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1 Implications of hyposaline stress for
2 seaweed morphology and biomechanics

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9

10 1. Introduction

11 Seaweeds are foundation species of coastal and estuarine ecosystems. They are high-yielding
12 primary producers (Reed et al., 2008) that form important habitats for invertebrates and fish
13 (Christie et al., 2009). In addition to the biological and ecological importance of seaweeds,
14 they have many commercial uses, with seaweed-derived components (such as hydrocolloids)
15 being used in cosmetics, pharmaceuticals, and food processing (Lucas and Southgate, 2012).
16 Seaweeds are also central to Integrated Multi-Trophic Aquaculture methods (Chan et al.,
17 2006; Chopin and Sawnhey, 2009; Lamprianidou et al., 2015) and have been successfully
18 tested as tools for bioremediation (Fei, 2004; Wu et al., 2017). Additionally, seaweeds are an
19 ideal source of biomass for production of third generation bio-fuels (Hughes et al., 2012;
20 Wargacki et al., 2012).

21 The high utility of seaweeds and increasing global demand necessitate large scale
22 farming (seaweed aquaculture), where biomass accrual rates should be maximised, while
23 maintaining seaweed health (and product quality, Hughes et al., 2012). These objectives
24 present a practical engineering challenge for the design of seaweed farms that optimally
25 utilise light and nutrients, yet constrain the effects of hydrodynamic forcing to prevent
26 mechanical failure (Lucas and Southgate, 2012; Buck and Langan, 2017). Seaweed growth
27 rates are highly dependent on currents, which transport nutrient rich water into seaweed
28 farms, and turbulence of various scales, which enhances mass exchange (Hurd, 2000; Hurd et
29 al., 2014). For example, blade scale turbulence favours the renewal of the boundary layer,
30 replacing depleted water with nutrient rich water (Koch, 1994; Stevens et al., 2003).
31 Designing seaweed farms that effectively utilise natural hydrodynamics, yet are not destroyed
32 during extreme events (storms) is an ongoing challenge. The design of aquaculture farms is
33 usually addressed by either reduced scale physical modelling or numerical simulations
34 (O'Donncha et al., 2013). Both of these approaches require input data on organism
35 hydrodynamics (e.g. drag forces and drag coefficients) and mechanics (e.g. breaking stress
36 and bending modulus). It is critical that these input data are of high quality and free of any
37 systematic errors or biases.

38 Previous studies of flow-seaweed interactions and seaweed biomechanics have
39 investigated how seaweeds have evolved to survive in habitats characterised by extreme drag
40 forces (e.g. Koehl and Wainwright, 1977; Denny, 1988; Hurd and Stevens, 1997; Denny and
41 Gaylord, 2002; Harder et al., 2004; Boller and Carrington, 2006; Martone et al., 2012).

42 Detailed investigations of seaweed reconfiguration mechanisms are commonly performed in
43 artificial flumes (e.g. Hurd and Stevens, 1997; Boller and Carrington, 2006; Boller and
44 Carrington, 2007; Vettori and Nikora, 2019). Due to technical limitations (e.g. preventing
45 pump corrosion), these tests are sometimes performed in freshwater rather than
46 saltwater/seawater (e.g. Harder et al., 2004; Buck and Buchholz, 2005; Mach, 2009; Xu et al.,
47 2018; Vettori and Nikora, 2019). While it is practically convenient to test seaweeds in
48 freshwater, it has not been established how hyposaline stress can affect their mechanical
49 properties and, therefore, their hydrodynamics. Seaweeds are also temporarily exposed to
50 hyposaline conditions (typically referred to as brackish water) in a range of natural
51 environments, for example: seawater dilution by river water, or heavy runoff in estuaries and
52 the nearshore zone (Kirst, 1989; Hurd et al., 2014); seawater dilution by ice-shelf melting in
53 boreal coasts (Bold and Wynne, 1985; Karsten, 2007; Spurkland and Iken, 2011); and direct
54 exposure to rain at low tide in the intertidal zone. For structural and economic reasons,
55 seaweed aquaculture is likely to develop at nearshore sites such as fjords, lochs, or inlets,
56 where seaweeds may be frequently exposed to temporary hyposaline conditions. The effects
57 of environmental stresses such as temperature, salinity and desiccation on seaweed
58 physiology have been recently investigated (e.g. Biskup et al., 2014; Flores-Molina et al.,
59 2014; Wang et al., 2019). While it is accepted that salinity variations affect seaweed
60 biochemistry and physiology (Hurd et al., 2014), we are not aware of any study focusing on
61 how seaweed biomechanics may change. This knowledge gap must be addressed before
62 laboratory data on flow-seaweed interactions can be used to design large scale seaweed farms
63 (Vettori and Nikora, 2018).

64 This work focuses on the kelp *Saccharina latissima* (order Laminariales), a seaweed
65 species widespread along the shores of the North Atlantic that has high commercial and
66 ecological value. *S. latissima* is an euryhaline species (Druehl, 1967) that can live in water
67 with salinity as low as 10‰ (Karsten, 2007; Spurkland and Iken, 2011; Mortensen, 2017).
68 However, Nielsen et al. (2014) suggested that the growth of *S. latissima* is already reduced at
69 salinity as low as 20‰ in the Baltic Sea. Both Karsten (2007) and Spurkland and Iken (2011)
70 reported a strong reduction in photosynthetic activity and health status of blade tissues of *S.*
71 *latissima* exposed to hyposaline stress in boreal coasts. The aim of this paper is to report the
72 effects of short-term exposure to hyposaline stress on morphological parameters and
73 mechanical properties of blades of *S. latissima*. Morphological parameters of the blades were
74 characterised prior to and after exposure to freshwater. Mechanical properties of the blades

75 were evaluated via tensile and bending tests performed on samples after exposure to
76 freshwater. These results are compared to the mechanical properties of blades presented in
77 Vettori and Nikora (2017), which are used as a control (i.e. no exposure to freshwater). In
78 particular, we test the hypotheses that seaweed blades exposed to freshwater undergo: (1)
79 morphological modifications; and (2) changes to their mechanical properties, such as bending
80 modulus and toughness.

81 2. Materials and methods

82 2.1 *Seaweed collection and storage*

83 Independent individuals (sporophytes) of *S. latissima* were collected on the 10th of February
84 2015 from long-lines deployed by Loch Fyne Oysters Limited in Loch Fyne, Scotland (56.08
85 N, 5.28 W). Only sporophytes free from epiphytic bryozoans and other fouling epiphytes and
86 without obvious signs of deterioration were collected. The mean salinity and temperature in
87 February where the seaweed samples were collected was approximately 30‰ (Gillibrand,
88 2002) and 7°C (<http://www.bodc.ac.uk>). Sporophytes were transported to the University of
89 Aberdeen in barrels filled with seawater, then transferred to a 125 L aerated seawater storage
90 tank within 8 hours of collection. The storage tank was kept outdoors in such a way that the
91 sporophytes were exposed to natural temperature and light conditions. During the study
92 storage water temperatures fluctuated between 3 and 8°C. Seawater in the tank was replaced
93 every 3-4 days with seawater from the North Sea collected near Aberdeen with a mean
94 salinity of approximately 34‰ (Janssen et al., 1999). Sporophytes were stored for up to 14
95 days until the tests were completed. Sporophytes that showed signs of deterioration (e.g.
96 flaws, nicks, fissures) were discarded.

97 2.2 *Experimental design*

98 In the current study we used 23 independent sporophytes of lengths varying between 150 and
99 650 mm. Sporophytes were exposed to freshwater for different times ranging from 5 to 60
100 minutes by immersing them in a 10 L plastic container filled with freshwater at room
101 temperature (13-15°C). Sporophytes were exposed to freshwater in separate containers, one
102 for each sporophyte. Before exposing a sporophyte to freshwater, it was kept indoors in a
103 container filled with seawater until water temperature reached 10-13°C. This way, we
104 exposed sporophytes to room temperature gradually and minimised any effect of temperature
105 shock. The morphological properties of the blades were determined prior to and after

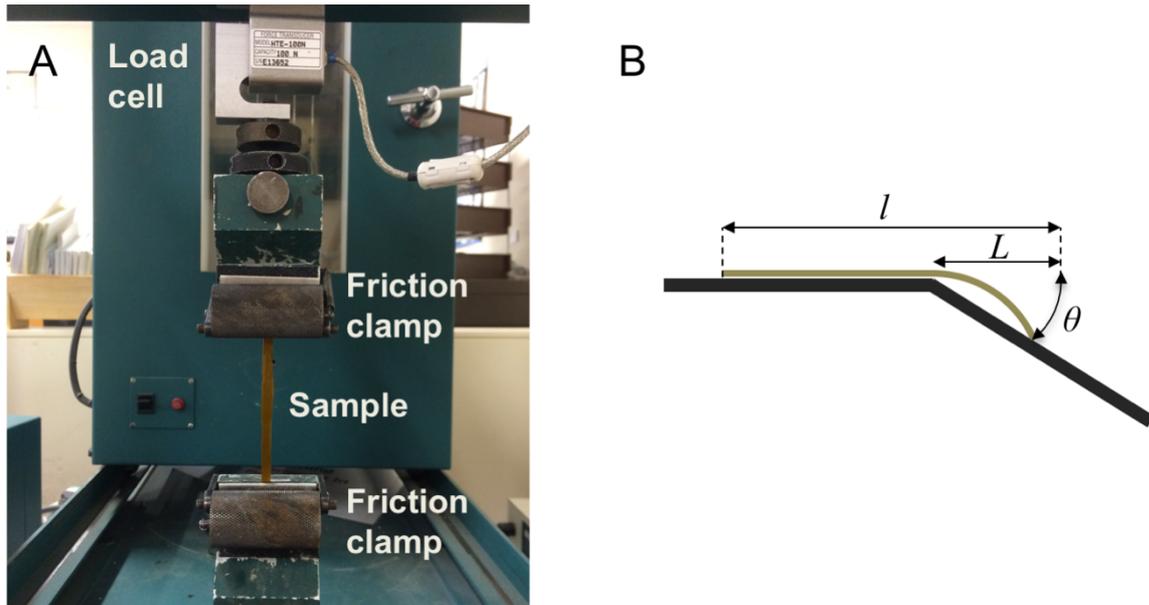
106 freshwater exposure. The mechanical properties of the blade material were investigated after
107 the morphological analysis, as mechanical tests required damaging the blade by cutting
108 samples from it.

109 *2.3 Determination of morphological parameters*

110 This study focused on seaweed blades so the stipe was detached from each sporophyte prior
111 to any test or measurement. For morphological assessment of a blade, a standard procedure
112 was followed: (i) water from the blade surface was removed and then the blade was weighed
113 using a digital scale; (ii) photos of the blade were taken with a calibrated digital camera on a
114 light table to evaluate full-one-side blade surface area using MATLAB® (The MathWorks,
115 Inc., Natick, Massachusetts, US); (iii) blade length, maximum width, minimum thickness,
116 and maximum thickness were measured using rulers and callipers; and (iv) blade volume was
117 measured by volumetric displacement in a measuring cylinder partially filled with freshwater
118 at room temperature. Since measurements of volumetric displacement lasted a few seconds,
119 we assumed that they did not affect results of morphological measurements or mechanical
120 tests carried out subsequently. The morphology of 23 seaweed blades was assessed.

121 *2.4 Determination of mechanical properties*

122 Mechanical properties of seaweed blades were determined from tension and bending tests
123 following the procedure described in Vettori and Nikora (2017). Samples were cut from
124 seaweed blades along the central fascia and were prepared carefully to avoid any flaws or
125 nicks. The length to width ratio of samples was equal to or higher than 10 to avoid substantial
126 end-wall effects (Niklas, 1992).



127
 128 **Figure 1** Benchtop testing machine used to conduct tensile tests to sample breakage and cyclic loading-unloading tests (A);
 129 testing plate used to conduct Peirce’s cantilever tests (B) with the parameters l , L , and θ used to calculate the bending
 130 Young’s modulus.
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132 Uniaxial tensile tests were conducted with a benchtop testing machine (Figure 1A;
 133 H10K-S UTM, Tinius Olsen, Salfords, UK) equipped with a 100 N load cell (HTE, Tinius
 134 Olsen, Salfords, UK). Two types of uniaxial tensile tests were performed: (i) tests to sample
 135 breakage; and (ii) cyclic loading-unloading tests. Prior to a test, the sample ends were secured
 136 by two friction clamps, with a sample length of 60 mm between the clamps (see also Vettori
 137 and Nikora, 2017). During the test, the upper clamp moved with a constant speed of 20
 138 mm/min. The data on force F and displacement δ were recorded with a dedicated software
 139 supplied by Tinius Olsen, and were later converted to nominal stress σ and strain ε using the
 140 formulas $\sigma = F/A$ and $\varepsilon = \delta/l_0$, where A is the sample cross-sectional area, and l_0 is the
 141 sample length prior to testing. The relative error of the force reading was 1.5% for force
 142 below 2 N and 0.1% for force above 2 N, calculated via independent calibration.

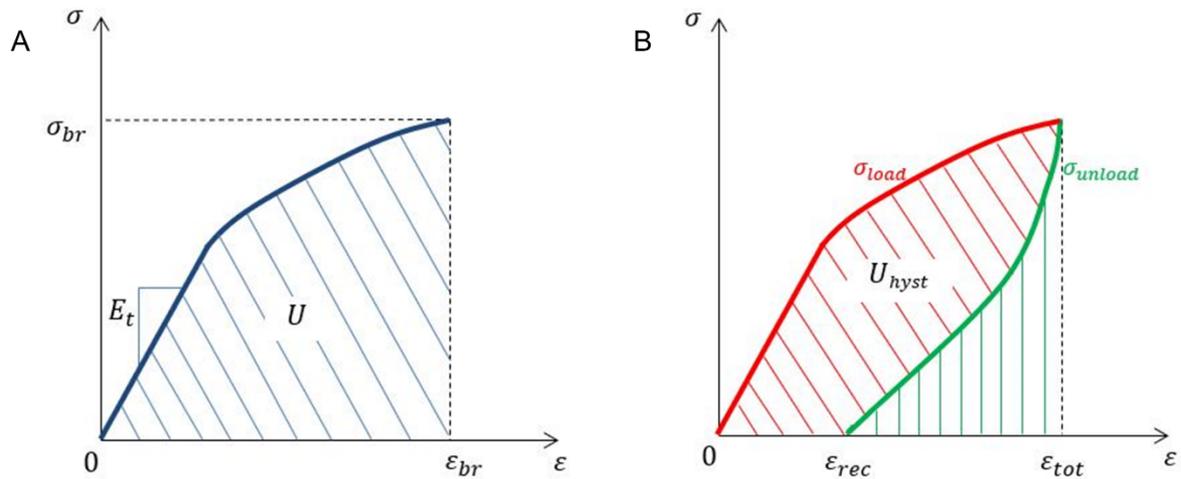
143 **Table 1** Summary of symbols and definitions of mechanical properties considered in the current study

Mechanical property	Symbol	Definition
Tensile Young’s modulus	E_t	$E_t = \sigma/\varepsilon$ where σ is nominal stress and ε is nominal strain (i.e. E_t is the slope of $\sigma = f(\varepsilon)$ in the linear region at small ε , Figure 2A).

		$E_b = \frac{3 mg L^3 \cos(\theta/2)}{2 w l t^3 \tan \theta}$
Bending Young's modulus	E_b	where g is gravity acceleration; m , l , w , and t are the mass, length, width and thickness of the sample; θ is the inclination of the testing apparatus and L is the cantilever length (Figure 1B)
Breaking stress	σ_{br}	Value of stress when a sample breaks (Figure 2A)
Breaking strain	ε_{br}	Value of strain when a sample breaks (i.e. maximum strain, Figure 2A)
Toughness	U	$U = \int_0^{\varepsilon_{br}} \sigma d\varepsilon$ i.e., amount of energy per unit volume a sample can dissipate before breaking (Figure 2A)
Elastic hysteresis	U_{hyst}	$U_{hyst} = \int_0^{\varepsilon_{tot}} \sigma_{load} d\varepsilon - \int_{\varepsilon_{rec}}^{\varepsilon_{tot}} \sigma_{unload} d\varepsilon$ where ε_{tot} is the maximum strain and ε_{rec} is the residual strain (due to plastic deformation) after the sample has been unloaded (Figure 2B)
Resilience	R	$R = \int_{\varepsilon_{rec}}^{\varepsilon_{tot}} \sigma_{unload} d\varepsilon / \int_0^{\varepsilon_{tot}} \sigma_{load} d\varepsilon$ as illustrated in Figure 2B)

144

145 Tensile tests to sample breakage were used to determine: tensile Young's modulus E_t ;
 146 breaking stress σ_{br} and strain ε_{br} ; and toughness U , which is the amount of energy per unit
 147 volume (J/m^3) that the sample can dissipate before breaking (Table 1, Figure 2A; Vettori and
 148 Nikora, 2017).



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Figure 2 Representation of stress-strain curves for: (A) tensile tests to sample breakage and (B) cyclic loading-unloading tests. In (A) the diagonal hatched area represents toughness. In (B) the diagonal hatched area represents elastic hysteresis (adapted from Vettori and Nikora, 2017).

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Cyclic loading-unloading tests were performed by stretching the sample to a strain of 20% and then unloading it (with the cycle repeated three times). These tests were used to determine the elastic hysteresis and resilience. The elastic hysteresis U_{hyst} can be defined as the energy per unit volume dissipated internally during a loading-unloading cycle (Table 1, Figure 2B; Niklas, 1992). The resilience R is the ratio of the energy recovered by the sample during the unloading phase to the energy dissipated during the loading phase within a cycle (Table 1, Figure 2B; Vettori and Nikora, 2017).

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Bending tests to obtain the bending modulus E_b were conducted using Peirce's cantilever test (Peirce, 1930). This test was used successfully by Henry (2014) and Vettori and Nikora (2017) to estimate the bending modulus of seaweeds. It is conducted on a plate with inclination θ , and it requires measuring the so-called cantilever length L from which the bending modulus of a sample can be estimated (Table 1, Figure 1B; Henry, 2014).

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The number of samples that were prepared from a blade depended on the size of the blade; however at least two samples for tests to sample breakage were prepared from each blade. Further, it was assumed that samples sourced along the same blade were independent of one another. It is important to note that bending tests required the use of samples substantially longer than those for other tests (Vettori and Nikora, 2017), thus the number of bending tests performed was smaller than the number of tensile tests. The numbers of samples used in each type of measurement or test are listed in Table 2 grouped by the types

173 of tests and five ranges of freshwater exposure times. The number of samples used in
 174 mechanical tests at exposure times lower than 20 minutes is limited because after
 175 morphological measurements were conducted, blades had to be stored in freshwater while
 176 samples were prepared and tests conducted (Table 2). In this study we also make use of
 177 biomechanics data on *S. latissima* reported in Vettori and Nikora (2017) as a control - that is,
 178 with no exposure to freshwater – comprising 25 tests to breakage, 14 cyclic tests, and 11
 179 bending tests.

180 **Table 2** Numbers of samples used for morphological measurements and mechanical tests grouped by exposure times.

Freshwater exposure time (mins)	Morphological measurements	Tests to breakage	Cyclic tests	Bending tests
1-9	6	0	0	3
10-19	5	1	6	3
20-39	6	17	3	4
40-60	6	13	9	0
>60	0	23	6	4
Total	23	54	24	14

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182 2.5 Statistical analysis

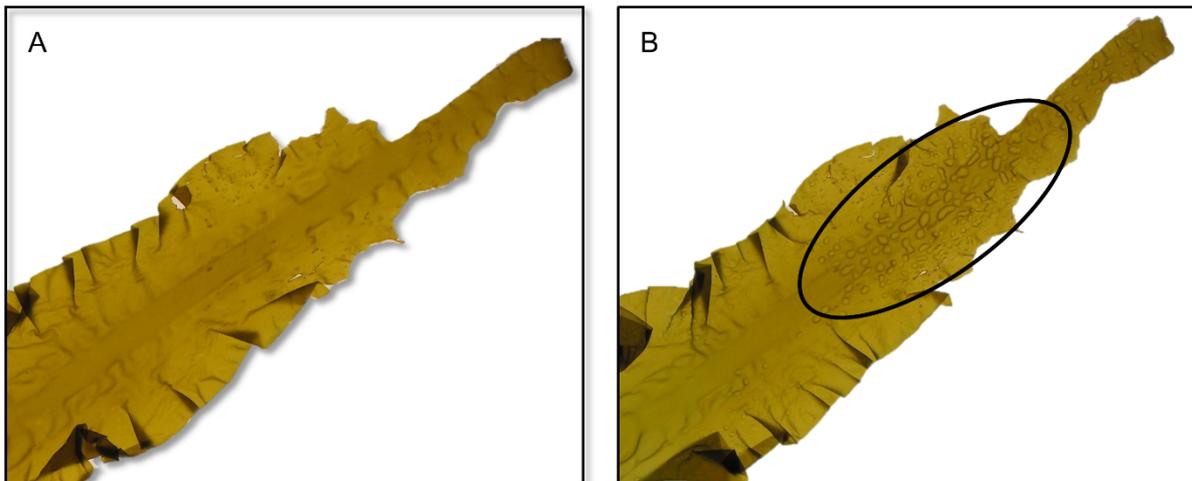
183 To investigate potential effects of hyposaline stress on blade morphology, variations in
 184 morphological parameters were standardised for each sample using $\Delta_x = 100(x_{post} - x_{pre})/$
 185 x_{pre} , where x_{post} is the value of a parameter after treatment, and x_{pre} is the value of the
 186 same parameter before treatment (using the Lilliefors test of normality we verified that Δ_x for
 187 each morphological parameter was normally distributed; homogeneity of variance was
 188 confirmed via visual inspection of the residual plots). To test the hypothesis that blade
 189 morphological parameters vary as a function of time t of exposure to freshwater, each Δ_x was
 190 analysed by applying one-way analysis of variance to linear regression. To test the hypothesis
 191 that mechanical properties of blade material vary as a function of t , we applied one-way
 192 analysis of variance to linear regression for each mechanical property introduced in the
 193 previous section. To evaluate the effect of the storage time (i.e. in the aerated storage tank) on
 194 the mechanical properties of blade material, we checked if any significant correlation
 195 between them existed. To do so, we used one-way analysis of variance to test if the slope of
 196 the linear regression between the storage time and a mechanical property differed
 197 significantly from 0. We found no significant effect of storage time on mechanical properties
 198 (ANOVA: for E_b $F_{1,26} = 1.14$, $p = 0.30$; for E_t $F_{1,77} = 2.38$, $p = 0.13$; for σ_{br} $F_{1,77} = 2.29$, $p =$

199 0.13; for ε_{br} $F_{1,77} = 1.38$, $p = 0.24$; for U $F_{1,77} = 0.02$, $p = 0.90$; for U_{hyst} $F_{1,33} = 0.99$, $p =$
200 0.33; for R $F_{1,33} = 0.08$, $p = 0.78$). Data processing and statistical analysis were conducting
201 using MATLAB with the Statistics and Machine Learning Toolbox Version 2016a (The
202 MathWorks, Inc., Natick, Massachusetts, US). Significance for all analyses was set at $\alpha =$
203 0.05.

204 3. Results

205 3.1 Morphology

206 When exposed to freshwater, the seaweed blades experienced morphological changes that
207 became apparent within 1 hour. Over time, the blades appeared to wither/bleach and blisters
208 filled with water developed underneath the cortex in the distal region (Figure 3B). These
209 effects were in qualitative agreement with the findings of Karsten (2007) and Spurkland and
210 Iken (2011) on tissue samples cut from blades of *S. latissima* from Svalbard (Norway) and
211 Alaska (USA), respectively.



212

213 **Figure 3** Visual comparison of an upper portion of blade prior to (A) and after (B) 60 minutes exposure to freshwater. The
214 response to hyposaline stress consists of a change in colour and the formation of water blisters beneath the cortex (area where
215 blisters formed is highlighted with a black oval in B).

216

217 Average blade width and full-one-side surface area were significantly reduced after
218 exposure to freshwater (Table 3), indicating that blades shrank as a response to hyposaline
219 stress. The change in full-one-side surface area occurred at an average rate of -0.13% per
220 minute (ANOVA: $F_{1,22} = 21.3$, $p < 0.001$) and the change in average width at -0.12% per

221 minute (ANOVA: $F_{1,22} = 26.5$, $p < 0.001$; Table 2). Simultaneously, average blade thickness
 222 (ANOVA: $F_{1,22} = 11.4$, $p = 0.003$) and weight (ANOVA: $F_{1,22} = 6.3$, $p = 0.02$) increased
 223 significantly, with an average rate of 0.31% and 0.14% per minute, respectively (Table 3). In
 224 the treatment with one hour exposure time, the morphological changes were significant (e.g.
 225 full-one-side surface area was reduced by 7.8% and average thickness increased by 18.8%)
 226 with implications for flow-seaweed interactions. The length of seaweed blades did not show
 227 significant patterns depending on the time of exposure to freshwater. It is worth noting that
 228 the coefficient of determination (R^2) was quite low for linear regressions for all
 229 morphological parameters (Table 3). This illustrates the substantial scatter of the data, which
 230 is likely due to random variability between samples, or other factors which were not
 231 accounted for.

232 **Table 3** Variation in morphological parameters of seaweed blades as a function of time of exposure to freshwater, results of
 233 one-way ANOVA applied to linear regressions (intercept was set equal to zero). Confidence interval at $p = 95\%$ is reported.
 234 The p-value associated with the hypothesis that the slope of the linear regression is null is reported.

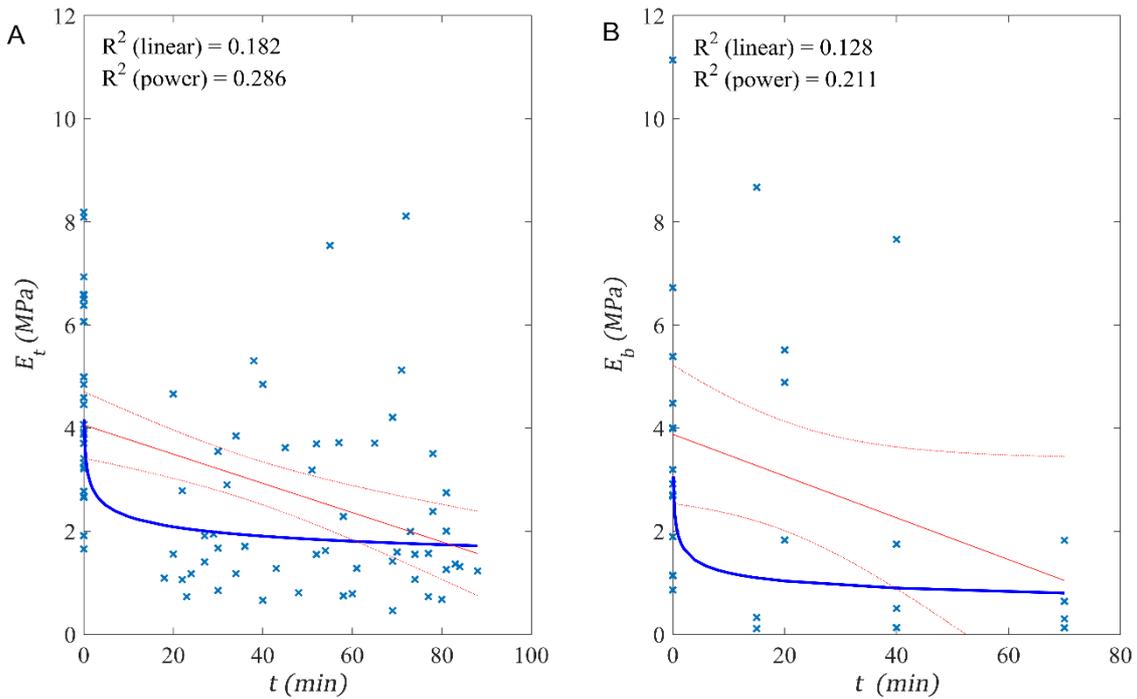
	Lower C. I.	Mean	Upper C. I.	p-value	R²
	Slope (%/min)	Slope (%/min)	Slope (%/min)		
Length	-0.025	-0.007	0.012	0.478	0.050
Width (avg.)	-0.173	-0.124	-0.074	<0.001	0.335
Thickness (avg.)	0.121	0.313	0.505	0.003	0.184
Surface area	-0.187	-0.129	-0.071	<0.001	0.279
Volume	-0.045	0.171	0.388	0.125	0.057
Weight	0.025	0.145	0.266	0.020	0.122

235

236 3.2 Biomechanics

237 The Lilliefors test rejected the hypothesis that E_t , σ_{br} , U and R are normally
 238 distributed, however data were not transformed because we can safely assume the sample size
 239 (i.e., 79 for tensile tests, 35 for cyclic tests) is large enough to prevent bias due to sample
 240 non-normality (Underwood, 1997). Homogeneity of variance was checked via visual
 241 inspection of the residual plots and such inspection did not reveal any obvious deviation from
 242 the assumption of homoscedasticity. Blade material became more flexible (at small
 243 deformations) in both tension and bending, which was reflected by significant reductions in
 244 tensile Young's modulus E_t (ANOVA: $F_{1,77} = 17.1$, $p < 0.001$) and bending modulus E_b
 245 (ANOVA: $F_{1,26} = 3.8$, $p = 0.062$) with t (Figure 4). For one-hour exposure to freshwater this
 246 manifests as E_t decreasing from 4 MPa to 1.7 MPa, and E_b decreasing from 4 MPa to 0.8

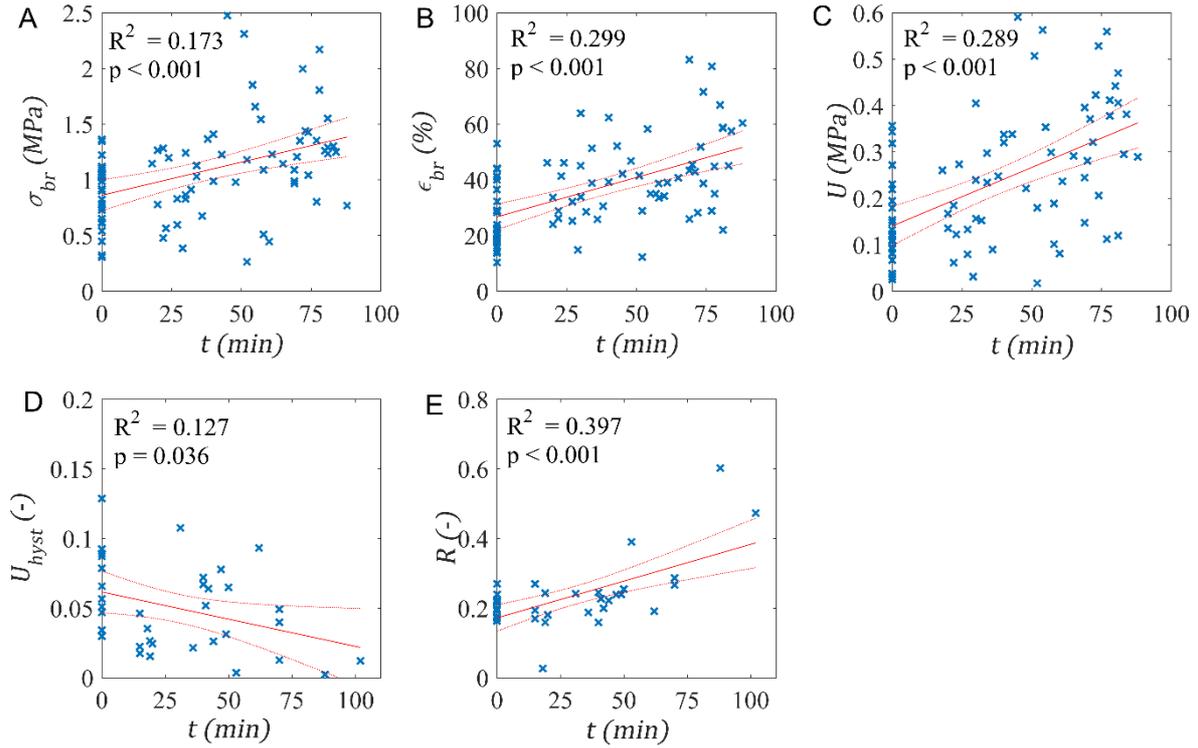
247 MPa, a reduction of 57% and 80%, respectively. In Figure 4 both linear and power law
 248 regressions are shown for E_t and E_b . Linear regressions are used to test if changes in time are
 249 significant, whereas power-type approximations fit the data better (see R^2 in Figure 4) and are
 250 able to account for the physical reality that moduli will not change indefinitely with a
 251 constant rate (as implied for linear regressions). The power-type regressions plotted in Figure
 252 4 are $E_t = 3.084t^{-0.131}$ and $E_b = 1.907t^{-0.205}$, respectively.



253
 254 **Figure 4** Scatter plots of tensile (A) and bending (B) Young's moduli versus freshwater exposure time with linear regression
 255 and confidence interval at $p = 95\%$ (dashed lines), and power law regression. In each plot the coefficient of determination for
 256 both linear and power law regressions is reported.

257

258 Unexpectedly, all parameters at breakage revealed a significant positive trend as a
 259 function of t (ANOVA: for σ_{br} $F_{1,77} = 16.1$, $p < 0.001$; for ε_{br} $F_{1,77} = 32.8$, $p < 0.001$; for U
 260 $F_{1,77} = 31.3$, $p < 0.001$), meaning that after exposure to freshwater the material became more
 261 resistant to tensile stress and more energy was required to break it (Figure 5A-C). After 90
 262 minutes of exposure to freshwater, σ_{br} , ε_{br} and U showed increases of 63%, 100% and 150%
 263 respectively. Increased flexibility with exposure times also led to significant changes in
 264 properties determined from the first cycle of cyclic loading-unloading tests, with the elastic
 265 hysteresis U_{hyst} decreasing (ANOVA: $F_{1,33} = 4.8$, $p = 0.036$) and the resilience R increasing
 266 (ANOVA: $F_{1,33} = 21.7$, $p < 0.001$) (Figure 5D-E).



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Figure 5 Scatter plots of mechanical properties versus freshwater exposure time with linear regression and confidence interval at $p = 95\%$ (dashed lines). In each plot the coefficient of determination and the p -value associated with the hypothesis that the slope of the linear regression is null are reported. From tests to sample breakage: (A) breaking stress, (B) breaking strain, and (C) toughness. From the first cycle of cyclic loading-unloading tests: (D) elastic hysteresis, and (E) resilience.

Even though mechanical properties are significantly affected by exposure to freshwater, it is worth noting that the coefficients of determination for linear regressions have low values ($R^2 = 0.127$ to 0.397 in Figure 5). The results of one-way analysis of variance applied to linear regressions of mechanical properties versus t are reported in Table 4.

Table 4 Variation in mechanical properties of seaweed blades as a function of freshwater exposure time, results of one-way ANOVA applied to linear regressions. The elastic hysteresis and resilience are reported for the first cycle only. The p -value associated with the hypothesis that slope of the linear regression is null is reported.

	Samples	Linear regression equation (t is time (min))	p -value	R^2
E_b (MPa)	28	$E_b = 3.88 - 4.05 \times 10^{-2}t$	0.062	0.128
E_t (MPa)	79	$E_t = 4.06 - 2.84 \times 10^{-2}t$	<0.001	0.182
σ_{br} (MPa)	79	$\sigma_{br} = 0.861 + 5.94 \times 10^{-3}t$	<0.001	0.173
ϵ_{br} (-)	79	$\epsilon_{br} = 0.267 + 2.84 \times 10^{-3}t$	<0.001	0.299
U (MJ/m ³)	79	$U = 0.140 + 2.52 \times 10^{-3}t$	<0.001	0.289
U_{hyst} (MJ/m ³)	35	$U_{hyst} = 6.16 \times 10^{-2} - 3.91 \times 10^{-4}t$	0.036	0.127
R (-)	35	$R = 0.172 + 2.11 \times 10^{-3}t$	<0.001	0.397

280 4. Discussion

281 4.1 Morphology

282 The main physiological process via which seaweeds adapt to salinity variations is referred to
283 as turgor pressure regulation (Kirst, 1989). Blade morphological change is a consequence of
284 the osmotic gradient between a blade and the medium in which it is immersed, with a blade
285 achieving a new steady state via osmotic adjustment (Kirst, 1989; Hurd et al., 2014). In the
286 present case, freshwater was absorbed by the blades causing blisters to develop underneath
287 the cortex in some locations on the blades. This mechanism can damage seaweed tissue and
288 cause cell walls to burst (e.g. Hurd et al., 2014). As a countermeasure, some cells can release
289 metabolites to lower turgor pressure and contribute to osmotic adjustment (Niklas, 1992). We
290 suggest this be the case for blades of *S. latissima*, which secreted a sugary liquid after being
291 immersed in freshwater. This liquid is assumed to be mannitol, which is present in high
292 concentrations in *S. latissima* (e.g. Adams et al., 2009), and was reported by Reed and Wright
293 (1986) to be excreted by *Pilayella littoralis* (a brown macroalga) in response to hypoosmotic
294 stress. Turgor pressure was not measured during this study, so it is unknown how it varied
295 with freshwater exposure time. However, it is generally accepted that turgor pressure in
296 seaweeds increases in response to hyposaline conditions (e.g. Hurd et al., 2014).

297 The morphology of seaweed blades used in the present study was significantly
298 modified by short-term exposure to hyposaline stress. The blades absorbed freshwater, which
299 increased the blade thickness, weight and volume. The increase in blade thickness caused
300 corresponding reductions in blade width and blade surface area. Decreasing surface area
301 might be a self-defending mechanism, as it allows blades to reduce the area through which
302 exchange of fluids with the surrounding hyposaline water occurs, hence limiting the intake of
303 hyposaline water and secretion of metabolites. Reduction of blade surface area may also have
304 physical implications, for example to lessen viscous skin friction exerted on the blade, thus
305 decreasing the overall drag force (Vettori and Nikora, 2019). However, it is important to note
306 that seaweed responses to hyposaline stress reported in this study may be specific of
307 seaweeds living in waters with high salinity (salinity at the site is around 30‰) and
308 supplementary research conducted with samples from different environments (e.g. the Baltic
309 Sea) would help validate our results.

310 4.2 Biomechanics

311 Tensile and bending Young's moduli are crucial parameters for describing the deformation of
312 a body exposed to hydrodynamic forces. We found that both tensile and bending moduli
313 decreased significantly with time of exposure to freshwater (Figure 4), with typical
314 reductions of around 57% and 80% in one hour, respectively. These results are in contrast
315 with previous findings – for example, Reed et al. (1980) reported an increase in volumetric
316 elastic modulus of cells from a red alga in hyposaline conditions - and expectations, since we
317 would expect seaweed blades to become stiffer as the turgor pressure increases. To explain
318 why blade material flexibility is increased by hyposaline stress we propose the following
319 three reasons:

- 320 (i) Simple geometrical considerations following findings of seaweed
321 morphological changes: samples increased their volume keeping constant
322 length, leading to increased cross-sectional area, with a consequent reduction in
323 the value of Young's modulus obtained from tests. These morphological
324 considerations can account for about 20% of total reduction reported here.
- 325 (ii) Seaweed cell walls contain cellulose (Hurd et al., 2014), which is reported to
326 become stiffer as it gets drier (Niklas, 1992). As seaweed blades absorb
327 freshwater (for turgor pressure regulation), cell walls are more exposed to water
328 and thus become more flexible.
- 329 (iii) The secretion of metabolites from parenchyma tissues (for osmotic adjustment)
330 lowers turgor pressure and, consequently, causes a reduction in material
331 Young's modulus (Niklas, 1992).

332 Cyclic tests are useful to study how seaweed material 'reacts' to periodic loads, such as
333 those experienced due to waves. In this study we pulled samples to 20% deformation in each
334 cycle, hence applying a loading that could occur under extreme conditions (e.g. large waves)
335 in natural settings. A reduction in the elastic hysteresis U_{hyst} indicated that less energy is
336 dissipated for the same deformation after exposure to freshwater. While this reduction was
337 particularly significant for the 1st cycle, it also had a considerable effect on the 2nd and 3rd
338 cycles. Associated with a reduction in U_{hyst} was an increase in the resilience R , which
339 indicated that blades experienced reduced plastic deformation when exposed to freshwater,
340 i.e. they experienced limited permanent deformations and were able to recover better from
341 previous loadings.

342 The fact that σ_{br} , ε_{br} , and U were positively correlated with the time of exposure to
343 freshwater was unexpected and suggests that either: (i) seaweed tissues are strengthened as a
344 response to hyposaline stress; or (ii) unstressed seaweeds have a survival strategy that
345 facilitates blade rupture prior to reaching the maximum capabilities of the blade materials.
346 The first speculation would indicate that the observed biomechanical responses to freshwater
347 exposure are a beneficial trait that evolved in seaweeds to enable them to better withstand the
348 environmental conditions characterising the nearshore zone. This, however, appears to be
349 unlikely considering the short time scale of the treatment and the reduction in health status of
350 seaweed tissues exposed to hyposaline conditions reported by Kartsen (2007) and Spurkland
351 and Iken (2011). The second hypothesis could relate to the fact that *S. latissima* blades lose
352 distal portions when growing older (Lee, 2008). This strategy can prevent seaweeds from
353 experiencing extreme drag forces by reducing their surface area, particularly in winter, and
354 could somewhat be disabled when seaweeds experience strong hyposaline stress. As the
355 mechanical behaviour of an organism is regulated by the properties of all tissues comprising
356 it, to shed light on the processes behind the mechanical variations reported in the present
357 work, a study on the effects of hyposaline stress on individual tissues would be required.

358 It is important to note that the coefficient of determination for linear regressions was
359 quite low for both morphological parameters and mechanical properties (Tables 3-4). It
360 follows that the regressions presented cannot describe the variance of the data fully and
361 cannot give accurate predictions, but only general trends. For morphological parameters this
362 was likely caused by the high variability of seaweed blade morphology associated with the
363 local conditions in which samples were grown (e.g. Gerard, 1987). For mechanical properties
364 low goodness of fit was representative of the high variability in seaweed biomechanical
365 characteristics, which was likely caused by the presence of tissues of different ages
366 (Krumhansl et al., 2015) and blade adaptations to localised hydrodynamics. This variability
367 was exacerbated by the use of blades of various lengths (from 150 to 650 mm) and samples
368 being prepared from different positions along the blades (Vettori and Nikora, 2017). Further,
369 we note that any linear regression presented here should not be used to extrapolate values of
370 morphological parameters or mechanical properties, because the rates of change reported in
371 this study would not apply indefinitely. Power-type approximations shown in Figure 4 for E_t
372 and E_b , on the other hand, are more likely to represent the trends for a wider range of
373 exposure times.

374 The freshwater treatment used in this study represents an extreme case for natural
375 settings, where changes in salinity usually occur more slowly. However, in the nearshore
376 zone, seaweeds may be temporarily exposed to very low salinity during: low tide and river
377 floods in estuaries (e.g. Hurd et al., 2014; Mortensen, 2017); strong ice melting phenomena in
378 boreal coasts (e.g. Spurkland and Iken, 2011); and rain events if seaweeds are exposed at low
379 tide. While it is of limited direct ecological relevance, using an abrupt change in salinity
380 allowed us to gain insight into changes that could not be easily detected otherwise and that
381 we expect to also occur when seaweeds are exposed to hyposaline conditions more gradually.
382 Based on the results presented, we can speculate that seaweeds experience lower drag forces
383 when exposed to hyposaline stress (due to increased flexibility and morphological changes)
384 and are less susceptible to breakage (due to increased breaking stress, breaking strain,
385 toughness and resilience).

386 Findings of this study can have implications for the prediction of seaweed
387 hydrodynamics and mechanical failure due to hydrodynamic forcing, with direct applications
388 in the farming of seaweeds in nearshore areas and testing of seaweeds in freshwater in
389 laboratories (e.g. Buck and Buchholz, 2005; Mach, 2009; Xu et al., 2018; Vettori and Nikora,
390 2019). Seaweed farming structures are designed based on the drag forces acting on the
391 structure and the seaweeds attached to it (Lucas and Southgate, 2012; Buck and Langan,
392 2017). If seaweeds experience lower drag forces when exposed to hyposaline stress, that
393 would have to be accounted for in the design phase. In hydraulic laboratories it is often
394 convenient to test seaweeds in freshwater (e.g. Buck and Buchholz, 2005; Xu et al., 2018),
395 but it is critical that data of drag forces acting on seaweeds are free of biases or errors that can
396 be induced by water salinity (Vettori and Nikora, 2019). In this context, being able to assess
397 variations in seaweed biomechanics is important for predicting the forces seaweed samples
398 experience and the forces required to induce mechanical failure. Supplementary research with
399 sporophytes collected from different environments would be of scientific value and help
400 validate our results.

401 It is well established that exposure to hyposaline conditions affect seaweed
402 physiology (e.g. Spurkland and Iken, 2011; Mortensen, 2017). This study provides evidence
403 that seaweed morphological parameters and mechanical properties are also significantly
404 affected. This has important implications for how seaweeds interact with flow and should be
405 considered when studying seaweeds in laboratories, estuaries and the intertidal zone. Our
406 results showed that in one hour Young's modulus in tension (E_t) and bending modulus (E_b)

407 typically decreased by 57% and 80%, respectively, suggesting that seaweeds become
408 significantly more flexible. The data also indicated that blade material becomes much more
409 difficult to break (i.e. toughness increased by 130% in an hour). Another important factor was
410 the reduction of blade surface area, which has implications for both physical and biological
411 processes. Findings of this work have direct relevance for the development of seaweed
412 farming in the nearshore zone and the study of seaweed hydrodynamics in hydraulic
413 laboratories where saltwater cannot be employed.

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