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Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea

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Abstract

The aim of the presented investigation was to test the sensibility of macroalgal aquaculture in offshore wind farms in the North Sea and to find arguments for the choice of appropriate sites among the planned wind farms. Based on experience with an offshore aquaculture farm of *Laminaria saccharina* conducted in 2002, we assessed the maximum hydrodynamic forces affecting farmed algae by applying the model software "WaveLoad". Drag measured in a towing tank was considerably higher on algae with a more ruffled margin and wider blade collected from sheltered environments than on flat and narrow farmed *Laminaria* despite comparable blade areas. Drag varied according to frond size, current velocity and acceleration reaction. Dislodgement of laminarian holdfasts and the forces necessary to break the stipe depended on blade length and surface area. Neither did our measured nor our calculated values of drag exceed those forces, provided the algae had been grown in a current >1 m s^{-1}. Even in storm conditions with maximum current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m can cultivated *L. saccharina* withstand the high energy environment.

Keywords: *Laminaria saccharina*; Kelp; Offshore aquaculture; Mariculture; Drag; Drag coefficient; Attachment strength; Dislodgement; Breaking force; Resistance

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1. Introduction

Along the German North Sea coast the occurrence of kelp of the genus *Laminaria* is restricted to the surroundings of the rocky island of Helgoland, the only hard substratum area in the wider German Bight. Due to the nature reserve status of Helgoland, harvesting of wild growing *Laminaria saccharina* is prohibited while aquaculture of this endemic species would be acceptable. Mariculture in offshore areas might help to meet the future demand for single species and clean macroalgae grown under well-controlled conditions for pharma-

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ceutical or cosmetic use (Buck and Buchholz, 2004).

Various efforts to find suitable locations for the establishment of aquaculture facilities for macroalgae in the German Bight were unsatisfactory, due to the lack of appropriate natural substrate and adverse hydrographic and weather conditions (Lüning and Buchholz, 1996; Buck, 2002). They cause a generally very rough wind wave climate in combination with strong tidal currents in the North Sea (e.g., Ducrotoy et al., 2000). Moreover, the bottom topography of the German Bight, which becomes rather shallow in the southern part, contributes to the wave impact. Current velocities at the surface can reach 2–2.5 m s^{-1} or even 3.4 m s^{-1} in some nearshore areas (Mittelstaedt et al., 1983; Dick et al., 1992). Wave heights of 5–6 m are common during storms (BSH, 2003).

Generally, the National Park “Wadden Sea” (NPG, 2001) in the south of the German Bight with its sheltered tidal mud flats as well as the seaward sandy beaches of the belt of Frisian islands does not offer suitable locations for mariculture endeavours. An exception is the highly regulated bottom culture of blue mussels (*Mytilus edulis*) and oysters (*Crassostrea gigas*). Cultivation of other marine organisms is not permitted (Boysen, 1991) and would most likely raise stakeholder conflicts in nearshore areas (Buck, 2002; Buck et al., 2004).

An alternative for the development of marine aquaculture is the utilisation of existing or projected offshore constructions (Krause et al., 2003; Buck et al., 2004). The attachment of culture units to rigid platforms could prevent damage or even loss of whole culture modules. Presently, the obvious aims of such aquaculture considerations are the planned offshore wind farms in Europe. These wind farms will probably cover larger areas of the North Sea and hold potential for multifunctional uses.

Moving to the offshore area of a wind farm to cultivate macroalgae would be a way to overcome the conflicts of space allotment and utilisation. Laminarians characteristically grow in tidal habitats with continuous but varying water motion. In offshore areas these plants must cope with violent currents and high waves causing acceleration reactions. In contrast to other seaweeds with a relatively rigid and upright stipe (e.g., *Eisenia arborea*, *Pterygophora californica* or *Laminaria hyperborea*) *L. saccharina* has a flexible stipe, which is capable of quickly reorienting and thus becoming aligned with the direction of the current. However, the response of cultured algae to this high energy environment of the North Sea is still unknown. If cultured kelp can be expected to stay in place while growing in the rough offshore environment, this would facilitate a commercially successful mariculture, provided culture techniques concerning seeding strategies and the design of culture constructions will be improved (Buck and Buchholz, 2004). The multifunctional use of offshore habitats could moreover combine the needs of stakeholders, such as wind farmers and fishermen, who would probably run the maricultures.

While Kawamata (2001) has been the only one so far to use culture derived *Laminaria* seedlings (*L. japonica*) for his biomechanical investigations, Gerard (1987) conducted her experiments on *L. saccharina* collected from the sea. The present study describes the resistance of maricultured and wild grown *L. saccharina* to the impacts of tidal currents and wave action. Morphological parameters of laminarian blades were taken into account, drag coefficients were determined, dislodgement and breaking forces, and hydrodynamic field conditions were measured and evaluated.

2. Material and methods

2.1. Origin of experimental plants

The experiments were conducted with wild and cultured *L. saccharina* from the German North Sea (Fig. 1). Wild specimens were collected by divers from habitats around the island of Helgoland (Hgl; 54°11′N, 7°54′E) (right inset in Fig. 1) from a water depth of 1–4 m. Cultured *L. saccharina* were taken from a new ring construction designed for cultivation of algae (Buck and Buchholz, 2004). The ring was located at an experimental offshore aquaculture farm adjacent to the lighthouse “Roter Sand” (53°49.9′N, 8°8.7′E), at a distance of 17 nautical miles from the city of Bremerhaven. At this location water depth and the sandy bottom do not normally allow settlement and growth of benthic algae, and the hydrodynamic conditions are rougher than in

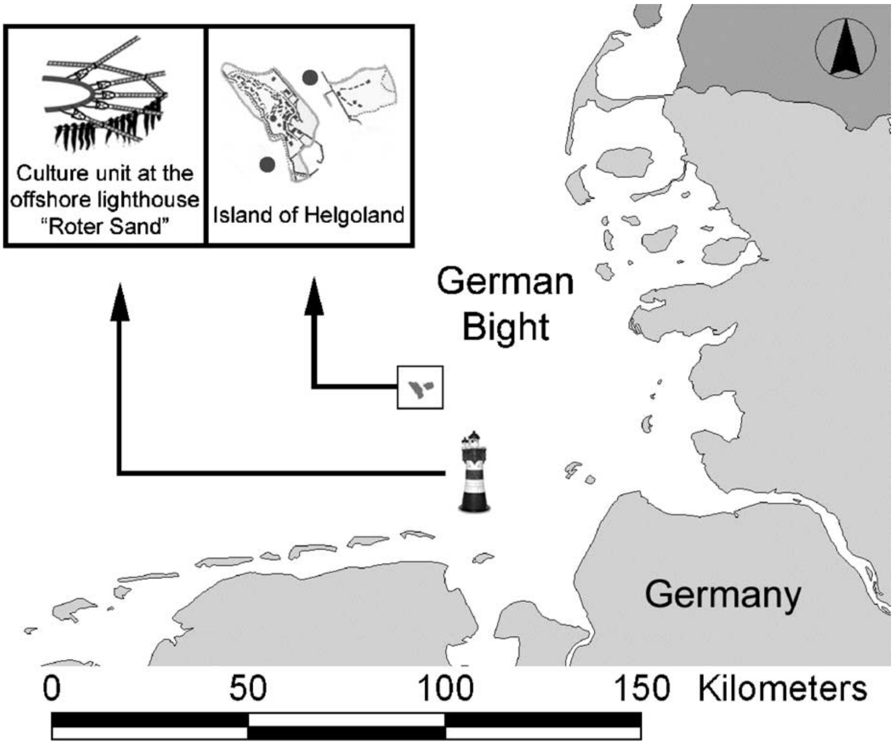

Fig. 1. Map of the German North Sea region. Right inset: Enlarged island of Helgoland, where specimens of *L. saccharina* were collected (black spots). Left inset: Culture unit for *L. saccharina* located at the aquaculture farm near the offshore lighthouse "Roter Sand".

natural *L. saccharina* beds. The cultured algae were grown on 6 mm ropes attached to a culture unit at a depth of 1 m below the water surface (left inset in Fig. 1).

2.2. Determining site-specific, environmental conditions

In order to describe the local hydrodynamic conditions at the experimental farm, current velocities and directions were measured by the Water and Shipping Agency (WSA) Bremerhaven with an acoustic Doppler current meter (RCM 9, Aanderaa). The sensor was placed in the vicinity of the offshore aquaculture farm for 1 month. Data on significant wave height, direction of waves with the absolute energy maximum, wave length, periods of wind waves and swell were obtained by a wave following buoy (Waverider, Datawell). The buoy was deployed by the Federal Maritime and Hydrographic Agency (BSH) 4 nautical miles NE of the aquaculture farm "Roter Sand" in early 2002 and recorded data for 300 days.

2.3. Morphometric analysis of L. saccharina fronds

Morphological data of *L. saccharina* thalli were acquired to assess growth patterns (length, width, surface area, volume) and test their possible correlations with drag, dislodgement and breaking forces, and effects on acceleration reactions.

For measurements, sporophytes were individually collected at sea from culture lines or from the natural habitat. Blade length was measured from the transition zone between stipe and blade to the blade tip. Blade width was recorded well beyond the meristematic zone or for larger algae at 15 cm distance from the transition zone. To test the correlation between blade length and blade width 1300 algal fronds of different sizes from two seaweed culture constructions in the

German Bight (Buck and Buchholz, 2004) were measured. From these results standard algae were calculated for a length of 50 cm (Standard 50=S50) and 100 cm (Standard 100=S100) in order to additionally scrutinize the drag coefficient (C_D) relevant to all sizes of laminarians.

Blade area was assessed by two different methods in order to find an appropriate technique for further investigation. The tapering of the distal and proximal blade ends was neglected by simply multiplying length and width of the lamina. In addition, algae of different sizes were cut in pieces, pressed between two glass plates and photocopied ($n=50$). A plate marked with a grid (one square=1 cm^2) was superimposed and the “real” blade area (single-sided) measured to the nearest cm^2 (Koehl and Alberte, 1988; Koehl, 2000).

For calculation of the blade volume the fronds were sectioned at 15 cm distance from the transition zone and the thickness of the blade’s margin (T_{Mar}) and centre (T_{Cen}) measured using a micrometer screw (Fig. 2A). The shape of the blade’s cross-section was copied on graph paper (one square=1 mm^2) and the area measured to the nearest mm^2. Volume of fronds was calculated from cross-section area and length. To simplify this rather awkward procedure we tried a second method by multiplying length, width, and thickness. For this purpose we assumed that the lamina’s cross-section has an extended double-trapezoid shape, the width of which can be divided into three equal parts (W_1–W_3). Two thirds, the left (W_1) and the right (W_3) margin of the lamina, had an identical isosceles trapezoid profile. The inner section of the lamina (W_2) had a rectangular shape (Fig. 2A). Section volumes of the lamina (V_{Lam}) were calculated using the equation:

$$V_{\mathrm{Lam}} = \underbrace{[(W_1 \cdot T_{\mathrm{Res}}) + (W_1 \cdot T_{\mathrm{Mar}})]}_{\text{left trapezoid}} + \underbrace{(W_2 \cdot T_{\mathrm{Cen}})}_{\text{inner section}} + \underbrace{[(W_3 \cdot T_{\mathrm{Res}}) + (W_3 \cdot T_{\mathrm{Mar}})]}_{\text{right trapezoid}} \quad (1)$$

In this equation W is the lamina’s width with the thirds W_1–W_3, T_{Mar} is the thickness of the blade’s margin, T_{Cen} the thickness in the blade’s centre and T_{Res} the result of $T_{\mathrm{Cen}} - T_{\mathrm{Mar}}/2$. If the right and the left margins of *L. saccharina* blades have an identical thickness, a simplified version of the Eq. (1) can be used:

$$V_{\mathrm{Lam}} = \underbrace{\left(T_{\mathrm{Cen}} \cdot \frac{W}{3}\right)}_{\text{inner section}} + 2 \cdot \underbrace{\left[\left(\frac{T_{\mathrm{Cen}} + T_{\mathrm{Mar}}}{2}\right) \cdot \frac{W}{3}\right]}_{\text{left and right trapezoid}} \quad (2)$$

2.4. Device for measurements of dislodgement forces and drag

For measurement of dislodgement (F_{Dis}), breaking (F_{Brk}) and drag forces (F_{Drg}) a digital force gauge, “Centor Dual” (Andilog Technologies, France), was employed. The gauge had two sensors, an external sensor with a force range of 0 to 50 N (Sensor I), and an internal sensor with a force range of 0 to 250 N (Sensor II). It was possible to read both sensors

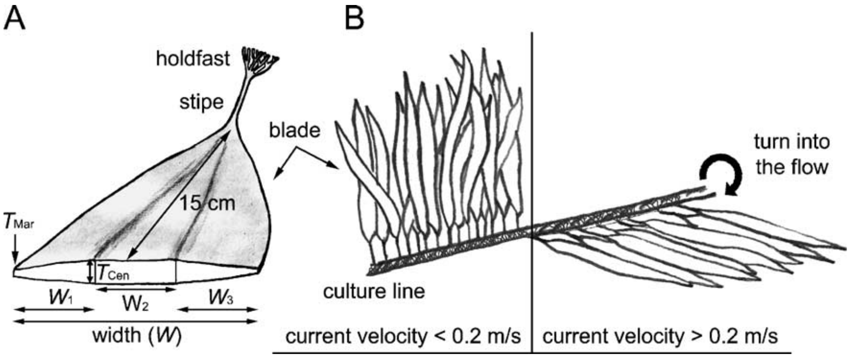

Fig. 2. (A) Drawing of a cultured *L. saccharina* blade in cross-section. The blade thickness was measured in the centre (T_{Cen}) and at the margins (T_{Mar}) at 15 cm distance from the transition zone. W=blade’s width. (B) Drawing of *L. saccharina* growing on the culture line. In steady flow the sporophytes are oriented downstream rotating the culture line into the same direction.

simultaneously. On the graphic screen display of the gauge a simultaneous readout of the actual and the maximum values and the complete force curve (force $=F_{(t)}$) provided a comprehensive overview as the test was progressing. An interface (RS232, Andilog Technologies, France) connected to the gauge allowed the data transfer to a PC via a serial output port. The software "R-SIC" (Andilog Technologies, France) facilitated the transfer to Microsoft Excel spreadsheets.

2.5. Measurement of dislodgement forces of L. saccharina from culture lines

L. saccharina grown on 6 mm culture lines in the North Sea (Buck and Buchholz, 2004) were divided into a group of densely growing algae ($n=94$) with holdfasts growing on top of each other and one of individual algae with single holdfasts attached to the culture line ($n=37$). The third group of seaweeds, which grew on ropes but were adapted to sheltered low current conditions (≤ 0.2 m s^{-1}), were taken from a holding tank kept in the laboratory facilities of the AWI ($n=60$).

A string, thick enough to avoid damage of the tissue, was knotted to the holdfast in a manner that every extension of the holdfast was wrapped (excluding some very small haptera). In this way the dislodgement force affected the complete holdfast, and no part of the stipe was involved. The string was then connected to the digital gauge, which was fixed to a rigid bar. In contrast to Carrington (1990) and Kawamata (2001), who pulled the string parallel to the substratum, it was necessary to remove the holdfast in the direction of the stipe, because under culture conditions the laminarians including their holdfasts and the culture rope, which is a supple substratum, turn into the direction of the flow (Fig. 2B). Therefore, the holdfast was torn-off by rapidly pulling down the string into the direction of the stipe, which was in a right angle to the culture rope. Only one single attempt to tear off the holdfast was allowed in order to avoid eventual weakening of the attachment strength by repeated pulling (c.f. "post-storm sampling" Milligan and DeWreede, 2000). It was helpful to watch the display of the digital gauge to ascertain the characteristics of the complete graph. Acquired data were only accepted if the curve of the dislodgement force showed a rapid decrease. Both sensors (I, II) of the digital gauge were used for this purpose.

An additional experiment was conducted testing whether holdfast or stipe were the predetermined dislodgement or breaking points. The stipe, disconnected from the lamina, was wrapped with a string on both sides and torn apart pulling longitudinally at one side. The breaking force was measured by the same digital gauge.

2.6. Measurement of drag on L. saccharina

A towing tank (length 80 m, width 3.8 m, depth 3 m) of the Hamburg Ship Model Basin (HSVA, Hamburg) was used to determine the drag coefficient (C_D) for *L. saccharina* (Fig. 3A). The length of the tank allowed sufficiently long measuring times.

Clean specimens of wild ($n=4$; W1–W4) and cultured ($n=4$; C1–C4) *L. saccharina* were prepared for measurements of drag by removal of the holdfast (Table 1). A thin thread was knotted around the proximal end of the stipe (Fig. 3B). This thread was directed over a guide reel fixed to the bottom of a beam (Fig. 3C). A cavity within the beam allowed the thread to be hooked onto the digital gauge, which was placed on the control panel of the carriage. The beam had a drop-like shape to minimize friction and was fastened to the base frame of the towing tank's carriage. It was lowered 1 m deep into the tank filled with fresh water (Fig. 3D). Blades tied to the thread of the gauge were towed through the tank by the carriage at velocities of 0.5, 1.0, 1.5, 2.0, and 2.5 m s^{-1}. *L. saccharina* of different sizes, originating from the wild and from the farm, as well as "Standard 50" and "Standard 100" algae were used. To assess drag of a group of blades, a bunch of laminarians ($n=13$) was measured as well. Force data were recorded when the carriage had reached the designated velocity. Sensor-I was employed for these entire experiments.

The drag measurements of each *L. saccharina* thallus were used to calculate the dimensionless coefficient of drag (C_D) by applying the equation:

$$C_D = \frac{2F_{\mathrm{Drg}}}{\rho A v^2} \tag{3}$$

In Eq. (3) F_{Drg} denotes the measured drag, ρ the density of water, A is the blade area exposed to the

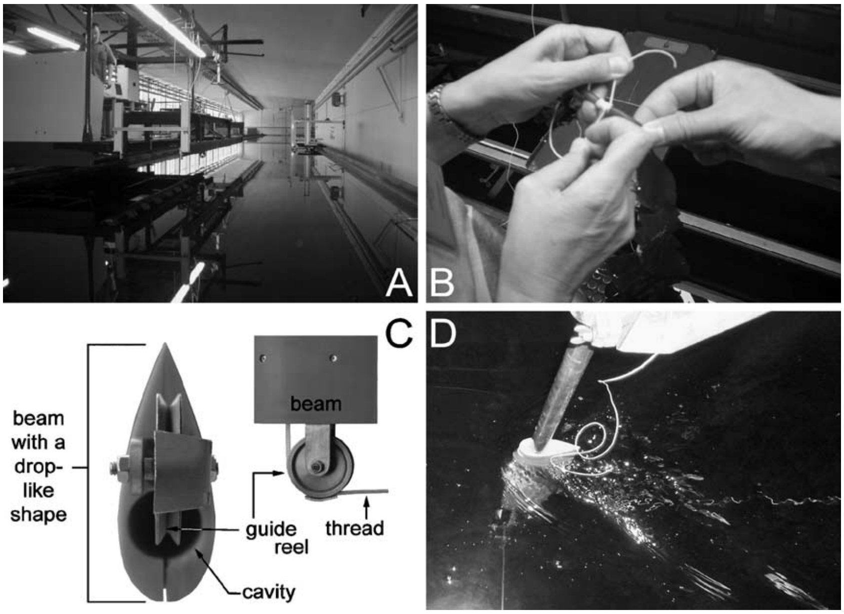

Fig. 3. (A) Towing tank of the HSVA used for drag measurements on *L. saccharina* blades in steady flows. (B) A thin thread, connected to the digital gauge, was knotted around the proximal end of the stipe. (C) Lateral view on the beam and the guide reel used to tow the laminarian blades in the towing tank. (D) Beam with its drop-like profile to minimize friction during towing.

current of velocity *v*. While for relatively rigid or bluff organisms the projected area of the organism across the flow is generally used (e.g., Vogel, 1984; Denny, 1988), we decided on the maximum plan area (single-sided) of the thallus as it is recommended, e.g., by Koehl (1986), Vogel (1984) and Gaylord et al. (1994) for flexible organisms like macroalgae.

Table 1
Cultivated and wild *Laminaria saccharina* used for the drag force experiment

Origin of algae	Seaweed denotation	Phylloid length (cm)
Cultivated algae from offshore farm "Roter Sand"	C1	161
	C2	101.4
	C3	64.8
	C4	49
	S50	50
	S100	100
	Bunch	34.95 ± 8.97
	($n=13$)	(mean ± S.D.)
Wild algae from Helgoland	W1	137.6
	W2	123
	W3	80
	W4	45

2.7. Estimations of drag for natural conditions

For solid objects being accelerated in fluid in addition to drag a force occurs which is commonly described as *acceleration reaction* (e.g., Daniel, 1984; Denny et al., 1985; Denny, 1988). In order to take orbital motions into account the drag F_{Drg} from Eq. (3) has to be written in vector notation, and an acceleration term is added (Morison et al., 1950):

$$\vec{F}_{\mathrm{Drg}} = C_{\mathrm{D}} \cdot A \cdot \frac{1}{2} \cdot \rho \cdot |\vec{v}| \cdot \vec{v} + C_{\mathrm{M}} \cdot \rho \cdot Q \cdot \frac{\mathrm{d}\vec{v}}{\mathrm{d}t} \tag{4}$$

where C_{M} is the dynamic drag coefficient and Q the volume of water displaced by the object. In order to initially avoid uncertainties with C_{D} and the area A for flexible organisms it is useful to write the first term in Eq. (4) in terms of dynamic pressure ($\vec{F}*$), which can be exactly computed from current measurements:

$$\vec{F}* = \frac{\vec{F}_{\mathrm{Drg}}}{C_{\mathrm{D}} \cdot A} \tag{5}$$

i.e.

$$\vec{F}* = \frac{1}{2} \cdot \rho \cdot |\vec{v}| \cdot \vec{v} \tag{6}$$

For a detailed demonstration of the time history of drag forces occurring under the action of tidal currents, wind wave and swell model calculations were carried out using the software "WaveLoads" developed by Mittendorf et al. (2001), which solves Eq. (4) for offshore structures. The forces were computed for a hypothetical test body (cylinder) of 2 m in length and such a diameter that the area exposed to the current corresponded with that of the plan area of the algae as determined before. The drag coefficients measured in the towing tank experiments were used instead of the ones determined for cylinders. The cylinder was exposed perpendicular to the flow direction. The results render information on the distribution of horizontal and vertical forces which act on the alga.

2.8. Statistical analysis of data

The data on blade lengths and widths were split into four obvious groups and the regression calculated separately for each growth phase. To determine if regressions of two groups within a class were significantly different (coefficient of determination/stability index) z-tests with an initial Fisher z-transformation were used (blade surface area, growth periods at length to width ratio) (Steel et al., 1997; Birkicht, 2004). F-tests (one dimensional, $f=n-1$) were conducted to prove homogeneity of variance as a prerequisite for applying the average-t-test (blade length, blade surface area). Difference-t-tests with pre-assigned F-test were used to show differences between two sample groups and data pairs (dislodgement and breaking force; blade surface area) (Birkicht, 2004).

The limit for acceptable correlations was set at $R^2 \geq 0.5$. Diagrams, plotting algal size against forces were fitted with logarithmic trend lines, because growth processes often follow a logarithmic pattern.

Standard deviations (S.D.) were calculated and applied in graphs as appropriate using Excel 2000 software; these are shown in bars.

3. Results

3.1. Hydrodynamic conditions

The wave and current conditions varied tremendously during the period of measurements even at a single location. Thus, *L. saccharina* within our offshore aquaculture farm "Roter Sand" experienced a wide range of sea states (Fig. 4A–D). The algae encountered rapid tidal currents flowing in one direc-

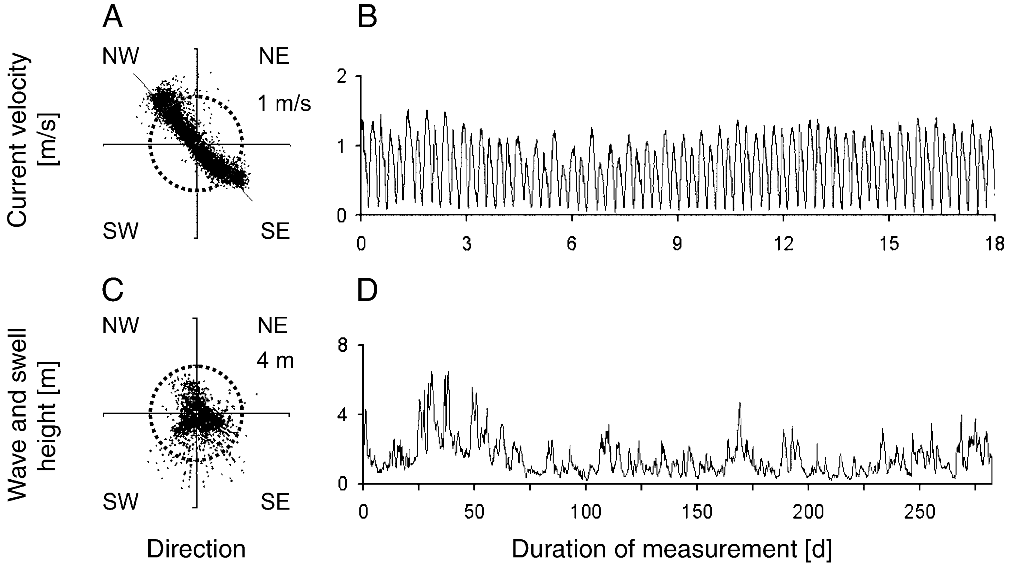

Fig. 4. Wave climate and current velocities near the offshore farm "Roter Sand". (A) shows the directions of currents at all velocities and (B) shows the current velocity over an 18-day period ($n=5188$). (C) demonstrates the direction of waves of all heights and (D) shows the wave heights over a 293-day period ($n=2259$). Dotted circles: (A) 1 m s^{-1}, (B) 4m.

tion for some hours, slowing and stopping at slack tide, and then flowing rapidly in the opposite direction. NW and SE are the main tidal current directions in the semi-diurnal tidal regime at the experimental farm. Maximum current velocity measured at the aquaculture farm in the 2002 measuring campaign was 1.52 m s^{-1}.

The mean significant wave height during the 300 days of measurements was recorded at 1.49 m ± 1.01 (mean ± S.D., $n=2259$). Maximum wave height including swell came to 6.46 m with the waves of the absolute energy maximum being predominantly directed southward towards the coast. Wave lengths of wind waves and swell ranged from 7.8 to 334 m (67.02 ± 43.49, $n=2259$) and wind wave periods varied from 2.6 to 9.8 s (4.95 ± 1.25, $n=2259$).

3.2. Morphometric analysis of *L. saccharina* fronds

While plants harvested from the less exposed natural habitat had relatively wide blades with a ruffled margin (Fig. 5A) algae from the mariculture under offshore conditions had an elongated shape with a narrow and flat phylloid (Fig. 5B,D). Cultivated algae from the offshore farm had holdfasts densely growing on top of each other (Fig. 5C). One typical bunch or aggregation from the culture rope is displayed in Fig. 5D.

In cultivated algae of known age we found a significant positive correlation between blade length and blade width ($R^2=0.98$) during the first year of plant growth. However, the data shown in Fig. 6A reveal that the entire growth phase can be subdivided into four consecutive periods ($p<0.001$). Up to a blade length of 5 cm width development is relatively fast with a slope of 0.24x ($R^2=0.88$). In the next group up to a blade length of 60 cm development of blade width declines to a slope of 0.06x ($R^2=0.94$). The third group between 60 and approximately 150 cm blade length shows more variation in its growth pattern and an even slower increase in blade width (slope 0.05x, $R^2=0.75$). Longer *L. saccharina* were

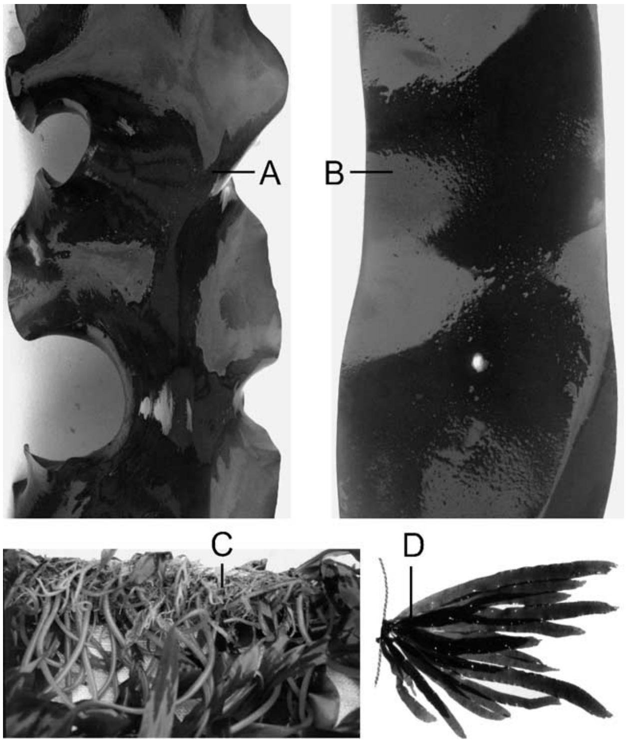

Fig. 5. Plants used for towing tank experiments. (A) *L. saccharina* from a sheltered site with a wider blade and ruffled margins and (B) cultivated *L. saccharina* from the offshore site with a streamlined shape. (C) depicts a culture line with holdfasts growing densely on top of each other. (D) represents the laminarian bunch used for drag experiments in the towing tank.

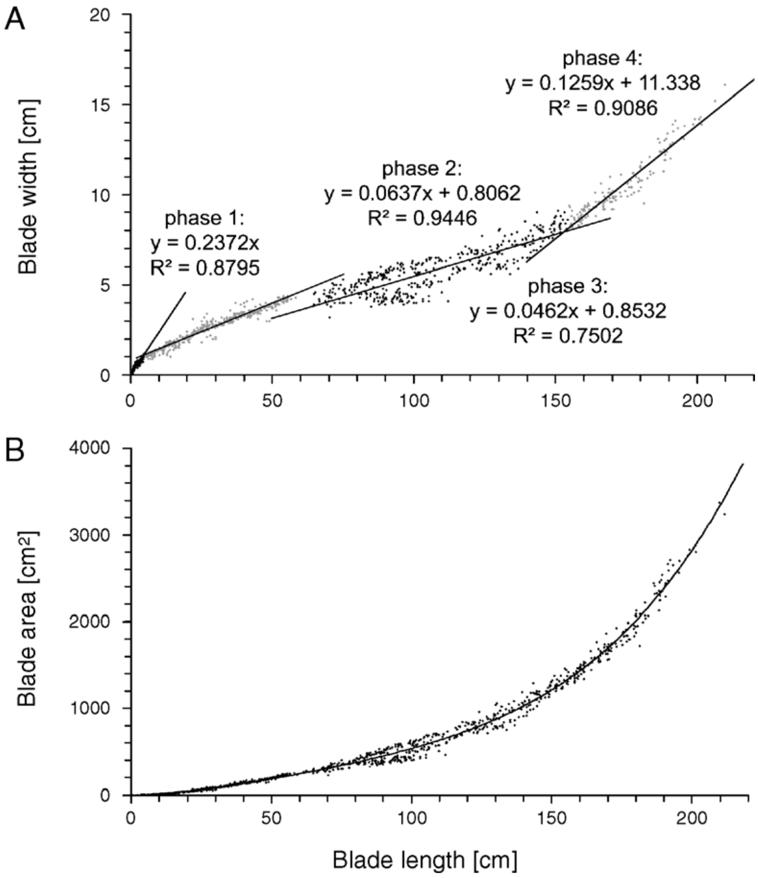

Fig. 6. Morphometric data of *L. saccharina* cultured at an offshore site ($n = 1300$). (A) shows the blade length to width ratio revealing four consecutive periods ($p < 0.001$) of plant growth. (B) shows the blade surface area to blade length ratio with roughly the same consecutive growth periods.

increasing their blade area by an again intensified transversal growth at a slope of 0.13x ($R^2 = 0.91$). Results of the determination of blade surface area show, that there is no significant difference whether grid measurement or simple multiplication of length and width are used ($p < 0.5$). Thus, a significant positive correlation ($R^2 = 0.99$) can be described for the ratio of blade length to blade surface area using the multiplication method (Fig. 6B). The four previously described morphometric stages from the length–width measurements (Fig. 6A) can be found to a lesser extent.

From the large data set of blade length/width relations standard algae were defined as Standard 50, 50 cm long 4.3 cm wide and Standard 100, 100 cm long and 5.8 cm wide.

Volume data of both, field algae and cultivated algae, followed a positive correlation to blade length as well as blade surface area. At a given length field algae always had a greater volume than cultivated algae.

3.3. Drag on *L. saccharina* in steady flows

The plot of measured drag against various flow velocities (Fig. 7A) shows the increase of drag with increasing velocity of flow. Three of four plants from wild habitats show by far the highest drag exposure. Only the smallest of the wild plants blends in with the group of cultured specimens. The “standard” algae, 50 and 100 cm long, which were chosen from cultured *L. saccharina* belong into this group of algae encounter-

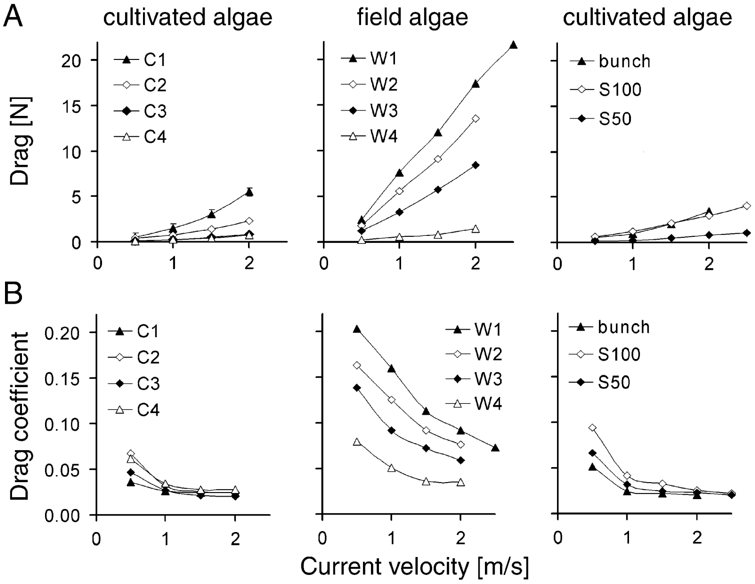

Fig. 7. Results from the towing tank experiments ($n = 50$) with cultivated (C1–C4, S50, S100, bunch) and field (W_1–W_4) *L. saccharina*. (A) Drag as a function of current velocity. (B) Drag coefficient C_D as a function of current velocity.

ing less drag at the chosen flow velocities. At a comparable blade area of about 200 cm^2 the wild grown *L. saccharina* W4 is exposed to almost twice as much drag as the cultured C3. W4 being the shortest of the wild algae towed (blade length 45 cm) is the only one to group with the cultured specimens. Cultured C1, the longest (blade length 161 cm) of all the measured algae, is nearest to specimens from the field, but even though its blade area exceeds that of the longest field specimen W1 by 170 cm^2, only a fifth to a third of the drag was recorded for the cultured specimen. The differences in drag became more pronounced with increasing current velocities. The left diagrams represent conditions for *L. saccharina* growing individually on the culture line. Growing in an aggregation, as it is usually the case, reduces the drag on the individual (Fig. 7A, far right). At a similar cumulative blade area of a bunch of *L. saccharina* (1136 cm^2) compared to the cultured *Laminaria* C1 (1115 cm^2), measured drag of the aggregation of algae was smaller at higher current velocities than that of the individual alga.

Considering the drag coefficient C_D as a function of velocity (Fig. 7B), the grouping of the cultured versus the field algae becomes even more evident. The drag coefficient C_D of cultured *L. saccharina* of "Helgolandian morphology" without bullae and hardly any undulation was calculated at velocities of >0.5 m s^{-1} to range between 0.024 and 0.034 independent of the size of the algae. The graphs for cultivated algae (C1–C4, S50, S100, bunch) show a pronounced bend at a velocity of 1 m s^{-1}. This appears to approximately mark the minimum speed required for orientation of the plants into downstream direction. When comparing the bunch with a single cultivated alga of similar surface area (C1) the drag coefficient of the bunch was about 30% higher at the lowest current velocity (bunch 0.052 versus C1 0.036 at 0.5 m/s), but became very similar to that of C1 at faster velocities. At higher velocities ≥ 1.5 m s^{-1}, C_D is almost a constant for individual algae as well as for the bunch and is independent of current velocity. The progress of reconfiguration into lower drag-shaped blade morphology seems to be accomplished. Contrastingly, laminarian fronds from less exposed sites (broader and with more undulated margins) appear distinctly different in the diagrams. Their reconfiguration, at least of larger plants, was not yet completed at 2 m s^{-1}, while the small plant W4 had already acquired its final shape of minimized exposure to the current.

Based on our empirical data the drag expected for various current velocities and possible blade areas of *L. saccharina* is depicted in Fig. 8. At a maximum current velocity of 1.5 m s^{-1}, like that measured near “Roter Sand” in 2002, large algae would be exposed to forces of ≥ 16 N.

While the empirical determination of C_D of solid bodies is a well-established procedure it is complicated for flexible plants, because they are changing their shape in the flow. To describe the relative reduction in drag for flexible bodies as they reconfigure with increasing flow velocity, Vogel (1984) proposed the determination of the proportionality between speed and drag and several authors followed his suggestion (e.g., Armstrong, 1989; Carrington, 1990; Gaylord et al., 1994; Koehl, 2000). In order to compare the performance of *L. saccharina* in currents to that of other algae, we also determined the “figure of merit”, B (Vogel, 1984; Koehl et al., 2003): The log transformed “specific drag” F_{Drg}/v^2 was plotted against log transformed current velocity and the slopes (B) of the graphs determined. They are called “figure of merit” (Vogel, 1984) and are listed in Table 2.

The values are typically negative. The higher absolute values of field algae demonstrate that they could experience more relative drag reduction by morphological reconfiguration than our cultured laminarians (Vogel, 1984; Koehl, 2000; Gaylord et al., 1994; Koehl et al., 2003).

Table 2
“Figure of merit” B of cultivated and field *Laminaria saccharina*

Origin of algae	Seaweed denotation	Current velocity (m/s)	B	R^2
Cultivated algae from offshore farm “Roter Sand”	C1	1–2	−0.10	0.79
	C2	1–2	−0.39	0.94
	C3	1–2	−0.39	0.92
	C4	1–2	−0.30	0.87
	Bunch	1–2	−0.25	0.98
	S50	1–2.5	−0.49	0.99
	S100	1–2.5	−0.69	0.99
Field algae from Helgoland	W1	1–2.5	−0.84	0.99
	W2	1–2	−0.72	0.99
	W3	1–2	−0.62	0.99
	W4	1–2	−0.52	0.84

B=slope; R^2=goodness of fit for $y=\log F_{\mathrm{Drg}}/v^2$; $x=\log v$.

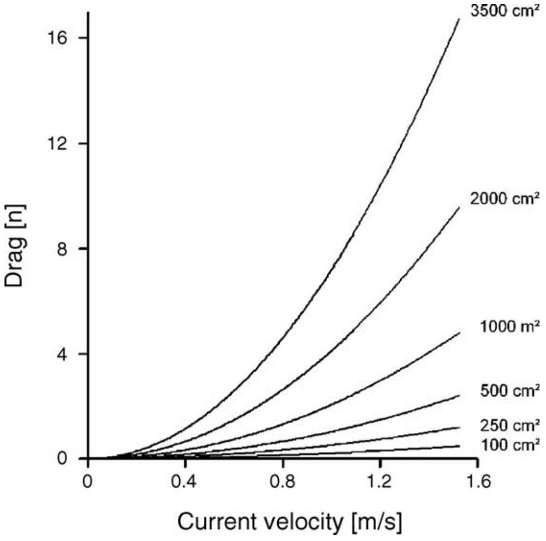

Fig. 8. Drag at various current velocities for different plant sizes (blade surface area) based on measurements in the towing tank experiment and morphometric data of *L. saccharina* from the offshore site.

3.4. Estimation of drag for natural conditions

The observations at “Roter Sand” are dominated by a combination of tidal currents, wind waves, and swell, which is characteristic for the shallow areas of the German Bight.

To better assess the highest forces probably impacting *L. saccharina* at an offshore location we employed the numerical model “WaveLoads” (Mittendorf et al., 2001). Typical oceanographic parameters to supply the model were chosen from the field measurements at “Roter Sand”, and the necessary structural parameters were taken from the morphometric data gained on the algae in the towing tank experiments. The parameters chosen for selected runs of the model are summarised in Table 3 together with the computed maximal drag.

Three comments on the relationships between drag and water movements for the environmental conditions prevailing in this study shall precede the presentation of the results of the model calculations.

Firstly, a rough estimation shows that the second term in Eq. (4) is very small compared to the first one and can be neglected: The volume of the algae was determined in the order of $Q=200$ cm^3. Multiplication by the density of seawater $\rho=1025$ kg m^{-3} and

Table 3
Drag forces under natural conditions

	Period (s)	Wave height (m)	Tidal velocities (m/s)	C1 (N)	C2 (N)	C4 (N)
Wind waves	5	2	2	11.7	4.9	–
Swell	10	2	2	12.4	5.5	–
Storm waves	6	6	2	34.3	14.6	4.4
Storm swell	10	4	2	23.0	10.9	–

assuming the worst case $C_M = 1$ for the dynamic drag coefficient results in $C_M \cdot \rho \cdot Q = 0.205$ kg for the mass of water displaced by the algae. Thus, a large orbital acceleration of 3 m s^{-2} (about a third of the acceleration of gravity) provides a dynamic force of 0.31 N while the first term reaches 35 N. The "WaveLoads" model takes the acceleration term into account, but uncertainties with C_M will not have a noticeable effect.

Secondly, because of the non-linear relationship between drag and velocity the combined action of orbital wave motion and tidal currents enhances the total forces considerably. For example, if a tidal current has the same velocity as the amplitude of the horizontal orbital velocity, the total force increases by a factor of 4.

Thirdly, due to the shallow depth of 12 m at the experimental farm the orbital velocities of long swell waves are increased, because they make the transition to shallow water waves.

The above mentioned phenomena were confirmed by the numerical model "WaveLoads". One has to bear in mind that the forces are calculated for a symmetrical test body which represents the real alga with respect to its two fluid mechanical properties, drag coefficient and constant area exposed to the currents. Three examples for the distribution of horizontal and vertical drag on the test body are presented in Table 3. Fig. 9A visualizes calculations for the cultivated alga C1 with wind waves at normal conditions (height: 2 m) at various current velocities (0, 1, 2 m s^{-1}) and Fig. 9B shows worst cases (height: 6.4 m; current velocity: 2 m s^{-1}) for cultivated *L. saccharina* of different lengths and blade areas (C1, C2, C4). The selected waves propagate in the direction in which the tidal current flows. The starting point of each curve, indicated by a small marker circle in the diagram, corresponds to the moment, when a wave crest passes the site. Without tidal currents the results of the model for horizontal and vertical forces show a symmetrical

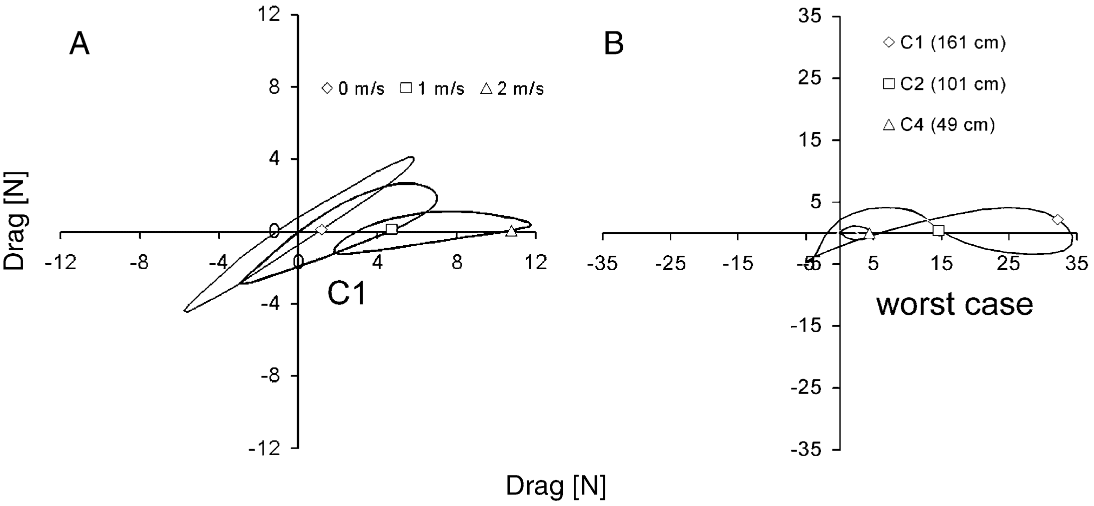

Fig. 9. Drag on cultivated algae under natural conditions derived from the model "WaveLoads" (Mittendorf et al., 2001). (A) shows the increasing drag as a function of current velocity (0, 1, 2 m s^{-1}) experienced by the algae C1 at wind waves of 2 m height and 5 s period. (B) shows the drag on the algae C1, C2 and C4 under worst case conditions (height of wind wave 6 m, period 6 s, current velocity 2 m s^{-1}).

ellipse which is elongated and shifted into downstream direction with increasing tidal velocity. Fig. 9B shows a worst case scenario, when storm conditions boost the drag experienced by cultivated algae. The largest alga (C1) has to withstand the highest drag of approximately 35 N.

3.5. Dislodgement of holdfasts and stipe breaking forces

After the assessment of wave generated forces affecting *L. saccharina* cultured offshore the second step was to determine what it takes to detach our cultured algae from their substrate. It can be expected that either the holdfast is torn from its substrate or the stipe breaks. The results of our experiments are shown in Fig. 10 with dislodgement force of the holdfast on the abscissa and breaking force of the stipe on the ordinate. If both forces were equal all values would be found on the bisector of the angle. The first two diagrams show that in individually growing *L. saccharina* as well as in those growing in aggregations, greater force had to be employed to break the stipe than to detach the holdfast. Algae that were retrieved from a tank with water movement only from air bubbles had a very weak resistance to any of the applied stresses and were dislodged or broke at less than a fifth of the force needed for laminarians exposed to a 2 m s^{-1} current.

L. saccharina displays a significant positive correlation of blade length to blade surface area (Fig. 6B, $p<0.01$, $R^2=0.99$). To assess dislodgement and breaking stresses on *L. saccharina* stipes the respective forces (F_{Dis} and F_{Brk}) were normalized by blade area and plotted against the length of the blades (Fig. 11). The basic trend is towards a decreasing resistance to adverse forces with increasing size. *L. saccharina* cultured "singly grown" and in currents up to 1.52 m s^{-1} require the highest forces to be broken off at their stipes ($p<0.001$). Dislodgement forces (F_{Dis}) between singly grown algae (current velocity > 1 m s^{-1}) and those in aggregations (densely growing and current velocity > 1 m s^{-1}) are statistically indifferent, even though growing singly and therefore directly attached by their holdfasts to the culture line seems to give them an advantage at least when they are still small. For densely grown laminarians the force per cm^2 needed to either dislodge them from the culture line or break their stipes can likewise not be statistically differentiated.

L. saccharina grown in an almost current-free environment were far more susceptible to dislodgement and breaking stresses than algae adapted to currents.

4. Discussion

The question we posed in our present investigation was, whether it seemed sensible to try the aquaculture of macroalgae in the projected North Sea offshore wind farms. A second problem to be tackled would be the selection of appropriate sites among those locations. A closer look at the conditions in an offshore algal farm that existed in 2002 should help to find answers. The seaweeds cultured on the ring

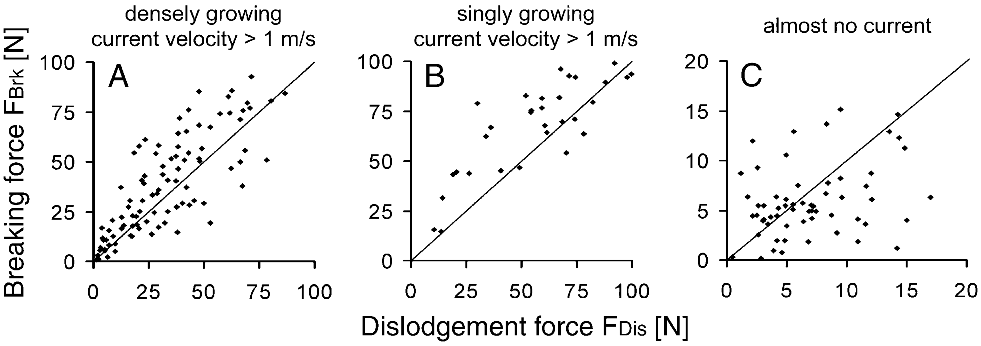

Fig. 10. Forces necessary to break the stipe (ordinate) or to dislodge the holdfast (abscissa) of *L. saccharina* grown in exposed conditions (singly grown, $n=37$; densely grown, $n=94$) and in sheltered conditions (almost no current, $n=60$). The bisector of the angle indicates where both forces would be equal (breaking force = dislodgement force).

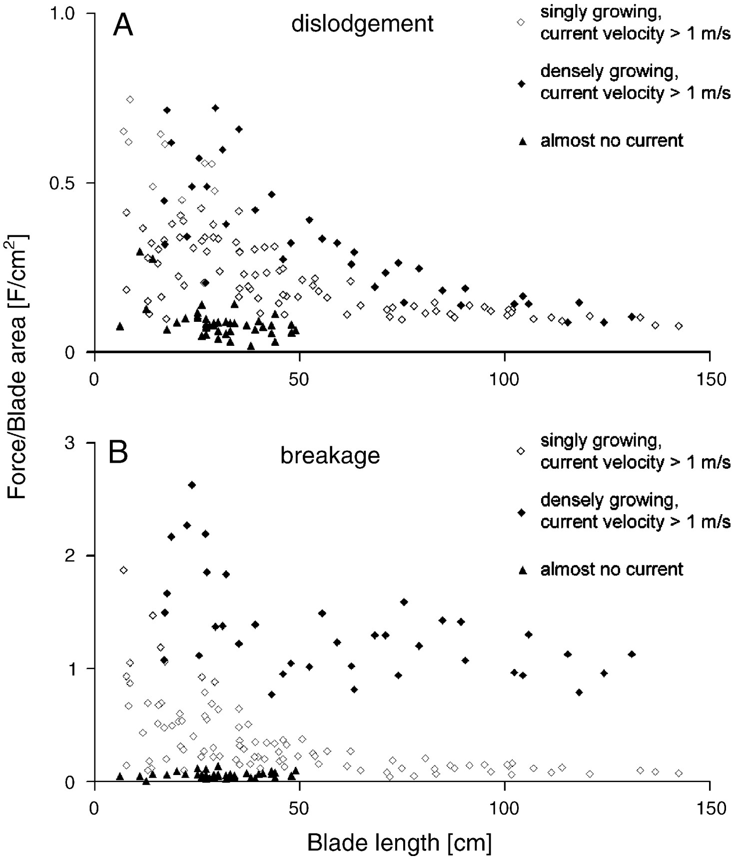

Fig. 11. Susceptibility to dislodgement (F_{Dis}) (A) and breaking (F_{Brk}) (B) forces per area of individual *L. saccharina* as a function of blade length. Single plants versus plants grown in aggregations both in water currents and plants grown in almost no current.

system (Buck and Buchholz, 2004) at the farm near the lighthouse "Roter Sand" were subject to various stress factors in the wave-swept environment. Current velocities of 1.52 m s^{-1} and wave heights of up to 6.4 m at wave periods of 2.6 to 9.8 s caused complex impacts on *L. saccharina*. These impinging forces stress the phylloid, the stipe and the holdfast exerting "tension, friction, shear forces, bending, and twisting" (Koehl, 1982, 1986). The behaviour of cultured *L. saccharina* as well as some field specimens towards hydrodynamic forces resulting in dislodgement of the holdfast, breaking of the stipe, and general drag was examined in detail.

The highest drag in steady flows expected from the extrapolation of our drag measurements in the towing tank related to current velocity amounts to 16 N for cultured Helgolandian type *L. saccharina*. It holds true for algae possessing a blade area of about 0.3 m^2 in a realistic one season culture period (Fig. 8). The results of the model calculations of drag on *L. saccharina* under natural conditions including current velocity in combination with wind waves or swell affect the algae at normal sea states with up to 12 N. This is the same order of magnitude and only in the worst cases of storm conditions can drag of up to 35 N be expected (Table 3, Fig. 9). These figures were computed under the assumption of rigid test bodies representing blade area and drag coefficient of the algae. In contrast to solid bodies algae change their area exposed to currents by adjusting their shape until minimum drag is reached (e.g., Daniel, 1984; Denny et al., 1985; Denny, 1988). To account for the complex interactions between algae and currents, elaborate physical–mathematical models have been developed (Gaylord and Denny, 1997; Gaylord, 2000; Gaylord et al., 2003). Within the scope of our investigation we restricted ourselves to estimations of worst cases and used the solid body formula. The use of the solid body approach is supported by the finding that for velocities >1 m s^{-1} the drag coefficients of cultivated algae were found to be almost independent of velocity (Fig. 7). Deviations in favour of drag avoidance by the flexible plants are probable, judged from observations on, e.g., *Chondracanthus exasperatus* (Koehl, 2000) and on *Hedophyllum sessile* (Armstrong, 1989). Nevertheless, the order of magnitude in our "worst case" calculations is thought to be realistic.

Drag on the bunch of *Laminaria* blades was smaller than the total drag of all solitary blades. Johnson (2001) explored this topic in some detail for *Chondrus crispus* and found similar results, where forces decreased with increasing canopy density. While Carrington (1990) determined that the ratio of the drag from a clump of blades to the sum of the individual drag forces of *Mastocarpus papillatus* never dropped below 0.8 the ratio was 0.35–0.38 in the laminarian case (bunch consisted of 13 blades). This difference can be explained by the fact that a bunch of streamlined laminarian blades experiences a lower drag increase with increasing current velocity than thalli with a bushy shape. In contrast to *L. saccharina* occurring at the Isle of Man with deep bullations on the blade *L. saccharina* originating from the island of Helgoland were described to have a smooth shape (Lüning, 1975). Such regional differences may be the adaptive result of the local wave and current climate of these two islands.

Morphological characteristics of *L. saccharina* like blade area and volume were needed to determine the drag coefficient C_D and to parameterise the model. To get an idea of how these parameters develop over time and to assess their interrelation to impinging forces in the field, lengths and widths of 1300 blades were measured on cultured *L. saccharina* from "Roter Sand" in 2002. We observed four consecutive growth phases in the development of blade length and blade width (Fig. 6A). All phases seem to mirror the environmental conditions in which the laminarians grew at the time. Phase (1) took mainly place under laboratory conditions. Sporophytes were very small and grew in all dimensions, while moderate currents interacted with the phylloids. During phase (1) plants were transferred to the sea to meet the wind induced turbulent water conditions of winter and early spring. The morphological plasticity of *L. saccharina* allowed them to react with an intensified length growth in phase (2) and to reach a more streamlined shape. It is well-known that laminarians exposed to wave action or high current velocities have narrower blades than plants from calm and sheltered areas and also differ in length and thickness (e.g., Parke, 1948; Svendsen and Kain, 1971; Gerard, 1987). During summer corresponding to algal sizes of stage (3), weather conditions were calmer resulting in a variety of length to width ratios. The variance of lengths and widths may moreover be attributed to shading effects among the plants. In size phase (4) of samples collected in late summer, sea conditions seemed to allow a higher increase in blade width. If this growth pattern were the rule, which future annual cultures will have to show, *L. saccharina* would ecologically sensible have gained blade area for the onset of sorus in autumn. For site selection in mariculture strategies the information displayed in Fig. 6 together with the expected drag impinging on algae of different sizes will help to identify the adequate marine environment for a given plant size.

While Fig. 10 shows the quality of haptera attachment to the substrate versus the resistance against breakage of the respective stipe independent of algal size, Fig. 11 depicts the individual vulnerability to drag of each *Laminaria* plant in relation to its blade area, the target for drag. In relation to blade area, the strength of the individual algae relative to dislodgement as well as breaking forces becomes smaller with increasing blade length and area before levelling off (Fig. 11). Nevertheless, we found that the absolute forces (not shown) that can be applied prior to dislocation are smaller (≤35 N of the "worst case") in small size classes (Fig. 6, phase 1 and phase 2). This might be expected and may be partly counterbalanced by the lower individual vulnerability of small algae, but does not explain, how larger algae cope with the higher drag they experience at comparable current velocities (Fig. 7A). The material properties of laminarians of different sizes that in addition to morphological characteristics determine their sturdiness towards adverse forces are yet to be examined more closely in a quantitative biochemical study.

Algal resistance to hydrodynamic forces depends on several ecological conditions. Firstly, a relatively strong current at an early age of the sporophyte is an absolutely necessary prerequisite for any mentionable attachment strength of the holdfast as well as tensile strength of the stipe resisting breakage (Fig. 10) (Buchholz and Buck, unpublished data). A further important factor is, whether they had a chance to anchor their holdfasts in the culture line (Tovey and Moss, 1978), growing singly, or whether they grew in aggregations with their holdfasts on top of those of their neighbours (Fig. 5C). Individually growing specimens developed a distinctly higher resistance towards breakage of the stipe and a clearly visible, if slight, better resistance towards dislodgement. This has long been promoted in Asian aquacultures, where algae are singled out after some grow out time, which in addition enhances individual growth (Ohno and Critchley, 1997; Scoggan et al., 1989). We found the forces needed to remove *L. saccharina* growing in aggregates generally smaller, but could detect a drag coefficient comparable to that of cultured individuals particularly at higher current velocities, when a bunch of laminarians reconfigured into a better hydrodynamic shape. The “figure of merit” of the bunch, characterising the relative drag reduction dependent on increasing current velocity, is also well within the range of individual algae (Table 2). A third influence on algal resistance to adverse forces is determined by its morphology. Our cultured algae looked like typical *L. saccharina* from high current locations around Helgoland, having grown in a likewise exposed environment. Comparing them with specimens of the same species with a more undulating (ruffled) border from less exposed field sites showed that the narrow and flat blades of the cultured algae experienced distinctly smaller drag than the field algae (Fig. 7). Gerard (1987) postulated that strong currents enhance hydrodynamic streamlining of the Laminarian frond, while at the same time such morphological adaptation reduces the mechanical stress on the thallus (Armstrong, 1989). Moreover, they were almost perfectly adjusted to the flow at much lower current velocities than the “ruffled” field algae and their drag coefficients were almost constant at ≥ 1 m s^{-1}. In our experiment with the ruffled laminarians they had not yet reached a perfect profile at a current velocity where the drag coefficient would not have decreased any more (Fig. 7; probable exception: W4). The “figure of merit” B (Table 2) for field algae, at current velocities ≥ 1 m s^{-1}, additionally indicates that a reduction of drag could be expected for current velocities beyond 2.5 m s^{-1}. More reliable values for B could probably be generated at these higher current velocities, but the carriage of the towing tank was limited to a velocity of 2.5 m s^{-1}. Fortunately, higher current velocities are uncommon for the German areas of the North Sea and it can be assumed that under such conditions stipes may break or holdfasts become dislodged.

B, frequently also named E, as the value of the “figure of merit” determined in the region of the graph “without inflection” (Vogel, 1984) shows a negative slope for cultured as well as field algae. The negative value of the slope results from the relative reduction of F_{Drg} experienced by *L. saccharina* as it reconfigures with increasing flow velocity. While for cultivated algae B ($B_{\mathrm{C1–C4}}$ and B_{bunch}) was determined at the value of -0.29 ± 0.12 (mean ± S.D.) field algae were found to have a greater B ($B_{\mathrm{W1–W4}}$) of -0.68 ± 0.14 (mean ± S.D.) (Table 2). The greater the absolute value of B the greater the reduction of F_{Drg} and the greater the ability of the blades to get streamlined.

Our results on cultured laminarians and more ruffled wild ones correspond to those described by Armstrong (1989), who reported that ruffled individuals with bullations of the brown macroalga *Hedophyllum sessile* originating from protected sites had a steeper descending slope than those having a strap-like blade morphology occurring at more exposed sites. In addition, mean values of B for *L. saccharina* fit into the range of values collected in Carrington (1990) and Koehl (2000), where values of B for seaweeds with comparable blade-like morphology vary from -0.28 to -1.2.

In experimental offshore cultures of laminarians on floating ring systems (Buck and Buchholz, 2004) an artificial canopy was created that certainly further reduced flow and therefore the impact of drag at least on the more centrally placed algae. The lower resistance to dislodgement or breaking forces of *L. saccharina* algae growing in aggregations versus those growing singly (Fig. 11) is probably balanced by a neighbourhood protection against the full impact of currents. Reduction of drag by natural canopies has been reported, e.g., for large kelp canopies of *Nereocystis* or *Macrocystis* (Koehl and Alberte, 1988; Jackson, 1984) or the smaller red algae like *Mastocarpus* and *Chondrus* (Dudgeon and Johnson, 1992; Johnson,

2001) or *Chondracanthus* (Koehl, 2000). The latter might better compare to conditions in young *Laminaria* cultures.

5. Conclusion

Forces generated by local currents and waves at “Roter Sand” were not strong enough to dislodge *L. saccharina* holdfasts or to break their stipes. While drag increased with the square of velocity, the drag coefficient remained constant at velocities >1 m s^{-1} due to the reorientation of the laminarian fronds into a streamlined shape. This mechanism functions as an adaptation to offshore forces. A prerequisite for this adaptation is the early transfer of young cultured sporophytes into the sea, which requires a well-organised seeding and pre-cultivation strategy and needs familiarity with site-specific parameters of a certain area. Due to the fact that singly grown plants withstood stronger forces, offshore areas with current velocities >2 m s^{-1} and waves higher than 6 m require cultures with less densely seeded sporophytes. Provided the above mentioned prerequisites are met, extensive aquaculture of *L. saccharina* in the high energy environment of the German Bight appears to be feasible.

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