This Work package examined chemical and biological preservation methods for cultivated *Saccharina latissima* to extend the processing window and maintain carbon content for downstream use. Acid preservation with sulphuric, formic, and acetic acid effectively prevented microbial degradation over nine months, with sulphuric acid at pH 2.9 giving the best results. This treatment reduced ash content and increased theoretical carbon availability by up to 10% per tonne of wet biomass as compared with other types of acid. Biological preservation using the organic acid-producing inoculum achieved stable storage under mild, non-sterile conditions. Effective acidification occurred only when mannitol was added, indicating that fermentation depended on available carbon substrates. Carbon retention remained high but was slightly lower than in chemically preserved samples. Together, the results show that both preservation methods can stabilise seaweed biomass, with chemical acidification offering higher efficiency and biological fermentation representing a sustainable alternative.

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1 WP7 Tasks

Key tasks of WP7 are pre-treatment and stabilization of seaweed biomass for transportation and storage, long term (weeks to months) storage to extend the processing window, and recovery of valuable side-streams from dripping loss (Fig 1).

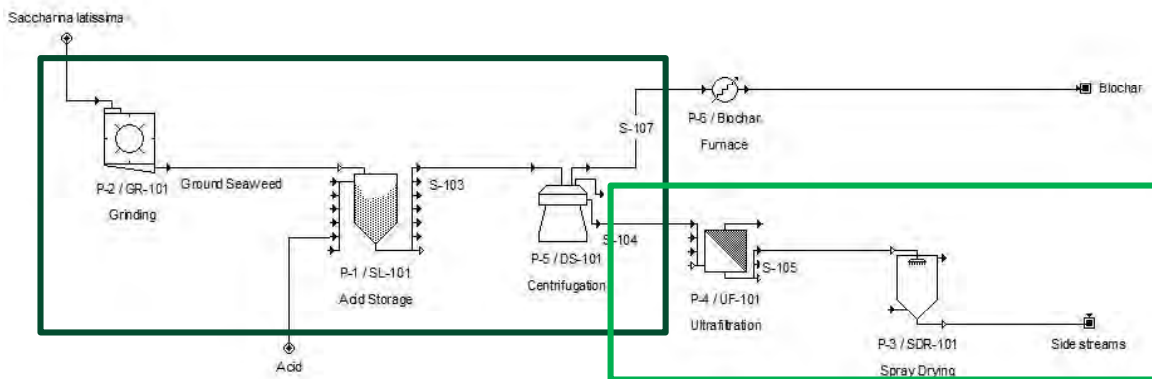


Figure 1 Process flowchart for biomass processing once the seaweed is delivered on land. Long term, bench scale acid preservation experiment encompasses the initial stages of the process (blue bracket). Recovery of valuable compounds from exudate collected from acid preserved biomass is representative of the side stream highlighted in the green bracket.

2 WP7 Methodology and Rationale

Due to the poor stability of seaweed biomass, extensive research has been conducted on preservation of the harvested biomass to expand the stability and processability window¹⁻³. In acid preservation of seaweed, the quality of the biomass is the outcome of a long list of processes that will change the structure and composition of the biomass over time. Degradation of proteins and polysaccharides due to the low pH will change the mechanical properties of the seaweed and affect processing. Changes to the cell wall structure and the changes in chemical character of the liquid fraction of the biomass will change the osmotic pressure and solubility of various biomass components, resulting in loss of organic compounds as exudate⁴. Most importantly, microbial activity can reduce the quality of the biomass by consuming organic matter and releasing it as gas. Seaweed biomass is commonly preserved by lowering the pH with addition of acids, which is the established methodology for preservation of seaweed for applications in the food industry or as raw material for biorefining, with focus on the effects on the most economically important components of brown seaweeds, alginate². Acid preservation reliably inhibits microbial growth, which is the main source of quality loss, but will affect many of the quality parameters of the biomass. Targeting biochar production rather than food application changes the desired quality parameters. This means that optimum storage conditions for biomass intended for biochar production cannot be inferred from existing literature, and new experiments had to be designed and performed. In preservation of biomass for food applications, flavour and odour parameters are most important. Production of off-flavours and changes in colour are therefore the main parameters assessed. In preservation for biorefining, the size and structure of alginate are the most important quality parameters. In preparation of biomass for biochar production, the main quality parameter desired is the dry matter content of the biomass, as well as carbon and ash contents of the solid fraction. Preservation in JIP is therefore an adaptation of established methods to a new application. In JIP, we tested a range of acid types and pH levels commonly applied to preserving the seaweed as means to stabilize and improve the qualities of seaweed as a raw material for biochar production.

2.1 Bench scale acid preservation of seaweed

Sulfuric, formic and acetic acid were selected as preservatives. Sulfuric acid was selected for its strong acidifying effect (two protons per mol) and low price, formic acid is considered the optimal acid for seaweed preservation while being the most expensive, and acetic acid has shown to be strongly antimicrobial at a higher pH level. Sulfuric acid was used to store the biomass at the lowest starting pH 2.9, formic acid at pH 3.5, and acetic at 4.2.

In July 2023, freshly harvested *Saccharina latissima* biomass was ground with a meat grinder equipped with a 2 mm die, separated into three batches and adjusted to the desired pH. Acid was added as dilute solution (1% w/v) to facilitate mixing and ensure uniform exposure to acid for the entire volume of the biomass. The biomass was then stored as 200 g samples in plastic jars at 13°C (Figure 2 Biomass samples stored at 13°C.). The temperature was selected to reflect the average temperature in Trøndelag in summer and autumn. At monthly intervals, two samples for each acid treatment were processed to collect data on biomass quality changes. The solids were separated from the liquid phase with gentle centrifugation (5 minutes, 100xg). Separation method was selected based on the ease of replicating the results on a large scale. While laboratory centrifuges can run at 20000xg and separate the solid and liquid fractions completely, the method was selected to approximate gentle mechanical separation and generate results more likely to be reproducible at scale. Solid and liquid fractions were weighed separately to estimate the change in biomass solids content. Solid fraction was lyophilized before and after weighing to determine the dry weight. The ash content of the samples was determined by weighing out 0.50 grams of lyophilized material into crucibles. The samples were dried at 105°C overnight, then cooled to room temperature in a desiccator. Further, the pre-dried samples were incinerated in an ashing furnace at 550°C for 12 hours. The ash content was calculated as a percentage of the original dry weight using Equation 1.



Figure 2 Biomass samples stored at 13°C.

Equation 1

$$\text{ash} [\%] = \frac{\text{ash weight} [g]}{\text{dry weight} [g]} * 100 [\%]$$

Lyophilized samples of the solids were analyzed for content of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S). The elemental composition of the samples was determined by weighing out pre-dried and milled material (4-5 mg) into tin capsules. These samples were then analyzed with a Vario EL Cube Elemental Analyzer.

2.2 Large scale acid preservation of seaweed

Based on the results from small scale storage experiments, a scaled-up experiment on preservation of biomass was performed during the 2024 harvest. The biomass was collected from the Storflua site and processed freshly on the shore to approximate the conditions in the small-scale samples evaluated over time the previous year. 840 kg of biomass was stored in barrels and monitored over time to determine the impact

of scale on the preservation efficiency. In order for the biomass to be preserved, it must first be cut or ground to expose maximum possible surface area to the added acid. Ultrafiltration was tested as a means to recover and separate the valuable components of the liquid fraction of stored biomass. The valuable streams contained in *S. latissima* biomass can be separated by size, with fucoidan having the highest molecular weight (400 kDa and above), laminarin being a small polysaccharide (ca. 3 kDa).

2.3 Recovery and characterization of side streams

During the grinding and storage, some of the soluble compounds present in the seaweed biomass will exude into the liquid fraction of stored slurry. Recovery of these compounds (laminarin, fucoidan, polyphenols, mannitol), could improve overall process economics and generate valuable products from what is considered a waste stream.

The liquid fraction recovered from acid-preserved *S. latissima* biomass represents a highly complex and heterogeneous mixture of carbohydrates, proteins, small and large molecular weight metabolites, and the products of their degradation and acid-induced reactions. Due to this complexity, most conventional analytical methods are unable to accurately quantify all major compound groups in the seaweed exudate. To obtain an estimate of the potential content of key value streams (proteins, laminarin, fucoidan, and polyphenols) the liquid fractions from samples stored for six months under each acid treatment were fractionated by ultrafiltration. Two molecular weight cut-off (MWCO) membranes were employed: 30 kDa and 2 kDa. The retentate from each fraction (R30K and R2K) was collected, lyophilized, and weighed to determine the mass yield. Elemental analysis (CHNS) was subsequently performed on each retentate.

2.4 Bench scale microbial preservation of seaweed

Following the assessment of data on acid-preserved biomass and the recovery of valuable liquid-phase side streams, a complementary experiment was conducted to evaluate whether biological acidification using organic acid-producing bacteria could serve as a natural alternative to chemical acid treatment. LCA analysis of the acid preservation process has indicated that removing the acid addition from the emission balance sheet has the highest potential for further reduction of environmental impact. An alternative to addition of acid is production of acid in the stored biomass through anaerobic fermentation of the dissolved carbohydrates by lactic acid producing bacteria. Compared to chemical acid preservation, the fermentation approach offers a gentler and more sustainable method for long-term stabilization of seaweed biomass, while also generating liquid fractions that may contain recoverable metabolites like those identified in the acid-preserved side stream recovery study. Microbes used in fermentation can be cheaply propagated in labs to produce the starter cultures for each harvest season, and require only seaweed biomass to grow, representing a large emissions saving compared with production and transport of acids. Replacing the use of acid with organic acid producing bacteria, such as *Lactobacillus plantarum*, could further improve the process economics and reduce the environmental impact. Lactic acid which is produced by the bacteria, and production of acid by microbes consuming carbohydrates such as mannitol will have a very different effect on the biomass⁵. Based on the results from previous experiments and after consulting with industry partners and internally at SINTEF, we decided that the best course of action for microbial preservation would be a bench scale experiment conducted in similar way to the acid preservation experiments, for comparable results.

S. latissima collected from the Storflua site on the 25th of June 2025 was ground with a meat grinder equipped with 2 mm grinder plates. The biomass was subsequently supplemented with an ensilaging additive (PIG 400, European Protein AS, Denmark) at two different concentrations. The low concentration

(Low) corresponded to 0.01 mL or 0.01 g per kilogram of wet biomass as recommended by the manufacturer, while the high concentration (High) corresponded to 0.1 mL or 0.1 g per kilogram of wet biomass. The higher microbial loading was included in order to test whether the biomass composition difference between the intended use (grass, fodder) and seaweed biomass is in any way detrimental to microbial cultivation, and if it could be overcome by increasing the inoculation rate. Each treatment was prepared in triplicate and left undisturbed at 13°C until final sampling, 21 days after inoculation. Before closing the containers, the headspace was flushed with nitrogen to ensure anaerobic conditions. Sampling and processing were conducted following the same procedure as described for the acid treatment experiment performed in 2023. In brief, the pH of the samples was recorded, and samples were separated into solid and liquid fractions by gentle centrifugation (5 min, 100 ×g), selected to mimic large-scale mechanical separation rather than complete laboratory-scale sedimentation. The solid and liquid fractions were weighed separately to estimate changes in solids content. The solid fraction was subsequently lyophilized before and after weighing to determine dry weight. Elemental composition was determined by CHNS analysis. In contrast to the previous study, only a single sampling point was included, taken after 48 days of incubation, and no determination of ash content was performed. To establish how fast can microbial fermentation drop the pH to levels in the range of those desired in literature on seaweed preservation, a set of samples was prepared containing additional mannitol, ensuring that the acid production was not limited by substrate availability. These consisted of two replicates each for the Low and High treatments, as well as two replicates where 10 g L⁻¹ mannitol was added in combination with the Low and High PIG 400 concentrations, respectively. pH was measured at 24 and 72 hours to assess the early fermentation dynamics.

3 WP7 Results

3.1 Bench scale preservation of seaweed

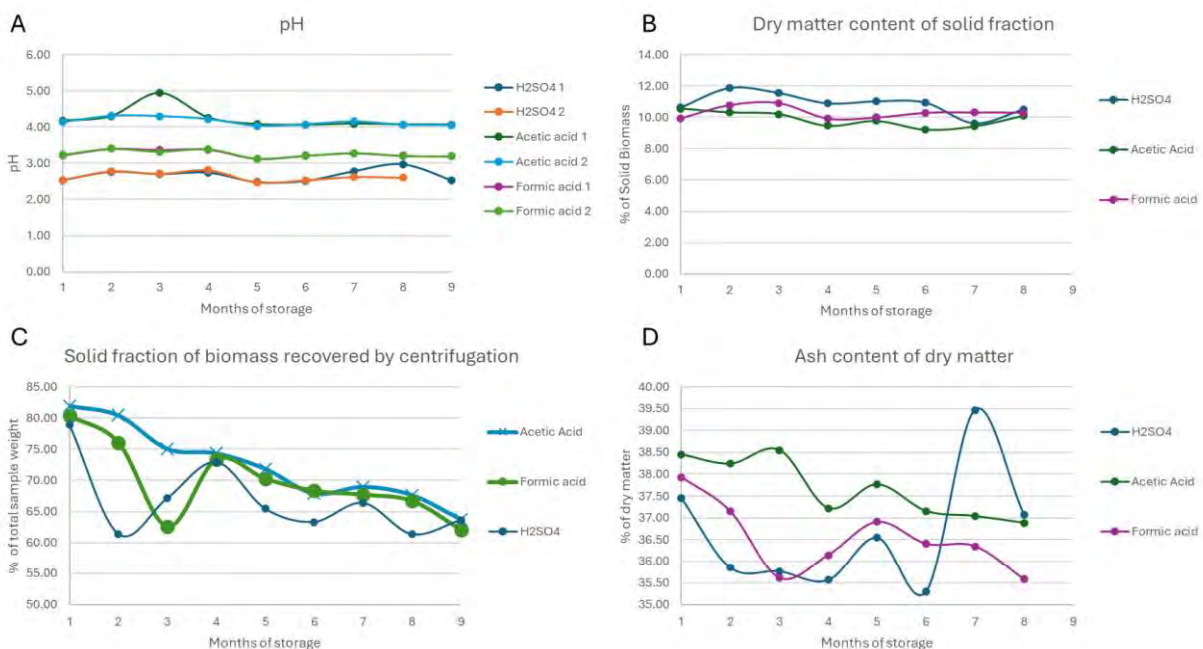


Figure 3 Physical and compositional parameters of *Saccharina latissima* biomass in long term storage. A: The pH of all three acids remained constant, with minor reproducibility issues between the technical replicates. All three acids kept the pH stable over the duration of the experiment. B: Dry matter content of the solid fraction recovered by centrifugation has not changed significantly for any of the treatments.

C: Solid fraction as a percentage of total weight of the sample. During long term storage, some fractions of the biomass are released from the solid fraction as exudate. All three storage conditions resulted in a gradual reduction of the solid fraction weight over time. D: Ash content of the dry matter fraction: ash, which is the term describing all inorganic compounds and minerals present in the biomass, was reduced with time.

Small-scale storage experiments were conducted between July 2023 and March 2024, corresponding to a total storage period of nine months. The key parameters evaluated in the study included (i) changes in pH over time, reflecting biomass stability and long-term antimicrobial activity, (ii) the fraction of solid biomass recoverable by gentle centrifugation, (iii) the dry matter content of the solid fraction, (iv) the elemental composition of the biomass (C, N, S), and (v) the theoretical maximum available carbon per tonne of wet biomass at each sampling point. The pH remained stable throughout the nine-month storage period across all acid treatments (Figure 3A). Minor variations between technical replicates were observed, but no significant drift occurred over time. The stability of pH suggests that all three acids effectively maintained conditions inhibitory to microbial growth. This was supported by visual inspection and the absence of off-odors during sample handling, indicating negligible microbial or fermentative activity. After nine months of storage, a few samples exhibited localized fungal (blue mold) growth on biomass exposed to headspace gas, likely due to partial drying and oxygen exposure following liquid leaching. The experiment was concluded at that stage, as the obtained dataset covered a longer time frame than the expected storage duration in large-scale biochar production scenarios.

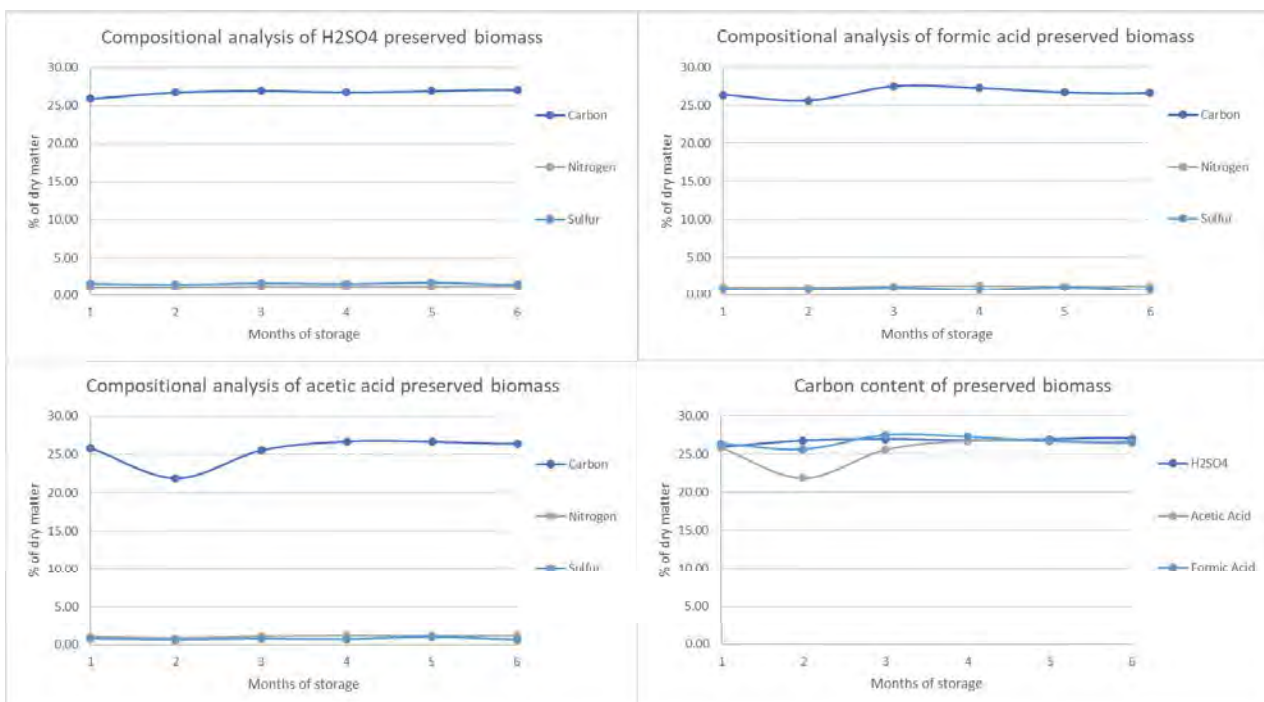


Figure 4 Changes in elemental composition (carbon, nitrogen, sulfur) of the solid fraction of long-term stored biomass. **A:** The relative content of C, N, S in sulfuric acid preserved samples. **B:** The relative content of C, N, S in formic acid preserved samples. **C:** The relative content of C, N, S in acetic acid preserved samples. **D:** carbon content of biomass preserved with all three acids.

The dry matter content of the centrifuged solid fraction remained largely unchanged over time (Figure 3B), indicating good preservation of the organic matrix during long-term storage. However, the proportion of recoverable solids relative to total sample weight decreased gradually across all treatments (Figure 3C). This reduction continued even after six months, suggesting a slow but continuous release of soluble components into the liquid phase. Despite a reduction of more than 15% in solid fraction weight, the overall dry matter

content remained stable. This indicates that the lost material primarily consisted of inorganic or low-solids components, a conclusion supported by the concurrent decline in ash content (Figure 3D). The observed reduction in ash content is particularly noteworthy, as it represents a desirable effect for biomass intended for biochar production. Lower ash content implies an increased organic fraction and improved carbon retention potential. This effect was most pronounced in samples preserved with sulfuric acid, which consistently produced solids with the lowest ash fraction.

Elemental analysis was used to monitor changes in the relative composition of carbon (C), nitrogen (N), and sulfur (S) in the solid fraction of stored biomass. Carbon content serves as a proxy for carbohydrate levels, nitrogen for protein, and sulfur for fucoidan, a particularly valuable polysaccharide present in *S. latissima*. As shown in Figure 4 the relative proportions of C, N, and S remained stable across all treatments and sampling times, with no evidence of selective leaching of proteins or carbohydrates into the liquid phase. Although the relative composition of the biomass was maintained, gravimetric data (Figure 3) suggest subtle shifts in the overall mass balance and carbon distribution. To quantify these effects, the total carbon content was expressed as kilograms of elemental carbon per tonne of wet biomass (Figure 4). While the differences between treatments were modest, sulfuric acid preservation consistently yielded higher carbon availability than the untreated control throughout the entire storage period. The effect was most pronounced during the first two to three months, indicating that sulfuric acid offers superior short-term stabilization of *S. latissima* biomass.

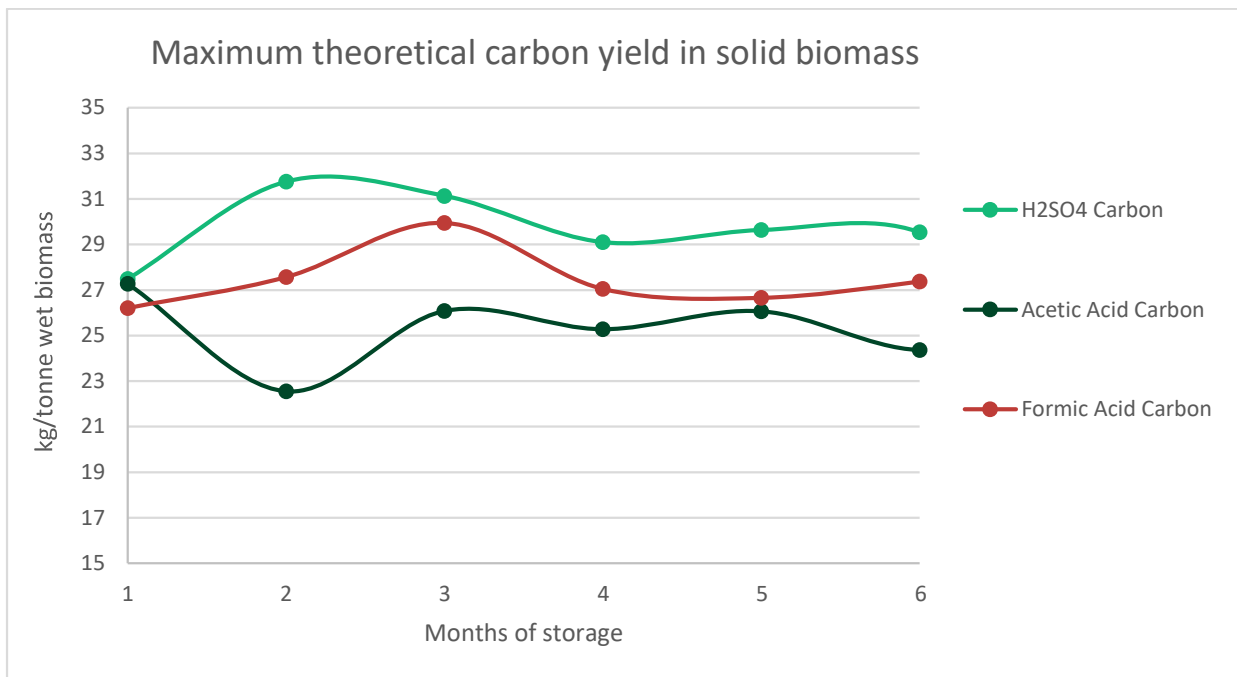


Figure 5 Carbon content of stored biomass as kg of elemental carbon per ton of wet weight of starting biomass.

3.2 Pilot scale acid preservation of seaweed

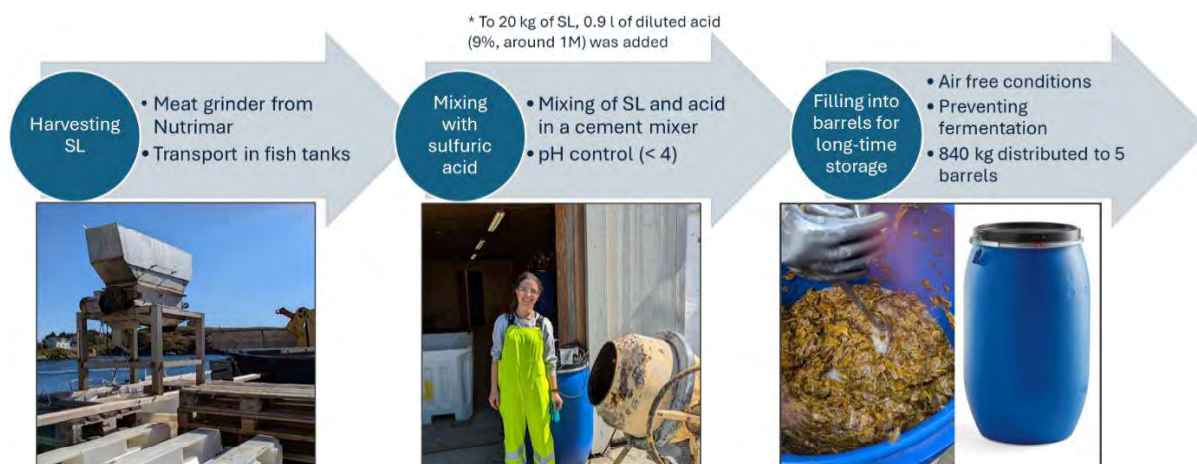


Figure 6 Summary of the workflow for scaled up preservation trial conducted in June 2024.

Biomass harvested at the Storflua farm was transported to the Mausund field station, where it was grounded into 5-10 cm² pieces using an industrial size meat grinder (Figure 6). Ground biomass was then mixed with diluted sulfuric acid based on the ratios used in the small-scale experiment. Biomass was mixed with the acid solution using a concrete mixer to ensure even distribution. A total of 840 kgs of ground, acid treated biomass was divided between five plastic barrels, sealed and left outdoors without temperature control. Despite using an experimentally derived amount of acid and more, the pH of the biomass slurry remained higher than desired (3.8-4). When the barrels were opened for sampling four months later, the biomass in each of them has shown growth of mold. The size and shape of the barrel have also contributed to the fouling issue, as the high and narrow shape of the barrel allowed the biomass to stick above the surface of the exuded liquid exposing the biomass to air. The scaled-up preservation was therefore unsuccessful.

3.3 Recovery of side streams

The results of the ultrafiltration and elemental analysis are summarized in Table 1. The carbon content (C) of the <30 kDa fraction was used as an indicator of laminarin concentration, nitrogen (N) was used to estimate protein content across both molecular weight fractions, and sulfur to determine if the fucoidan was present in the high or low MW fraction.

The high content of sulfur in the retentate of the 30 kDa membrane (R30K) indicates that despite the long-term exposure to low pH, the fucoidan remains in the high MW fraction, which makes it easier to recover and means the fucoidan has retained some of its bioactivity. The nitrogen was present in both fractions, which suggests that the protein content of the exudate has a wide range of molecular weights, and the separation methods would have to be optimized to separate a clear protein fraction. The high content of carbon in the >3k fraction suggests that laminarin could be collected this way. Low molecular weight (<3kDa) was not collected due to issues in sourcing nanofiltration membranes in the bench scale range, however this fraction could still be collected and purified in larger scale. Based on the results for the sulfuric acid preserved biomass, which appears to be the most successful in providing high quality biomass with reduced ash content, each tonne of wet biomass preserved with sulfuric acid would exude 258 L of liquid (Table 2) that with a combination of ultrafiltration and drying could produce nearly 1 kg of the fucoidan rich fraction and over 0.5 kg of laminarin rich fraction. Estimating the exact value of these side streams is beyond the scope of the project, and the value would be highly dependent on the bioactivity and quality of the polysaccharides

and the protein, however the volumes and the fact that the compounds are recoverable with a cheap and scalable methodology like ultrafiltration is highly promising.

Table 1 Elemental composition of the liquid fractions obtained by ultrafiltration after six months of storage under different acid treatments and estimated yields of each retentate. The content of N, C, H and S are given as % of dry weight.

Acid	R30K				R2K			
	N [%]	C [%]	H [%]	S [%]	N [%]	C [%]	H [%]	S [%]
H ₂ SO ₄	0.31	20.27	3.68	5.25	0.15	25.50	4.23	0.32
Acetic	0.71	21.99	3.85	6.15	0.46	10.91	1.55	0.36
Formic	0.57	22.09	3.96	6.71	0.26	19.61	3.12	0.47

Table 2 Exudate volume, dry matter content and estimated yields of high and low MW sidestreams.

Liquid volume [L]:	Dried weight [kg]:	Yield of R30K [g]	Yield of R2K [g]
258.52	1.57	940	627

3.4 Bench scale microbial preservation of seaweed

The microbial formulation PIG 400 - an ensiling inoculum for cattle feed - was selected for fermenting the *Saccharina* biomass. The product is commercially available, and contains *Lactobacillus plantarum*, *Pediococcus acidilactici*, and *Pediococcus pentosaceus*, lactic acid bacteria strains known to produce lactic acid from carbohydrates present in plant biomass, and closely related to strains described in literature on seaweed preservation⁵. *L. plantarum* has previously been tested in preservation of seaweed biomass. The microbial loading of biomass, and the fermentation's effect on pH development, biomass stability, and elemental composition of *S. latissima* was evaluated over a 48-day incubation period.

Temporal changes in pH are presented in Figure 7. Notable differences are observed between the treatments with and without mannitol. In both the Low and High inoculation treatments, the pH remains stable around 5.3 – 5.4 in the first 72 hours and gradually increased to 6 after 48 days. In contrast, both treatments supplemented with mannitol exhibit a pH drop during the first 72 hours, indicating immediate metabolic activity of lactic acid-producing bacteria present in the inoculum. This result also indicates that the acid production is fast and the window for spoilage, when the pH is not controlled is relatively short. The pH dropped from around 5.3 on day 1 to approximately 3.8–3.9 on day 3 and remained stable near this level throughout the 48-day period, confirming that the bacteria were viable, and metabolically active in the seaweed biomass slurry. These results show that the lactic acid production is highly dependent on mannitol concentration in the stored slurry and must be accounted in planning further preservation work. The low mannitol concentration is attributed to the fact that the biomass was stored in a plastic container with added seawater under transport, approximately for 24h prior to experiments, which diluted the mannitol contained in the biomass. In large scale preservation using lactic acid producing bacteria, the concentration of mannitol present on the biomass should be sufficient, as presented in literature⁵, or the concentration of fermentable sugars could be increased by a mechanical pre-treatment to remove some of the exudate water and therefore increase the starting mannitol concentration. The inoculum level alone did not influence the outcome, both Low and High inoculations performed similarly when mannitol was present. This indicates that the acidification process was limited by substrate availability rather than by the number of viable cells.

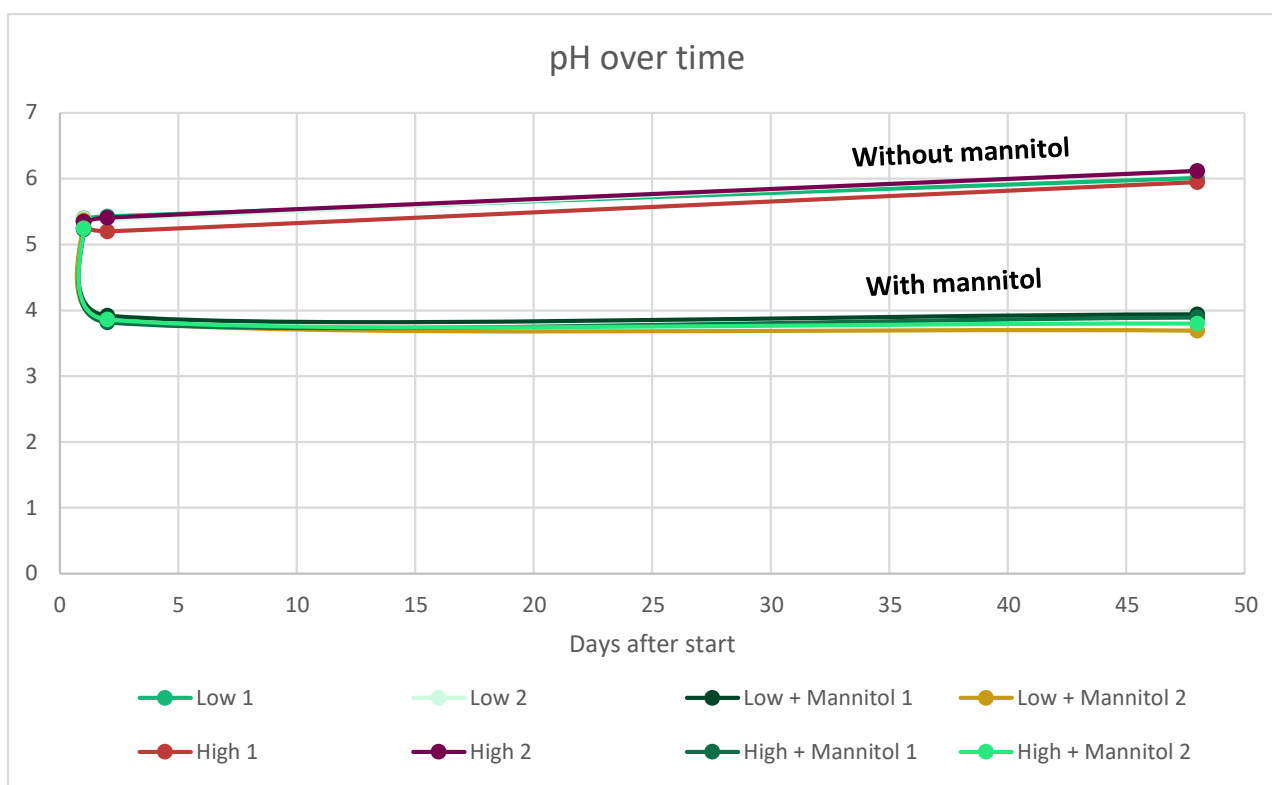


Figure 7 Development of pH in *S. latissima* biomass inoculated with PIG 400 over 48 days of storage at 13°C. Treatments include low (Low) and high (High) inoculation levels, with and without supplementation of 10 g L⁻¹ mannitol. Each line represents a biological replicate. Samples with mannitol showed an initial drop in pH within the first 24 hours, while samples without mannitol remained at pH 5.3-5.4.

The solid fraction of the biomass remained visually intact during storage, but clear signs of microbial activity were noticed. Strong fermentation odors developed, indicating active bacterial metabolism. No gas formation or visible mold growth was observed, but the pronounced smell suggests that volatile compounds were produced as a result of ongoing spoilage. The headspace odor combined with the increased pH indicate that the biomass was not preserved by the lactic acid bacteria added, but rather by the native microbiome present on the seaweed biomass. After 48 days, the dry matter content (Table 3) was slightly higher in the Low inoculation (7.9 %) compared to the High inoculation (6.1 %). The lower dry matter recovery in the High treatment likely reflects additional metabolic activity by the lactic acid bacteria, contributing to the microbial degradation and solubilization of organic material into the liquid phase.

Table 3 Final pH and dry matter (DW %) of the solid fraction of *S. latissima* biomass after 48 days of storage at 13°C with low and high inoculation levels of PIG 400.

Sample	pH	DW [%]
Low	6.88	7.88
High	7.07	6.05

Elemental analysis was carried out to assess the relative composition of carbon, nitrogen, hydrogen, and sulfur in the solid fraction after 48 days of storage (Table 4). Carbon content was similar in both treatments (25.2–25.6%), suggesting that the total amount of organic carbon was not affected by the higher inoculation level. Nitrogen content was slightly higher in the High treatment (4.34%) compared with the Low (4.04%),

indicating possible enrichment of microbial biomass within the solid fraction. Hydrogen levels were comparable (around 4%), consistent with a stable organic matrix and limited oxidation or dehydration during storage. Sulfur content was relatively high in both treatments and most pronounced in the High inoculation (9.40% versus 7.75% in Low). This enrichment may reflect the retention of sulfur-containing polysaccharides such as fucoidan or microbial uptake of sulfur compounds during fermentation. The overall stability of the elemental composition suggests that the main changes during storage occurred in the liquid phase rather than in the solids. Combined with the gravimetric data, these results indicate that the solid fraction remained compositionally stable, while increased solubilization in the High treatment likely transferred some organic material to the liquid fraction.

Table 4 Elemental composition of the solid fraction of *S. latissima* biomass with low and high inoculation levels of PIG 400. Values are given as percentage of dry weight (%).

Sample	N [%]	C [%]	H [%]	S [%]
Low	4,04	25,21	4,05	7,75
High	4,34	25,60	3,90	9,40

Collectively, these results demonstrate that the seaweed biomass is relatively stable in anaerobic storage, despite the failed acidification attempt. Fermentation with the native microbiome proceeded without visible spoilage and maintained stable physicochemical properties over 48 days.

Although the total carbon content of the solid fraction remained relatively stable, carbon retention was somewhat lower than in the chemically preserved biomass. This likely reflects the partial transfer of dissolved organic compounds into the liquid phase during microbial fermentation. Nevertheless, the maintenance of overall carbon levels and the absence of extensive degradation indicate that biological acidification can preserve the main carbon pool of *S. latissima* under favorable substrate conditions, suggesting that microbial preservation may complement acid-based methods where lower process intensity or improved sustainability is desired.

4 Conclusion

All three conditions during acid preservation have shown good antimicrobial effects and protected the biomass from undesired fermentation. Acid preservation was shown to be a reliable method for extending the processing window for cultivated seaweed biomass at the bench scale. From the three preservation conditions, the lowest pH (2.9) preservation with sulfuric acid appeared to be the most promising. Drop in ash content was the fastest and most pronounced for storage in sulfuric acid, and the treatment resulted in biomass with higher theoretical max of available carbon per tonne. Sulfuric acid treatment, especially in the 1–3-month window is the best treatment, as it's the cheapest, increases the relative carbon content, reduced the ash content, and results in a biomass with up to 10% more carbon content per tonne wet weight.

pH adjustment is a complex process and must be adjusted to the conditions and the quality of the biomass on the site at the time. Water content, composition of ash fraction and content of polyanionic polysaccharides (alginate, fucoidan) as well as the biofouling with crustaceans which contain high amounts of calcium carbonate affect the buffer capacity of the biomass and the amount of acid required. The unsuccessful scaleup attempt has demonstrated that the preservation methods must be adapted to the exact conditions and composition of biomass at the time of harvest.

Bench scale experiments on recovery of side streams have shown that the exudate carries significant amounts of valuable biochemical components. The study was very preliminary and warrants extensive further research on method development and quality of recovered protein and polysaccharides. The calculated potential yields indicate that recovery of polysaccharides and protein from exudate can be a factor in determining the process economics.

The microbial preservation tests using PIG 400 showed that microbial acidification is highly dependent on upstream processes and the available fermentable carbon sources. Biomass was stored in conditions that left too little mannitol to sustain efficient acid production, resulting in only minor pH reduction. When mannitol was added, rapid acidification to pH 3.8 was achieved and maintained, demonstrating that the bacteria in the inoculum were active and capable of driving fermentation under mild, non-sterile conditions. Overall, carbon preservation in the biologically acidified biomass remained good, but slightly lower than in the acid-preserved treatments, likely due to partial transfer of soluble carbon compounds to the liquid phase. Based on the samples of biomass treated with the ensilaging agent in the presence of additional mannitol, the microbial preservation route holds promise as the microbial activity dropped the pH to relevant levels and within a relatively short time. Unfortunately, due to the low mannitol content we were not able to obtain data on the carbon balance associated with microbial metabolism and its impact on the biomass.

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Report

JIP Seaweed Carbon Solutions

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Biochar for soil improvement (WP9)
FINAL REPORT

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1 Introduction

Due to alterations to the project budget, i.e., a significant reduction compared to the originally planned budget, the total scope of work packages 8 and 9 had to be somewhat adapted. The work focuses on the most critical parts of the biochar value chains and the results of the to work packages are presented the following section.

2 Work Package 8 – Biochar processing and quality assessment

Biochar is an efficient and comparably cheap option for carbon storage, that has gained increasing popularity in the last years due to the possibility of carbon sink certification. The classic feedstock for biochar production is wood, as it leads to beneficial properties such as a high carbon content and a high surface area. However, a fast-developing biochar market and large-scale consumers of woody biochar (metal industry) necessitate alternative feedstocks in biochar production. Aquatic feedstocks, such as seaweed, have a high potential, as they to a much lesser extent compete with food and feed production as well as with alternative use.

2.1 Seaweed processing and drying

The fresh sugar kelp was supplied by Seaweed Solutions and delivered in insulated plastic containers carrying approximately 100 kg of fresh seaweed each. The seaweed was delivered within a few hours from the time of harvest. The fresh seaweed was stored at 4°C for up to 7 days prior to being dried or preserved in batches. The texture, colour and rigidity of the seaweed noticeably changed over this period. Differences were also observed between seaweed at the top and bottom of the containers. The seaweed was laid out in crates to allow excess water to run off and shaken by hand prior to measuring wet weights. The changes in the fresh seaweed over the storage period and the lack of automated dewatering facilities may result in differences in the moisture content of different batches prior to drying.

The fresh seaweed was processed in three ways: dried immediately without washing, rinsed in water before drying, preserved in ethanoic acid prior to drying. The acid-preserved seaweed was stored in two barrels and for different durations prior to rinsing and drying.

Based on the mass of the fresh, unwashed seaweed and dried, unwashed seaweed given in Table 2.1, the moisture content is 93.9%. However, this is an overestimate of the true moisture content due to the presence of water on the surfaces of the fresh seaweed.

The water-rinsed seaweed was rinsed by repeatedly adding and draining 150 L of fresh water to 32 kg of the unwashed, fresh seaweed. The submerged seaweed was stirred before draining the water. This process was performed three times. The similar ratios of dry weight to fresh, unwashed weight for treatments, PT1 and PT2 in [Table 1](#), suggest the fresh water rinsing is not effective in removing salt. However, the challenges

in fresh weight measurements may have obscured the effectiveness. It was also observed that the weight of the water-rinsed seaweed increased by 23% due to the process of washing in fresh water and that the seaweed was noticeably wet after 10 hours of drying. It was dried for approximately 15 hours before weighing.

Table 1 Fresh and dry weights of kelp for different pretreatments

Designation	Fresh seaweed treatment	Weight of fresh seaweed as received (kg)	Dry weight (kg)	Dry to fresh kelp weight ratio
PT1	Unwashed	154.1	9.40	0.061
PT2	Water-rinsed	32.0	1.92	0.060
PT3	Preserved in ethanoic acid for 20 days	14.0	0.55	0.039
PT4	Preserved in ethanoic acid for 135 days	18.0	0.84	0.046

The acid-preserved seaweed was stored whole in 60 L fermenting barrels. Each barrel contained a 2:1 mass ratio of 0.9 M ethanoic acid to fresh seaweed. The ethanoic acid had a pH of 2.4 prior to addition of the seaweed, which increased to 2.94 with the addition of the seaweed. The pH remained lower than 3.5 for the duration of preservation. The seaweed was rinsed in water prior to drying by repeatedly adding and draining 60 L of water to 14 kg of seaweed. This rinsing process was performed three times. The dry and fresh weights in [Table 1](#) suggest less mass loss for the seaweed that was preserved for the longer period time. The difference may be partly due to differences in the rinsing procedure, which was undertaken by different operators.

However, it is unlikely that differences in the rinsing procedure could account for such a large difference. Alternatively, it may be due to differences in the water content of the fresh seaweed when it was originally weighed due to the challenges already discussed. However, it is also possible that physicochemical processes during the storage period actually do result in a decrease in the net transfer of material to solution.

The seaweed was air-dried in batches at 60 °C for 10 to 24 hours.

Approximately 6 kilograms of the dried, unwashed seaweed was washed in water and then dried again. Although two drying processes is unlikely to be optimal from an economic standpoint, washing the dried seaweed was considered likely be more effective for salt removal than washing the fresh seaweed and is therefore interesting for comparison purposes when interpreting the results of plant trials. The dried seaweed was placed in two mesh bags with a mesh size of 1 mm. Fresh water was added to the dried seaweed in a 20:1 mass ratio (60 kg of water for 3 kg of dried seaweed) and was left for 1 hour to rehydrate. The mesh bag was then removed from the solution and left to drain onto a crate for five minutes. Each bag of rehydrated seaweed was transferred into a barrel with 60 L of fresh water and agitated for five minutes before being transferred back onto crates and left to drain for five minutes. This rinsing process was

performed one more time. The solution from the rinses was put through a 125 μm sieve to measure the mass loss of particles above this size. Less than 5 g of particles (dry weight) were captured by the sieve. [Table 2](#) summarises the weights through the drying/washing/drying process.

Table 2 Kelp weights through dry/wash/dry process.

Mass of fresh, unwashed seaweed (kg)	98.3
Mass of dried, unwashed seaweed (kg)	5.99
Mass of dried seaweed after rehydrating, washing, and drying (kg)	2.86
Dry matter loss (%)	52.3

Additional test batches investigated the effect of grinding the acid-preserved seaweed. The seaweed was preserved in ethanoic acid for 20 days in the same way as has already been described. The seaweed was water-rinsed prior to grinding. The seaweed was fed by an auger to a rotating cutter above a perforated plate with 6 mm holes. The 14 kg of fresh seaweed as received weighed 10.6 kg of after preservation, washing and draining.

This produced 10.3 kg of ground seaweed. The 2.7% weight loss is thought to be mostly due to seaweed that remained in the grinder. The grounded seaweed was divided into three batches of equal weight. One batch was dried without additional washing. One batch was washed in water, and the remaining batch was washed in 0.91 M ethanoic acid (pH=2.4) and then washed in water, prior to drying. [Table 3](#) shows the weights of the batches through the process. The 2.7% weight loss has been subtracted from the fresh, unwashed, as-received weight.

Table 3 Fresh and dry weights of acid-preserved and grounded kelp.

Processing procedure	Fresh, unwashed seaweed as received (g)	Fresh weight after preservation and grinding (g)	Dry weight (g)	Dry to fresh (as-received) kelp weight ratio
Stored in acid, washed in water, ground	4539	3447	207	0.046
Stored in acid, washed in water, ground, washed in water	4539	3447	183	0.040
Stored in acid, washed in water, ground, washed in acid, then water	4539	3447	179	0.039

The dry to fresh (as-received) weight ratios in Table 3 shows that there is an approximately 12% loss of dry matter from washing the grounded seaweed. There was little difference between washing with water or with ethanoic acid.

2.2 Biochar production and properties

The seaweed was pyrolysed in two electrically-heated furnaces: a vertical tube furnace, and a muffle furnace with an inert gas box. The tube furnace comprises a vertical tube, electrically heated, equipped with a condenser and gas analysis system.

The muffle furnace inert gas box has a 3 L capacity. The box is gas tight apart from an inlet tube for carrying an inert purge gas to the box and an outlet tube that provides an exit path for the purge gas and pyrolysis gases.

A 6 mm inner diameter tube carries the purge gas inside the box and injects it towards the floor of the box through six holes in the tube. Five thermocouples are installed in the box. The positions of the thermocouples and the purge gas injection holes are shown in Figure 1 (a) Nitrogen injection points (pink arrows), and thermocouple positions. are shown in Figure 1.

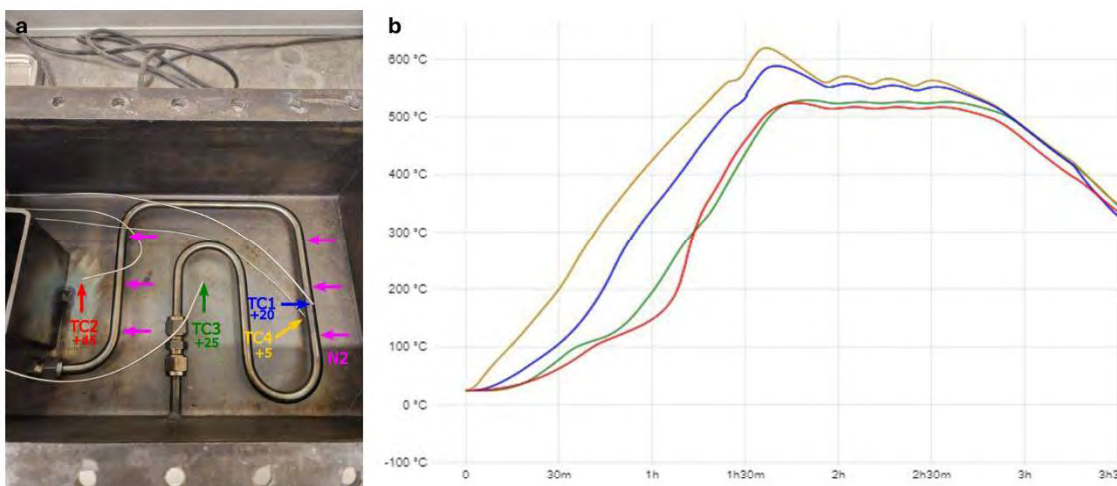


Figure 1 (a) Nitrogen injection points (pink arrows), and thermocouple positions.

The gas box temperature set point was controlled using a thermocouple located next to the exit port of the gas box (to the left in the image shown in Figure 1 (a)). This thermocouple measures the temperature of the gases exiting the box. The gas box set point temperature was increased at 5 K/min until it reached 500°C. The temperature was held at this temperature for 1 hour. The gas box was then air-cooled over 1-3 hrs before opening. Nitrogen was supplied to the vessel continuously at 5 slm. Peak temperatures measured by the four other thermocouples in the vessel were between 500°C and 625°C, as shown in Figure 1 (b).

In previous and parallel projects at SINTEF Energy, extensive tests on the influence of production conditions on seaweed biochar had been performed. Due to the high ash content of the feedstock, an increase in production temperature does not lead to a relative increase in carbon content, as is the case for woody feedstocks. Hence, a lower pyrolysis temperature was selected as it is more economical. Table 4 shows the composition of biochar produced from unwashed seaweed (used on the planting trials of this study).

Table 4 Composition of seaweed biochar produced at 500°C

Property	Unit	Value
Mass yield		54%
<i>Proximate composition</i>		
Moisture	[wt%]	4.1
Ash	[wt%], dry	63.3
Volatiles	[wt%], dry	12.5
Fixed Carbon	[wt%], dry	20.5
<i>Elemental composition</i>		
C	[wt%], dry	28.9
N	[wt%], dry	1.1
N	[wt%], dry	2.29
O	[wt%], dry	4.41
<i>Atomic ratios</i>		
H/C	[-], molar	0.20
O/C	[-], molar	0.16
<i>Inorganics composition</i>		
NiO	[mg/kg]	60
MgO	[mg/kg]	3420
Al ₂ O ₃	[mg/kg]	670
SiO ₂	[mg/kg]	7400
P ₂ O ₅	[mg/kg]	25200
SO ₃	[mg/kg]	70900
Cl	[mg/kg]	252000
K ₂ O	[mg/kg]	272000
Na ₂ O ₃	[mg/kg]	97000
Fe ₂ O ₃	[mg/kg]	790
BaO	[mg/kg]	210
CuO	[mg/kg]	50
ZnO	[mg/kg]	260
As ₂ O ₃	[mg/kg]	20
Br	[mg/kg]	1710
SrO	[mg/kg]	4740
Y ₂ O ₃	[mg/kg]	20
Rh	[mg/kg]	30
I	[mg/kg]	1930
CaO	[mg/kg]	4440
Sum	[mg/kg]	813000

The carbon content (both fixed carbon and total carbon) of seaweed biochar is comparably low, which is a result of the high ash content. H/C and O/C ratios are low, which is in line with requirements for assessing chemical stability, permanence and CDR certification.

The chlorine content is very high, and due to the biochar being produced from unwashed seaweed. Bromine content is noticeably higher than in biochars from terrestrial biomasses. This is due to bromine being inherent to seawater. Common biochar standard to not specify an upper limit for bromine, but phytotoxic effects may be possible.

2.3 Energy balance

Seaweed differs substantially from lignocellulosic feedstocks in both composition and processing requirements. Its high moisture and ash content lead to lower biochar yields and higher energy demand for drying and handling. To assess the feasibility of seaweed biochar as a soil amendment or carbon sink, it is essential to quantify the material flows and energy input throughout the production process.

The considerations presented in this section are based on simplified and idealized assumptions. They do not account for all losses, process inefficiencies, or scale-dependent effects that would occur in full-scale or continuous operations. Instead, the aim is to provide a first-order estimation of mass flows and energy demands to support broader evaluations of the environmental and economic viability of seaweed biochar production. These results should therefore be interpreted as indicative of the order of magnitude, rather than exact values applicable to real-world systems.

Figure 2 shows a process scheme that is used to set up a simplified energy balance.

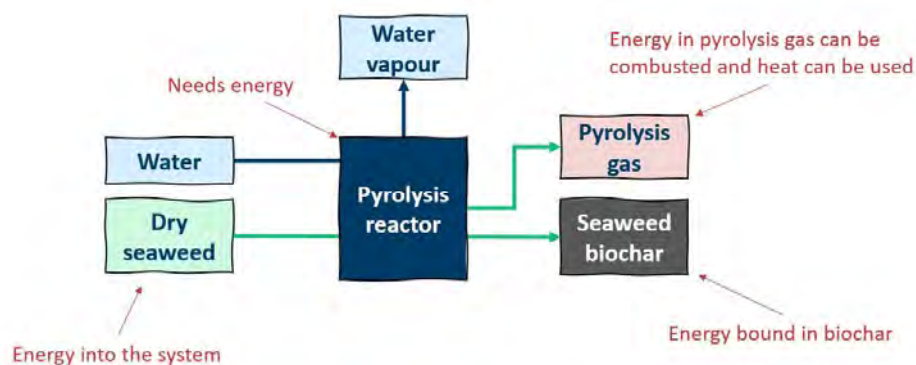


Figure 2 Simplified process scheme for setting up energy balance

The figure illustrates the main inputs and outputs in the pyrolysis of seaweed. In the present considerations, the feedstock is assumed to enter the reactor as a mixture of dry seaweed and water.

The system requires energy to dry the seaweed (i.e. evaporate the water entering the reactor) and heat the dry seaweed to process temperature. Dry seaweed is converted into two main products: biochar (solid) and pyrolysis gas (a mixture of combustible vapours and gases). The energy in the pyrolysis gas can be captured by combustion and reused as heat in the process. Some energy is also stored in the resulting biochar, which can serve as a carbon sink. The diagram highlights that external energy input is needed to start and maintain the process, particularly to deal with the high water content of seaweed.

The following assumptions and steps were made for estimating the energy balance:

Input into the system (values taken from actual experiments):

- **Dry seaweed.** The dry seaweed is assumed to have the following composition (dry basis): 29.7% C, 3.6% H, 24.87% O, 38.9% ash

Based on this composition and Dulong's formula, the heating value is estimated to be 10.74 MJ/kg.

- **Water.** As mentioned above, the feedstock is considered a stream of two separate materials, i.e., dry seaweed and liquid water. The water content is not predefined, but remains variable in this consideration, allowing for a sensitivity analysis.

Out of the system

- **Biochar,** the main product of the process, binds a significant amount of carbon from the feedstock. Thereby, it also stored energy. The biochar is assumed to have the following composition (dry): 29.8% C, 2% H, 2.47% N, 6.83% O, 58.9% ash
The resulting heating value is 11.71 MJ/kg, whereas this unit is specific for the biochar.
Biochar is produced with a yield of 54 %. Therewith is the energy of the feedstock, which remains bound in the biochar 6.39 MJ/kg.
- **Gas.** In the system considered here, liquid products are not condensed but combusted together with the permanent gases. The energy bound in this gas can be calculated as the energy entering the system with the feedstock minus the energy bound in the biochar.

Heat consumers. There are two processes that require heat.

- **Drying.** It is assumed that drying happens at an energy consumption of 1 kWh/kg of water dried.
- **Pyrolysis** of the dry feedstock. Here, a value of 1.65 MJ/kg is assumed¹.

Heat suppliers.

- Heat is generated by the combustion of pyrolysis gas.

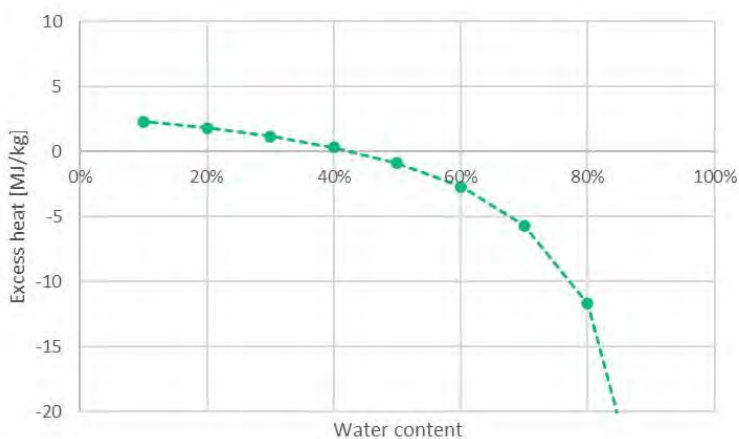


Figure 3 Heat produced or needed as a function of the feedstock's water content

Figure 3 shows the result of a sensitivity analysis, i.e., the heat demand or supplied as a function of the feedstock's water content. According to the assumptions described above, **the system does not require excess energy if the seaweed is pre-dried to around 45% moisture.**

¹ Daugaard and Brown. Enthalpy for Pyrolysis for Several Types of Biomass. Energy & Fuels 2003, 17, 934-939

It should be pointed out that this is a theoretical evaluation and would require correction for practical applications, such as losses for the different steps etc. The actual feasibility is likely worse than indicated here. However, these assumptions provide a first indication that seaweed pyrolysis could be self-sustaining.

2.4 Conclusion from Work Package 8

The following conclusions have been drawn from the work performed in Work Package 8:

- Seaweed biochar has a comparably high mass yield, which is due to the high ash content.
- The carbon content and fixed carbon are considerably lower than in woody biochar, reflecting the mineral-rich nature of the feedstock.
- Nonetheless, the low H/C and O/C molar ratios indicate high chemical stability, which meets the threshold for carbon dioxide removal (CDR) certification.
- Elemental analysis revealed a very high content of Cl and elevated Br, which are typical of marine biomass but may limit the biochar's suitability for soil applications due to potential phytotoxicity or salinity issues.
- A simplified energy balance indicates that the pyrolysis of seaweed can theoretically be self-sustaining if moisture content is sufficiently reduced before entering the reactor. However, real-world inefficiencies, including energy losses during drying and pyrolysis, must be accounted for.
- Seaweed's high initial water content and low energy density emphasize the importance of efficient drying and heat recovery if the process is to be viable at scale.

Further optimization of **pre-treatment strategies**, **drying efficiency**, and **product end-use pathways** is recommended to enhance the economic and environmental performance of seaweed biochar production.

3 Work Package 9 – Biochar for soil improvement

To create carbon sinks from seaweed biochar, a permanent storage option is desired. There are several approved biochar carbon sinks, such as soil amendment or concrete. Whereas adding biochar to concrete only serves the purpose of carbon sequestration (without expected improvement of concrete properties), adding biochar (or biochar-based substrates) to the soil may have other benefits such as improved soil fertility and plant growth. However, these effects have been shown for woody biochar with its large surface area and high carbon content. There is little experience using seaweed biochar in planting experiments.

The goal of Work Package 9 was to conduct planting experiments in the greenhouse using seaweed biochar and comparing plant growth and crop yield to a reference. The Work Package was originally planned to also cover composting and fermentation. However, due to a budget reduction, the scope was ultimately reduced to standard pot trials.

3.1 Literature overview on seaweed biochar in soil amendment

Although biochar addition to soil has a long tradition, the majority of studies have been carried out using terrestrial biochar feedstocks, in particular wood. For such feedstocks, the high surface area and porosity is attributed to beneficial properties for soil, such as high water holding capacity and nutrient retention.

There are a few studies with a focus on seaweed biochar in soil:

Roberts et al.² have discussed the potential of seaweed biochar for soil amendment. They produced biochar from six different seaweed species, three brown ones (*Gracilaria*, *Eucheuma*, *Kappaphycus*) and three green ones (*Saccharina*, *Undaria*, *Sargassum*) – sourced from different locations. Their key findings include the relatively high biochar yield (45-62%), the low carbon content, high concentration of nutrients (notably nitrogen, phosphorous, potassium, calcium, and magnesium). The authors found a substantial variability in nutrient content, depending on the species and origin. Some general trends were found, e.g., red seaweed had more potassium and sulfur, brown seaweed had more carbon and hydrogen. The biochars were alkaline (pH 7.6-11.2), especially high in brown seaweed biochars. Roberts et al. point out that the seaweed biochars are fundamentally different from biochars from woody feedstocks, and that their nutrient content resembles a manure-derived biochar. The authors have not tested soil amendment in practice, but conclude from the nutrient content that seaweed biochar may be beneficial, especially for degraded soils. The high Na content, which stems from salt in the seaweed, is pointed out as a potential limitation. The authors highlight that Na is leachable and lay out mitigation options: leaching biochar before application, applying biochar well before planting to allow for natural leaching of salt by rain or irrigation, or blending seaweed biochar with woody biochars to dilute Na content.

² Roberts et al. Biochar from commercially cultivated seaweed for soil amelioration. *Scientific Reports* 5:9665 (2015)

Cárdenas-Aguiar et al.³ have conducted a study on the physico-chemical properties of biochar derived from three marine macroalgae, the green algae *Ulva* spp., the red algae *Sargassum* spp., and the red algae *Gracilaria* spp. and evaluated their potential as soil amendment. The authors find high ash and mineral content, pH valued ranging between 7.4 and 10.4, low surface area and low fixed carbon content and high nutrient levels, in particular potassium, calcium, magnesium, and sodium. The high electrical conductivity indicates salt content. The authors did not conduct a practical planting experiment, but draw some conclusions based on the characteristics. The high nutrient content may improve soil fertility and the liming effect positive for acidic soils. Salinity poses a risk that requires careful management and the authors recommend blending with lignocellulosic biochar or pre-treatment to mitigate these risks.

Essa et al.⁴ have evaluated the suitability of biochar made from seaweed waste (*Sargassum muticum* and *Ulva lactuca*) for agricultural use. Their study includes a practical greenhouse trial. The biochar characterization shows a high ash content and moderate nutrient levels, an alkaline pH, low fixed carbon and surface area. Heavy metal content were determined to be acceptable for agricultural use. The seaweed was washed with tap water before pyrolysis. In greenhouse trials, the authors tested the effect of different application rates (up to 10 %) on lettuce (*Lactuca sativa*) grown in pots. Both neutral and acidic soil were tested. While the lower application rates led to a positive effect in acidic soil on plant growth, nutrient uptake, and chlorophyll content, high amounts of seaweed biochar had a negative impact on plant growth. In neutral soil, improvements with small doses of biochar were not statistically significant, and the highest addition rate led to a negative effect. Despite the washing step, the resulting biochars still had relatively high electrical conductivity and salt content, which seems to be causing phytotoxic effects in the higher application rates. Pre-treatment reduces, but does not eliminate, salinity concerns in seaweed biochar.

Based on literature data, it may be expected that

- Seaweed biochar is high in nutrients, which may be beneficial for soil amendment
- Washing is needed to reduce salt content, but salinity cannot be eliminated
- As a result of remaining salinity, high doses of seaweed biochar may be phytotoxic.

Two sets of planting trials were executed as part of this project, a large-scale greenhouse trial at Mære landbruksskole and a smaller climate chamber trial at SINTEF Energy.

³ Cárdenas-Aguiar et al. Characterization of Biochar from Beachcast Seaweed and its Uts for Amelioration fo Acid Soils. *Land*, 13, 881, 2024

⁴ Essa & Razzky. *Ulva lactuca* Biochar: From Sea to Soil for Enhancing Sustainable Agriculture. *Egyptan J. of Phycol.* 60 Vol. 26, 48-60, 2025

3.2 Greenhouse trials

The greenhouse trials were conducted at Mære Landbruksskole, who could provide infrastructure, competence and experience in testing biochar in pot trials.

3.2.1 Procedure

The following **treatments** were tested:

- Control
- EBC
- Biochar from unwashed seaweed
- Biochar from acid-preserved seaweed
- Biochar from water-rinsed seaweed
- Biochar from dried and water-washed seaweed

The control group was a set of plants planted without any addition of biochar. “EBC” refers to biochar certified for soil amendment after the European Biochar Certificate (EBC).

Two different **soil types** were tested: a standard **peat soil**, which is commonly used at Mære Landbruksskole for food crop production. In addition, a **sandy soil** of low quality was used to test more extreme conditions, in which the effect of biochar may be more pronounced.

Two different fast growing food **crops** were planting, **spinach** and **radish**. These plants have short growing cycles, and are therefore popular in conducting such planting trials.

Biochar is added to the soil in different amounts, referred to as **application rate**. This application rate may vary significantly, and in the past, rates ranging from 0.1 – 30 tons/ha have been applied. For the greenhouse trials, three different application rates were tested, **10 t/ha**, **20 t/ha**, and **30 t/ha**.

Due to the limited available amount of seaweed biochar as well as area in the greenhouse, not all combinations could be tested. The following matrix gives an overview of the blends tested during the greenhouse trials. The first column shows the treatment, with the biochar type (respective feedstocks) in bold.

Table 5 Experiment matrix for greenhouse trials

Crop type:	Radish						Spinach					
	Peat soil			Sandy soil			Peat soil			Sandy soil		
Soil type:	Peat soil			Sandy soil			Peat soil			Sandy soil		
Application rate [t/ha]:	10	20	30	10	20	30	10	20	30	10	20	30
EBC	•	•	•	•	•	•	•	•	•	•	•	•
Unwashed seaweed	•	•	•	•	•	•	•	•	•	-	-	-
Acid-preserved seaweed	•	•	-	-	-	-	•	•	-	-	-	-
Water-rinsed seaweed	•	•	-	•	•	-	•	•	-	•	•	-
Dried and water-washed seaweed	•	•	•	•	•	-	•	•	•	•	•	•

For each tested combination, ten repetitions were tested. The tests were performed in a temperd greenhouse with artificial lighting. Watering was performed with a flood and drain system. In each pot, 5 seeds of either radish or spinach were planted. After germination, up to two plants were removed. This thinning process aims to ensure that there are equal numbers of plants in each pot, despite variations in germination rate. A different planting table was used for each soil-crop combination, with edge pots on all sides and tables. *Figure 4* shows the greenhouse setup for the trials.



Figure 4 Greenhouse trials at Mære Landbruksskole

After completion of the growing period, all plants were harvested. For spinach, the above-ground biomass was weighed. Radish plants were separated into leaves and roots, and each of them weighed separately. All plants were dried and the dry weight recorded in addition to the fresh weight.

3.2.2 Results

3.2.2.1 Radish in peat soil

The fresh and dry weight of radish leaves in peat soil are shown in Table 6 and Figure 5 (a, b). The control plants had a mean fresh weight of 27.85 g and a mean dry weight of 2.51 g. The results for EBC biochar are in the same range. Biochars from seaweed, regardless the pretreatment method, had a negative impact on plant growth, with all measured leaf weights significantly below the control values.

Table 6 Fresh and dry weight of radish leaves in peat soil, weight per pot [g], (standard deviation)

Radish leaves, peat soil	Fresh weight			Dry weight			
	Application rate [t/ha]:	10	20	30	10	20	30
Control		27.85 (4.44)			2.51 (0.44)		
EBC		27.87 (3.49)	29.51 (3.07)	27.97 (4.02)	2.39 (0.27)	2.61 (0.40)	2.36 (0.55)
Unwashed seaweed		16.81 (3.54)	9.67 (5.38)	5.73 (2.18)	1.38 (0.28)	0.80 (0.45)	0.54 (0.29)
Acid-preserved seaweed		23.97 (4.35)	22.11 (4.39)	-	1.78 (0.24)	1.70 (0.55)	-
Water-rinsed seaweed		12.65 (6.29)	6.75 (5.16)	-	0.99 (0.53)	0.31 (0.69)	-
Dried and water-washed seaweed		23.38 (3.17)	16.03 (4.61)	16.18 (3.11)	1.54 (0.28)	1.22 (0.32)	1.23 (0.27)

Some differences between the different types of seaweed biochar can be observed, such as that biochar from acid-preserved seaweed may yield slightly higher masses than the other types of seaweed. However,

since all seaweed biochars are inferior to both the control and the reference biochar, differences are not discussed any further. The higher the application rate, the more apparent the negative influence becomes.

Table 7 Fresh and dry weight of radish root in peat soil, weight per pot [g], (standard deviation)

Radish root, peat soil	Fresh weight			Dry weight			
	Application rate [t/ha]:	10	20	30	10	20	30
Control		150.34 (18.98)			7.08 (0.85)		
EBC		146.85 (10.27)	154.47 (13.73)	153.01 (13.26)	7.09 (0.60)	7.76 (0.54)	7.75 (0.61)
Unwashed seaweed		22.31 (13.53)	9.11 (6.81)	2.40 (2.49)	1.14 (0.65)	0.72 (0.65)	0.11 (0.21)
Acid-preserved seaweed		91.41 (22.59)	55.49 (14.13)	-	4.71 (1.20)	2.79 (0.83)	-
Water-rinsed seaweed		22.31 (13.53)	9.11 (6.81)	-	0.88 (0.92)	0.46 (0.66)	-
Dried and water-washed seaweed		66.87 (31.89)	33.14 (15.63)	19.43 (14.48)	3.25 (1.33)	1.81 (0.71)	1.05 (0.70)

Table 6 and Figure 5 (c and d) show the corresponding fresh and dry weight of the radish root in peat soil. The negative influence of all seaweed biochars is more apparent on the radish root than on the leaves. While the control group as well as the reference biochar yielded an average fresh weight somewhere around 150 g per pot, radish roots planted in unwashed seaweed biochars were as low as 2.4 g, i.e., meaning that no root had actually developed. Acid preservation and washing after drying yielded somewhat better results than unwashed seaweed. They remain however significantly lower than control and EBC.

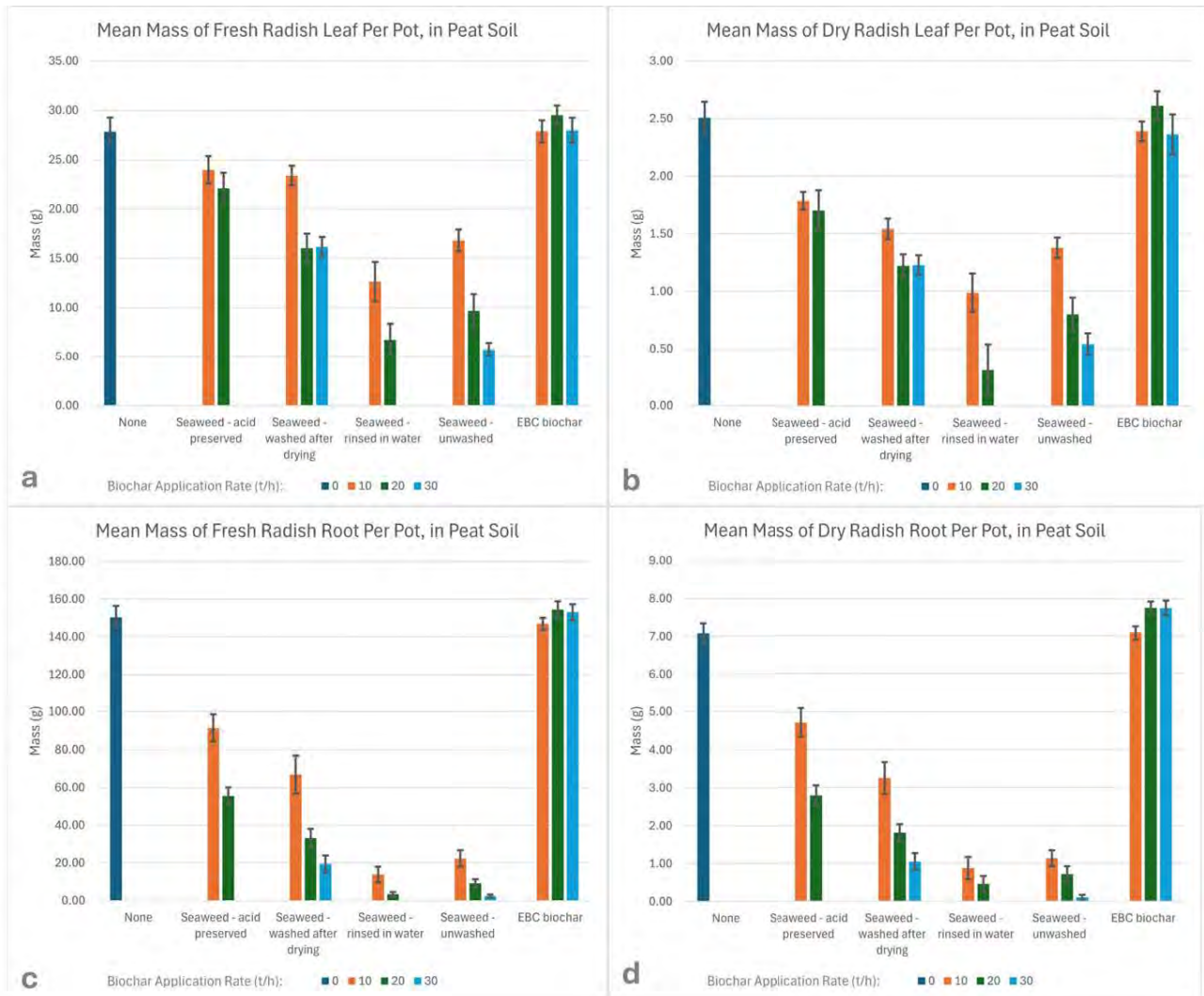


Figure 5 Mean mass of fresh radish leaves (a), dry radish leaves (b), fresh radish roots (c) and dry radish roots (d) of radish plants in peat soil, harvested after the greenhouse planting trial.

As for the leaves, the higher the application rate, the worse the outcome. The trends are the same for the dry weight of radish root.

3.2.2.2 Radish in sandy soil

In degraded soils, biochar tends to generally have a more pronounced effect. This seems also the case for the negative impact that seaweed biochars have on plant growth. Table 8 and Figure 6 (a and b) show the fresh and dry weights of radish leaves in sandy soils, Table 9 and Figure 6 (c and d) the corresponding values for radish root.



Table 8 Fresh and dry weight of radish leaves in sandy soil, weight per pot [g], (standard deviation)

Radish leaves, sandy soil	Fresh weight			Dry weight			
	Application rate [t/ha]:	10	20	30	10	20	30
Control		15.10 (3.07)			1.81 (0.38)		
EBC		15.74 (3.58)	13.20 (2.58)	14.18 (3.41)	2.33 (1.30)	1.44 (0.47)	1.67 (0.45)
Unwashed seaweed		2.09 (5.04)	-	-	0.20 (0.44)	-	-
Acid-preserved seaweed		-	-	-	-	-	-
Water-rinsed seaweed		2.35 (3.90)	1.21 (3.07)	-	0.23 (0.35)	0.12 (0.31)	-
Dried and water-washed seaweed		7.50 (4.86)	5.48 (5.54)	0.72 (2.29)	0.81 (0.59)	0.57 (0.58)	0.10 (0.33)

The control groups results in fresh weight of radish leaves around 15 g per pot. EBC-biochar addition leads to comparable results. Adding seaweed biochar to the soil results in a significant drop in leaf weight, just 2 g per pot for unwashed seaweed biochar. A quick rinse in water does not seem to give much better results than the biochar from unwashed seaweed. Washing after drying seems to perform slightly better. Nevertheless, all seaweed biochars are significantly poorer in their performance as soil amendment.

The trends seen for radish leaves in sandy soil are similar for radish root in sandy soil. Despite the pretreatment method, seaweed biochar addition led to very poor results. High application rates seem to completely inhibit the development of the root.

It should be noted that the standard deviation (given in the parentheses in all tables, ten pots per combination) is very large for some groups, sometimes even larger than the average value. This shows the high variation in growth despite the same treatment.

Table 9 Fresh and dry weight of radish root in sandy soil, weight per pot [g], (standard deviation)

Radish root, sandy soil	Fresh weight			Dry weight			
	Application rate [t/ha]:	10	20	30	10	20	30
Control		69.15 (16.59)			5.15		
EBC		57.50 (16.49)	51.83 (13.61)	59.29 (14.42)	4.19 (2.11)	4.29 (1.21)	4.48 (0.49)
Unwashed seaweed		10.19	-	-	0.61 (1.36)	-	-
Acid-preserved seaweed		-	-	-	-	-	-
Water-rinsed seaweed		7.36 (11.95)	5.83 (17.84)	-	0.54 (0.78)	0.46 (1.32)	-
Dried and water-washed seaweed		39.21 (23.18)	24.80 (19.34)	-	3.33 (2.03)	1.81 (1.42)	-

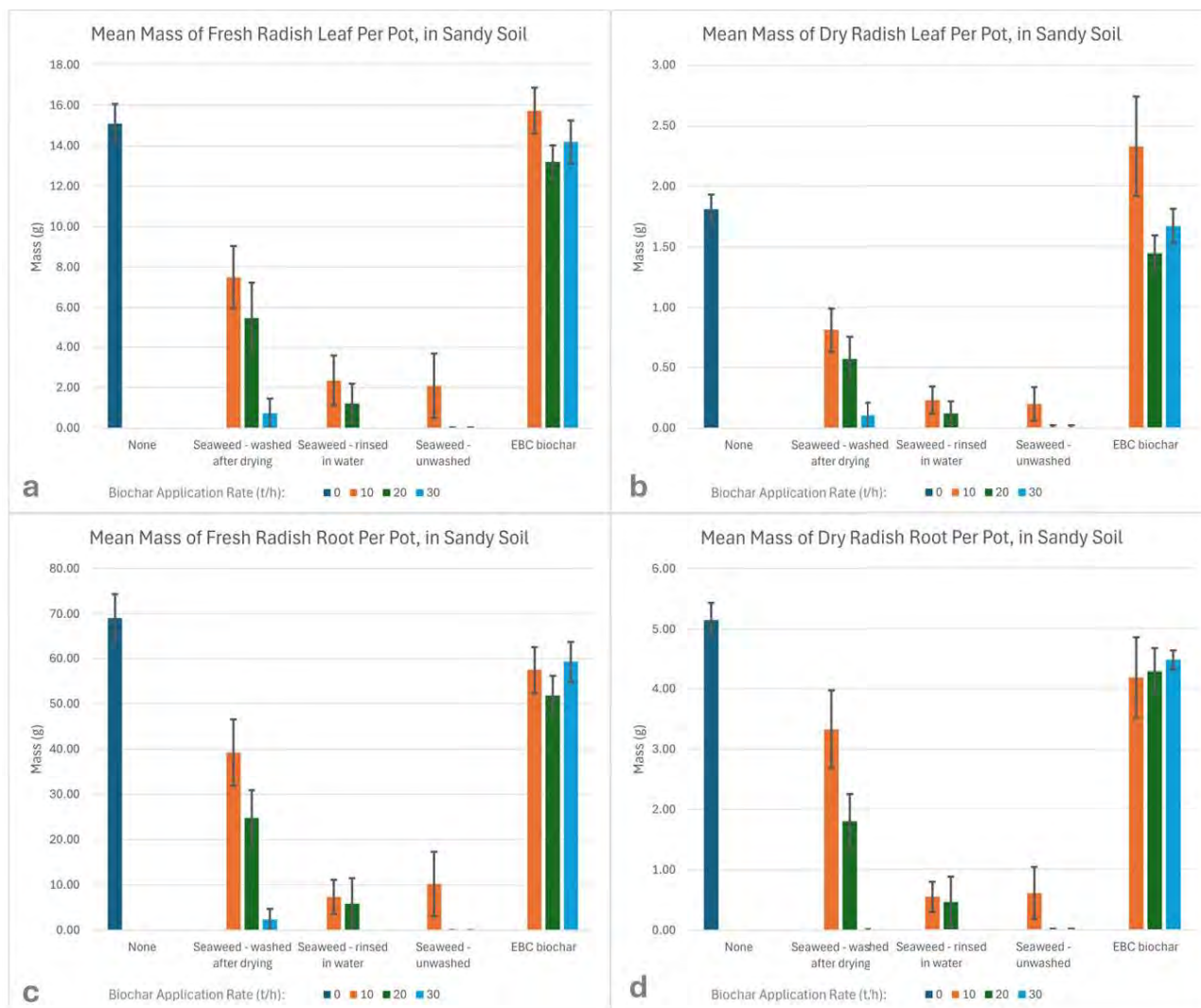


Figure 6 Mean mass of fresh radish leaves (a), dry radish leaves (b), fresh radish roots (c) and dry radish roots (d) of radish plants in sandy soil, harvested after the greenhouse planting trial.

3.2.2.3 Spinach in peat soil

Table 10 and Figure 7 show the fresh and dry weight of spinach (above-ground biomass) in peat soil, planted with the different treatments.

Table 10 Fresh and dry weight of **spinach in peat soil**, weight per pot [g], (standard deviation)

Radish root, sandy soil	Fresh weight			Dry weight		
	Application rate [t/ha]:			Application rate [t/ha]:		
	10	20	30	10	20	30
Control	34.98 (5.35)			3.22 (0.60)		
EBC	34.29 (5.03)	35.63 (4.65)	37.29 (2.93)	3.11 (0.52)	3.26 (0.49)	3.46 (0.40)
Unwashed seaweed	17.11 (2.90)	6.11 (2.61)	3.34 (1.31)	1.43 (0.36)	0.48 (0.13)	0.34 (0.15)
Acid-preserved seaweed	25.80 (7.19)	16.60 (6.11)	-	2.10 (0.58)	1.48 (0.52)	-
Water-rinsed seaweed	7.55 (3.18)	3.74 (1.77)	-	0.72 (0.30)	0.35 (0.33)	-
Dried and water-washed seaweed	24.05 (4.57)	10.94 (7.29)	11.46 (6.09)	1.93 (0.34)	0.93 (0.54)	0.93 (0.38)

The mean fresh weight per pot of spinach grown without any biochar is 34.98 g. Adding EBC-certified biochar to the soil gave results that were comparable to the control, both in fresh and dry weight. Adding biochar from seaweed to the soil resulted in fresh weight values as low as 3.74 g (for biochar from water-rinsed seaweed). Acid preservation and washing after initial drying seem to have led to somewhat better results. However, the overall assessment shows that seaweed biochar had a negative effect across all types and application rates.

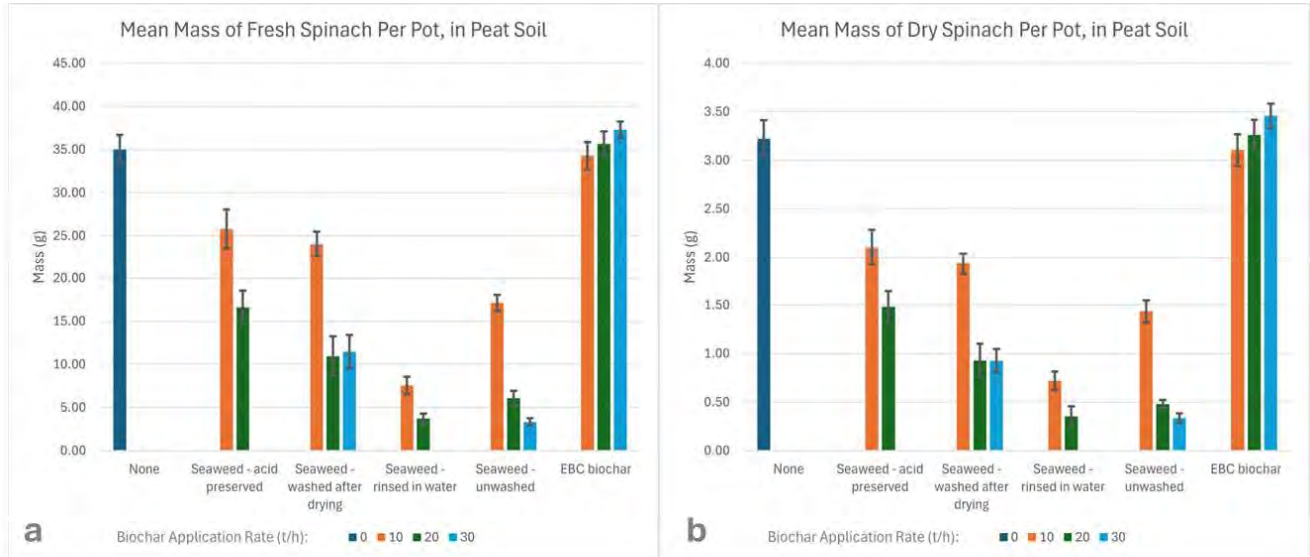


Figure 7 Mean mass of fresh spinach leaves (a) and dry spinach leaves of spinach plants in peat soil, harvested after the greenhouse planting trial.

3.2.2.4 Spinach in sandy soil

The results are similar for spinach grown in sandy soil, Table 11 and Figure 8. The poorer conditions led to lower weights for all groups compared to their counterparts in peat soil. The average fresh weight of spinach for the control was 6.82 g. Addition of EBC biochar led to comparable results. As before, seaweed biochar worsened the outcome significantly, the lowest average fresh weight was measured at 0.51 g. As mentioned above, the large standard deviation should be pointed out. Due to limited quantities of seaweed biochar available, unwashed and acid-preserved seaweed biochar could not be tested on spinach in sandy soil. However, the results can be assumed to follow the trends seen in all other trials.

Table 11 Fresh and dry weight of spinach in sandy soil, weight per pot [g], (standard deviation)

Radish root, sandy soil	Fresh weight			Dry weight			
	Application rate [t/ha]:	10	20	30	10	20	30
Control		6.82 (1.76)			0.91 (0.31)		
EBC		6.29 (1.50)	6.97 (1.71)	7.69 (1.23)	0.87 (0.31)	0.87 (0.25)	1.06 (0.22)
Unwashed seaweed		-	-	-	-	-	-
Acid-preserved seaweed		-	-	-	-	-	-
Water-rinsed seaweed		1.95 (1.44)	0.51 (1.47)	-	0.21 (0.16)	0.06 (0.18)	-
Dried and water-washed seaweed		4.94 (1.71)	4.88 (2.71)	0.67 (1.49)	0.57 (0.24)	0.53 (0.26)	0.07 (0.15)

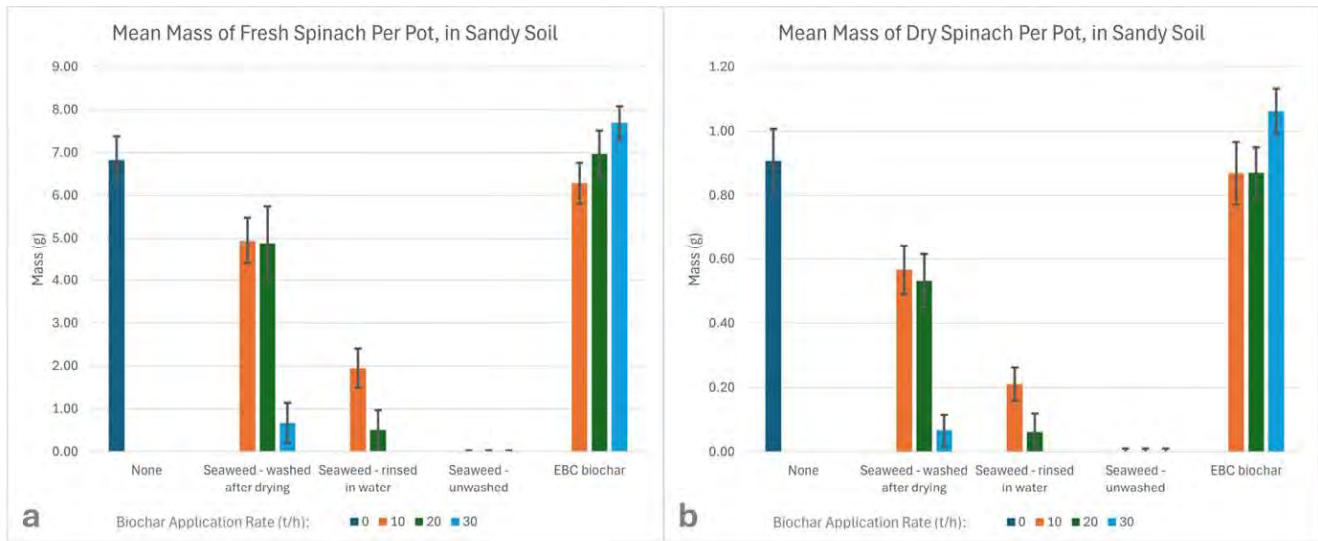


Figure 8 Mean mass of fresh spinach leaves (a) and dry spinach leaves of spinach plants in sandy soil, harvested after the greenhouse planting trial.

3.2.3 Conclusions from greenhouse tests

The greenhouse planting trial performed in the course of this project was quite comprehensive and, to our knowledge, the largest of its kind conducted with seaweed biochar.

The following conclusions are drawn after these tests:

- Seaweed biochar has a phytotoxic effect on radish and spinach, both in peat and sandy soils
- The fresh and dry weights of all plants treated with seaweed biochar are significantly lower than the control
- The higher the application rate of seaweed biochar, the more severe the negative effect
- Washing and/or preservation of the feedstock has some effect, slightly improving the outcome
- Quickly rinsing the feedstock with water before pyrolysis did not seem to improve the outcome compared to unwashed seaweed
- EBC-certified biochar does not seem to have a notable effect on plant growth compared to the control in the conditions tested

Based on these conclusions, it cannot be recommended to apply seaweed biochar produced under the conditions in this study to soil. On the contrary, it must be pointed out that seaweed biochar seems to be phytotoxic, severely inhibiting plant growth.

Literature data (see above) has shown that washing of feedstock does reduce but not eliminate salinity. This was confirmed by this study. It is generally pointed out by other authors that seaweed biochar might be

beneficial for soil amendment due to its high nutrient content. However, the negative effects seem to outweigh nutritional benefits by far.

3.3 Climate chamber trials

Due to the very poor results of seaweed biochar in the greenhouse trials, it was decided to conduct an additional small-scale planting trial in climate chamber. The goal was to understand the reasons for the poor outcome as well as improve the results compared to the trials conducted at Mære.

3.3.1 Procedure

The small-scale trials were conducted in a climate chamber. The chamber's temperature was set to 18 C and the relative humidity to 50%. The plants were exposed to artificial lighting for 14 hours per day. Radish was used in these tests. As before, five seeds were planted per pot. A regular pre-fertilized bagged gardening soil was used. For those groups tested with biochar addition, biochar was added at 20 t/ha. After germination, up to two plants were removed. When harvesting, leaves and roots were separated. Fresh weight (per pot, i.e. for all plants in the pot) was recorded. Radish roots were then dried in a drying oven at 60 °C for at least 48 hours (longer, if not completely dry), and the dry weight recorded. (The trends of dry weight follow those of fresh weight. With limited available drying capacity, it was decided to not measure dry weight of the leaves.)



Figure 9 Climate chamber trials at SINTEF Energy

The goal of this trial was to investigate the reasons for the poor performance of seaweed biochar in the large-scale greenhouse trials. As salinity is a likely reason for the biochar's phytotoxicity, this trial focused on testing the effect of different salt concentration on plant growth.

In addition to the control, salt was artificially added to the soil in an attempt to isolate its effect. Salt was added in three different concentrations, without biochar addition. EBC-certified biochar was used, without salt addition as well as with different added salt concentrations. Biochar from unwashed seaweed was added

to one of the groups. Lastly, washed seaweed biochar was used. This biochar was produced from unwashed seaweed (same conditions as the other seaweed biochar in this trial), but the biochar was washed with tap water after production.

There were six repetitions for each treatment. No edge pots were used in this trial.

The following **treatments** were tested:

- Control
- Salt addition, concentration 0.14 g/L (no biochar)
- Salt addition, concentration 1.4 g/L (no biochar)
- Salt addition, concentration 2.8 g/L (no biochar)
- EBC (wood biochar)
- EBC with salt addition, concentration 0.14 g/L
- EBC with salt addition, concentration 1.4 g/L
- EBC with salt addition, concentration 2.8 g/L
- Biochar from unwashed seaweed
- Washed biochar from unwashed seaweed

3.3.2 Results

The fresh and dry weights of radish leaves is shown in Table 12, and Figure 10 to Figure 12. Due to the lower number of repetitions, the standard deviation was not calculated.

The average fresh weight of radish leaves without biochar or salt addition is 12.38 g. The addition of salt in lower quantities to the soil does not seem to have a clear effect. Neither does the addition of woody biochar and woody biochar with salt.

The impact of biochar from unwashed seaweed however is significant. The average fresh weight is only 1.8g. Washing of the seaweed biochar however led to an average fresh weight of 13.07, slightly above the corresponding valued for the control and biochar-added groups.

Table 12 Fresh and dry weight of *radish leaves*, weight per pot [g].

Radish leaves	Fresh weight [g]
Control	12.38
Salt addition 0.14 g/L	12.80
Salt addition, 1.4 g/L	11.99
Salt addition, 2.8 g/L	9.33
EBC	12.21
EBC + salt, 0.14 g/L	13.72
EBC + salt, 1.4 g/L	11.41
EBC + salt, 2.8 g/L	11.41
Seaweed biochar	1.80
Seaweed biochar, washed	13.07

Table 13 Fresh and dry weight of *radish root*, weight per pot [g].

Radish root	Fresh weight [g]	Dry weight [g]
Control	3.44	0.22
Salt addition 0.14 g/L	2.86	0.17
Salt addition, 1.4 g/L	3.04	0.16
Salt addition, 2.8 g/L	2.47	0.15
EBC	3.15	0.19
EBC + salt, 0.14 g/L	3.87	0.23
EBC + salt, 1.4 g/L	3.44	0.21
EBC + salt, 2.8 g/L	3.69	0.20
Seaweed biochar	0.09	0.01
Seaweed biochar, washed	4.27	0.24

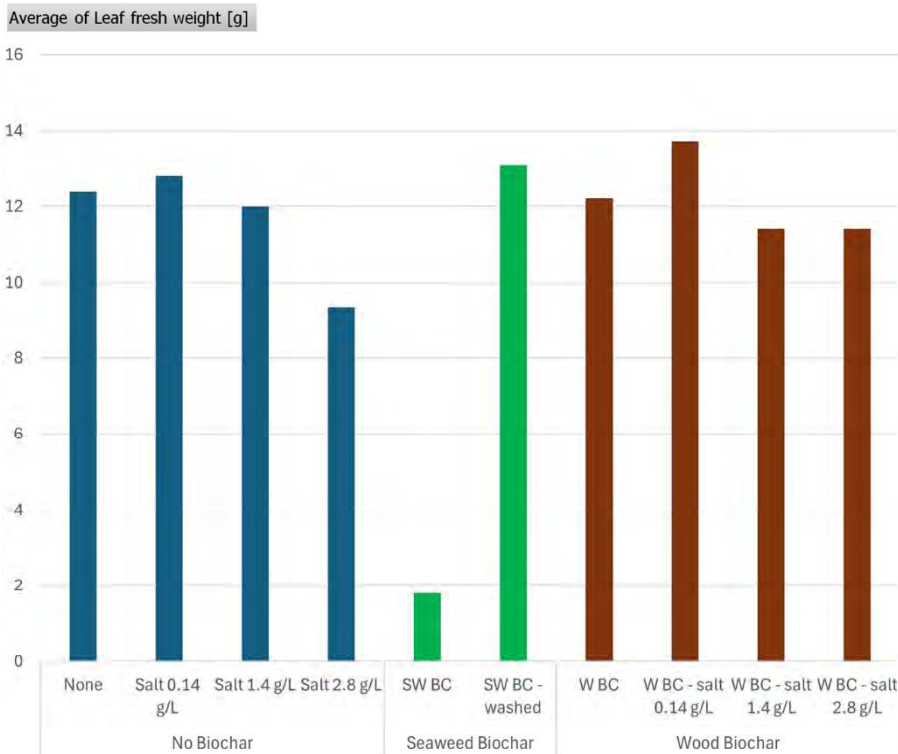


Figure 10 Average leaf fresh weight of radish plants harvested after planting trial in climate chamber

The average fresh weight of radish root of the control group was 3.44 g. Salt addition led to a slightly lower yield, when no biochar was added. Wood based biochar addition (with and without salt) did not seem to affect the plant growth significantly negatively. The addition of biochar from unwashed seaweed to the soil had a devastating effect, completely hindering the development of radish roots. However, washed seaweed biochar achieved the highest yield, with an average of 4.27g.

Average of Radish Root fresh weight [g]

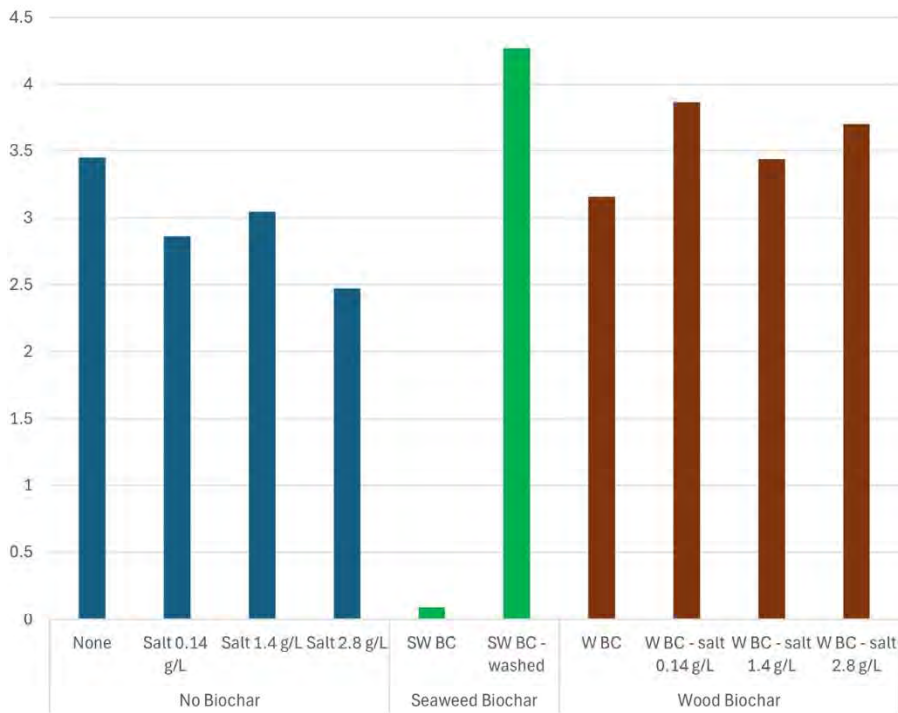


Figure 11 Average **root fresh weight** of radish plants harvested after planting trial in climate chamber

Average of Radish Root dry weight [g]

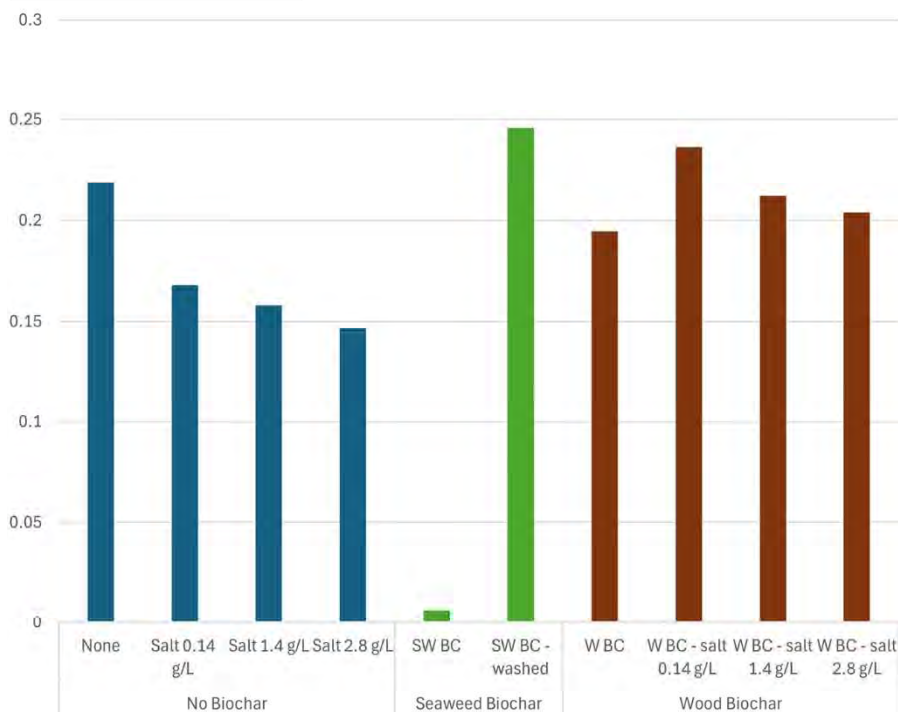


Figure 12 Average **root dry weight** of radish plants harvested after planting trial in climate chamber

The relatively low root biomass compared to leaf biomass should be pointed out. The root weight is significantly lower than one would expect from radish. This is likely due to the very high plant density in the pots, which may have limited space and resources for root expansion while still allowing aboveground growth. For the sake of this experiment, i.e. comparison of different treatment, this is acceptable and does not influence the conclusions from the study.

3.3.3 Conclusions from climate chamber tests

The climate chamber trial was conducted to further investigate the reasons for the poor plant performance observed in the greenhouse tests, with a particular focus on the role of salinity. The following conclusions are drawn from this test:

- The addition of unwashed seaweed biochar had a strong phytotoxic effect on radish, with severely reduced leaf biomass and nearly complete inhibition of root development.
- Artificial salt addition (at levels corresponding to estimated salt content in biochar) reduced plant growth only moderately and did not reproduce the strong negative effect of seaweed biochar.
- Woody biochar (EBC-certified), with and without added salt, did not significantly impact plant growth compared to the control.
- **Washing the seaweed biochar after pyrolysis fully mitigated the phytotoxic effect and resulted in the highest radish yield across all treatments.**
- **The results indicate that the negative impact of seaweed biochar cannot be explained by salinity alone. Other factors, such as organic residues or unknown inhibitory compounds in the unwashed material, may contribute to phytotoxicity.**
- The root biomass was generally low compared to the leaf biomass in all treatments, likely due to the high plant density per pot. This does not affect the relative comparison of treatments, which was the primary objective of the trial.

Based on these results, post-treatment of seaweed biochar (e.g. washing) is essential to reduce phytotoxic effects and unlock its potential for soil application. Further research is needed to identify the exact causes of growth inhibition and optimize biochar treatment protocols.

4 Outlook

This study provides an assessment of seaweed biochar production, properties, and potential for soil-based applications. The results highlight that while untreated seaweed biochar presents significant challenges for soil use due to phytotoxicity, it also offers clear opportunities for carbon removal and material-based applications, especially if production and post-treatment steps are carefully managed.

- The biochar produced from seaweed in this study may be considered chemically stable, based on the low H/C and O/C molar ratios, qualifying it as a durable carbon sink under leading CDR certification frameworks.
- However, its low carbon content and very high ash, chlorine, and bromine levels pose constraints for soil application and raise environmental concerns.
- Phytotoxic effects observed in greenhouse trials could be mitigated after washing the biochar post-pyrolysis. After adequate pretreatment, seaweed biochar could be added to soil and performed well in comparison to woody biochar.
- From an energy perspective, seaweed pyrolysis could be self-sustaining if feedstock moisture is reduced to an acceptable value, but this requires efficient drying systems and ideally integration with waste heat sources.

Recommendations

- **Explore non-agronomic applications** for seaweed biochar:
 - Due to its chemical stability and mineral-rich profile, **use in concrete, asphalt, or bricks** may be more viable than soil application. These applications **unlock carbon credit potential** while avoiding phytotoxicity issues.
 - Work with partners in the **construction and materials sector** to assess performance and acceptance criteria for biochar integration.
- **Utilize residues instead of fresh seaweed:**
 - To improve environmental performance and reduce emissions associated with harvest, logistics, and drying, it is recommended to **source seaweed side streams** such as processing residues from other seaweed products.
 - This supports **cascading use** principles and improves allocation of environmental impacts across product systems.
- **Implement efficient drying strategies:**
 - Drying is a major energy bottleneck in seaweed biochar production. Future systems should prioritize **low-temperature drying using waste heat**, and integration with **industrial processes** that produce surplus thermal energy.
- **Investigate targeted washing or purification methods:**
 - Simple rinsing before pyrolysis is insufficient. Post-pyrolysis washing shows clear benefits and should be developed into a **scalable, resource-efficient treatment step**.

2. **Conduct techno-economic and lifecycle assessments:**

- To support decision-making and commercialization, detailed **LCA and TEA** models should be developed, reflecting realistic processing steps, transport logistics, and multiple use cases (e.g., soil vs. materials).

3. **Advance policy and certification dialogue:**

- Seaweed biochar differs significantly from woody biochar and needs **tailored guidelines** for use and certification. Engaging with CDR frameworks to clarify criteria for marine biochar feedstocks will help accelerate adoption.



JOINT INDUSTRY PROJECT SEAWEED CARBON SOLUTIONS

MID WAY REPORT WORK PACKAGE 10

SINTEF Ocean

Report No.: 2025-0956, Rev. 1

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1 INTRODUCTION

This report presents the deliverable of the work conducted in Work Package 10 of the Seaweed Carbon Solutions Joint Industry Project. It focuses on the pathway towards verifiable carbon credits from seaweed carbon dioxide removal, followed by a life cycle assessment for the greenhouse gas emissions of seaweed biochar production. The report discusses improvements of the current project value-chain and concludes with recommendations for further steps towards carbon dioxide removal with seaweed biochar.

2 VERIFICATION OF CARBON CREDITS FROM SEAWEED CARBON DIOXIDE REMOVAL (CDR)

Through photosynthesis, seaweed captures CO₂ in its biomass (CDR). The carbon can then be stored through multiple pathways, either in the ocean or on land (Fig. 1).

Carbon pools from seaweed farming



Figure 1 – Possible carbon pools from farmed seaweed.

2.1 Carbon pools from seaweed

The potential carbon storage options in the ocean include either active or passive sinking; Active sinking is when seaweed is farmed and deposited in the ocean for CDR purposes. This project focuses on the fragmentation and deposition of biomass particles naturally occurring during the growth phase, hereby referred to as **passive sinking**. This carbon can end up in multiple potential lock-away pathways by:

- Sinking to the ocean floor (as particulate organic matter or dissolved organic matter) and being covered in ocean sediments for sedimentary storage.
- Ending up in the deep-sea currents where it is unlikely to reach the atmosphere for at least 100 years.
- Turning into recalcitrant dissolved organic matter (RDOC) which is believed to be stable for a long period of time (for more info, see results from WP6).

The rate at which carbon from a seaweed farm ends up in any of these storage options is highly dependent on the location of the farm, the bathymetry, currents, substrate types, depths, and other factors. Large uncertainties exist

regarding how to measure and model these, the amount of carbon that ends up in long-term storage, and the permanence of the different storage options.

However, most of the carbon captured by seaweed is within the biomass, which can be harvested and processed for sequestration purposes. This project focuses on harvesting the seaweed for biochar production, one of the few mature and available options for carbon storage with biomass.

2.2 Carbon crediting methodologies

To generate carbon credits, the carbon storage option must be verified in accordance with a carbon crediting methodology. Leading companies in verifying and setting standards for carbon crediting include Verra, Puro.Earth, and Gold Standard;

An assessment of existing standards from these parties was done to understand which methodologies could be applied to generate carbon credits in the project.

2.2.1 CDR pathway: Passive sinking

For oceanic storage pathways, these methodologies have not yet been developed due to the immaturity of the topic and existing knowledge gaps. These gaps make monitoring the fate of the carbon, and thus carbon accounting, challenging. However, there has been significant recent attention on blue carbon and the ocean's role in carbon storage. Currently, there are multiple new methodologies under development for blue carbon projects, including for seaweed farming through, e.g. Verra.

2.2.2 CDR pathway: Biochar production

In the project, most of the carbon captured in the seaweed is harvested and brought to land to produce biochar. Biochar is considered one of the more mature solutions for carbon capture and storage currently on the market and is recognized by the *European Carbon Removal Certification Framework*. Of sold carbon dioxide removal credits, credits from biochar make up 90%. In 2023, more than 80 000 tonnes of biochar credits were issued, and prices have ranged from 100-180\$ the last few years.

Both Puro.Earth and Verra have developed carbon crediting methodologies for biochar that could be relevant for this project. One of the main differences between the two methodologies, which is of particular relevance for the project, is that Verra's methodology is restricted to waste biomass as feedstock for biochar production, while Puro.Earth's methodology is open to other types of biomasses (Puro.Earth 2024; VCS, 2022). Consequently, Verra's methodology is not applicable to the project as long as the seaweed used is purposely grown for biochar production.

To generate carbon credits, a project must demonstrate that it is reducing greenhouse gas (GHG) emissions to the atmosphere through a Life Cycle Assessment (LCA) approach. To determine whether the seaweed value chain in the JIP can generate carbon credits, an LCA of the current value chain was conducted, along with an examination of different scenarios for future optimisations.

3 LIFE CYCLE ASSESSMENT FOR GHG EMISSIONS OF SEAWEED BIOCHAR PRODUCTION

To enable the generation of carbon credits from farmed seaweed, the project owner needs to demonstrate a carbon net negative value chain. This is to ensure that the carbon sequestered in the seaweed is not outweighed by the carbon emissions released in the process of producing the product.

Currently, no Product Environmental Footprint (PEF) category rules have been established for seaweed production. As a result, a wide variety of methods have been used in seaweed Life Cycle Assessments (LCAs) published so far, making them difficult to compare. Thomas et al. (2024) recently provided a harmonized recalculation of inventory data from a collection of published seaweed LCAs to enhance comparability. The study identified key hotspots in seaweed production, including fuel use on vessels, impacts from farm infrastructure, and energy use for drying and processing. However, the studies vary considerably in goal and scope, and there is a lack of studies on offshore and commercial farming.

The LCA study in this report explores the potential for carbon dioxide removal (CDR) with biochar made with cultivated seaweed biomass from an offshore seaweed farm outside Frøya, Norway. Please note that these figures are based on estimates provided by the data providers. The production volumes of 500 tonnes of seaweed (fresh weight) per year at the respective farms which is assumed in this study, as well as the subsequent production of seaweed biochar, have not yet been demonstrated.

3.1 System boundaries

The equipment of the seaweed farm was modelled with data from the Ecoinvent 3.9.1 and Biosphere3 databases. Data for the life cycle inventories were provided by SINTEF Ocean and Seaweed Solutions. Where additional details were needed – for instance, when the equipment consisted of several components of different materials – information was obtained from the equipment producers, like the buoys supplied by Polyform and Ovun.

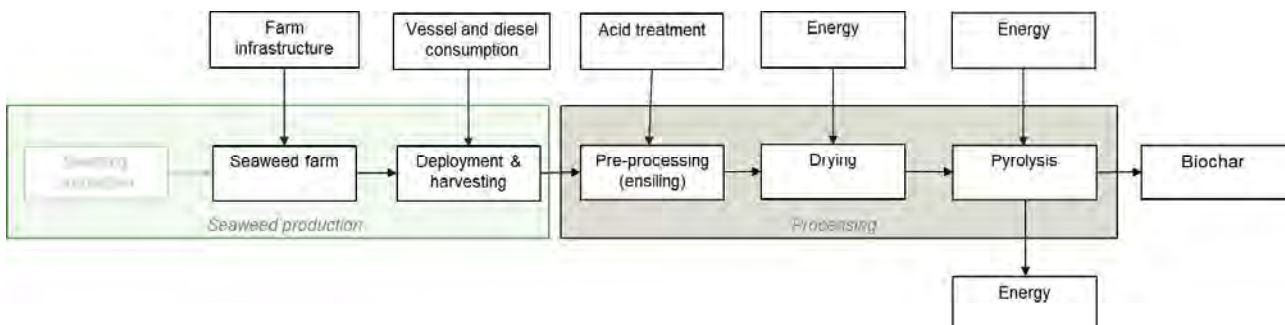


Figure 2 - Farm-to-gate system boundaries for the LCA, starting with the installation of the seaweed farm and ending with produced seaweed biochar as a product. The main inputs and outputs for the different steps are also included.

The farm-to-gate system boundaries encompass the installation of the seaweed farm, the deployment and harvesting of seaweed, pre-processing to stabilize the fresh biomass, the drying of seaweed, and pyrolysis to produce biochar. Seeding production is excluded from this study due to its assumed low impact compared to other parts of seaweed farming, as indicated by findings from existing LCA studies on seaweed farming (Hasselström & Thomas., 2022; Thomas et al., 2024). The final application of the biochar as an end-product is also excluded. The production volume is considered to be 500t a year, which corresponds to a yield of 10kg/m growth line (fresh weight).

Below is a detailed discussion on each segment of the value chain for seaweed biochar production.

3.2 Breakdown per value chain stage

3.2.1 Farm infrastructure

The seaweed farm at Storflua (locality number 45189), was used to provide seaweed biomass for this project, and is a **state-of-the-art facility designed for farming in offshore conditions**. Offshore farming can enhance seaweed yield and scalability, but it also necessitates robust infrastructure to withstand the challenging offshore environment.

Origin

Where information on the origin of materials/equipment was given, this was applied in the model. When absent, assumptions were made based on the best available knowledge on global supply and comparison with other equipment on the farm of the same material. Although some of the equipment, like the buoys, were produced in Norway, the polystyrene foam (EPS), polyethylene (PE) and steel originates from Norway, Mexico/Europe and Latvia, respectively. Most of the lines are sourced from India, and some from England and Denmark. Most of the remaining steel components originates from China (see Appendix 1 for more details).

Lifetime

The farm infrastructure components had a lifetime ranging from 1-20 years (Appendix 1). For most steel components like anchors and chains, this was 20 years and 10 years for plastic components like lines and buoys. To account for this when considering a yearly seaweed harvest, the environmental footprint of the equipment was divided by the respective estimated certified lifetimes. For instance, the anchors had a lifetime of 20 years, thus the yearly impact was found by dividing its environmental footprint by 20.

End-of-life

It is assumed that all plastic and steel materials are recycled at the end of their life cycle. Additionally, instead of using the steel processes available in the Ecoinvent database, the steel processes were modified according to the recommendations from the World Steel Organisation. This modification accounts for the fact that, on average, 30% of the input in steel production comes from recycled scrap steel, and 90% of the steel is considered recycled at end-of-life (World Steel Organisation, 2017). The life cycle equation for this process can be found in Appendix 2.

Results

The GHG-impact of the Storflua farm infrastructure totals 14 920 kg CO₂e a year. Components made from steel contributed to 70% of the emissions, while lines and buoys contributed to 30% of the emissions from the farm infrastructure (Fig. 3). Note that some of the buoys also contain steel parts which is the main contributor to their associated emissions.

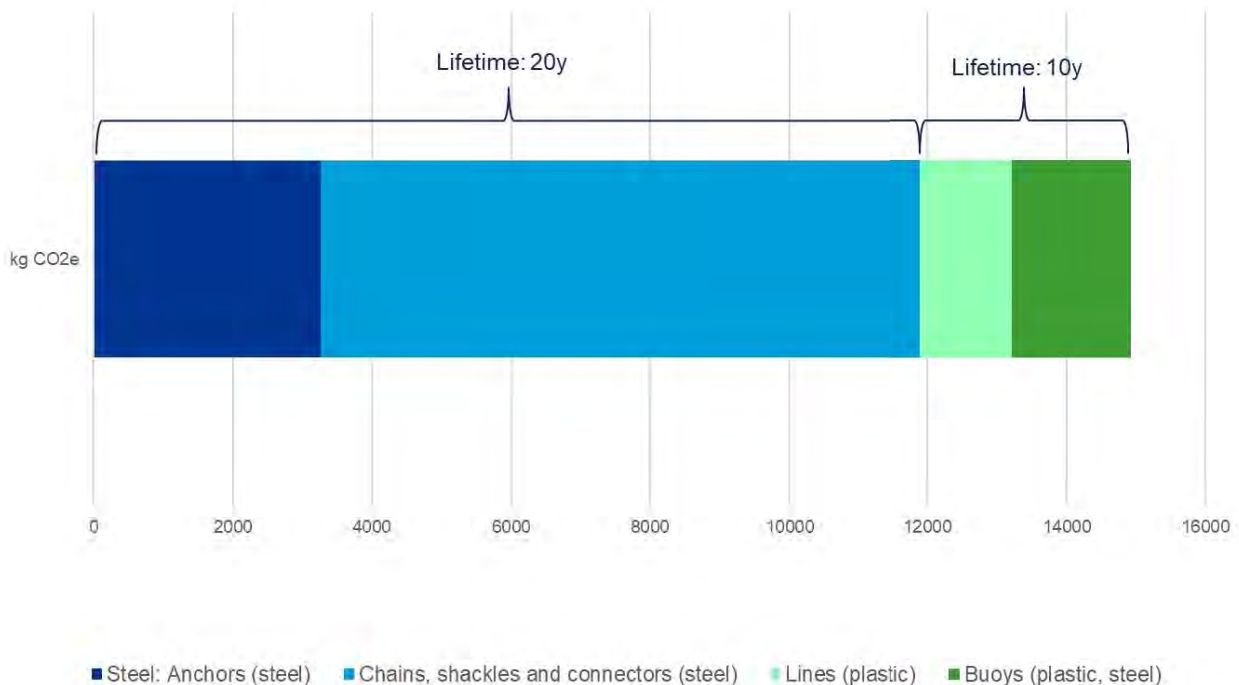


Figure 3 - Overview of the annual emissions from infrastructure at the Storflua farm, measured in kg CO₂e equivalents.

3.2.2 Vessel operations

Methods

To model the vessel used for installing the seaweed farm, the Ecoinvent process “diesel, burned in fishing vessel” was applied in line with the NPCR 031 Part B for Seabased aquaculture components (EPD-Norway, 2023). This approach is also supported by a recent seaweed LCA review study by Thomas et al. (2024) who compared two different alternatives to model the boat emissions by: tkm and diesel consumption. The study recommended using diesel consumption, as it is more measurable and accurate due to a lack of reliable processes in the Ecoinvent database for use of small to medium scale vessels.

Vessel operations are required for the installation of the farm, deployment of seedlings, various site visits during the growth period, and harvesting. The diesel consumption estimates for the installation are based on the actual installation of the Storflua seaweed farm in 2023. The diesel consumption for deploying and harvesting 500 tonnes of seaweed is estimated based on the assumption that deployment can be completed in 5 days using a small catamaran service vessel similar to or equivalent to MS Frøyvind (MMSI: 257518900), and harvesting can be done in 10 days using two vessels of the same type. For more details on diesel consumption estimates, please refer to Appendix 1, provided by SINTEF Ocean.

The burden from the installation phase is distributed over 10 years, aligning with the expected lifetime of most farm equipment (excluding anchors and chains) and the anticipated replacement of these components. The remaining vessel operations occur for each farming cycle, which is assumed to be once a year, and are accounted for accordingly.

Results

The CO₂ emissions associated with diesel consumption during deployment and harvesting operations represent a major hotspot in the seaweed farming value chain and contribute to around 2/3rds of the total emissions from the seaweed farming (Fig. 4). Since these emissions occur on a production cycle basis, they significantly outweigh those associated with farm installation and equipment, which are distributed over 10 or 20 years. When distributed over an annual production of 500t seaweed, GHG-emissions per kg of seaweed is 0.094 kg CO₂e.

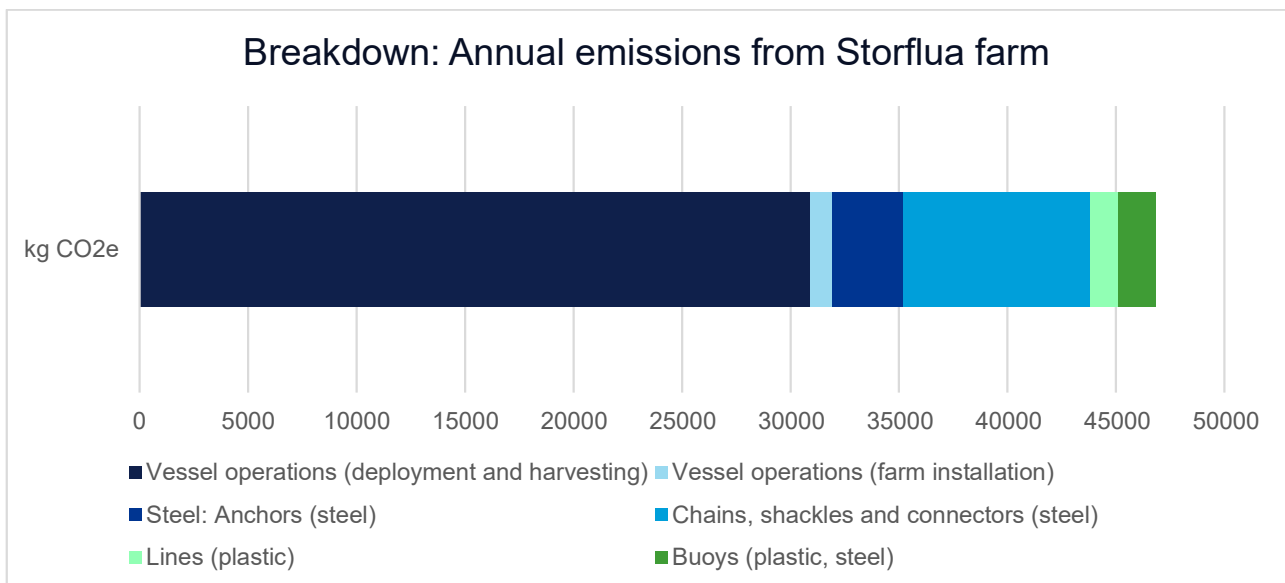


Figure 4 - Annual emissions from seaweed farming, including both farm infrastructure and vessel operations.

3.2.3 Processing

Freshly harvested seaweed contains approximately 85% water, most of which needs to be removed before pyrolysis. The biomass has a short shelf life after harvest and must be stabilized to prevent decomposition. However, facilities capable of drying 500 tonnes of seaweed within a few days are scarce, necessitating a pre-processing step to stabilise the biomass. This step provides all year supply and more flexibility, allowing for drying to be done over a longer period according to available drying capacity. One of the most efficient methods for stabilising large quantities of fresh biomass is ensiling, a technique well-known in e.g. the agriculture sector for preserving grass for cattle. Ensiling was therefore tested as a pre-processing method for seaweed in this project. See results from WP7 for more details.

The seaweed is processed through two steps: 1) pre-processing in IBC containers with sulfuric acid, and then 2) dried in an electricity-powered dryer. It is assumed that 300L of sulfuric acid (0.1 M) is needed to preserve 1 tonne of fresh seaweed (estimates from SINTEF Industry), and that 8800 kWh of electricity is needed to produce 1 tonne of dried seaweed, as described in (Nilsson et al. (2022); Almås et al. (2024)). It is assumed that 1 tonne of fresh seaweed is

needed to produce 1 tonne of pre-processed seaweed (indicating for simplicity that no biomass is lost), and that 10 tonnes of pre-processed seaweed is needed to produce 1 tonne of dried seaweed.

In the study, the Ecoinvent process for the average Norwegian electricity mix is used as default. Although Norwegian electricity mix is almost entirely based on renewables, how we account for energy mixes is impacted by the Guarantees of Origin, introduced by the EU's Renewable Energy Directive. It aims to give consumers the option to choose renewable energy by purchasing a certificate claiming that the energy is generated from renewable sources. A result of this is that renewable energy is reserved from the overall energy pool, leaving a residual electricity mix which includes a higher portion of non-renewable electricity for consumers that do not purchase such a certificate. Norway is part of this system, resulting in the average Norwegian electricity mix includes European residual mix which contains traces of electricity based on gas and coal. A sensitivity analysis was performed for the electricity mixes to better understand the impact of this on the analysis. Fig. 5 shows that there is a major difference between the two electricity mixes for the emissions associated with drying.

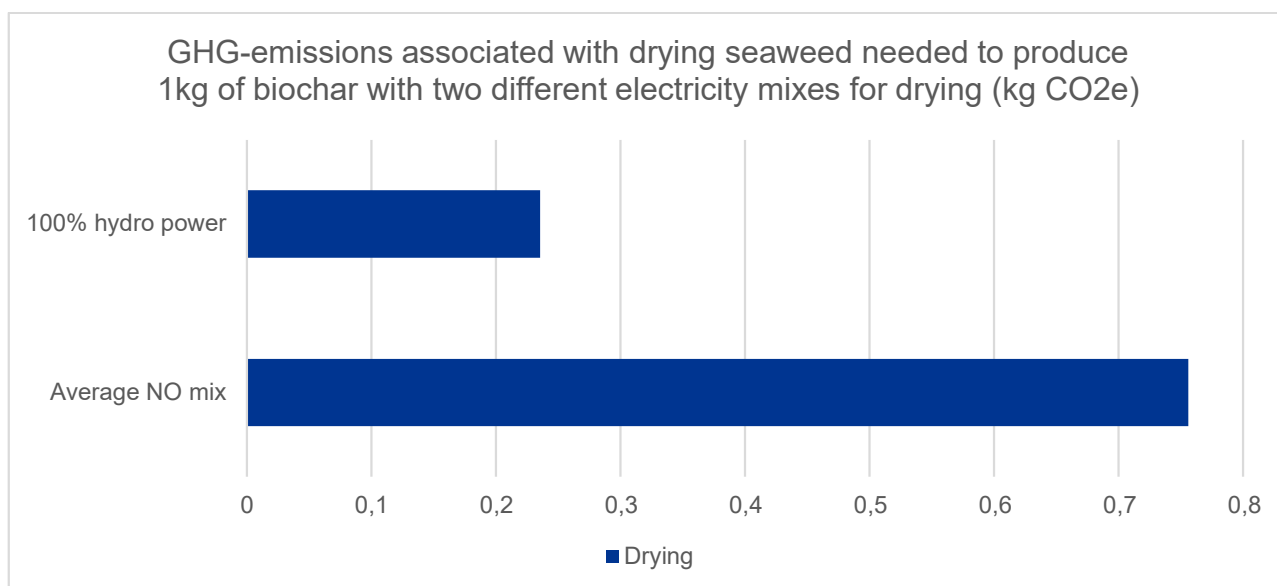


Figure 5 - CO₂e emissions associated with drying the seaweed needed for the production of 1kg seaweed biochar, comparing two different electricity mixes for the drying process; electricity sourced from 100% hydro power, and the average Norwegian electricity mix.

3.2.4 Pyrolysis

Depending on the nature of the feedstock (e.g. heating value and water content), the pyrolysis process will either need energy or produce excess energy. With carbon rich, dry feedstock, such as woody biomass, pyrolysis is likely to produce excess energy. The seaweed biomass has a comparably lower heating value. As pyrolysis of seaweed biomass has been limited to small-scale tests, there are still uncertainties in what would be the most optimal pyrolysis temperature and time, and water and salt content of the feedstock. The energy input and outputs are for simplicity considered net zero in this study due to these uncertainties. Hence, there are no burdens associated with the pyrolysis process itself, but it is important to note that approximately half of the original carbon in the seaweed biomass is burnt in the pyrolysis process and will be emitted as biogenic CO₂. Future projects should look further into how the seaweed feedstock can be optimized for the purpose of carbon sequestration and minimize GHG-emissions from the value-chain.

3.2.5 Biochar application

An end-user for the seaweed biochar has not been part of the project; hence, the biochar application has not been taken into consideration in this LCA. The application of biochar should be in accordance with carbon crediting methodologies for biochar. For instance, the VCS Methodology VM0044 (2022) requires that the biochar be applied within 200 km of the production site (although some exemptions exist). In addition to transport, the emissions from machinery used to apply the biochar should be considered.

As seaweed is a novel feedstock for biochar production, it is important to ensure that its application does not adversely affect crops.

3.2.6 Carbon sequestration and net carbon accounting

When aiming for negative emissions and carbon sequestration, it is important to understand how the carbon sequestered in the seaweed and the emissions associated with its production change throughout the seaweed biochar value chain.

The carbon sequestration potential of 1kg of seaweed biochar is considered to be 1,08kg CO₂e before accounting for emissions from the production. This is based on the assumption of a 33% carbon content in the biochar, and a permanence factor over a 100-year global warming potential horizon of 89% as according to VM0044. 500t of fresh seaweed sequestered approximately 50t of CO₂e which is assumed remaining in the seaweed through pre-processing and drying. Considering a biochar yield of 33% from dry seaweed, 50t of seaweed (DM) yields 16,5t seaweed biochar, estimated to contain approximately 17,82kg CO₂e.

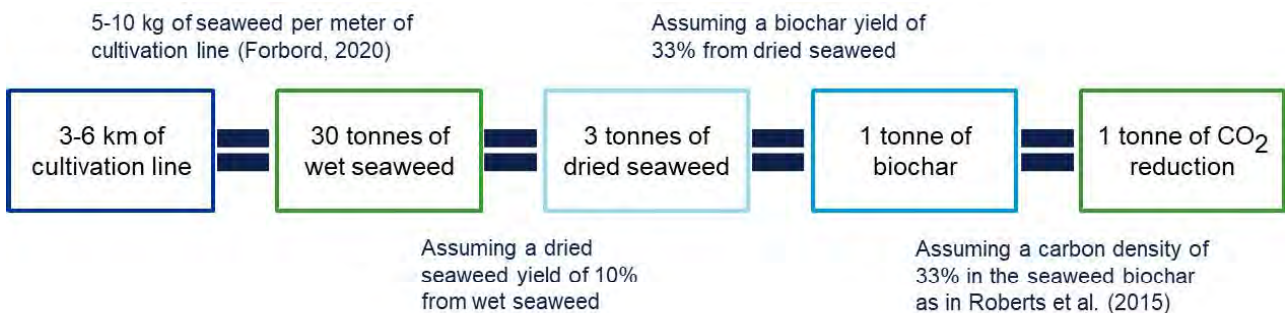


Figure 6 – High-level overview of the volume of seaweed needed to achieve 1 tonne of CO₂e stored in biochar.

The emissions associated with the production considering the current value-chain design used in the project, are estimated to 4.12 kg CO₂e – currently almost 4 times as high as the carbon sequestration in the biochar (Fig. 7).

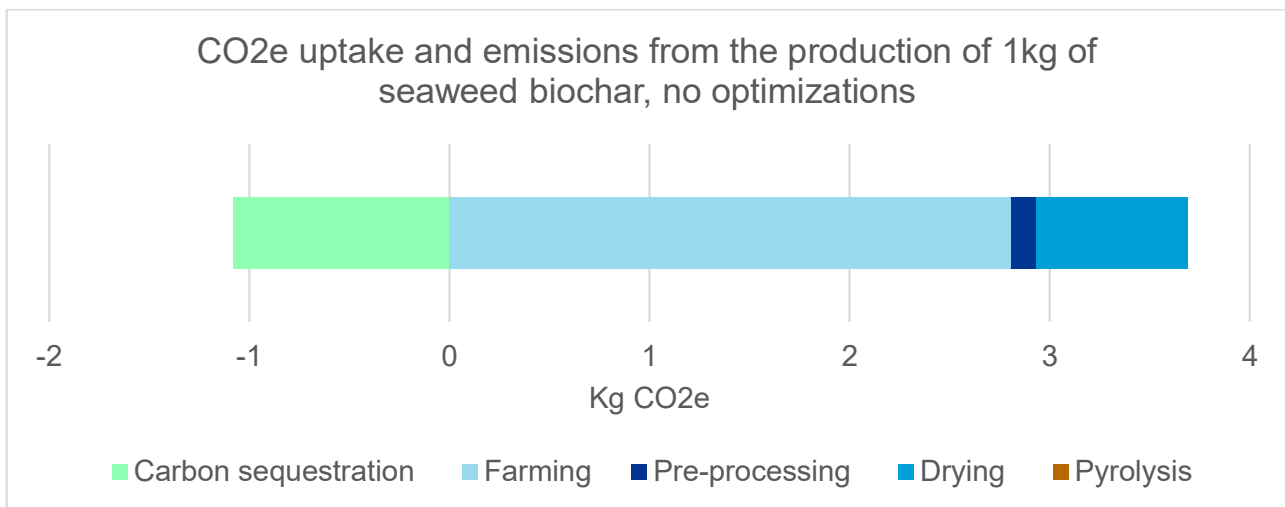


Figure 7 - Net CO₂ uptake and emissions from the different parts of the seaweed biochar value-chain.

3.3 Comparison: offshore vs inshore seaweed farm

With the current value-chain design of the SCS JIP project, farming is the largest hotspot in the seaweed biochar value chain. A farm comparison was done to better understand how the offshore seaweed farm compares to a more traditional near-shore commercial farm. The near-shore farm has been in commercial operation for several years and can produce comparable yields to Storflua (500 t/y), although based on a yield of 5kg/m cultivation line. As the Storflua farm, it is situated in proximity to Frøya but in a more sheltered area (Fig. 8).



Figure 8 – Map showing the two seaweed farms (red) and their landing base (blue) at Sistranda, Frøya. Map sourced from The Norwegian Fisheries Directorate.

Farm infrastructure comparison

The Storflua farm uses more steel-based equipment compared to the near-shore farm. This is mostly due to the mooring solution at Storflua (see detailed info from WP2), which mainly consists of anchors and steel chains. In comparison, the near-shore farm is moored with a combination of lighter anchors and bolts and uses more rope for mooring purposes. Comparably, the weight of the steel used for anchors and bolts is 283% higher and chains 700% higher at Storflua compared to the near-shore farm. The production of steel is emission-intensive but also relatively costly. At Storflua, chains are the equipment type with the largest contributions in terms of weight, cost and CO₂-emissions.

When comparing the use of plastic-based equipment, the near-shore farm has a higher usage of buoys and ropes compared to the Storflua farm (Fig. 9). This is due to 1) the mooring and carrying infrastructure being based on ropes and round slings to a larger degree than the Storflua farm, and 2) due to a different farm design with horizontal ropes which uses floating tubes to ensure buoyancy as the seaweed grows and adds weight to the lines.

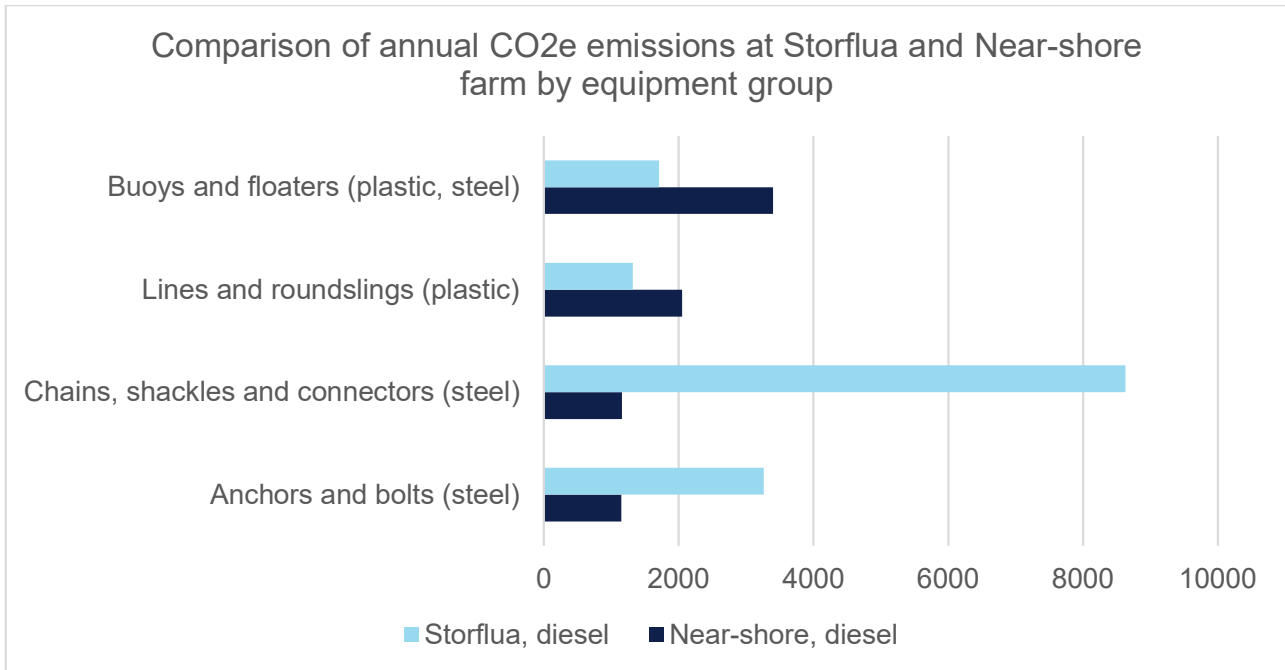


Figure 9 - Comparison of annual emissions of main equipment group at Storflua (exposed) and Near-shore (near-shore) seaweed farms.

Diesel consumption comparison

When comparing the GHG-emissions from the diesel consumption between the two farms, the emissions associated with the farm installation are relatively similar, although a bit higher for Storflua. When comparing emissions associated with deployment and harvesting, the emissions are around 35% higher at Storflua (Fig. 10).

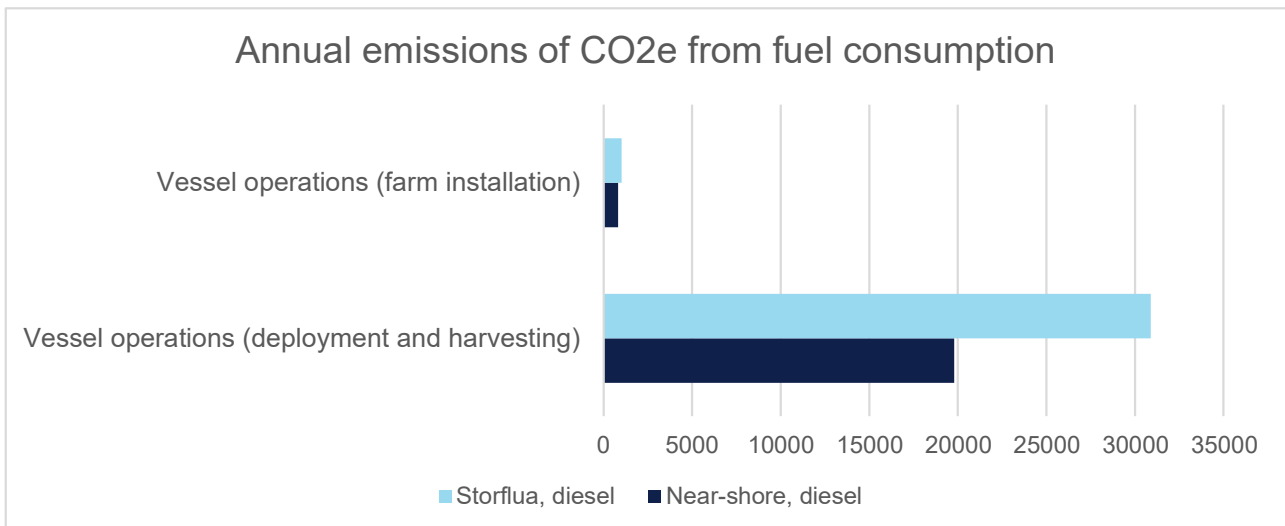


Figure 10 - Annual emissions associated with installation, deployment and harvesting at the Storflua (offshore) and the near-shore (inshore) seaweed farms for production of 500t seaweed.

The near-shore farm is located closer to shore which saves transport time to and from the farm and the associated CO2-emissions. In general, more but smaller boats are involved in the deployment and harvesting at the Near-shore farm. At Storflua, larger but fewer vessels are used for operations and the distance between farm and landing site at shore is longer (see Fig. 8).

3.4 Optimization strategies

The design of the value-chain currently used in the project reflects the most cost-efficient and available equipment and services at present time. There is a potential for optimization throughout the value-chain to design for minimized CO₂-emissions and thus improve the potential for negative emissions.

3.4.1 Vessel operations

Diesel consumption from vessel operations is currently the largest hotspot in the seaweed biochar value-chain at both farms. Changing from diesel fuelled to electric work vessels for all operations can reduce the emissions considerably by 63% at Storflua and 72% at Near-shore (Fig. 11).

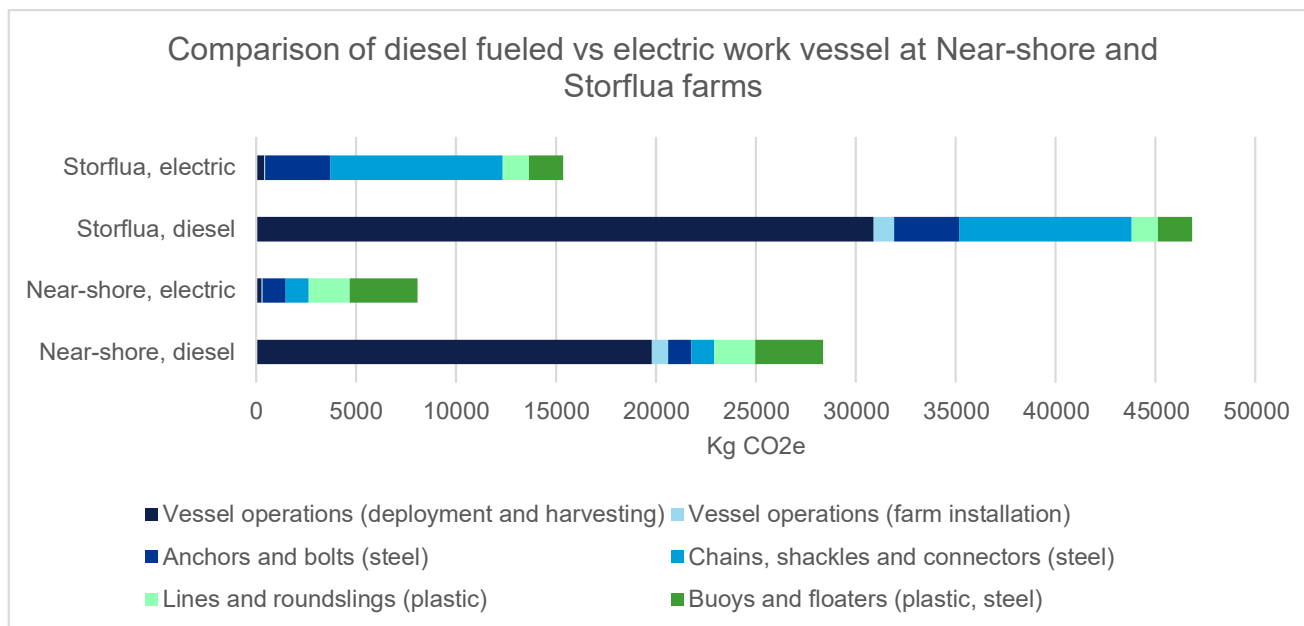


Figure 11 - Comparing annual CO₂e emissions from seaweed farming with diesel fuelled and electric work vessels as Storflua and a near-shore seaweed farm.

Fortunately, the transition to electric work vessels is not far out of reach. Electric and hybrid-electric work vessels are already in use within the Norwegian aquaculture industry. Frøy, the local company supplying work vessels for operations at Storflua, already has hybrid-electric vessels in their fleet. However, some operations required for installing the seaweed farm, such as stress testing anchors, are particularly energy-intensive and will likely continue to require diesel-generated energy for some time.

3.4.2 Processing

Although it is not one of the major contributors to the GHG-impact of seaweed biochar, the pre-processing by use of sulfuric acid to ensile seaweed biomass is still at an early stage, and one can assume that there is room for improving the procedure. This can for instance be done by changing from acid preservation to fermentation by lactic bacteria. The GHG-impact from fermentation is presumably much less than using formic or sulfuric acid, but it will require optimization of bacteria strains which are tailored for fermenting seaweed biomass.

The drying of the seaweed biomass is currently a large contributor to the emissions in the value-chain. The drying process can be optimized through either sourcing from 100% renewable energy sources for drying or by utilizing excess heat from waste incineration plants, gas refineries or other local industries.

3.4.3 Optimization scenarios

Fig. 12 shows the CO₂-emissions per kg of biochar produced in a scenario where a range of optimizations have been implemented:

- All operations with work vessels and boats are electric (including stress-testing).
- Assuming 100% renewable power has been sourced for all electric processes.
- The seaweed is dried using excess heat from other industries, assuming no additional energy input needed for drying, but includes a transport stage by an electric boat.
- GHG burdens and benefits from the pyrolysis process is assumed to be net zero.

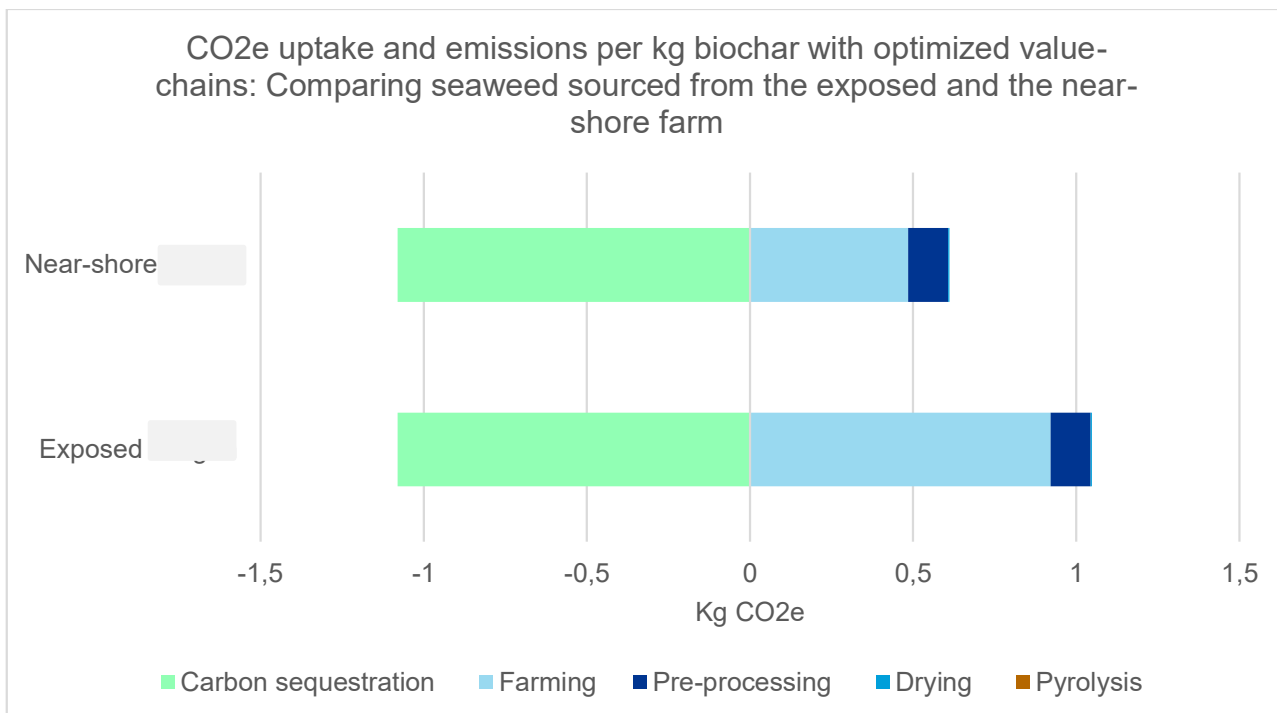


Figure 12 – Comparing the net CO2 uptake and emissions from seaweed biochar produced at both farms in an optimized scenario. Note that the emissions associated with drying in this scenario is minimal, and for pyrolysis is 0.

- ➔ **If all the abovementioned optimizations are implemented, biochar production has the potential to become carbon negative with the current farm design at the near-shore farm. The Storflua farm has the potential to become close to carbon neutral.**

3.4.4 Farm infrastructure

Fig. 12 shows that it is possible to generate negative emissions if a range of optimization strategies are implemented. The main impacts remaining are from the farm infrastructure which is currently in place at the farm and difficult to remove. One could, however, draw on the findings from this assessment in the planning of future farm designs. Limiting the amount of steel on the farm should be a priority, as steel contributes the most to GHG-emissions from the current farm. Another strategy could be to increase the lifetime of the equipment where possible (see discussion from WP2 for more details).

3.4.5 Increasing production volumes

Another strategy to lower the GHG-emissions per kg of seaweed produced, and hence biochar, is to produce more biomass with the same farm and equipment. Higher yields will significantly impact the carbon balance, as the increased output of carbon capture and storage will help shift the equation towards carbon negativity. As seen in numerous agricultural and aquaculture productions, yield improve over time when farming practices are optimized. In countries such as Korea and Japan, where similar seaweed species to those farmed in Norway have been farmed for generations, the yield can be up to 20-25kg/m (Hatch Innovation Services, 2023). It is likely that optimizations in e.g. seedling production and timing of deployment and harvest of the seaweed can result in better yields in the short run. Furthermore, genetic improvements for more suitable seaweed strain will most likely also lead to better yields. However, seaweed breeding is not currently allowed in Norway.

Figure 13 compares GHG emitted and sequestered when producing 1kg of biochar with two different yields at the near-shore farm: 5kg/m and 10kg/m. That would mean a total yearly production of 500t and 1000t respectively. Increased yields would also require more energy (diesel or electricity, depending on vessel type) for harvesting. In these scenarios, we assume that all possible optimizations discussed in this chapter are implemented, including use of electric vessels. Doubling the yield would reduce the total GHG-emissions per kg of biochar by about 23%.

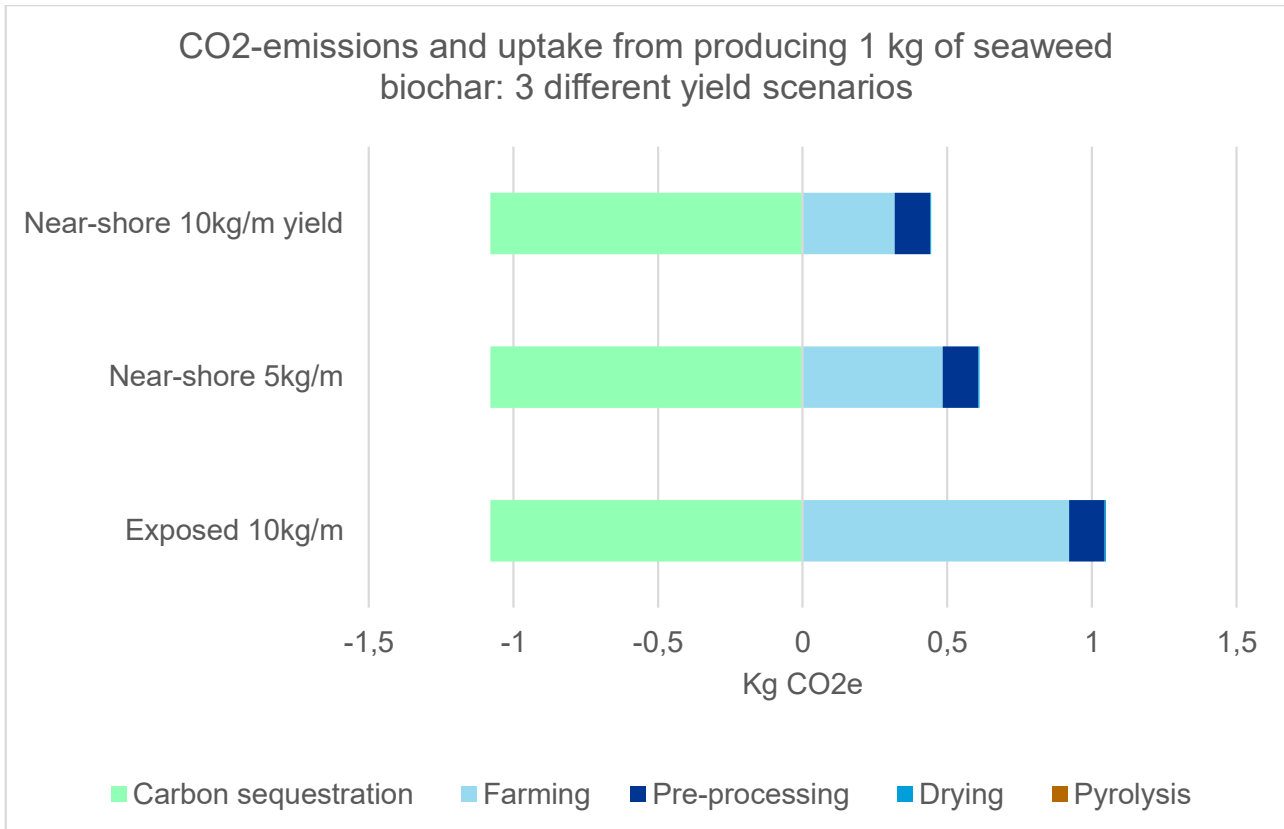


Figure 83 - Comparing the CO₂-emissions and uptake from producing 1kg of biochar in an “all optimizations scenario” with seaweed from the near-shore farm with two yield scenarios: 5kg/m and 10kg/m, and seaweed from the exposed farm with 10kg/m yield.

4 DISCUSSION

4.1 Verification of carbon credits

4.1.1 From passive sinking

Methodologies for passive carbon sequestration in the ocean from farmed seaweed are currently under development. It is important to note that this falls under the broader discussion about the permanence and monitoring, reporting, and verification (**MRV**) of blue carbon in general, which may take some time to resolve. However, measuring or modelling the carbon storage pathways from passive sinking can potentially be a time-consuming and costly exercise. When comparing the potential storage benefits, it might not be worth the effort until seaweed farms have reached a certain scale.

4.1.2 From biochar

As the SCS JIP project is currently designed, it can only be eligible for Puro.Earth’s biochar methodology which is open for purposely grown biomass. However, if the Norwegian and European seaweed industry is able to scale, it might generate waste biomass from the production of other, high-value products, such as food or biostimulants. This could also open for using Verra’s biochar methodology, and it could also improve the carbon footprint as most of the environmental burdens would be attributed to the main product.

4.2 Carbon footprint of the seaweed biochar value-chain

There are several benefits of farming biomass in the sea, but there are also some drawbacks, which show themselves in the resource-intensive operations to farm and process the seaweed. Regarding CO₂ emissions, apparent **hotspots** in the seaweed CDR value-chain are:

- 1) material use in infrastructure associated with the seaweed farm
- 2) diesel consumption of vessels for deploying and harvesting the seaweed and
- 3) energy consumption needed for drying the seaweed.

These findings are in line with earlier conducted LCA studies on seaweed farming (Thomas et al., 2024).

Additionally, roughly half the carbon content sequestered in the seaweed is lost in the pyrolysis process to produce biochar. In the future, it might be possible to use CCS to also sequester this carbon.

Uncertainties in pre-processing and pyrolysis.

Several steps in the seaweed biochar value chain, such as pre-processing and pyrolysis of seaweed biomass, are still at the research or pilot stage. As a result, there are significant uncertainties regarding how these processes would be executed and optimized for industrial-scale production.

Increased yield

Since farming contributes to the largest single impact on the final biochar product, emissions per kg of biochar is highly dependent on how much seaweed a farm can yield. In the LCA scenarios presented, an average yield of 5kg/m growth line was assumed for the near-shore farm, and 10kg/m for the Storflua farm. The near-shore farm yield is based on operational experience since the farm was established in 2014. The Storflua yield estimation is based on modelling and pilot testing over the production cycle of 2023-2024, hence there are some uncertainties regarding this estimate. Project results following the harvest in 2025 will provide more information on expected yields at this farm.

Passive sinking

If passive sinking can be accounted for, this will increase the carbon sequestration. A fresh study by Neves et al. (2025) indicates that from a 500t production in high latitude seaweed farms, a portion of the seaweed biomass can end up being stored in sediments as POC and as RDOC. Read more about this in the results from WP6. However, from a MRV perspective, there is still a way to go to accurately measure and quantify these carbon pools in the ocean.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Reaching for carbon negativity

5.1.1 Value-chain improvements

In order to comply with any biochar carbon crediting methodology, the largest task for the SCS JIP project is to demonstrate carbon negativity.

The current value-chain for seaweed production and processing needs major changes to reduce CO₂-emissions. Recommendations for optimizing the value-chain:

- The change that can make the largest impact on reducing GHG-emissions, is using **electric work vessels** instead of diesel or petrol fuelled ones.
- **Reducing the use of steel components** can make a large impact on reducing emissions. Locating new seaweed farms in more sheltered areas could be a short-term solution to reduce the carbon footprint of farming operations. In the longer term, exploring alternative materials and designs that lower GHG emissions and can withstand offshore conditions is essential. Additionally, there is an advantage to situating farms in areas with hard bottom substrates, where mooring with bolts instead of anchors is possible.

However, it is important to acknowledge that obtaining a license for seaweed farming can be challenging, and farmers often do not have the luxury of selecting their ideal locations.

- Ensure that the electricity mix used in energy-intensive processes like operating work vessels and drying are based on **renewable energy sources**, also on paper.

- The pre-processing currently has a considerable environmental impact mainly due to the use of formic acid. Further work should investigate possibilities for reducing acid use or **alternative treatment methods for stabilising the biomass**.
- Drying seaweed with a high water content is energy intensive. The best option would be to **utilize excess energy from other industries**. The second-best option is to ensure the energy used for drying is fully renewable. To reduce energy use and transport costs, further work should also investigate possibilities for de-watering before the drying process.
- **Improving yields** is an important part of the carbon accounting picture and can help fast track the way to carbon negativity.

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7 APPENDIX 1 – LCI FOR STORFLUA SEAWEED FARM

Decription	Tot weight (kg)	Origin	Lifetime	Material
Royal-FL-40 - eyes with cover hitch into ring	1694,5	IN	10	Mixed polyolefin
Royal-FL-40 - eyes with cover hitch into ring	2154,0	IN	10	Mixed polyolefin
Royal SN 28 - eyes with cover hitch into ring	1058,4	DK	10	Modified polypropylene filaments
Royal SN 28 - eyes with cover hitch into ring	999,6	DK	10	Modified polypropylene filaments
80mm Supertec 8 strand - eyes with hitch into ring	478,5	EN	10	Polypropylene
80mm Supertec 8 strand - eyes with hitch into ring	427,5	EN	10	Polypropylene
Royal 8 FL 56 - eyes with hitch into ring	574,0	IN	10	Polypropylene
Connection Plate 90T Galv 16 holes	2112,0	CH	10	Steel
Connection Plate 140T Galv 16 holes	1443,0	CH	10	Steel
H-Shackle trawlex 60T MBL Aqua	765,1	CH	5-10	Steel
H-Shackle trawlex 90T MBL Aqua	81,0	CH	5-10	Steel
H-Shackle trawlex 150T MBL Aqua	464,4	CH	5-10	Steel
18mm Lankoforce rope - eyes on both ends with cover.	25,7	LT	10	Aramidfiber (UHMW-PE HMPE multifilament)
Akker Vonin 1500 Kg	16500,0	CH	20	Chromium steel
Aker Vonin 1000Kg	11000,0	CH	20	Chromium steel
Chain 60mm Grade 3 71 kg/m	51120,0	CH	20	Steel
Chain 54mm Grade 3 66 kg/m	11880,0	CH	20	Steel
80mm Supertec 8 strand - eyes with hitch into ring	800,7	EN	10	Polypropylene
Royal 8 FL 63 - eyes with cover hitch into ring	1283,5	IN	10	Polypropylene
Royal 8 FL 56 - eyes with cover hitch into ring	2234,4	IN	10	Polypropylene
Aqua Buoy 250L yellow	1056,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
Aqua Buoy 1350 yellow	472,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
Aqua Buoy 1130 yellow	380,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
Aqua Buoy 2000 yellow	720,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
Activa FFB 3300	680,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
Activa FFB 4400	1180,0	NO	10	Polyethylene (PE), polystyrene foam (EPS), steel chain
AIS Markerbuoy for fish farm	60,0	NO	10	Battery, steel, polyethylene (PE), polystyrene foam (EPS)
A3 Buoy red	1116,0	NO	10	Polyvinyl chloride (PVC)

Purpose	Vessel type	Total days	Diesel/ day (l)	Total diesel (l)
Installation	Service vessel, large catamaran - farm installation	6	585	3510
Installation, interruptions due to weather	Frøy Multi - interruptions due to weather	4	390	1560
Installation, waiting at location	Frøy Multi - waiting at location	2	425	850
Deployment	Service vessel, small catamaran	5	365	1825
Harvest	Service vessel, small catamaran	10	365	3650
Harvest	Service vessel, small catamaran	10	365	3650

8 APPENDIX 2

For modelling the steel processes with EOL, the equation from the Life Cycle Inventory Methodology Report from World Steel Association (2017) was used:

$$\text{LCI for 1 kg of steel product including recycling} = X - (\text{RR} - \text{S}) Y(\text{Xpr} - \text{Xre})$$

Where:

X is the cradle-to-gate LCI of the steel product

(RR - S) is the net amount of scrap produced from the system:

RR is the end-of-life recycling rate of the steel product. This value is dependent on the goal and scope of the product being studied and the value selected should be justified.

S is the scrap input to the steelmaking process – this is the net scrap consumed in the steelmaking process and does not include internally generated scrap. Home scrap is considered when the scrap comes from a process which occurs on the steelmaking site, but does not contribute to any of the production stages of the product.

Y(Xpr - Xre) is the LCI value of steel scrap:

Y is the process yield of the EAF (more than 1kg scrap is required to produce 1kg steel).

Xpr is the LCI for 100% primary metal production. This is a theoretical value for steel slab made in the BOF route, assuming 0% scrap input.

Xre is the LCI for 100% secondary metal production from scrap in the EAF (assuming 100% scrap input).



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