FUCOSAN

Result Report
Algae sources, cultivation and collection

Interreg
Deutschland - Danmark

EUROPEAN UNION

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Imprint

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Project management

DSN Connecting Knowledge
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This result report presents a compilation on the key findings provided by the partners working in the work package:

- WORK PACKAGE 1 — Project management
- WORK PACKAGE 2 — Project communication & PR
- WORK PACKAGE 3 — Algae sources, cultivation and collection
- WORK PACKAGE 4 — Fucoidan characterisation and database development
- WORK PACKAGE 5 — Pilot developments in medicine and cosmetics
- WORK PACKAGE 6 — Organisation and business models

The FucoSan project

Algae from the North and Baltic Sea serve as an important but yet under-exploited marine bio resource. Brown algae contain fucoidan - a polysaccharide with highly health-promoting activities that could be used in medicine and cosmetics. Fucoidans are also valued for their positive influence on inflammation, vascular supply and tissue regeneration.
With their antimicrobial properties, infections in the bone could potentially be treated. However, fucoidan varies in structure, composition and modifications such as degree of sulfation or molecular weight - depending on the origin and other factors. This leads to different, sometimes even opposing effects.

The FucoSan project aimed at generating systematic knowledge of fucoidans and their modes of action. In various test systems, the project partners investigated on the optimal fucoidan for each particular application. Over the last three years, the project established a network in the German-Danish cross-border region pooling the expertise of companies and research institutions. They are active in the fields of extraction and purification as well as in chemical and biological characterisation of fucoidans.

March 2017 – August 2020

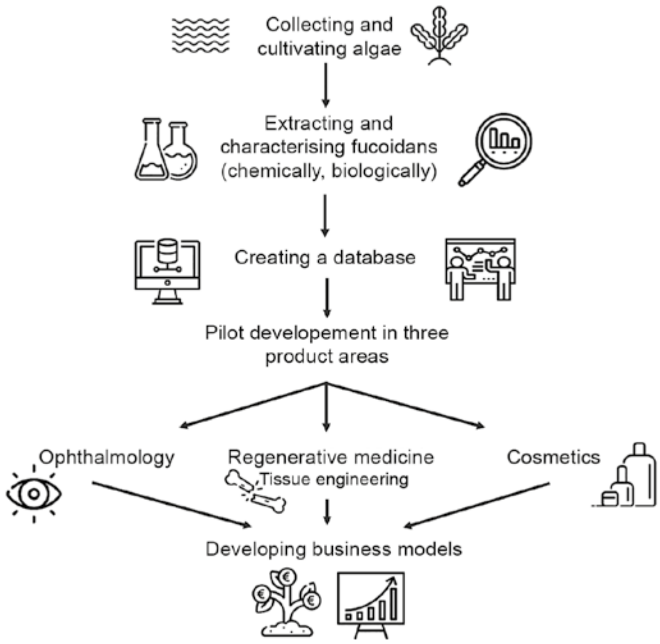
3.8 million Euros budget,
thereof 2.2 million Euros funds

8 partner organisations from
Denmark and Germany

Project aims

- ✔ Development of economically and ecologically sustainable processes to obtain brown algae from the Baltic Sea
- ✔ Setup of a database for the identification of suitable fucoidans
- ✔ Pilots for fucoidan-based applications in ophthalmology, regenerative medicine (tissue engineering) and cosmetics
- ✔ Establishment of a German-Danish value chain around the use of fucoidans

The FucoSan process chain



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Introduction

What are algae? Broadly speaking, all photosynthetically active eukaryotes (organisms with a true cell nucleus) apart from land plants (mosses, ferns, seed plants) can be considered as algae. Within this very diverse group of ca. 44,000 known species (the actual number is estimated to be much higher), most species are unicellular microscopic organisms called microalgae. Only a few microalgal lineages formed multicellular macroscopic forms in the course of evolution, which are nowadays categorised as macroalgae or "seaweeds". The three most prominent macroalgal groups are green, red and brown algae, named after their typical colours, which result from different combinations of photosynthetic pigments. Red algae are the largest macroalgal group with about 7,200 species, followed by brown algae (ca. 2,000 species) and green algae (ca. 1,800 species). They range in size from millimetres to more than 50 metres in the giant kelps. Most macroalgae live in marine habitats, and only a small number colonise freshwater environments. Macroalgae are typically found on rocky shores, because most species need a hard substratum to attach to, in order to maintain their position against currents or waves. Attachment is performed with a special holdfast organ called a rhizoid; most macroalgae also have a kind of stalk, called a cauloid. Finally, the part responsible for photosynthesis and reproduction is called a phylloid, because it often resembles a plant leaf.

Red, green and brown algae are not closely related; therefore, their chemical composition is very different. For instance, they differ with respect to their main cell wall sugars: red algae contain agars and carrageenans, green algae contain ulvans and brown algae contain alginates and fucoidans as cell wall sugars. As the focus of the FucoSan project was to elucidate the chemical properties and biological activities of fucoidans from different sources, only brown macroalgae were used as source material. CRM (Coastal Research & Management, Kiel, Germany) was responsible for providing the other project partners with suitable algal material for the extraction of fucoidans. But where can one obtain brown algal biomass?

Seaweeds have been used for millennia as food for humans, as medicine and as feed for livestock, especially in coastal cultures. Originally, the biomass was just collected from the shores during low tide. Over time, people also started cultivating some species, especially in East Asia, which is nowadays the biggest market for seaweed products. Today, about 30 million tons of seaweed biomass are produced in farms (i.e. seaweed aquaculture) worldwide, and only 1 million tons are collected from wild stocks. In comparison, the total quantity of fish caught by fisheries is about 80 million tons/year (see FAO 2018). As mentioned before, the majority of seaweed production takes place in East Asia. In Europe, there are only a small number of farms along the Atlantic Coast, and wild material is collected in countries such as Norway and France. Along the German and Danish Baltic Sea coast, i.e. in the project area, there are only a few seaweed farms, which all produce sugar kelp (*Saccharina latissima*). The only German farm is operated by the company CRM. Other brown algae of interest for the project, like species of the genus *Fucus*, have not been domesticated yet. At the same time, sustainable harvesting of brown algal biomass is also in its infancy in the project area.

Therefore, three approaches were used to provide brown algal material to the project partners. First, biomass of different brown algal species was purchased from farms located along European coasts. Second, a test farm was established in Kiel, Germany, to experimentally cultivate two *Fucus* species in the Baltic Sea. Third, CRM collected experimental quantities of seaweed from the local Baltic Sea coast, and also pursued developing a sustainable harvesting method for commercial purposes in negotiation with the German and Danish authorities. The precise methods and results of this part of the project are shown on the following pages.

Seaweed in the North Sea and Baltic Sea is a valuable but still underutilised marine bioresource, which is regarded as extremely promising, because it serves as a carbon sink, and it can be used for a wide range of purposes, from nutrition to pharmaceutics. One of the beneficial ingredients in seaweed is fucoidan, which can be extracted from the brown algae and transformed into different value-added products. The tasks of work package 3 (WP 3) were fundamental, because they laid the foundation for all other work packages. Therefore, WP 3 was indispensable to the success of the project.
The aim of WP 3 was to develop a common knowledge base on the use of macroalgae (brown algae)

for the utilisation of fucoidan. During the literature research and interviews, a list of algae species was compiled that are sustainable as well as suitable for (industrial) extraction of fucoidan (activity 3.1). Based on this list of candidates, the project partners were provided with raw material for extraction, testing and chemical analysis. Seaweed from suitable reliable sources was also provided, to develop prototypes of products or extracts containing fucoidan.
Algae cultivation is classified as highly sustainable and provides a controlled quality of algae and fucoidan. Therefore, the cultivation of algae containing fucoidan was tested regionally in this WP (activity 3.2).
The collection of natural macroalgae stocks can also be sustainable, if strategies are examined with regard to ecological sustainability and economy (activity 3.3).
This work package includes project partners with expertise in cultivation and collection methods of macroalgae and their evaluation. Further project partners in this work package were available as dialogue partners.

Supply with seaweed

CRM defined possible macroalgae candidates containing fucoidan based on accumulated experience and literature research. We developed contacts with different suppliers for brown algae from the Baltic Sea, North Sea and North Atlantic. Sustainability in wild harvesting and/or cultivation with organic certification are the essential requirements of this project (see literature: CRM 2002, Bak 2019).

For scientific purposes as well as for economical upscaling, quantities ranging from kilogrammes [kg] to tons [t] of seven different brown macroalgae containing fucoidan are available from the following seven companies:

- Dried powder (*Fucus vesiculosus*; Biocéan, France [kg])
- Dried flakes and whole algae (*Ascophyllum nodosum, Alaria esculenta, Laminaria digitata, L. hyperborea, Saccharina latissima*; Bláskel, Iceland [kg])
- Fresh algae (*F. vesiculosus*; Organic Seaweed, Denmark [t]; F. *vesiculosus*, *F. serratus*, *F. evanescens, S. latissima*; sampling in Kiel Bay, Germany [kg])
- Frozen algae (*L. digitata*; Ocean Veg (="Islander Rathlin Kelp"), Ireland; *S. latissima*; KosterAlg, Sweden; Ocean Rainforest, Faroes; Seaweed Energy Solutions, Norway [t])

BIOCEAN
ICELANDIC Blue Mussel & Seaweed
ORGANIC SEAWEED EBELTOFT VIG
ISLANDER RATHLIN KELP
KOSTER alg
SEAWEED ENERGY SOLUTIONS AS
OCEAN RAINFOREST SUSTAINABLE NORDIC SEAWEED

The seaweed species purchased and processed are compiled in a list of sources of supply (fig. 3) on page 9 and a chart (fig. 4) on page 10.

WP 3 has achieved the overall aim, i.e. identifying sustainable sources of industrially usable seaweed. We defined a source to be sustainable based on the following criteria: i) type of cultivation, ii) harvest practice, iii) certification of supplier and seaweed. At this point it can be stated that sustainable sources exist. These comprise commercially available as well as cultivated seaweed. Furthermore, harvesting from natural populations can also be regarded as sustainable. For this to be the case, the natural dynamics must be professionally evaluated in terms of quantity and quality of the seaweed, as well as the relevant ecological variables. Depending on the specific source, different qualities of fucoidan are achievable, and different applications and markets can be accessed.

Profiles of seaweed

***Laminaria hyperborea* (fig. 1, left)**

L. hyperborea or tangle is a very large kelp (up to 4 m) which forms enormous underwater forests, where the individuals appear like upright trees due to their very rigid and long cauloid. This species typically occurs along highly saline coasts of the North Atlantic, where it grows permanently submerged at up to more than 20 m in depth. It is an ecosystem engineer, creating a habitat for fish offspring and a rich invertebrate fauna. It is used primarily for the production of alginate.

***Laminaria digitata* (fig. 1, right)**

L. digitata or oarweed is a North Atlantic species which also colonises the Western Baltic Sea. It grows to sizes of up to 2 m and is typically found in the subtidal zone. In contrast with *L. hyperborea*, it has a flexible cauloid, hence its underwater forests are not as upright as the ones of the former species. It is used for alginate production and in cosmetics.

***Saccharina latissima* (fig. 1, right)**

S. latissima or sugar kelp forms large very elongated phylloids (up to 4 m), which are only connected to the ground by a little cauloid and holdfast. As with the two species before, it colonises the zone below the lowest tidal level. It can be found not only in the Atlantic and the North Sea, but also in the Baltic Sea, including Kiel Bay. This species is the number one cultivated species in Europe, and can be purchased from many seaweed farms all along Northern European coasts. It is used as food and in cosmetics.

Figure 1:
Left: Laminaria hyperborea (left basin) and its close relative L. ochroleuca (right basin), both with a very rigid cauloid.
Right: Laminaria digitata (smooth brown blades) and Saccharina latissima (rippled brown blade) in a tidal pool in France (Atlantic).

Alaria esculenta (fig. 2, right)

Like the three species mentioned before, this species also belongs to the so-called kelps ("winged kelp"). It is found in similar habitats to *S. latissima*, and also has a very similar shape - albeit with a smaller size. The main characteristic by which the two can be distinguished is a conspicuous midrib, which only *A. esculenta* has in its elongated phylloid. The species name "esculenta" indicates that this species has been part of the cuisine of European coastal communities for centuries, and indeed it is used for food production due to its delicious taste.

Ascophyllum nodosum (fig. 2, left)

This species and the three *Fucus* species do not belong to the kelps, but are so-called wracks ("knotted wrack"). They do not colonise subtidal areas (i.e. the zone below the lowest tidal level) like the kelps, but can instead be found in the intertidal zone (i.e. between the high and low water level). Therefore, they have adaptations to survive temporal desiccation. *A. nodosum* is found in sheltered bays and has remarkable gas bladders, which lift the whole plant in the water column to ensure buoyancy and give better access to light. It forms one gas bladder at every branch per year. Thus, the age of the species can be determined, which is up to ca. 10 years. *A. nodosum* is mostly used for the production of compost for plants ("biostimulants") and food additives.

Figure 2:
Left: Ascophyllum nodosum in the intertidal zone during low tide in France (Atlantic). Right: Alaria esculenta

Fucus vesiculosus, Fucus serratus & Fucus distichus subsp. _evanescens_

The three *Fucus* species are found in the intertidal zone of Northern Europe. They live for several years and form so-called belts, which provide a habitat for a rich fauna of invertebrates and juvenile fish. *Fucus vesiculosus* (bladder wrack) and *Fucus* serratus (serrated wrack) are native seaweed species, whereas *F. distichus* subsp. *evanescens* (Arctic wrack) was introduced at the beginning of the 20th century from the White Sea. The three *Fucus* species can be distinguished by the form of their phylloids (*vesiculosus*: with air-filled vesicles, *serratus*: serrated, *evanescens*: claw-like). Currently, *Fucus* sp. are primarily used for the production of food additives and cosmetics.

Dictyosiphon foeniculaceus

In contrast with all species described before, this species is not perennial, but only lives for a few months, from spring to summer. So far, it is not used for any commercial purpose. However, it is very common in the Baltic Sea, and was therefore included in the FucoSan project, especially since nothing is known about fucoidan from this species. Its growth form and colour led to a very remarkable name, the "golden sea hair".
Species descriptions were extracted and compiled from www.algaebase.org and Lüning 1985. Pictures of the last four species described above are shown on page 15.

Charts

supplier	country	ocean	algae	wild harvest (w), cultivation (c)	fresh frozen (ff), dried (d)	price	homepage, contact person	comments
Alginor	Norway	North Sea	*Laminaria hyperborea*	w	d	poa	www.alginor.no Mr. Georg Kopplin	possibly also pure **fucoidan** (project AORTA); test harvesting in Haugesund; L.hyperborea does not grow in the Baltic!
Biocéan	France	North Atlantic	***Fucus vesiculosus***	w	d	19 €/kg	www.biocean-algues-marines.com/boutique-en-ligne/algues-alimentaires-bio/fucus-biologique-breton/fucus-vesiculeux/bl,product,103,0	
Bláskel	Iceland	North Atlantic	***Alaria esculenta***	w	d	6 €/kg	www.blaskel.is/skissa/english.htm Mr. Simon Sturluson	ca. 250 € transport costs for a 30 kg box, incl.custom service!! All these species, except SL, do <u>not</u> grow in the Baltic!!
			Ascophyllum nodosum	w	d	6 €/kg		
			Laminaria digitata	w	d	6 €/kg		
			Laminaria hyperborea	w	d	6 €/kg		
			Saccharina latissima	w, c	d	6 €/kg		
KosterAlg	Sweden	North Sea	*Saccharina latissima*	c	ff, d	50SEK (ff), 500 SEK (d); 10SEK=1€	www.kosteralg.se/en/homepage/	farm at the west coast (Skagerrak), Saccharina also in tanks; partner in the Baltic Blue Alliance project
			Laminaria digitata	c	ff, d	100 SEI (ff), 1000 SEK (d)		
maBitec	Germany (supplier) / France	North Atlantic	*Ascophyllum nodosum*	w	d	poa	www.mabitec.de/produktuebersicht/	Seagreens® Ascophyllum nodosum; supplier from Hamburg, Germany; the algae come from France, Brittany also **fucoidan** and dry Fucus extract
			Fucus vesiculosus	w	d			
			Himanthalia elongata	w	d			=thong weed, sea spaghetti harvesting by ship
			Laminaria digitata	w	d			
			Undaria pinnatifida	w, c	d			=wakame
Ocean Rain forest	Faroes	North Atlantic	***Saccharina latissima***	c	ff, d	5 €/kg (ff)	www.oceanrainforest.com/	
			Laminaria digitata	c	ff, d			
			Alaria esculenta	c	ff, d			
Ocean Veg	Northern Ireland	North Atlantic	*Alaria esculenta*	c	?		www.slanderkelp.com/products/	Brexit ?
			Laminaria digitata	c	ff			
			Saccharina latissima	c	?			
Organic Seaweed	Denmark	Baltic Sea	*Ascophyllum nodosum*	w	fresh, d (tablets)	223DKK (240 tablets); 7DKK=1€	www.organicseaweed.dk/ Ms. Mette Albrechtsen	harvesting licence from government for all macroalgae at two sites in Aarhus Bay, cooperation with CRM/oceanBasis Harvests CRM 16.5.18 + 9.10.18 (fresh algae)
			Fucus evanescens	w	fresh	5 €/kg fresh weight		
			Fucus serratus	w	fresh			
			Fucus vesiculosus	w	fresh; d (powder)			
			Halidrys siliquosa	w	fresh			=pod-weed, sea oak
			Saccharina latissima	w	fresh			
Seaweed Energy Solutions	Norway	North Sea	*Saccharina latissima*	c	ff	5 €/kg	www.seaweedenergysolutions.com/en	farm in Froya (near Trondheim)
Wild Irish Seaweed	Ireland (western)	North Atlantic	*Laminaria digitata*	w	ff, d *	price on application	www.wildirishseaweeds.com/shop/wholesale/	Brexit ? * whole leaf (1kg-20 t !) / chopped / 1mm to 10mm particle sizes / powder
			Saccharina latissima	w	ff, d *			
			Himanthalia elongata	w	ff, d *			
			Alaria esculenta	w	ff, d *			
			Fucus vesiculosus	w	ff, d *			
			Pelvetia canaliculata	w	ff, d *			=channelled wrack
			Ascophyllum nodosum	w	ff, d *			
			Fucus serratus	w	ff, d *			
			Laminaria hyperborea	w	ff, d *			
			Sargassum muticum	w	ff, d *			=Japanese Wire weed

Figure 3: Suppliers of brown macroalgae, contacts within the FucoSan project; green: Baltic Sea species; bold: algae purchased and processed further; red: possible purchase of other brown algae species

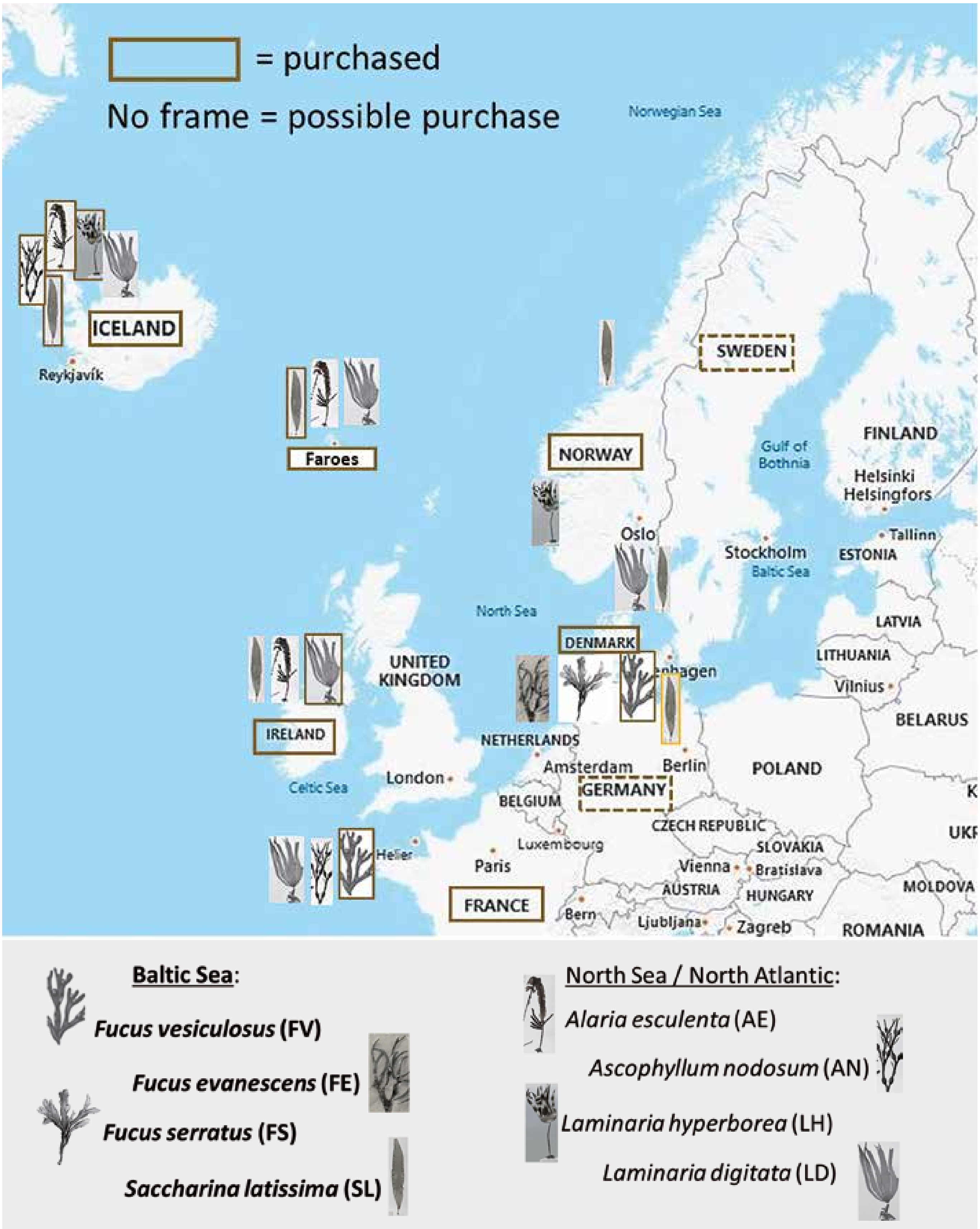


Figure 4: Map visualisation of brown algae purchased (countries and pictures with frame) and possible sources (pictures without frame) during the FucoSan project. Yellow frame: cultivated Saccharina latissima. Sampling of Fucus sp. in Germany and Denmark (s. chapter Collection p. 15)

Cultivation

Species of the brown algal genus *Fucus* are especially rich in fucoidans. In fact, *Fucus vesiculosus* was the first species in which fucoidan was discovered by Kylin in 1913, and named - like our current project - FucoSan. The fucoidan which is commercially available is also produced from *F. vesiculosus*. However, *Fucus* biomass offered on the market originates 100% from field collections, because no culture has been established yet and the species is not domesticated. In order to produce standardised fucoidans, e.g. for medical applications, a consistent biomass source would be advantageous, and therefore this project targets the development of a cultivation method for *Fucus* species in the Baltic Sea. But how can one cultivate an undomesticated seaweed species?

Generally, cultivation of macroalgae can be performed in two different ways. The first approach involves the production of unicellular stages like spores or gametes in the lab, and their seeding on cultivation substrata like long lines, which are hung in the sea where the macroalgae grow to harvest size. Sometimes a special microscopic multicellular stage must be cultivated beforehand in the laboratory, from which spores or gametes can be obtained. This is due to the complex life cycle of many macroalgae that involves two to three different life stages, only one of which is usually cultivated for harvest. This first approach is used to produce various algae for the world market, e.g. *Saccharina japonica* (kombu), *Saccharina latissima* (sugar kelp), *Undaria pinnatifida* (wakame) and *Porphyra* sp., which is known as nori and is used to wrap sushi.

The second approach is simpler, as it does not involve the cultivation of different life stages, but only the rearing of one stage, which is reproduced by vegetative reproduction. This is achieved by cutting the parental plant into small pieces, from which new organisms grow and produce harvestable biomass, some of which is used as 'seed biomass' for the next cultivation cycle, and the process is repeated. Usually, the seaweed is bound to ropes deployed in the sea, and after the harvest small pieces are bound to the ropes again. This method is applied for the cultivation of the red seaweeds *Kappaphycus*, *Eucheuma* and *Gracilaria*, which are all produced for the extraction of carrageenan, which is widely used as a thickener, e.g. in sauces and creams.

The second approach was chosen for the experimental cultivation of *Fucus* species, because it is known that some wild *Fucus* populations reproduce vegetatively. The two most common *Fucus* species of the Baltic Sea, *F. vesiculosus* and *F. serratus*, were used for experimental cultivation. The main questions to be answered during the course of this project were:

Is it possible to cultivate cut *Fucus* pieces (thalli) for long periods, or do they degrade over time?

Does the formation of sexual organs in the cultivated biomass interfere with the chosen cultivation method?

What growth rates can be achieved in *Fucus* cultivation, and are they sufficient for commercial production?

Does fouling (i.e. becoming overgrown by other organisms like small algae, barnacles or mussels) play a significant role in the cultivation process?

Short description of experiments

The *Fucus* thalli were cultivated in plastic baskets (28 x 28 cm edge length, volume: 14 litres), which were deployed at an experimental farm on the north-western shore of the Kiel Fjord (see fig. 5). The baskets were arranged in groups of three or eight, and kept floating by plastic pipes or JETFLOAT® elements. The baskets were protected by a 2 x 4 m pipe frame, to prevent destruction by waves. 20 g of *Fucus* thalli were put into each basket, and were cultivated for periods ranging from several months to two years. The growth of the cultures was monitored regularly by weighing the thalli. Before weighing, they were spun with a salad spinner for 15 s to remove water. In addition to monitoring thallus growth, the formation of sexual organs was checked regularly and also investigated in special experiments. One experiment was specifically dedicated to colonisation by surface fouling organisms (barnacles, mussels, bryozoans). It was tested if regular desiccation by air exposure is able to reduce the colonisation by fouling organisms, and how this desiccation treatment impacts the growth performance of the two *Fucus* species cultivated.

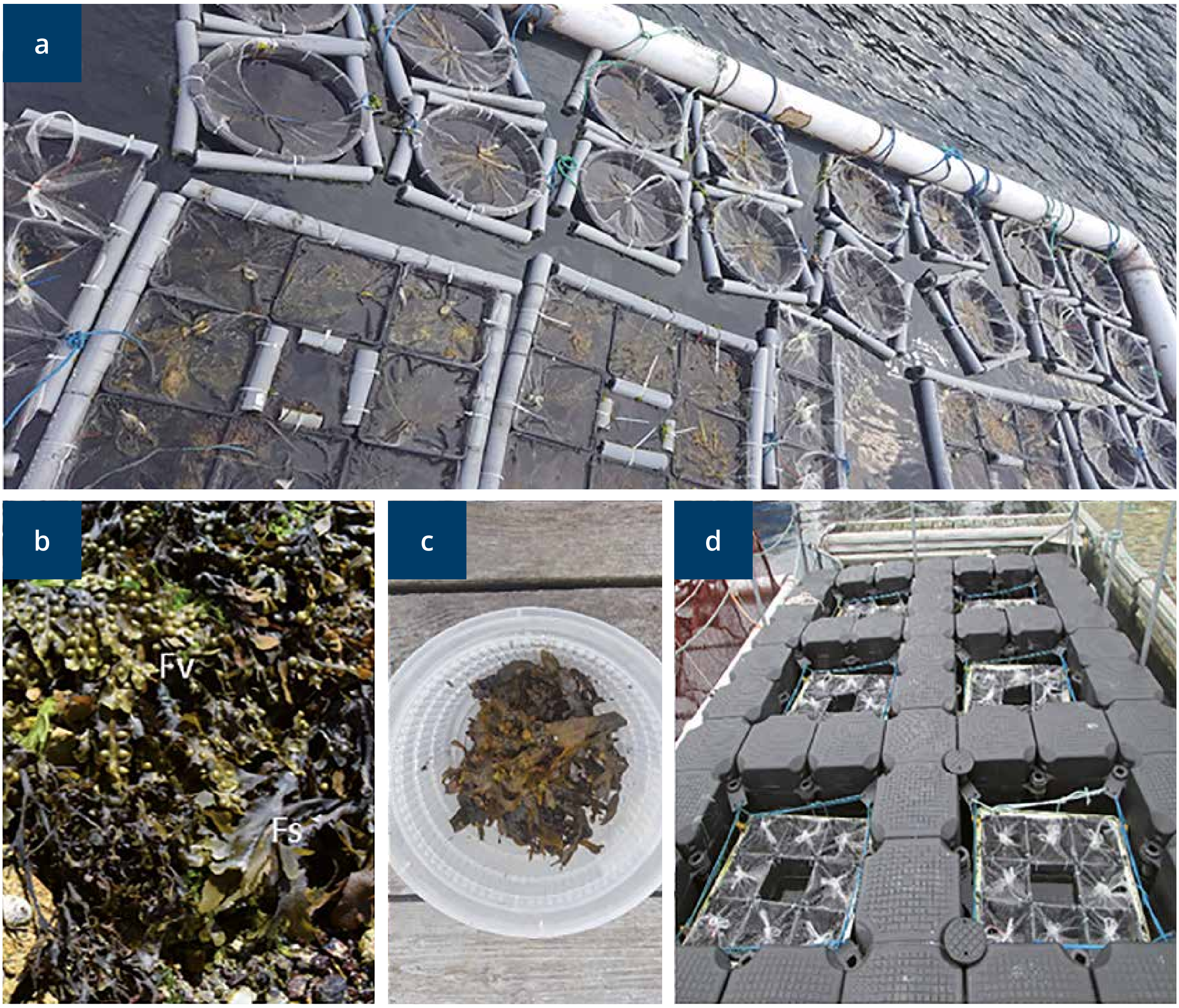


Figure 5: a, d: Cultivation baskets were deployed in the sea and kept floating by plastic pipes (a) or JETFLOAT® elements (d). b: F. vesiculosus (Fv) and F. serratus (Fs) grow next to each other in the field. c: Before weighing, the thalli were spun with a salad spinner for 15 s.

Result charts

It was possible to cultivate *Fucus* thalli for two years without degradation of the vegetative thalli. The growth was considerable, and an annual harvest of about 50 t/ha was estimated from the growth rates measured, under optimal conditions. However, the formation of sexual organs, which degenerate after some time, severely reduced the biomass (see fig. 6). Further, colonisation by fouling organisms proved to be an immense problem. It was possible to drastically reduce the colonisation by fouling organisms with regular desiccation, while the growth of the *Fucus* thalli was maintained despite the desiccation treatments (see fig. 7).

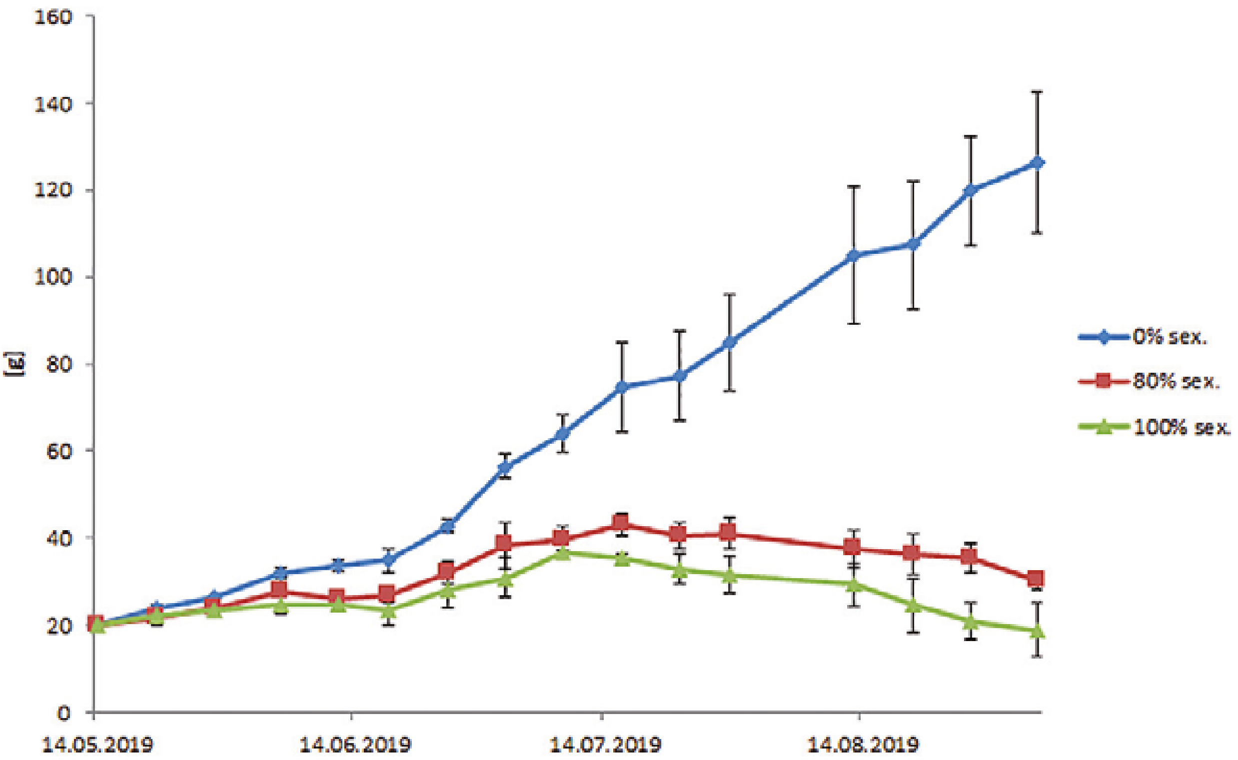


Figure 6: Fucus sp. growth in culture with different percentages of sexual organs in the seed biomass.

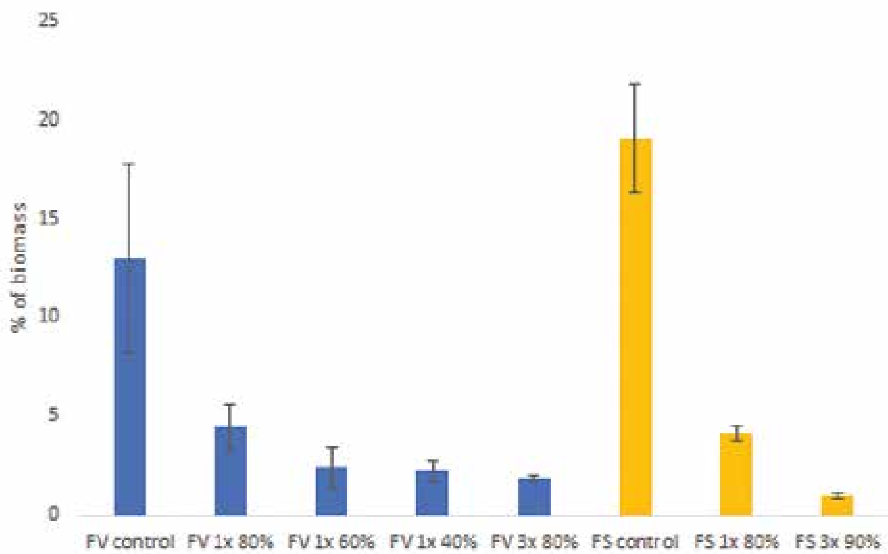


Figure 7: Percentage of fouling organisms of total harvested biomass after cultivation at different desiccation treatments (FV: F. vesiculosus, FS: F. serratus, 1x/3x: number of desiccations per week, control: no desiccation, 90%/80%/60%/40%: percentage of wet weight to which biomass was desiccated.)

Conclusion

From the results obtained in this study, it is concluded that *Fucus* cultivation is possible in the Baltic Sea, but only with individuals that bear no sexual organs (receptacles). As there are some wild populations that form no receptacles and only reproduce vegetatively (see Maczassek 2014), it would be an option to use these as ‘seed biomass’ for aquaculture. However, it must be investigated if these populations also retain their asexuality when cultivated.

The second major obstacle for successful cultivation proved to be the abundance of fouling organisms. It was possible to reduce this by regular desiccation. For the practical implementation of this method in large-scale aquaculture, it is necessary to develop a technical solution for this laborious process. Another option would be to perform cultivation in tanks with filtered seawater (i.e. no fouling organisms) or in water bodies that harbour fewer fouling organisms, such as low-salinity estuaries. However, it must be tested if the *Fucus* species can maintain their growth under these conditions.

Generally, the experiments showed that *Fucus* cultivation is possible, and yields growth rates suitable for commercial application. However, the obstacles described above require further research.

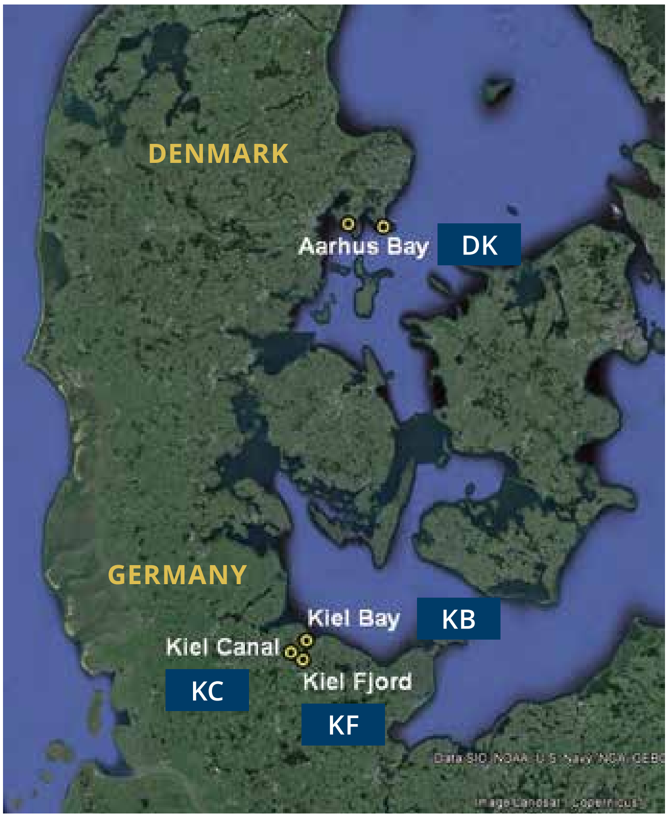
Collection

CRM explored suitable macroalgae collection sites in Kiel Bay, i.e. nearshore dense standing stocks of *Fucus* species. We only collected a few kilogrammes of each species for this project, to secure the current standing stocks and to enable future algae population development.

We sampled the three common Baltic Sea *Fucus* species in 2017 and 2018 over three seasons (spring, summer, autumn), and sampled *Fucus distichus* subsp. *evanescens* in winter 2019. This species, the Arctic wrack, has established itself in the Baltic Sea since the 1990s (see literature, Schueller & Peters 1994, LLUR 2014). It is found in nearshore dense stocks in the Kiel Canal, as well as within the standing stocks of the two native species bladder wrack, *Fucus vesiculosus*, and serrated wrack, *Fucus serratus*, in 0 to 2 m depth in Kiel Bay. Beside these three perennial algae, we sampled one annual brown macroalgal species in 2018, the golden sea hair, *Dictyosiphon foeniculaceus*, which only occurs in greater numbers in Kiel Bay during spring.

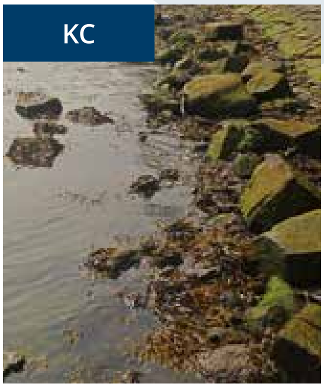
The algae samples were cleaned and stored frozen on CRM premises, ready to be delivered on call to our WP 4 partners (CAU-Pharma, Kiel, Germany; SDU-CEBET, Odense; DTU, Lyngby, Denmark) for extraction.

Commercial harvesting (more than a few kilogrammes for scientific purposes) of *Fucus* species from regional German resources currently conflicts with the environmental protection status of the *Fucus* belts as “Red List species and biotope” (see BfN 2013, 2017). CRM developed contacts with the company Organic Seaweed (OS) in Denmark, which possesses an organic certified harvesting license for macroalgae. Unlike in Germany, the *Fucus* species don’t have Red List status in Denmark (see HELCOM 2012, 2013). With the permission of OS, CRM harvested several dozen kilogrammes of *Fucus vesiculosus* in 2018. The further processing took place as described above.



Fucus vesiculosus

Fucus serratus



Fucus evanescens

Dictyosiphon foeniculaceus

Ecological concerns

Perennial macroalgae like kelps and wracks form very important habitats along rocky coasts all over the world. These underwater forests serve as nurseries for many species of fish, and provide a habitat for invertebrates of all kinds, like snails, sea urchins, crabs, barnacles, bryozoans, etc. Even some marine mammals like the sea otter occur specifically in kelp forests in the Pacific. However, many of these forests are at risk due to human impact. Some have suffered enormous declines of up to 95% of their former area within recent decades, like the *Macrocystis pyrifera* forests of Tasmania or the *Cystoseira* forests of the Canary Islands (see Edyvane 2003, Valdazo et al. 2017).

One of the main reasons for the worldwide changes in macroalgae populations is eutrophication, i.e. the input of excess nutrients into the sea due to intensive agricultural and industrial activities, which favours small, short-lived algae over large, habitat-forming ones. Another severe problem is overfishing and hunting of marine mammals, which significantly affects coastal ecosystems. Fish and marine mammals often prey on small invertebrates like sea urchins and snails. Once these top predators are artificially reduced by human activities, the invertebrates increase in number and graze down the seaweed forests. In addition, sea water warming due to climate change has predominantly negative effects on kelp forests.

The *Fucus* forests of the Baltic Sea experienced a drastic decline in the 20th century, especially due to eutrophication and stone fishery (i.e. fishing for boulders and blocks as construction material), which reduced the number of available substrata (Rohde et al. 2008).
Therefore, commercial harvesting of *Fucus* species from regional German biotopes conflicts with the environmental protection status “Red List biotope”. We discussed these frameworks and concerns with German authorities, namely the Department of Fishery and Aquaculture from the Ministry of Environment (MELUND, Kiel) and the state office for agriculture, environment and rural areas (LLUR, Flintbek) in Schleswig-Holstein.

After starting the FucoSan project, CRM established contact with Ms. Mette Albrechtsen, founder of the Danish start-up “Organic Seaweed” (OS). This was one of the early ‘cases’ within the Interreg project “Baltic Blue Biotech Alliance”. Denmark allows the licensed, sustainable harvesting of *Fucus* and other brown macroalgae. Both activities, discussing the Red List status of *Fucus* (in Germany with LLUR and MELUND) and developing a sustainable harvesting strategy in Denmark (and possibly in future in Germany, initially in trial fields), will be pursued further beyond the project duration of FucoSan. In other countries, an environmental assessment of sustainable macroalgae harvesting has been conducted, and is embedded in a government strategy for the commercial use of local seaweed resources (e.g. Marine Scotland 2016). This could also be a goal here, to develop a corresponding strategy for the German Baltic Sea coast.

Description of an idea for sustainable harvesting

The company Organic Seaweed holds a license to harvest wild *Fucus* stocks and other marine brown algae in the Aarhus Bay in Denmark. CRM is in contact with Ms. Albrechtsen from Organic Seaweed, and is involved in the harvesting of these seaweeds. There are strict rules to safeguard the sustainability of the harvesting method: only 10% of the standing stock may be harvested annually, and the status of the ecosystem, including the associated fauna, must be checked through regular monitoring by divers in the harvesting area. These measures allowed for the certification of the biomass as "organic".

Recent observations of increasing *Fucus* populations in the German Baltic Sea (LLUR 2008, CRM 2014) led to the idea for a new research project. How stable are *Fucus* populations at different sites in the Baltic in terms of climate change (higher temperatures, more storm occurrences, etc.)? How can fertilisation und growth rates be determined? To what extent can *Fucus* be harvested within a defined area, while maintaining or even boosting the population density and diversity of the *Fucus* biotope?

CRM has some experience in transferring *Fucus* individuals, growing on stones, to different nearshore sites (without *Fucus* biotopes) in Kiel and Lübeck Bay, and in monitoring standing stock development, growth and fertility (Sandow & Krost 2014).

The idea of *Fucus* test sites in Kiel Bay was developed during the FucoSan project. We provided a proposal to the relevant authorities MELUND and LLUR for further discussion and possible support. Finally, in November 2019, CRM started a new, independent research project and established three *Fucus* test sites in Kiel Bay (see fig. 8), exclusively funded by LLUR. The aim of this project is to gain additional information about recovery of marine protected biotopes in the Baltic within the next three years, including testing of sustainable harvesting of stable *Fucus* populations. Within FucoSan, some initial results concerning standing stock development of *Fucus* could be achieved in the last reporting period.

Figure 8: Test field with Fucus in Kiel Bay (left) with a HOBO data logger (monitoring water temperature and light intensities) on a white painted stone. Buttom: control field (seeding substrates) without Fucus; pictures taken in November 2019

Outlook and perspective

Despite the weakly-developed seaweed utilisation in Europe, our research resulted in a list of several sustainable sources of different brown macroalgae, including cultivation and harvesting from natural populations. We are in direct communication with the suppliers listed, and they are able to supply seaweed for industrial use of fucoidan within a short period of time – which we consider a prerequisite for further development of a sustainable blue bioeconomy on the basis of seaweed (and fucoidan) in the region.

Cultivation is not only a sustainable method for the production of well-known algal species, but also appears to be a feasible option for the production of local *Fucus* species in the Baltic Sea. The principal method of vegetative reproduction seems suitable - however, the right population (asexual) must be used for the start of cultivation. Long-term survival for more than two years has not been investigated yet, and requires further research. In addition, investigation of cultivation in low-salinity estuaries with fewer fouling organisms (barnacles, mussels etc.) is required, in order to develop cultivation methods with the potential to produce clean biomass ready for market needs. Finally, it will be necessary to upscale the cultivation from experimental conditions to commercial production. This process usually involves many new questions, which can hardly be foreseen based on the experience gained with small-scale cultivation. Therefore, a substantial amount of research and work lies ahead, but a general foundation to build upon has already been established during the FucoSan project.

In conclusion, sourcing of high-quality seaweed biomass in Europe requires contact with a variety of partners, from farmers and collectors to local government authorities. In a best practice scenario, the biomass is produced in a sustainable way, i.e. by farming with no negative environmental impact, or by collection of wild stocks, which is accompanied by regular monitoring to ensure the integrity and stability of the ecosystem from which the harvests are taken.

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