MACROSEA: A Knowledge Platform for Industrial Macroalgae Cultivation in Norway

Background, approach and *hypothesis*

Cultivation of the oceans is required to meet demands for food, feed, materials and energy for a growing global population. Norway, with one of the world's longest tempered and productive coastlines, can take a leading role. With MACROSEA (2016-2019; Figure 1), Norway has created an interdisciplinary knowledge platform on macroalgae production biology and technology, to make significant steps towards industrialization. The project was funded by the Research Council of Norway.

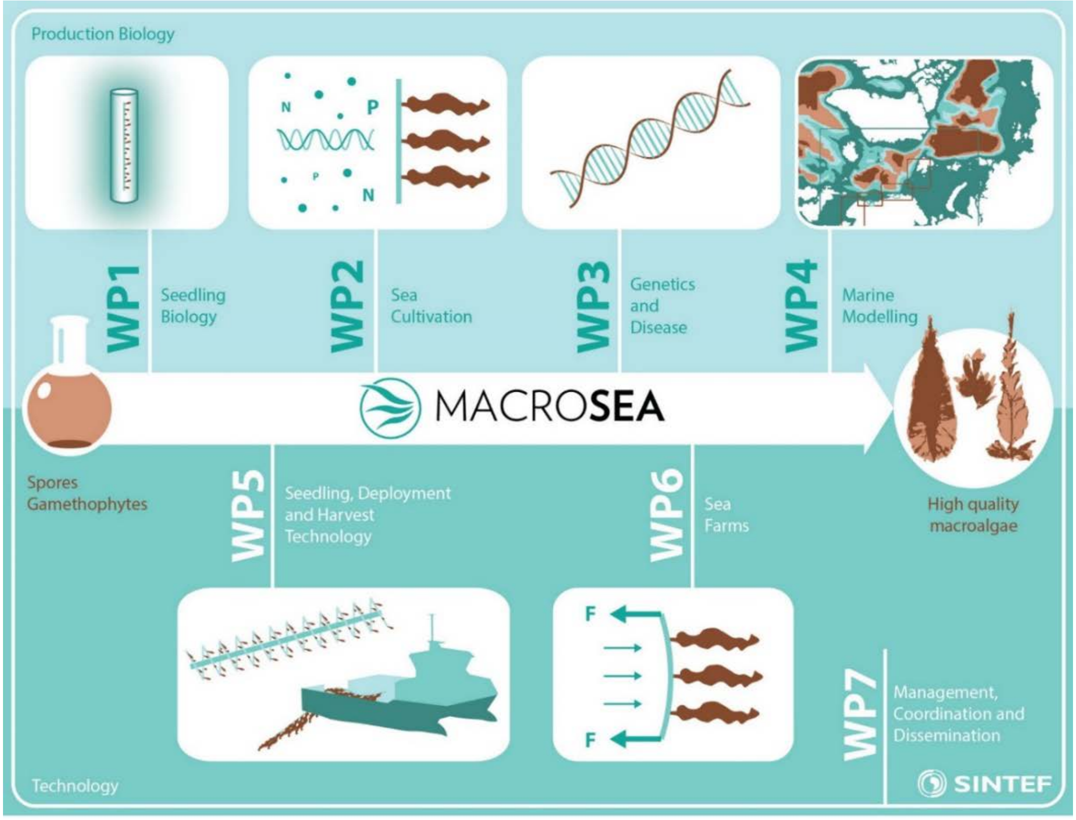

Figure 1. MACROSEA envisages an interdisciplinary knowledge platform on fundamental macroalgae production biology and technology, to make significant steps towards industrial cultivation in Norway.

The macroalgae cultivation phase consists of four main stages: seedlings production, deployment, on-growing and harvesting. Basic biological and technological knowledge is strongly needed in all these phases to enable industrial cultivation. The hypothesis in MACROSEA was that macroalgae cultivation can be industrialized. To test the hypothesis and fulfil the Research Council of Norway's Large-scale program for aquaculture's call for a fundamental knowledge platform for industrial macroalgae cultivation, the project addressed the following main challenges to reach scientific understanding and support industrial development: **i)** The potential for macroalgae cultivation along the wide range of climatic, ecological and physical regimes in Norway are not exploited, **ii)** threshold levels for environmental variables that regulate and modify growth and quality of macroalgae are not known, **iii)** the importance of ecological and physiological factors on biofouling are not understood, **iv)** technological solutions for industrial cost-effective cultivation does not exist and **v)** numerical tools for estimating biomass production potentials and dimensioning of sea farms does not exist.

Results

MACROSEA has contributed to systematic research and delivered generic knowledge on seedling quality, sea cultivation, and genetics of selected brown and red macroalgae species. Models of brown and red species have been developed and coupled to 3D hydrodynamic-ecosystem models to estimate site-dependent biomass production. Methods for efficient seedling, deployment and harvest have been assessed and drag forces and deformation of different farm systems determined at different sea states by using numerical tools.

Three prototypes of seaweed cultivation equipment, a model for kelp cultivation potential and a numeric tool for structural design of kelp farms have been developed. The project has reached out through 80 talks, 10 popular- and 10 scientific articles, 10 reports, 1 book chapter, 55 media articles and 4 movies, and contributed to the education of 6 PhDs and 10 MSc-students.

Seedling biology (SINTEF Ocean, NTNU, UiO, Aarhus University, Industry partners)

For cultivation of macroalgae in sea farms a sufficient number of seedlings of good quality on rope or other substrates is required. In MACROSEA the seedlings production protocols for sugar kelp *Saccharina latissima*, winged kelp *Alaria esculenta* and dulse *Palmaria palmata* have been improved to enable upscaled cultivation. For sugar kelp the industrialised cultivation protocol developed by SINTEF Ocean has been optimized suggesting 6 weeks cultivation on thin lines in large vertical flow-through incubators before transfer to thicker carrier ropes using a specialized "spinning-machine" before deployment at sea. Winged kelp is usually cultivated from gametophyte cultures due to a very short period with natural available spore containing sporophytes. MACROSEA have improved cultivation techniques including a method for fertility induction and for measurement of density and quality of gametophytes. Dulse is not cultivated commercially in Norway due to a complex life cycle and a very low yield of both seedlings for deployment and of harvestable biomass. MACROSEA has brought forward new knowledge on timing of natural fertility, induction of spore release, methods to increase the number of seedlings from the mother plants, methods for seeding of ropes and net, and testing of conditions for incubation of spores and seedlings. The work resulted in a successful sea cultivation trial with seedlings on nets in a sea farm in Mid-Norway.

Sea Cultivation (NTNU, SINTEF Ocean, APN, NIVA, UiT, Industry partners)

The variation in growth performance, biochemical composition and biofouling of cultivated *S. latissima* is mainly caused by seasonality and depth, varying systematically along a latitudinal gradient. The results from a monitoring program showed that maximum frond length and biomass yield occurred up to 2 months earlier at southern locations than at locations further north in Norway, suggesting a potential to supply the consumer market or processing industry for an extended period. Protein content showed a decreasing seasonal trend before onset of biofouling and the seasonal decrease was delayed at higher latitude. The same delay with latitude was observed for biofouling organisms, suggesting that a cultivation and harvesting strategy should follow these latitudinal patterns. Production, expressed in terms of frond length and biomass yield, was higher at shallow cultivation depths than deeper, whereas protein, ash and internal nitrogen compounds were generally higher at deeper depths. Salinity appeared to have an important impact by diminishing seaweed biomass yield and frond length, ash content and biofouling cover. Less light at deeper cultivation depths enhanced the protein content and altered the biofouling species composition.

Genetics (UiB, SAMS, IOCAS)

Sugar kelp is one of the most relevant species for cultivation in Norway, and a main object of MACROSEA was to examine genetic diversity and adaptation of sugar kelp along the coast. Growth and gene expression of sugar kelp cultures from Tromsø, Trondheim and Bergen cultivated together under laboratory conditions simulating the growth environment in North-, Mid- and South-Norway in May (sea temperature and day length) ("common garden experiment") showed a clear tendency of better growth of sugar kelp originating from the Tromsø culture. In order to examine the genetic structure and gene flow in populations of sugar kelp, samples from 21 stations, where 12 were placed in the coastal area from outer Oslofjord to Porsanger and nine in Hardangerfjord and Sognefjord, were analyzed. The results showed good gene flow and little genetic structure, except for a reduced gen flow between South- and North-Norway and between coastal stations and the innermost fjord stations. The results also suggested some degree of genetic adaptation of sugar kelp populations in the Skagerrak area and in the two fjords. Another study of sugar kelp was carried out on material collected from Scotland and the west coast of Sweden. The results of these studies show that gene flow between populations is strongly dependent on local currents, at the same time as clear genome-wide signatures of adaptation was evident.

Marine modelling (SINTEF Ocean, Clarkson University)

Maps of the potential for sugar kelp production along and outside the coat of Norway have been developed based on simulation results from the physical-biological ocean model system SINMOD coupled with a growth model for sugar kelp. The results will be made available for use in GIS-systems and googlemaps. Improvements to the biomass calculations have also been made based on the results from the field cultivation trials in MACROSEA. The model results supported maximum frond length and biomass yield up to 2 months earlier at southern locations than at locations further north in Norway. Estimates for biomass production (yields per unit ocean area) have also been made suggesting an average potential at 75 tons per hectare at harvest in June (range 20-220 tons per hectare depending on deployment time). The growth model for sugar kelp has been further developed to account for interactions with the light field (self shading). These developments entail an improved and more flexible system for calculations of kelp biomass production.

Seedling, deployment and harvest technology (SINTEF Ocean, Industry partners)

A lab system has been designed for automatic seedling production, allowing the seedlings to be grown in monitored, optimal conditions. An industrial production line for seedlings has been assessed and outlined based on state of the art for such systems. Methods for image processing of substrate for quantification of sporophytes and spore density have been developed enabling processing of many images with little effort, compared to manual counting. A prototype for preparation of substrate-spools has been made, spinning 300m of substrate line on two plastic cylinders in 90 sec. A machine referred to as a "seaweed spinner" has been developed to automate the wrapping of substrate line around a carrier rope before deployment at sea. Spools of seeded twine are loaded into the machine and rotated around the rope at a processing speed of 110m carrying rope in 14min. A design study targeting automation and standardization of kelp cultivation (SPOKe) has been performed. The concept encompasses circular modules to allow for an easy platform for automation. A gantry robot on rails is used to interact with the modules, equipped with tools depending on its task. A VR demo and a prototype, demonstrating the principle for control of the gantry robot are available for display at SINTEF Ocean.

Sea Farms (SINTEF Ocean)

Design and dimensioning of seaweed farms at sea are dependent on knowledge of forces exerted on the farm due to the e.g. sugar kelp being exposed to current and waves, and numerical methods that can simulate the sea farms when subjected to design conditions. Results from measurements of drag forces and tensile forces on cultivated sugar kelp from towing experiments in a closed test facility containing sea water showed a clear relation between the size of the sugar kelp and the drag forces. Numerical methods have been developed and are available as part of SINTEF Ocean's software FhSim for simulation of seaweed farms.

Outcomes and Impacts

Seedling Biology

- An industrial seedlings production protocol for *Saccharina latissima.*
- Pre-incubation of *S. latissima* seedlings gives superior growth at sea.
- Improved hatchery techniques for *Alaria esculenta*.
- An improved hatchery protocol for *Palmaria palmata.*
- Successful sea cultivation of *P. palmata.*

Sea Cultivation

- A Monitoring program showed a great potential for cultivation of *S. latissima* from 58 to 69°N, except in areas with high local environmental variations, as high freshwater run-off.
- A latitudinal pattern in a south to north gradient was found for growth (length and biomass), protein content and biofouling.
- Different deployment dates yields different amount of biofouling organisms, growth and shedding.
- Protein content can be manipulated by lowering cultivation lines during the growth period.
- Linear uptake of nitrate was found for substrate concentration up to 18 µM.

Genetics

- Growth of *S. latissima* was found to be higher in sporophytes from the Tromsø area than in sporophytes from the Bergen area, in conditions simulating the sea environment in Tromsø during mid-May.
- A population genetic analysis using microsatellites suggested good gene flow between stations with *S. latissima* along the coast, except between some fjord populations and coastal populations, and between coast stations in South-Norway (Skagerrak-Frøya) and North-Norway (Troms-Finnmark).
- Microsatellites potentially under selection or associated with a part of the genome under selection were found.
- Removing a microsatellite potentially under positive selection caused changes in the genetic structuring in the Skagerrak region and in some fjord populations, suggesting adaptation of populations.
- The results suggest that during cultivation of *S. latissima* special care should be taken to prevent exchange of genetic material between South- and North-Norway, and between the coast and enclosed fjords.
- A consistent method for dd-RADseq sequencing of *S. latissima* was developed allowing the development of high-resolution genome-wide SNP marker sets for genotyping and population analysis.
- Genome-wide selection scans and genomic-environmental association scans provided strong evidence for local adaptation and selection in *S. latissima* in Scotland and Sweden.
- Adaptive loci were found to be in association with numerous environmental variables including mean temperature, summer temperature, chlorophyll and minimum salinity.

Marine Modelling

- Model based maps and estimates for the cultivation potential of *S. latissima* along and outside the Norwegian coast.
- Some of the results (maps) available for use in site selection with google maps (DST).
- Dynamical growth model for bryozoan fouling on *S. latissima* fronds.
- Mechanistic light shading model for kelp cultures, taking into account the interactions between the kelp fronds and the light field.
- Updated *S. latissima* growth model.
- Simplified model based assessment for the cultivation potential for *P. palmata*.

Seedling, Deployment and Harvest Technology

- A lab system pilot for seedling production.
- Machine vision for rapid assessment of seedling quality (size and density) before deployment.
- An onspinning machine for seedling twine on cylinders.
- A spinning machine for deployment of seeded ropes (from cylinders to ropes).
- A design concept for Standardized Production of Kelp (SPOKe).

Sea Farms

- Increased knowledge of mechanical properties of *S. latissima*.
- Forces on ropes grown with *S. latissima* from steady currents for a variety of growth densities and specimen growth
- Parametrized force model for ropes grown with *S. latissima* – enables development of numerical methods and more precise modelling and design of seaweed farms.

Research Needs

Seedling Biology

- Cultivation technology to enable production of *P. palmata* seedlings on substrate including a program for controlled sorus induction, spore release, seeding, seedlings incubation, contamination control and cryopreservation.
- Better understanding of the seasonal and geographic impact for fertility in *A. esculenta* at different sites along the Norwegian coast, better methods for sorus disinfection and for contamination control of gametophyte cultures.

Sea Cultivation

- Pilot investigations of potential farm locations to determine site suitability and generate knowledge on suitable cultivation depths and the best deployment and harvesting windows.
- Registration of environmental data (salinity, currents, nutrients) during field cultivation experiments to support growth and biochemical results.
- Field cultivation experiments further north than 69 °N to look at the impact of high latitude on chemical content, growth and biofouling.
- Laboratory experiments testing effects of environmental factors and genes on seaweed defence and/or resistance to biofouling.
- Large scale sea cultivation of *P. palmata* for evaluation of environmental- and seasonal effects on growth, fouling and composition.

Genetics

- Baseline studies of population genetics of all macroalgae under consideration for cultivation.
- Studies of intrinsic and extrinsic factors influencing gene spreading in macroalgae.
- Population genetic studies linking functional traits to genotypes.
- In situ studies of “crop-to-wild” spread of genes from sea farms to local populations.

Marine Modelling

- Development of more detailed models for the content of interesting/valuable compounds (e.g. proteins, polyphenols, pigments, carbohydrates) in kelps and how these depend on and arise as interactions between external conditions, metabolism, and growth.
- Development of more detailed models for the content and accumulation of potentially unwanted components (e.g. iodine, heavy metals, environmental toxins) in kelps.
- Linking model parameters to genetics studies.
- More detailed modelling of fouling on kelps (also including other organisms such as hydroids). In particular, the spatiotemporal patterns of first appearance of fouling and dispersal of the larval stages of the fouling organisms.

Seedling, Deployment and Harvest Technology

- Development of optimal techniques, materials and equipment for automation of seeding operations.
- Further development of instrumentation methods for quantification of spore density and gametophyte biomass using machine learning.
- Detection of healthy kelp, unwanted growth and other categories using machine learning.
- SPOKe-specific: Principles of control and selection of mechanisms and actuation for the gantry robot and its movement around the submerged modules. Solutions for relative positioning measurements between the robot and the modules as it moves and deploys from the vessel.
- Optimal substrate geometry. This has a great impact on lab and farm design, and also deployment and harvesting equipment. In the proposed concept SPOKe, vector seeding is the basis, but the concept is not limited to 1D substrates. In order to select a geometry, the whole production line must be considered.
- Development and automation on harvesting equipment for various substrate geometry and farm designs.

Sea Farms

- Experiments yielding data for a larger variety in growth density, specimen growth and morphology.
- Experiments with growth ropes inclined to the loads (current and waves).
- Experiments to determine forces on sugar kelp ropes when exposed to waves.
- Experiments measuring the effect on the surrounding water flow from the kelp.

Publications

Scientific papers

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2. Alver MO, Solvang T, Dybvik H (2018a) State of the art Seedling, Deployment and Harvest technology. SINTEF.
3. Alver MO, Solvang T., Kvæstad, B (2018b) Proof of concept on seeding systems. SINTEF.
4. Bale ES (2017) Development of area efficient and standardized structures for macroalgae cultivation. SINTEF.
5. Broch OJ, Tiller R, Skjermo J, Handå A (2017). Potensialet for dyrking av makroalger i Trøndelag. SINTEF Ocean
6. Broch OJ, Skjermo J, Handå A (2016). The potential for large scale cultivation of macroalgae in Møre and Romsdal.
7. Dybvik H (2016) Concept development for macroalgae seeding, deployment and harvesting. SINTEF student report.
8. Eggesvik AT (2019b) SPOKe prototype. SINTEF summer student report.
9. Norvik C (2016) "Design of artificial seaweeds for assessment of hydrodynamic properties of seaweed farms". SINTEF summer student report.
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1. Balasubramaniam M (2017). Veksteksperiment av makroalger med kommersiell interesse; med hovedfokus på *Palmaria palmata*. UiO.
2. Brodahl GE (2018). The effects of variable environmental conditions on growth, nutritional state and protein content in cultivated *S. latissima* in Norway. NTNU.
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10. Næss T (2018). Analyses of population genetics of *Saccharina latissima* (sugar kelp) in Norway. UiB.

Book chapter

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3. Etter et al. Possibility of high quality macroalge production in IMTA by recycling nutrients from aquaculture.
4. Etter et al. Bioremediation potential by nitrate and ammonia assimilation in *Saccharina latissima*.
5. Etter et al. Importance of phosphate assimilation in *Saccharina latissima* for bioremediation potential.
6. Etter et al. Optimal configuration of environmental and economical macroalgae IMTA cultivation systems.
7. Forbord et al. Protein content and growth of *S. latissima* grown at various light and nitrate supply in open sea
8. Forbord et al. Initial short-term N-uptake responses in young *S. latissima* under N-saturated and N-limited cond.
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10. Matsson et al. Variations in biofouling as an effect of deployment. Can a prolonged growing season delay the onset of biofoulers?
11. Næss et al. Connections between cost and fjord populations of the kelp *Saccharina latissima* in Norway.
12. Saifullah et al. Seasonal variation in the carbohydrate composition of sugar kelp (*Saccharina latissima*) from different farming stations along the Norwegian Coastline.
13. Saifullah et al. Improving carbohydrate composition of sugar kelp (*Saccharina latissima*) through algal movement
14. Schmedes PS, Nielsen MM, Andersen KL, Petersen JK. Cultivation of *Palmaria palmata* in open water - the effect of seedling size at deployment and farm location on harvest yield.
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19. Thomson et al. Seascape genomics reveal strong adaptation and population structuring in sugar kelp across the heterogenous seascape of the Scottish west coast.
20. Thomson et al. Comparative regional population genomics and adaptive ecological signatures of selection in the brown algae *Saccharina latissima*.

Project accomplishment, utility value and communication

MACROSEA has been **accomplished** according to time and budget and most of the initial project plans. A considerable part of the work has involved PhD-education (6 PhDs), which has contributed to a dynamic shaping of the knowledge platform in consistency with the curriculum and educational plans of the PhDs' co-funding universities. The results have created **additional value** through: **i)** Outreach to society about the possibility of using macroalgae as renewable marine resources when moving from today's fossil-based to a low-carbon society by 2050, **ii)** creation of meeting places and establishment of new networks, which have resulted in **iii)** a range of spin-off projects and proposals in progress along the macroalgae value chain. The results will be **communicated** to industry, research environments, government and society through talks at conferences and trade fairs, movies, radio, TV and social media.

The results from MACROSEA will contribute to predictable production of biomass and development of enabling technologies for industrial macroalgae cultivation in Norway.

SINTEF, Clarkson, PE REEFS, UiT The Arctic University of Norway, Hortimare, Folia Alger AS, AlgeCenter Danmark, UiO Universitetet i Oslo, SAMS, NIVA, University of Bergen, Seaweed Energy Solutions AS, Austevoll Seaweed Farm, Akvaplan-niva, Biokraft, NTNU, Seaweed, Ocean Forest