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Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting

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ABSTRACT

The current work aimed to develop a cultivation method for macroalgae that can be applicable and economically profitable in the Atlantic Ocean. An offshore long-line macroalgal cultivation rig was designed by Ocean Rainforest Sp/f, tested in the Faroe Islands from 2010, and found suitable for cultivation in exposed and deep-water locations (water depth > 50 m). The economic risk related to lost cultivation structures was hereafter considered to be low. *Saccharina latissima* and *Alaria esculenta* were cultivated in commercial scale (5 km of growth lines). A high cost of seeding material and cost of deployment was reduced by testing multiple partial harvesting. Four non-destructive harvests were carried out in a two-year growth period without re-seeding of lines. In total, 3.2 t dry weight (dw) biomass was harvested and sold to customers within the food and cosmetic industries. The productivity was 1437.5 kg dw ha^{-1} yr^{-1} (including handling space). The 10-meter vertical growth lines had an average yield of 0.29 kg dw m^{-1} per harvest and four partial harvests were made over a 2-year period. An economic analysis showing the cost structure of important aspects of offshore macroalgae cultivation was conducted. The total cost per kg dw of cultivated *S. latissima* decreased when the number of possible harvests without re-seeding was increased (from € 36.73 to € 9.27). This work has demonstrated that large-scale kelp cultivation is possible using multiple partial harvesting in the Faroe Islands, and highlighted the need for further innovation to lower the cost per unit macroalgal produced.

1. Introduction

The need for food is increasing globally and, therefore, the efficient use of natural resources is increasingly vital. Most land areas are already utilized for the conventional agriculture of terrestrial plants. However, the oceans, that cover > 70% of the planet, potentially offer solutions for future sustainable large-scale biomass production. The use of macroalgae (seaweeds) has a long history, as does the cultivation at sea of a relatively small group of macroalgal species [1]. In North America and in Europe, macroalgae are a relatively underexploited resource, though they are the subject of an increasing interest for their potential as human food, animal feed, cosmetics, bioactive components, and biofuel [2–8]. The interest in macroalgal cultivation is driven by a market demand [1,2,8] and because of environmental concerns related to wild harvest of macroalgae [9–11].

Cultivation of macroalgae has important environmental benefits compared to harvesting wild populations. Instead of damaging natural ecosystems, new artificial marine forests are established with similar environmental functions as a nursery habitat for juvenile fish and as a food source for animals. The cultivated macroalgal biomass bioremediates nutrients and carbon (CO_2) from the surrounding environment as biomass [3,9,10]. There is therefore an ecological benefit to be gained from the cultivation of macroalgae.

The European macroalgal industry currently relies on wild harvesting, unlike Asian producers that mainly rely on cultivation. In 2015, Asia produced 27 million tonnes wet weight (ww) macroalgal biomass, corresponding to approximately 2.7 million tonnes dry weight (dw), whereas the yield in Europe was only a few hundred tonnes dw [12]. The cultivation methods developed in Asia through centuries are not easily applicable to the western countries. The reason is that the cultivation methods that are used are labour intensive, and the methods are not proven to be profitable in the Western world [2,13]. Zuniga-Jara et al. [14] made a feasibility study of offshore commercial kelp cultivation in Chile, and concluded that it was not profitable, as the sale

Abbreviations: MACR, MacroAlgae Cultivation Rig; MBSL, meter below sea level; dw, dry weight; ww, wet weight; SD, standard deviation; ha, hectare

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of the biomass was unable to cover the investment costs or the operation costs.

To reduce production cost, Burg et al. [2] described the importance of developing a cultivation system that enables multiple partial harvests. Furthermore, biofouling seems to be a major issue for cultivation in Europe [8,15–18], and the phenomenon appears to be coupled to relatively sheltered locations preventing the use of multiple partial harvesting [5,19]. Offshore cultivation, therefore, seems to be vital for a profitable macroalgal industry [5,20,21].

Offshore cultivation is defined as “the execution of activities in sites that are subject to ocean waves”, which is linked to distance from shore or lack of shelter from topographical features such as islands or headlands that can mitigate the force of ocean and wind-generated waves and sites with significant wave heights of two meters or above [22].

Producing macroalgae offshore is thus promising in terms of market potential and sustainability, but an extremely challenging endeavour [2–4,7,20,23–27].

Relatively few macroalgal species have been utilized for production [1], nevertheless, kelps have been exposed to some of the first pioneer cultivation trials in North America and in Europe. The two kelp species *Saccharina latissima* (Linnaeus) Lane, Mayes, Druehl and Saunders, commonly known as “sugar kombu” or “sugar kelp”, and *Alaria esculenta* (Linnaeus) Greville, with the common name “winged kelp”, have attracted commercial interest for human consumption as sea-vegetables [8,17,26]. *S. latissima* grows on the lower shore in semi-exposed areas, whereas *A. esculenta* is very tolerant to more severe wave exposure. Both algae are distributed along the northern Atlantic coasts and in Arctic areas. *S. latissima* is also found along the northern Pacific coasts and is distributed in oceans with higher temperatures and lower salinities than *A. esculenta*. The cultivation techniques are well developed for both species, and especially *S. latissima* is described as having good potential for commercial-scale cultivation in Europe and in the North Atlantic [2,28].

During the past decades, several macroalgal cultivation trials have been conducted in the Atlantic Ocean in particularly using *S. latissima* [26,28–35]. However, none of these cultivation trials have resulted in large-scale profitable cultivation [2].

This paper describes the work of several years innovative large-scale kelp cultivation in the Faroe Islands, documenting the use of a new concept for offshore cultivation installation: the Macroalgal Cultivation Rig (MACR). Also, the effect on economics of multiple partial harvesting of *S. latissima* and *A. esculenta* was described for the first time. The cultivation data reflects the large variation in growth and provides a reliable base-line study of pioneer kelp cultivation for the future use in European and North American oceans.

2. Material and methods

2.1. Cultivation site and environmental conditions

The macroalgal cultivation site was located at the mouth of Funningsfjørður in the Faroe Islands (62.3030° N, 6.9267° W; Fig. 1). The Faroe Islands are an archipelago situated in the Northeast Atlantic Ocean. The site had a water depth of 50–70 m, was exposed to currents of 15–25 $cm\,s^{-1}$ and was characterized as an exposed area with occasional significant wave heights of 3–6 m [36–39]. The North Atlantic Current, which originates from the warm Gulf Stream, runs past the Faroe Islands and brings warm currents to the area, providing a relatively stable seawater temperature ranging from 6 to 11 °C during the year [40]. The salinity was very stable at 35.0–35.2 [40]. Contrary to salinity, the irradiance and day length varied substantially through the year. Irradiance measured at land surface varied from < 50 $\mu E\,m^{-2}\,s^{-1}$ in November to February and up to 300 $\mu E\,m^{-2}\,s^{-1}$ in average during May [41]. There was a large drop in irradiance when penetrating sea surface due to reflection. In the seawater column light can penetrate down to 30–50 m below sea level (MBSL), though at these depths the irradiance was very low (< 10 $\mu E\,m^{-2}\,s^{-1}$). There was a linear relationship between the phytoplankton concentration and the attenuation coefficient, which varied between 0.05 and 0.3 m^{-1} [41].

2.2. Cultivation system

The Macroalgae Cultivation Rig (MACR) developed by the company Ocean Rainforest Sp/f was designed to withstand the conditions of the North Atlantic Ocean (Fig. 2). The MACR was constructed using lightweight and robust equipment. None of the parts were specially designed, as all equipment was bought from a local manufacturer selling fishing gear, aquaculture equipment, and equipment to the offshore industry.

The design consisted of a 500-m long polysteel fix line (30 mm in diameter) suspended horizontally at 10 MBSL (C, Fig. 2). Two main surface floats (D, Fig. 2) were connected to the fix line and 40% submerged in a static state. The mooring system consisted of four 120-m anchor lines, which were attached to the fix line and anchored to the seafloor with 1–1.5 t steel anchors (E, Fig. 2). One MACR occupied a sea surface area of 1 ha (one MACR has a nominal width of 10 m on each side of the fix line). The rig had approximately 250 growth lines (B, Fig. 2) of 10-m length attached to the fix line with a float fixed at the opposite end, stretching the lines in a vertical position.

The first test MACR was deployed in March 2010 and the growth lines attached were not seeded. After a successful structural testing period of three years, the growth lines were replaced with seeded lines with respectively *S. latissima* and *Laminaria hyperborea* (Gunnerus) Foslie. This deployment was meant as a biological test of growth. Unfortunately, these results were not consistent enough for scientific purposes, but important lessons were learnt in terms of practical handling of seeding, deployment, maintenance and harvesting. In November 2014, two more MACR's were deployed and these lines provide the data information on the growth and costs in this paper.

2.3. Seeding method

Seeding material was produced by the company Hortimare BV, located in Norway and the Netherlands, using a standard procedure for kelp sporulation [42]. Fertile *S. latissima* and *A. esculenta* were collected from wild populations in Funningsfjørður in January 2014. From the sterilized fertile sori, spore release was done by leaving the sori dehydrating and in darkness until next day. The spores were released to sterile and filtrated seawater and placed with aeration in red light at 10 ± 2 °C. The gametophytes were nursed till sufficient biomass was reached (cultivated in vitro for > 9 months). Hereafter, an induction period using white light was initiated. The gametophytes developed into juvenile sporophytes within two weeks (size < 1 mm). Density of the seeding material was approximately 0.04 $mL\,m^{-1}$ seeded line or a minimum of 200 sporophytes m^{-1}. The juvenile sporophytes were seeded on 2-mm lines using a binder-mixture produced by Devan Chemicals N.V. with the product code DG518. The seed lines were twined around coils and the juvenile sporophytes were cultivated in hatchery tanks for a three-week period before deployment. The cultivation conditions as light, nutrients, waterflow, etc. is IPR of Hortimare.

2.4. Deployment

The juvenile sporophytes were deployed at sea in November 2014. The day before deployment, the seed lines (A, Fig. 2) were twined around a growth line (B, Fig. 2) of 14-mm polypropylene three strained twisted rope. The growth lines with juvenile macroalgae were stored in seawater until transportation. These growth lines summed up to a total of 470, each of 10 m length and attached along the fix line (C, Fig. 2) with a 2-m interval and each line had a buoy attached in the opposite end to provide uplift. Two MACR's were completed with 4200 m of *S. latissima* growth lines and 500 m of *A. esculenta* growth lines. The two