The Offshore-Ring: A New System Design for the Open Ocean Aquaculture of Macroalgae

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The offshore-ring: A new system design for the open ocean aquaculture of macroalgae

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Abstract

Mass culture of benthic macroalgae under rough offshore conditions in the North Sea requires rigid culture support systems that cannot only withstand rough weather conditions but can also be effectively handled while at the same time retain the cultured species. Various carrier constructions and different mooring systems were tested. *Laminaria saccharina* grew on all of these carriers with initially high (up to 14.5% per day) and later decreasing length increments. Longlines, ladder and grid systems had certain disadvantages and these are discussed. The study results led to a new ring carrier (patent pending), first used in 1994/1995, which was gradually improved until 2002. This system now emerges as being superior, since it resists not only rough weather conditions (2 m s^{-1} current velocity, 6 m wave height) but also permits ease of handling when compared to other constructions. The ring allows various operational modes and can be equipped with culture lines that can be collected offshore or transported to shore facilities for harvesting. The modular nature of the tested ring system lends itself for future use in integrated aquaculture systems located in or attached to offshore wind farms.

Introduction

Aquaculture is presently one of the fastest growing aquatic food production sectors in the world due to the rapidly increasing demand and declining global fishery yields. Compared to the rapid augmentation of 117% (1993–2002) in fish, crustacean, and shellfish aquaculture, the cultivation of seaweeds still plays a less important but increasing role in the industry. The worth of the seaweed industry has grown about 26% between 1993 and 2002 to 6 billion US$ (McHugh, 2003; FAO, 2004).

Traditionally, mariculture of seaweeds has been conducted mainly in Japan and China for more than three centuries mainly for human consumption (Kawashima, 1993; Tseng, 1993, 2001; Ohno and Critchley, 1997; Critchley and Ohno, 1998). The culture of marine algae can be traced back to 1690, when the first recorded attempts to culture seaweed on the fences of fish cages were carried out in Japan (Tamura, 1966). Yet, scientifically supported culturing techniques resulting in a much more successful commercial production (Scoggan et al., 1989) were not initiated until as late as the early 1950s and then mainly in relatively protected inshore waters. In 2002, production levels of algae have been reaching 18.6 million tonnes (FAO, 2004). The FAO notes that in 2002 Europe had only a 6.3% share of the global production of brown algae (362 000 t FW) and about 0.3% of red algae (9400 t FW) with less than 200 t macroalgae produced in aquaculture. Norway, France, and Iceland are the main suppliers of brown seaweeds in western Europe, since their rocky coastal areas, unlike that of the German Bight, provide enough hard substrate to accommodate extensive kelp forests. This has given rise to a traditional harvest of naturally grown algae in these EU countries (Kain, 1991; FAO, 1998). However, the economic gains are low, due to limited access to the natural beds, harsh weather conditions and an unavoidable mix of species harvested in the field (Kain and Dawes, 1987). Contrastingly, 97% of the Asian production of brown seaweeds is grown as monocultures in aquaculture (Fei et al., 2000; FAO, 2004). This approach avoids the disadvantages of the traditional European fishery-based production systems that yield a high variability in terms of quality and composition. Often, a partial destruction of the seaweed beds accompanies this collection fishery.

Outside Asia only few algae are consumed directly, but many products marketed globally contain phycocolloids, extracted from algal cell walls that are used as stabilisers and emulsifiers in the food and cosmetic industries (De Roeck-Holtzhauer, 1991; McHugh, 2003). The long chains of algal polysaccharides can make up to 40% of dry weight (Smidsrød and Christensen, 1991). The global market for phycocolloids that include agar, carrageenans and alginates is estimated to be worth annually 585 million US$ (McHugh, 2003). Moreover, *Laminaria* can be used for waste water treatment and the partial recycling of nutrients particularly near fish farm effluents (e.g. integrated culture systems) Subandar et al., 1993). They have also been employed to absorb heavy metals from industrial sewage (Sandau et al., 1996; Stirk and van Staden, 2000).

In western countries macroalgal farming of brown algae in the sea was tried out at the Californian coast (Neushul and Harger, 1985; Neushul et al., 1992) and in Europe near the Isle of Man and Ile d'Ouessant (Kain, 1991; Perez et al., 1992). In Germany, a feasibility study on offshore algal mariculture in the North Sea was launched by the German Government in 1993 and conducted at the marine Station of the Biologische Anstalt Helgoland (BAH) off the island of Helgoland, North Sea (Figure 1). The study lasted for two years. One major component of this feasibility study was to develop an appropriate technical device to grow macroalgae. The system had to withstand the

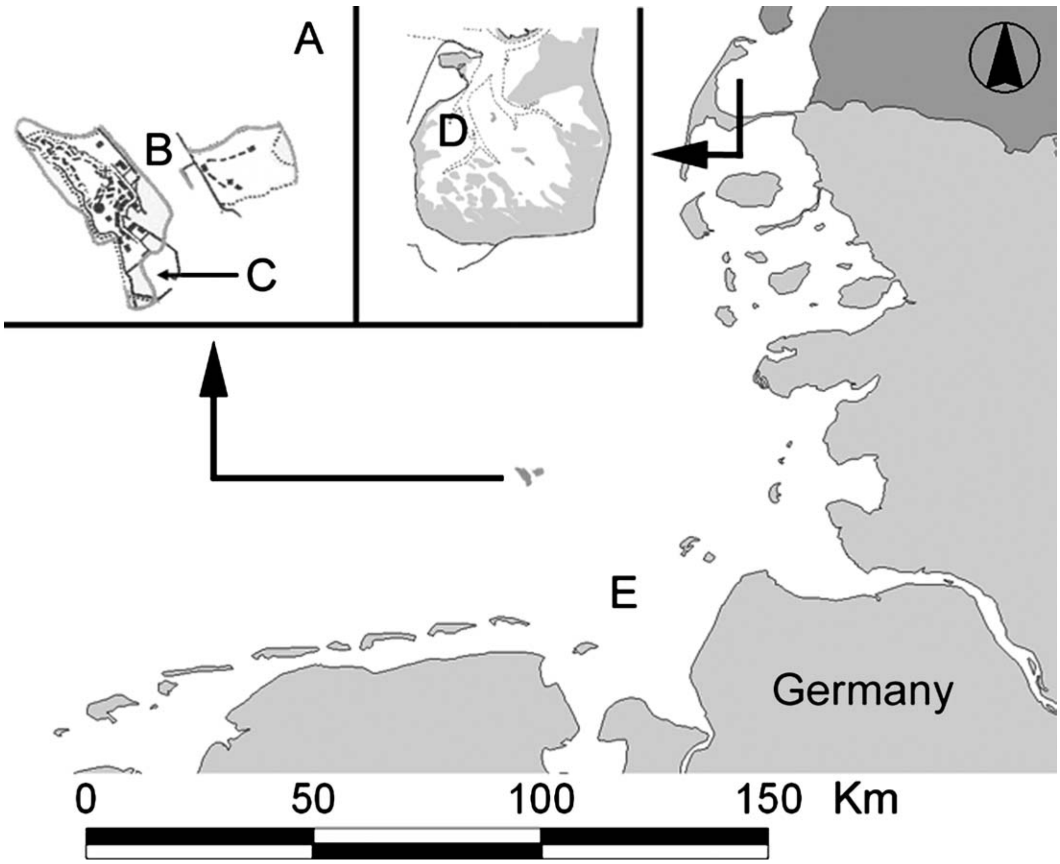

Figure 1. Map of the German North Sea region including the enlarged island of Helgoland (upper left) with the test locations (A) Helgoland farm, (B) Helgoland Roads and (C) Helgoland Harbour. The enlarged northern part of the island of Sylt (upper right) illustrates the test location (D) in the Sylt tidal flats backwaters. Location E indicates the Roter Sand test area.

harsh environmental conditions of the German North Sea shelf, where maximum wind speeds can be 150–180 km h^{-1} and wave amplitudes commonly reach 5–8 m during storms. Investigations were resumed in 2002 as part of a doctoral thesis (first author) aiming at using this new aquaculture technology in conjunction with offshore wind farms. Sheltered nearshore areas, suitable for mariculture, are already largely used as established nature reserves or as protected areas in general. Thus, future commercial cultivation of seaweeds will have to move to more exposed offshore areas.

Several known carrier designs for algal culture were built and deployed, subsequently resulting in the final modular construction used in this study. The performance of the various test designs under offshore conditions, length changes and, where possible, the biomass yield of *Laminaria saccharina* on these constructions were investigated at different locations.

The results are of high importance for the future utilisation of exposed offshore locations, especially when considering multi-user concepts combining wind farm installations with mariculture. Such projects as are currently developed along the German coast (e.g. Buck, 2002; Buck et al., 2003, 2004; Krause et al., 2003).

Material and methods

Study site and environmental conditions

Experimental mariculture of *Laminaria saccharina* was conducted in 1994 and 1995 at Helgoland, in 2002 near the island of Sylt and in the outer estuary of the river Weser (Figure 1). The study sites are characterised by various hydrographic features. Depth, condition of the sea bottom, salinity, turbidity and light, wave exposure, current velocity and significant wave heights (Mittelstaedt et al., 1983; Asmus et al., 2000; Dring et al., 2001; WSA, 2002) are shown in Table 1. Furthermore, nutrients (ammonium, nitrate and phosphate) and water temperature (Table 2) at the study sites were monitored for unusual events by examining the BAH's and WSA's long running time series of measurements (BSH, 2002; BAH, 2002, 2003; NLÖ, 2003). Peak wind velocities of ≥6 Beaufort and ≥8 Beaufort were noted down during years of the experimental studies.

Sporadically, photosynthetically active radiation (PAR) was determined with an 'Underwater Quantum Sensor' (LI.COR [μE m^{-2} $s^{-1} \approx$ mmol m^{-2} s^{-1}]), which recorded the light intensity in air near the water surface and underwater at the culture rope. Additionally, water temperature was recorded during the experiments.

Experimental plants and pre-cultivation of young sporophytes

For "seeding", reproductive specimens of *Laminaria saccharina* with a thallus length from 90 to 150 cm were collected by divers from nearshore areas around the island of Helgoland (Hgl; 54°11′N, 7°54′E) (Figure 1) from a water depth of 1–4 m in the winter months.

In order to obtain sporophytes attached to culture lines, zoospores were released from the sporogenous tissue (sori) of *L. saccharina* that had been meticulously cleaned by brushing in three pasteurised water baths. Sori from up to 12 different plants were

Table 1. Site-specific conditions at nearshore and offshore test locations.

Location	Depth at low tide (m)	Sea bottom	Salinity (psu)	Turbidity	Light (PAR) (mol · m^{-2}· s^{-1})	Wave exposure	Current velocity (m ·s^{-1})[a]	Significant wave height (m)[b]
Offshore								
Helgoland Farm	12–14	Sand	29–33	Low	No data	Exposed	0.3–1.2	0.5–4
Roter Sand	12	Mud/silt-sand	25–32	Moderate	100–1750	Exposed	0.5–2.1	0.5–5
Nearshore								
Helgoland Roads	6	Coarse gravel	29–33	Low-high	100–2590[c]	Partly exposed (strong currents)	0.3–1.5	0–3.5
Helgoland Harbour	5	Mud (clay)	29–33	High	No data	Sheltered	0.1–0.3	0–1
Tidal flats of Sylt	1	Mud (clay)	32–34	High	0–1600[d]	Sheltered	0.4–1.0	0–1.5

[a]Mittelstaedt et al. (1983).
[b]WSA (2002).
[c]Dring et al. (2001).
[d]Asmus et al. (2000).

dried in a moist chamber at 10 °C over night and allowed to sporulate the next day in fresh seawater. The spore suspension was poured into a 3000 L basin containing five large plastic frames, segmented for stability. Each frame was wrapped with more than 350 m of culture line. In a previous test various culture lines had been tested. Among 15 different lines a 6 mm polypropylene line, three-strand right hand soft lay, proved to be most suited to fulfil the requirements: This line was not toxic and ready for use after only two rinsing steps; the diameter of 6 mm was acceptable for space-saving at "seeding" time, but also strong enough to carry larger plants, which therefore did not have to be transferred to thicker ropes. The frames were arranged vertically and reversed every second day to accomplish a more even exposition to the artificial sunlight generated by Power Star HQI-TS 150W/NDL Neutral Weiss lamps by Osram, which yielded 10 μmol photon m^{-2} s^{-1} in the centre of the basin. The light regime was 10 h light per day. The seawater was filtered and supplemented with either Provasoli's solution (Provasoli, 1968) or 100 mmol L^{-1} $NaNO_3$ and 10 mmol L^{-1} sodium glycerophosphate once a month. At "seeding" and once per week for two weeks germanium (IV) oxide was added to prevent diatom growth. Approximately two months after seeding, the first cultured laminarian sporophytes reached an average length of 1 cm and were placed in the sea.

Design of the carrier systems

Four different cultivation systems were designed and deployed in the study area in order to find the most suitable design for offshore use: these included longline, ladder (tandem longline), grid and a ring-shaped design for attachment of algae seeded culture lines (schematic Figures 2a–2c and 3a–3c). Each of these different constructions varied in mooring design, floatation and culture units. Concrete blocks of 2.5, 4 and 4.5 tonnes were employed in a single, twin or radial mooring geometry in order to securely moor the carrier constructions. The ladder and grid constructions were oriented parallel to the main direction of the tidal current. Starting from the anchor stones, chains with a service load (SL) of at least 8 tonnes were used to connect the concrete with the mooring line (SL 12 tonnes). The service loads corresponded to a threefold collapse load. The mooring line itself held the culture unit, which was designed to float at or below the water surface. The floating system consisted of ball-like floaters or fenders, which were connected by ropes to the culture unit to provide sufficient buoyancy. All connections between ropes, chains, floaters and concrete blocks contained triple rings (SL 6 tonnes), shackles (SL 6.5 tonnes), warbles (SL 6.5 tonnes) and thimbles, in case of eyes at rope ends.

The *longline* consisted of a 50 m long, horizontal carrier rope anchored by a 4 tonnes twin mooring

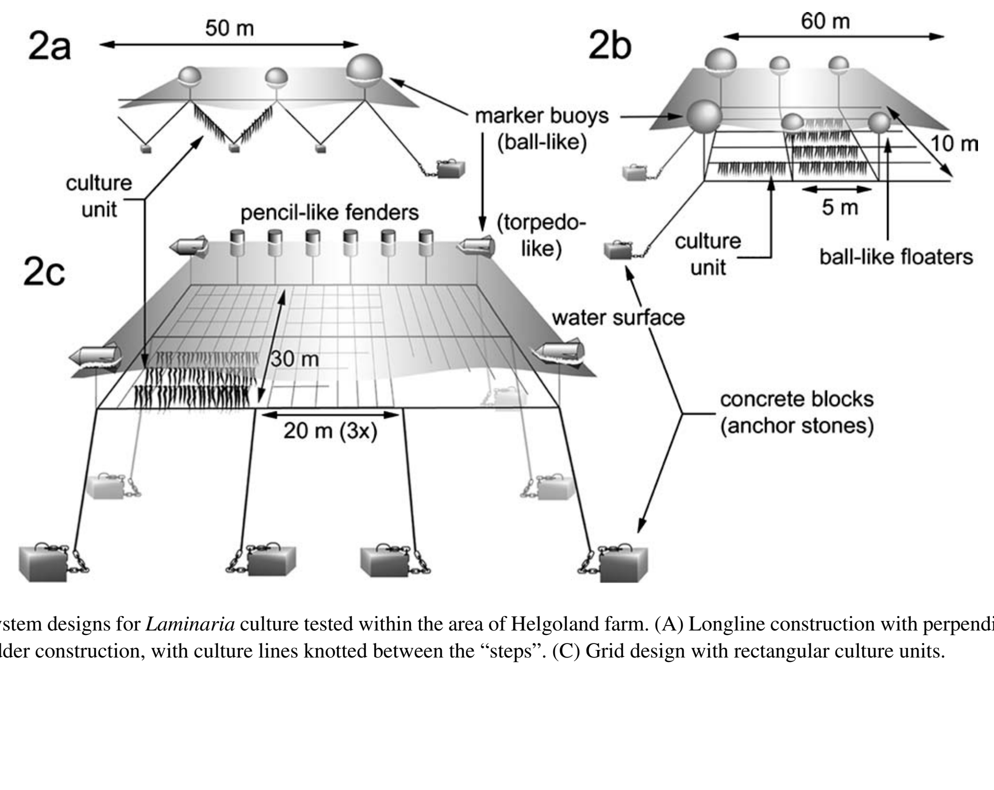

Figure 2. System designs for *Laminaria* culture tested within the area of Helgoland farm. (A) Longline construction with perpendicular culture unit. (B) Ladder construction, with culture lines knotted between the "steps". (C) Grid design with rectangular culture units.

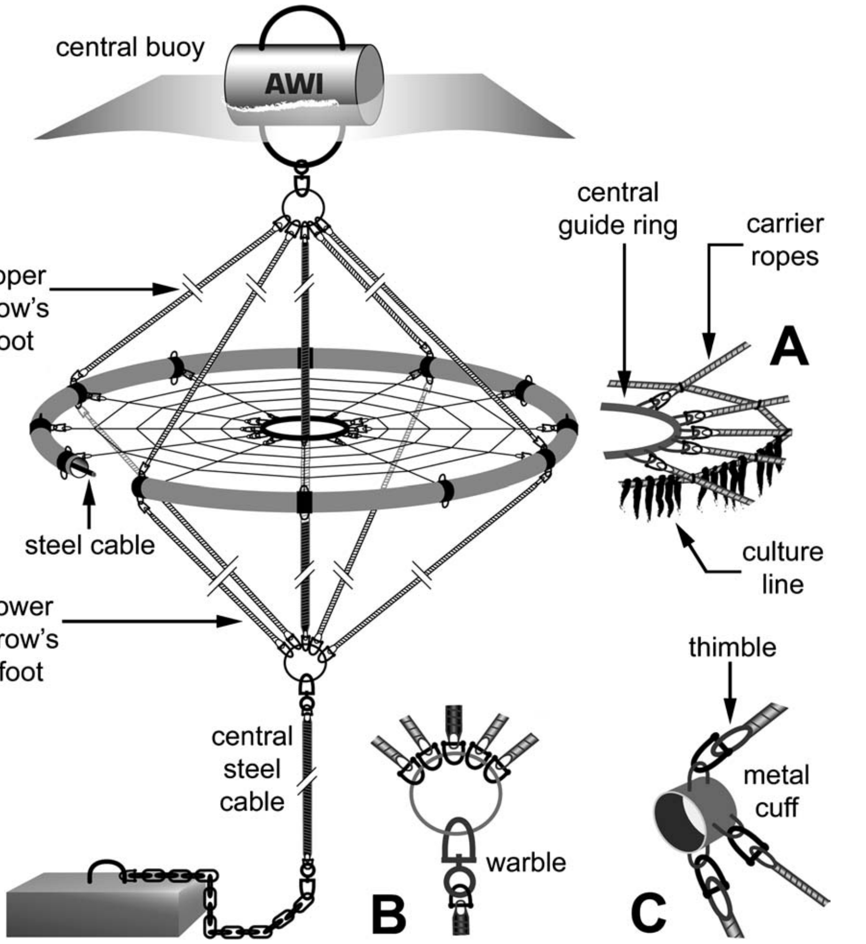

Figure 3. The successful ring design for the culture of *Laminaria* at offshore locations. The major elements of the system design are magnified: (A) central guide ring with attached carrier rope and culture line, (B) the transition between central steel cable of the mooring and that of the lower crow's foot, (C) metal cuffs, to which the crow's feet and the carrier ropes are attached.

system. It served to fasten culture lines perpendicular to the water surface, each kept straight by a concrete weight (2.5 kg) (Figure 2a). This method had been successfully employed by Kain and Dawes (1987) and Perez et al. (1992). Between December 1994 and April 1995, a total of 140 culture lines each 5 m long, with young *Laminaria* sporophytes were transferred from the laboratory and knotted at 3 m intervals to the horizontal carrier rope. Later, two adjacent 3 m long culture lines were connected at their lower ends (V-shape). *L. saccharina* on these lines were 2–3 mm at transplantation.

The *ladder* construction was 60 m × 10 m in size and was positioned horizontally 1 m below the sea surface by 24 concrete weights (each 1 kg under water) and air-filled buoys on the surface (Figure 2b). Ball-shaped buoys of 110 L at the corners of the ladder construction were meant to keep it afloat. It was suspended between four anchor stones (4.5 tonnes) in a double twin mooring shape. Five metres long culture lines were knotted in between the "steps". Experience from the "ladder" went into the construction of a grid system.

The *grid* systems had been in use off the Isle of Man (Kain, 1991) and in Brittany (Perez et al., 1992). Based on the above and our own experiences, a grid system depicted in Figure 2c was set up. The grid measured 60 m × 30 m and was submerged at a depth of 1.2 m. The grid was designed to hold 1400 m of culture line in an area of 0.18 ha. A radial mooring system was used with 10 concrete blocks (2.5–4.5 tonnes). The frame material employed here was "Herkules" rope, which is commonly used in commercial fisheries. This rope contains in its core several subcores, each made of six strands of steel. This way the rope was heavier than the surrounding seawater, which reduced the risk of potential damage at the weight attachment points. The inner supporting ropes of the construction were made of Polystar, a mixture of polypropylene and polyethylene, a material with excellent references in steel grades. Four metal torpedoes served as buoyancy devices at the corners, another 72 floats were pencil-like fenders with 23 kg buoyancy each.

The *ring* construction (patent pending) had a total diameter of 5 m and consisted of a polyethylene tube with a 10 mm thick wall and a diameter of 110 mm that was welded to rings. The rings were weighed down by a steel cable (30 mm in diameter) inserted into the tube and obtained their buoyancy through eight elongated fenders (23 kg buoyancy each). They consequently floated at a depth of 1.2–1.5 m. Carrier ropes were suspended radially and 80 m of culture line could be fastened like cobwebs on each ring. A crow's foot was used to fasten the ring on a common mooring system. Due to permanent chafing of the carrier ropes with the fender ropes and because the fenders themselves got entangled with each other a modified system was developed (Figures 3a–3c). This consisted of one centre buoy (300 kg buoyancy) with a connected reverse crow's foot and a centre guide ring to prevent chafing of the mooring line with the carrier ropes. Furthermore, all radial splices, which connected the carrier ropes to the polyethylene tube, were replaced with metal cuffs. Three loops were welded to these cuffs, one to the centre to fix the carrier ropes and the other two to the bottom and the top of the cuff, to connect both crow's feet.

An important feature common to all constructions was their ability to adjust the depth of culture lines to 1–1.5 m as this appeared to prevent possible PAR and UV damage to the young plants, while providing enough light for successful photosynthesis. Moreover, the most turbulent upper meter of the water column could thus be avoided.

Location for test deployment

In order to find the most suitable place for kelp cultivation in the German Bight different locations were selected which are considered to be representative of those where offshore aquaculture may develop and where depths, seabed material data, sedimentation load, current velocities and wave climate, light intensities, nutrient concentrations and distance to the main land varied. Two offshore and three inshore locations were tested during this study (Figure 1). The main testing area (offshore algal farm) was located 3.5 nm northeast of Helgoland (54°13.00′N, 7°57.00′E). Longline, ladder design, grid system and a ring construction were installed there. Additionally, another offshore location at the lighthouse known as "Roter Sand" was chosen (53°49.9′N, 8°8.7′E). The performance of the ring construction was tested at three nearshore test sites, Helgoland Roads (54°11.4′N, 7°53.8′E), Helgoland Harbour (54°10.4′N, 7°53.9′E) and in the tidal flats of the island of Sylt backwaters (54°59.5′N, 8°23.4′E). Table 1 gives an overview of site-specific conditions of all test locations.

Sampling and harvesting techniques

In the Helgoland experiments (1994–1995), sporophytes were collected at sea individually from the culture line for measurements of frond length in the laboratory. Few data are thus available for assessment of biomass m^{-1} of culture line over time. In the experiments performed at Roter Sand (2002) 1.5 m of culture rope was removed each month for frond length measurements. In all samples sporophytes ($n = 30$ in 1994/1995; $n = 40$ in 2002) of the largest size class were measured. Blade length was measured from stipe/blade transition zone to blade tip. Initial attempts to use the established technique of punching holes in the laminarian blade for calculation of growth rates (Parke, 1948; Kain, 1979; Lüning, 1979) had to be abandoned because of rough sea conditions.

To harvest seaweeds from longline, ladder or grid constructions, small boats were employed. To harvest the ring construction the rings were towed to shore and lifted by cranes. Harvest at sea was performed by divers or by boat-based cranes.

Calculation of length changes

The length change (LC) per day was calculated on the basis of mean blade lengths of *Laminaria saccharina* at each sampling date (t_1, t_2) modified according to the formula usually used for calculation of relative growth rates (Kain, 1987):

$$\mathrm{LC}(\%/\mathrm{day}) = \frac{\ln L_{t2} - \ln L_{t1}}{t_2 - t_1} \times 100 \qquad (1)$$

Statistical analysis

For all data, standard deviations (SD) or confidence limits (CL; $f = n - 1$, t-factor $= 95\%$) were calculated and applied in graphs as appropriate and shown as bars in the figures. Significance levels were determined using the Student's t-test ($p < 0.05$).

Results

Site-specific conditions at test sites

The temperature was above 19 °C on 3 days (4, 8, 11 August) at Helgoland in 1994, between 18 and 24 August in 1995, and at Sylt during 9 days in summer 2002. Nutrient (ammonium, nitrate, phosphate) concentrations varied between location and season (Table 2). Nevertheless, in all the experiments there was sufficient N and P in the surrounding water to sustain algal growth.

Technical results for different constructions

Longline. Only 65 of the 140 culture lines which had been fastened on the longline system were retrieved and 20 of these were evaluated. Due to very stormy weather between October 1993 and May 1994 the farm was visited only infrequently. However, every chance during calm weather was used to exchange horizontal carrier rope and supply it with new culture lines. The study revealed, however, that the weights on the culture lines were insufficiently heavy, so that they were frequently tossed across the carrier line resulting in the removal of the young *Laminaria* by friction and causing them to become entangled. Other culture lines, consisting of three twisted strands, were untwisted by the current and turbulences and consequently the individual strands were torn. Some improved performance of the longline was obtained by connecting pairs of only 3 m long culture lines at the lower end like a V-shape. Length data were taken from these lines.

Ladder. The ladder construction revealed problems in the durability of the frame material, the attached weights being potential breaking points. Moreover, the 110-L buoys at the corners were very instable and had to be exchanged several times. These drawbacks were taken into account for the development of the grid system.

Grid. The grid system proved much more stable compared to the "ladder" even though the mooring ropes could not be adjusted to their optimal length to accommodate the full tidal differences. The use of elongated fenders instead of ball floats protected the

Table 2. Nutrient concentrations and temperature at nearshore and offshore test locations.

		Nutrients (μmol/L)			
Location	Months	Ammonium	Nitrate	Phosphate	Temperature (°C)
Offshore					
Helgoland	Dec.–Feb.	3.0–6.8	12.5–110.3	0.8–1.1	2.2–9.0
Farm	Mar.–May	1.0–6.2	13.8–73.8	0.1–1.5	4.8–11.5
	Jun.–Oct.	1.7–10.4	0.4–24.8	0.1–1.1	11.1–20.2
	Sep.–Nov.	2.9–5.7	1.3–8.1	0.5–1.2	9.4–17.8
Roter Sand	Dec.–Feb.	0.3–4.4	1.1–13.4	0.1–0.4	1.8–5.0
	Mar.–May	1.8–5.9	6.1–55.4	0.2–0.9	6.1–11.3
	Jun.–Oct.	0.9–6.5	0.2–49.3	1.3–1.7	14.1–18.8
	Sep.–Nov.	0.3–6.6	0.9–10.2	0.1–0.5	18.2–2.1
Nearshore					
Helgoland	Dec.–Feb.	1.2–9.3	10.6–80.7	0.6–2.7	2.2–9.0
Roads	Mar.–May	0.7–7.0	29.0–136.0	0.0–1.2	4.8–11.5
	Jun.–Oct.	0.7–7.1	0.1–58.8	0.0–1.4	11.1–20.2
	Sep.–Nov.	3.5–8.8	0.6–32.5	0.7–1.9	9.4–17.8
Helgoland Harbour		No data	No data	No data	No data
Tidal flats of sylt	Dec.–Feb.	3.0–12.9	22.8–64.8	0.8–1.4	1.4–2.5
	Mar.–May	0.2–4.6	5.2–68.2	0.1–1.0	2.6–14.2
	Jun.–Oct.	0.4–4.5	0.1–4.0	0.1–1.0	14.8–19.9
	Sep.–Nov.	0.2–12.5	0.1–25.3	0.6–1.1	6.2–14.3

Data were provided by the long running time series of the BSH (2002), BAH (unpublished with reference of J. Van Beusekom), BAH (2003), and NLÖ (2003).

construction by better riding the swell which resulted in continuous vertical movement, while the balls used previously had resulted in jerking behaviour that created substantially more stress on all the materials. Culture lines were knotted into the grid from a small rowing boat, a procedure that needed smooth sea and calm weather and could only be managed during the period of slack tide (maximum 30 min). Culture lines (880 m) were transferred to the grid, but only some samples were retrieved. Unfortunately, the test unit was destroyed by the crew of a yacht who ignored the official signs, got entangled in the ropes and cut themselves out destroying also the frame construction. The weakened grid system no longer supported the culture lines, which led to their loss.

Rings. Individual rings of 5 m diameter showed a superior performance in comparison to the other tested carrier constructions. They remained stable and in place during all weather conditions, provided their moorings were tended regularly, at least after storms which imposed some wear on them. In addition, they allowed equipment with culture lines to be performed onshore, the rings subsequently being towed to their mooring locations and fastened relatively quickly during slack tide.

With the ring construction the harvesting period could be prolonged by moving complete rings onshore. Moreover, sampling of the seaweed culture was more easily done due to the possibility of heaving up the ring construction with a ship's crane.

Kinetics of length changes and biomass yield of Laminaria saccharina

The data on length changes (LC) of *Laminaria* fronds are presented in Figure 4, with the first column of diagrams showing results from all carrier constructions in the area of the algal farm near Helgoland in 1994–1995 (Figures 4a–4d), and the second column with data on ring carriers at different locations and years (1995, 2002), but during the same season (Figures 4e–4h).

Basically, LC were high immediately after transplantation, when *L. saccharina* sporelings were still small, and decreased with progression of the grow-out phase. The early differences in LC are concealed in the diagram of the 1994 ring "farm" (Figure 4d), because only one measurement 90 days after transplantation was possible and LC had to be equalised over the whole period. On the longline (Figure 4a) *L. saccharina* hardly grew in the month of July (days 63–93), while during the same month frond length increased by 9.4% d^{-1} (days 5–35) in the ladder system (Figure 4b), and on the farm ring (Figure 4d) increases were noticed as well. It should be noted that the culture lines for all three systems had been inoculated with the same mixture of zoospores on the same day (04.03.94), but transplanted into the sea at different dates. A minimum in length increment occurred in August with a slight increase again in September on the longline as well as on the ladder system (Figures 4a–4b). In the grid system (Figure 4c), supplied with algae on 8 May 1995 (inoculated on 6 February 1995), the algae did not perform as well as on the other three carrier systems (Figures4a–4b, 4d) in terms of adherence to the culture lines, susceptibility to fouling and growth.

In the ring experiments performed in 1995 or 2002 and all started in December or January (Figures 4e–4h), the values for length increase from December to February ranged between 5 and 15%. The maximum value of 14.5% d^{-1} occurred on the Harbour ring at Helgoland (Figure 4h) from December to January, while at the same time at Helgoland Roads (Figure 4g) less than half of this value was recorded, and in early April the obvious superiority of the harbour location at this stage became striking (Figure 5). Lower values of 5–7% d^{-1} were found for February seven years later at Sylt and Roter Sand (Figures 4e–4f). In all, but the harbour experiment, positive length changes were recorded until the end of the experiments between June and August (Figures 4e–4g). The Harbour experiment showed negative length changes from May to June parallel to heavy fouling by various epiphytes and epizoans, mainly *Ciona intestinalis*. In the end, many algae were basically reduced to the meristematic area in the Harbour ring.

Outside the harbour conditions clean blades with an average blade length of 1.5–2.0 m were obtained between June and August at different locations and in different years, while the blades in the harbour deteriorated (Figure 6a). The algae on the ring moored at Sylt exhibited lower increases in blade length throughout spring but reached a similar size to algae on the ring at Roter Sand and Helgoland Roads in summer (Figure 6a).

After three months of grow-out time at Roter Sand, significant differences ($p < 0.05$) were detected between blade length on the outermost culture line and the inner parts of the culture unit (Figure 6b). The same was true after two months at Sylt (data not shown).

The ring from Helgoland Roads was towed into the harbour in June 1995, lifted by a land-based crane (Figure 7), and the culture line with adhering algae

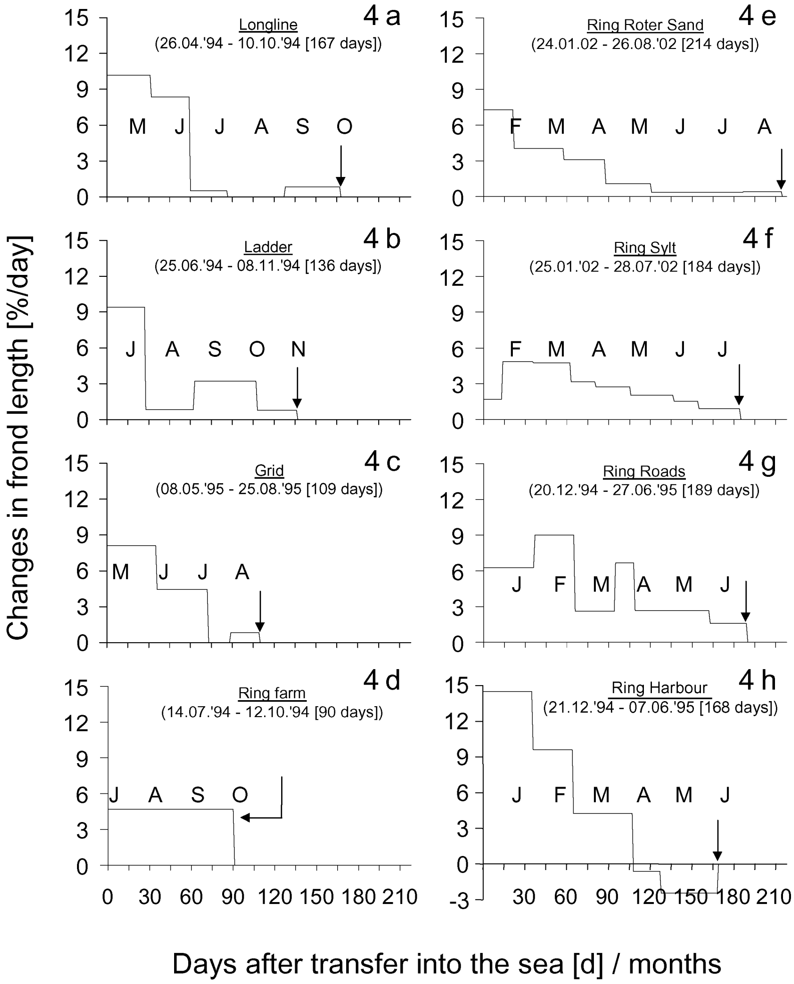

Figure 4. Kinetics of length changes (LC) in *Laminaria*. The left column shows results from the four system designs tested at the Helgoland farm, the right column demonstrates the results from the ring systems at four locations (a–d, g–h: $n = 30$; e–f: $n = 40$). Sampling days are indicated by the perpendicular lines. Arrows indicate the end of the experiments. Capital letters along the abscissa indicate months.

was retrieved. About 75% of the 84 m long culture line were fully covered by *Laminaria saccharina*, with a total fresh weight of 304 kg after six months of grow-out phase in the sea. Average biomass m^{-1} of algae covered culture line on the various culture constructions was 4 kg (mean value $\pm$ 1.1 SD, $n = 18$).

Discussion

An encouraging finding of the investigation was that *Laminaria saccharina* did grow on artificial substrates in all the carrier systems used, even under very rough circumstances (Koehl, 1998). Major key conditions for offshore culture were fulfilled such as the pre-cultivation of healthy plants that were well attached to the culture lines. Another key factor, the reduction of mechanical abrasion, was a major problem on the longline system, because of high turbulence. Longline systems are hence considered unsuitable for macroalgal culture under open North Sea conditions. The ladder system was more apt to damage than the improved grid system, e.g., at the fastening points of weights, and should therefore also be rejected in future considerations. A further problem of all carrier constructions except the rings was the necessity to fix them at permanent offshore sites. This led to the logistic and cost problems of efficient transfer of sporelings from the laboratory (or hatchery facility) to the grow-out location as well as appropriate tending of the carrier system under the prevailing rough weather conditions. Labour requirements were also enormous. Every single culture line had to be fastened to the carrier system from

Fig. 5

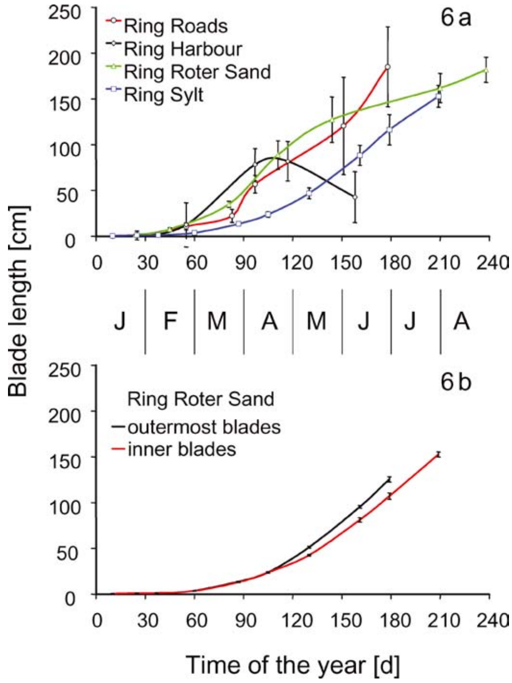

Fig. 6

Fig. 7

a small rowing boat, and this was only suitably done during slack tide. Work was seriously impaired by the difficulty of getting ship time and divers, while also waiting for calm seas and all of this at the 30 min of slack tide and during working hours.

The ring construction using its present dimensions has proven stable in offshore conditions (Helgoland farm, Helgoland Roads, Roter Sand). The new ring construction, with a central steel cable and central buoy, reduced tractive power and tension in high velocity currents and when being moved for sampling or harvest. The two crow's feet with the metal cuffs greatly prevented torsion of the ring when lifted. The depth of a ring could be adjusted by insertion of steel ropes into its cavity and the buoyancy of the central buoy could also be adjusted by changing its size. This way the ring could be kept at an appropriate depth to avoid exposure to stressful surface turbulence and admit sufficient light for algal photosynthesis even with increasing weight of algae.

A major advantage of the ring system compared to the other systems was that the ring could be equipped onshore with 80–100 m of culture line and subsequently towed to the mooring site, where it could easily be moored by the ship's crew. The reverse took place at harvest time and was also most advantageous. The ring diameter of 5 m could be managed by cranes from relatively small vessels (12 m in the case of RV "Aade"). This way the algae on the ring construction could be examined at most dates and at harvest while in the worst case it was at least possible to tow the ring into the harbour, where a larger crane could lift it onshore. The described characteristics and the modular nature of the ring construction promise to make it a sensible and effective choice to be used in aquaculture situations where offshore wind farms are located (Buck, 2002; Buck et al., 2003, 2004; Krause et al., 2003). Moreover, one could transfer the technique to less developed countries using suitable materials, e.g. bamboo or rattan, and the craftsmanship of local people. However, lifetime and stability of the ring systems using materials of these countries will have to be tested before large-scale employment.

In our mass cultivation the difficulties to relocate marked algae at the next date of examination prevented the use of the common method of punched holes for assessing growth rate in laminarian blades (Parke, 1948; Kain, 1979). We could only measure blade lengths, thereby integrating tissue production and distal blade loss over the preceding period between sampling dates. Laminarian blades behave like moving belts of tissue, eroding at the tips while growing at the bases, so that a total year's growth may amount to 1–5 times the initial length (Mann, 1972). As an example, the frond area lost in *L. saccharina* during the first year of life in the sea near Helgoland at 2 m water depth below chart level may amount to 70% during the period from May to October (Lüning, 1979). As another example, during the winter period *L. longicruris* lost almost 70% of the blade tissue grown in the previous summer (Chapman and Craigie, 1978). For practical and commercial purposes, however, exact data on growth rate and distal blade loss are not as important as the actual blade length and harvestable biomass at a given time, which are reported in the present investigation. Moreover, it seems possible and should be further investigated that distal blade loss in first year laminarians cultivated upside down in the pelagial on longlines or rings is probably not as prominent as in algae growing in the rocky intertidal, where they are mechanically battered on the rocky substrate by tides and wave action.

The length increments of young sporophytes of *L. saccharina* were initially high after transfer from the laboratory to the sea in the beginning of the year. This coincides with the well known rapid phase of seasonal growth during the first half of the year in *Laminaria* spp. as described by Parke (1948), Kain (1963, 1979) and Mann (1973) with optimum environmental temperature, nutritional and light requirements and a suitable phase of endogenous seasonal rhythmicity for active growth (Lüning, 1993). During the second half of the year, i.e., the period of slow growth (Parke, 1948; Kain, 1979), sporophytes of *L. saccharina* or *L. digitata* still exhibit noticeable growth activity although with a progressive decrease from month to month (Lüning, 1979; Creed et al., 1998), and this was again evident in

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Figure 5. Photograph of *Laminaria saccharina* sporophytes taken from the ring constructions and Helgoland Harbour (left) and Helgoland Roads (right) on 7 April 1995 after 3.5 months in the sea.

Figure 6. Average blade length of *Laminaria saccharina* on ring constructions at different locations (a), or at Roter Sand in the outer or inner parts of the ring (b). The numbers on the time axis indicate the day of the year. (a: mean values ± SD, $n = 40$; b: mean values ± CL, $p < 0.05$, $n = 40$).

Figure 7. Preparation of *Laminaria* harvest from the ring formerly located at Helgoland Roads in the harbour of Helgoland. The ring was lifted from the water by a land-based crane.

the length increments recorded on the various carrier systems in the present investigation.

The temperatures above 19 °C in August may have contributed to the reduction in length increase in the case of the algae dispatched on the longline and ladder in 1994, but cannot explain the poor performance of those plants attached to the grid, because in 1995 the high temperatures were found too late to be included in the experiment. In the case of the ring at Helgoland Roads the small length increment between day 55 and 83 of the grow-out phase was probably due to the unusually stormy weather in March 1995 with 13 days of winds of ≥8 Beaufort (mean of 30 years: 2 days). January was also very stormy and overall conditions did not allow for the same high length increase as was observed for algae from the same spore suspension and seeding badge on an identical ring in the harbour.

At Helgoland, storms resuspend a lot of sediment in the water column and can almost reduce light intensity in the water to zero. The calm waters of the harbour are less turbulent and allow faster re-sedimentation and consequently better light conditions in surface areas. Therefore, the algae at Helgoland Roads were probably light-limited at certain periods while those in the harbour were not. Light-limitation was also evident at Sylt, where the concentration of suspended material is always high due to the tidal currents in the backwaters. The shading effects did not prevent growth, but slowed it down. Additionally, the ring at Sylt had been exposed to air and had weighed down on some of the algae, battered by the receding and incoming tide causing blades to shorten. Due to the particularly nutrient-rich waters and the limited water exchange in the Sylt backwaters as well as in the Helgoland harbour, fouling occurred by organisms such as blue mussels, ascidians as epizoans and epiphytes, like *Fucus* and *Enteromorpha*, which settled on both rings and cultured algae. At Helgoland Harbour the heavy load of epizoans contributed to the loss of algal material and accounted for the marked negative length change. At Roter Sand and Helgoland Roads the strong currents largely prevented settling of fouling organisms. The high current velocities did not result in substantial loss of algae.

The results on changes in blade lengths showed that all algae eventually attained the same length. Standard deviation was higher in algae harvested from the 1995 rings, because smaller samples were collected, since small groups of *Laminarians* were plucked from the ring sometimes under harsh weather conditions. The rationale was to save a quantity as high as possible for the final harvest. The 2002 rings were sampled by regularly cutting out about 1.5 m of culture line and the choice of the largest size class to be measured was therefore greater. The algae on the ring at Helgoland Roads grew in the best conditions, they reached the greatest length a month earlier than the others. The slower length increase of Roter Sand sporophytes might be explained by stress through variations in salinity and also sometimes turbid water. The longer blades on the outer rope of the culture unit can be explained by the superior availability of space and light in contrast to shadowing by neighbouring plants among inner parts of the culture unit. Similar observations in 1995 served as an argument against singling out punched sporophytes at the periphery for conventional growth measurements.

The yield of 300 kg FW *L. saccharina* on the harvested ring may certainly be increased. The percentage of *Laminaria*-covered culture line could be raised by continuous movement of the spore collectors to allow efficient light harvest from the whole culture mat. On the covered part of the culture line sporophytes grew quite densely, thereby showing effects of intraspecific competition. This phenomenon, reported for *L. digitata* by Creed et al. (1998), resulted in different size classes of *L. saccharina* on the lines, an unwelcome feature biologically and for economic reasons. The largest size class competed successfully for light and constituted most of the biomass at harvest. Optimum density of sporophytes on the culture lines is still unknown and requires further well-designed investigations. It should leave sufficient space for the individual laminarian specimens to grow but also deny space for smothering by diatoms or macrophytes that compete for substrate. Besides the density problem at the start of the culture, harvesting can easily be scheduled too late. As was shown in later experiments with *L. digitata* (Buchholz, unpublished), further culturing could have resulted in "overgrowth" of phylloids by bryozoans. A timely harvest is an important objective to be incorporated into any logistic work plan.

Concerning the most favourable location for aquaculture of macroalgae, our experiments suggest that fairly exposed sites with rough conditions are suitable, however, only if the carrying support structure is sufficiently rigid to withstand the rough to extreme conditions encountered in most of the trials. Aquaculture in sheltered waters must avoid shallow areas, like in the Sylt backwaters, because of possible contact with the seabed and the high siltation and suspended solid load which creates low light conditions. Any location selected for seaweed culture should have a minimum depth of 5–8 m. Offshore areas like Roter

Sand and Helgoland Roads seem to be well-suited. Concentrations of dissolved O_2 and CO_2 and a good transparency of the water column stimulate algal growth. High current velocities provide sufficient nutrient supply, prevent fouling but do not impair plant performance. Sites like Helgoland Harbour could serve at times to pre-cultivate algae or store ring modules for some time before transferring them to offshore areas for grow-out.

As to the possible costs of seaweeds produced by open ocean culture on rings, one may expect a value of 40 € per ring, as based on a yield of 40 kg dry weight (corresponding to approx. 400 kg fresh weight) on 100 m culture line per harvested ring. If the costs for the fully mounted ring are 1000 € and the ring lasts for ten years, 100 € investment costs would be required per ring per year without any labour and ship costs. However, the situation would be changed if the present price of approx. 1 € kg^{-1} dry seaweed (e.g. Sandau et al., 1996) became substantially higher. Higher prices for seaweeds may be expected for several reasons. Fresh seaweed biomass may be sold as food to restaurants or as raw material to cosmetic companies at much higher prices than 1 € kg^{-1} dry seaweed. Examples are the successful production of the red alga *Chondrus crispus* in Nova Scotia (Canada) as exported food to Japan (Nakamoto, 2002) or the production of the red alga *Palmaria palmata* or the brown alga *Himanthalia elongata* in northern Spain (CMC, 2004) again as food. In addition, supply of seaweeds from natural stock in Europe may become legally restricted for environmental protection reasons, and open ocean aquaculture may help fill the gap.

Outlook

The combination of several ring modules requires some investigation into coupling techniques and the consideration of sea wave lengths exerting stress on the construction. The destruction of culturing devices by commercial shipping or pleasure yachts is unfortunately a rather frequent phenomenon offshore and has yet found little consideration in the planning of such constructions. The problem can probably be overcome by utilising offshore areas in a multi-functional manner. A combination of aquaculture with offshore wind farms (Buck et al., 2003, 2004), where strong legal shipping regulations are enforced, seems to be sensible. The pylons of the wind generators are fixed structures in the seabed and could serve to fasten culture modules like the rings in an offshore area.

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