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# Morphological and mechanical properties of blades of *Saccharina latissima*

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ABSTRACT

Interactions between water flow and aquatic vegetation strongly depend on morphological and biomechanical characteristics of vegetation. Although any physical or numerical model that aims to replicate flow-vegetation interactions requires these characteristics, information on morphology and mechanics of vegetation living in coastal waters remains insufficient. The present study investigates the mechanical properties of blades of *Saccharina latissima*, a seaweed species spread along the shores of the UK and North East Atlantic. More than 50 seaweed samples with lengths spanning from 150 mm to 650 mm were collected from Loch Fyne (Scotland) and tested. Seaweed blades had a natural 'stretched droplet' shape with bullations in the central fascia and ruffled edges in the area close to the stipe. Their morphological features showed high variability for samples longer than 400 mm. The blades were almost neutrally buoyant, their material was found to be very flexible and ductile, being stiffer in longer blades. The laboratory tests showed that estimates of tensile Young's modulus appeared to be similar to bending Young's modulus suggesting a reasonable degree of isotropy in studied seaweed tissues.



## 1. Introduction

In recent years, vegetation in coastal waters has been investigated for various applications. For example, it has been found to contribute to reduction of flow velocity (Fonseca and Koehl, 2006) and attenuation of waves (Möller et al., 1999; Sánchez-González et al., 2011), thus providing means for bio-inspired coastal management (e.g. Temmerman et al., 2013). Another example relates to macroalgae (seaweeds), which are among most common vegetation in coastal waters. They were employed in the Integrated Multi-Trophic Aquaculture (IMTA) (Chan et al., 2006; Chopin and Sawhney, 2009; Lamprianidou et al., 2015) and were proposed for bioremediation purposes (Fei, 2004; Mata et al., 2010). Several studies have also assessed the feasibility of seaweeds for the production of third generation bio-fuels (Hughes et al., 2012; Wargacki et al., 2012). In addition, seaweeds are a traditional source of food in East Asia (e.g. China, Japan, and South Korea), where they have been cultivated for centuries (Bardach et al., 1972). Nowadays seaweed farming is mainly confined to East Asia, because standard cultivation techniques necessitate a high amount of manual work and the associated costs are too high (Lucas and Southgate, 2012). The cultivation of seaweeds is expected to experience a continued expansion, prompted by the wide use of seaweed-derived components such as the hydrocolloids (Lucas and Southgate, 2012). This expansion, however, is conditioned by the development of innovative farming techniques that would make seaweed farming economically attractive (James, 2010).

Novel farming techniques and any of the above applications have to be supported by either numerical or physical modelling that requires a comprehensive understanding of the flow-seaweed interactions at a relevant range of spatial scales. These interactions control physical, biological and ecological phenomena concerning aquatic vegetation, and depend upon their morphological and mechanical properties (Nikora, 2010). In order to describe the motion of any streamlined body in flowing water, it is sensible to start with simple geometry considering a seaweed blade as a two-dimensional beam. For any type of application, the motion of the blade can then be described by an equation of motion such as:

$$\frac{m}{l}\frac{\partial^2 z}{\partial x^4} - T\frac{\partial^2 z}{\partial x^2} + EI\frac{\partial^4 z}{\partial x^4} = F_F \quad (1)$$

where $m$ is the body mass, $l$ is the body length, $x$ and $z$ are the longitudinal and vertical coordinates, $t$ is time, $T$ is the axial tension

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in the body, $E$ is Young's modulus of the material of which the body is made, $I$ is the second moment of area of the body and $F_F$ accounts for the forces per unit length acting on the body due to the flow action (e.g. Païdoussis, 1998; Connell and Yue, 2007). The first term in Eq. (1) represents inertia, the second term relates to the tensile force, and the third term is due to the bending force. Altogether these forces balance the forces imposed by flowing water, i.e., the total (viscous and pressure) drag force $F_F$. Equation (1) and its variants are involved in up-scaled models describing seaweed performance at a canopy scale and larger scales relevant to seaweed management and cultivation.

The second and third terms in Eq. (1) contain parameters characterising mechanical properties of the body. In addition, all four terms are influenced by the body morphology. It is, therefore, clear that the knowledge of mechanical and morphological properties of aquatic vegetation is of primary importance for understanding and predicting flow-vegetation interactions and, consequently, advancing the knowledge of their multiple effects. Reliable physical and numerical models for prediction of vegetation effects on the coastal flows and of vegetation performance in a variety of applications (e.g. IMTA, bioremediation, cultivation) can be developed only if relevant data on vegetation are available. In the literature, information on the mechanics and morphology of aquatic vegetation remains sparse. Mechanical data of seaweed tissues are provided by very few publications (Biedka et al., 1987; Hale, 2001; Harder et al., 2006; Boller and Carrington, 2007; Paul et al., 2014). Thus, for the development of reliable models concerning any aspect of flow-seaweed interactions, the obtaining of such data remains a priority task.

The present study focuses on *Saccharina latissima*, a seaweed species thriving along the shores of the North East Atlantic (Ramos et al., 2012). Studies of this species for the development of IMTA (Sanderson, 2006) and for bioethanol production (Wargacki et al., 2012) produced promising results. Therefore, the research reported in this paper aims at contributing to the knowledge of morphological and mechanical properties of coastal vegetation in relation to *S. latissima*. Section 2 is focused on methodological issues of the study, while section 3 reports and discusses the key results in relation to seaweed blade morphology and mechanical properties, keeping in mind the hydraulic conditions at the collection site.

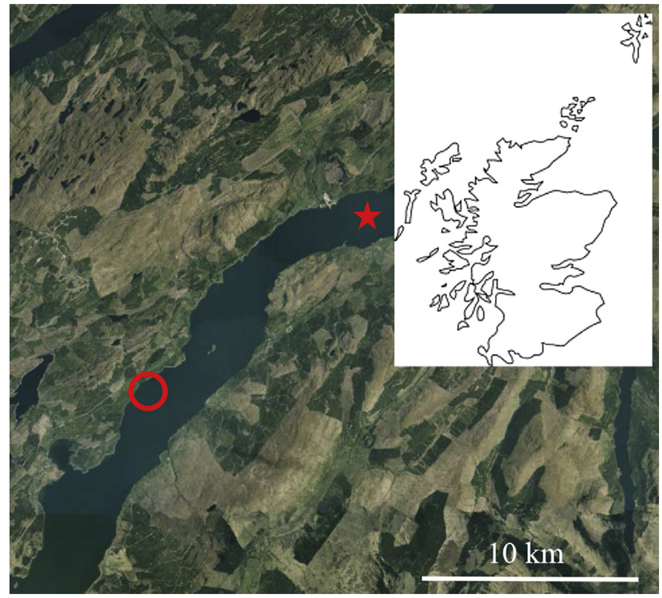


**Fig. 1.** The collection site in Loch Fyne is located in the area identified with a circle. The star represents the location of deployment of the current meter. The inset map (top right) shows the location of Loch Fyne in Scotland (adapted from http://digimap.edina.ac.uk/).

**Table 1**
Information about the current velocity data set recorded with a current meter in Loch Fyne and current velocity statistical parameters calculated by the authors.

| Characteristics of current velocity data set | | Current velocity parameters | |
|---|---|---|---|
| Location of current meter | 56.15 N, 5.15 W | | |
| Number of samples | 4656 | Mean (cm/s) | 11.1 |
| Start date (dd/mm/yy h:mm) | 20/11/1994 12:00 | Min. value (cm/s) | 1.4 |
| End date (dd/mm/yy h:mm) | 25/02/1995 10:00 | Max. value (cm/s) | 57.8 |
| Sampling interval (s) | 1800 | Stand. Dev. (cm/s) | 8.4 |
| Sea floor depth (m) | 100 | Skewness | 1.3 |
| Current meter depth (m) | 11 | Kurtosis | −0.7 |

## 2. Materials and methods

### 2.1. Seaweed collection and storage

Samples of *S. latissima* were collected with the help of *Loch Fyne Oysters Limited* on the 10th of February 2015 from long-lines deployed in Loch Fyne (Scotland). The coordinates of the collection site are 56.08 N and 5.28 W (Fig. 1). Due to the loch morphology, the most important forcing factors in the loch hydrodynamics are tides. Existing current meter data sets can provide useful information to characterise the hydraulic conditions within Loch Fyne and at the collection site. The data used in this study (available at http://www.bodc.ac.uk) were recorded with an Aanderaa RCM 7/8 Recording Current Meter mounted on a subsurface mooring approximately 10 km North East of the collection site (Fig. 1). The characteristics of the current meter data set and the bulk statistics of the current velocity calculated by the authors are reported in Table 1. The selected collection site on the loch can be considered to be sheltered and thus hydraulic conditions at this site may be biased low compared to the flowmeter deployment site (Fig. 1).

Prior to collection, seaweeds were visually inspected to assess their condition. Only seaweeds showing no signs of damage or deterioration and with no visible bryozoans on their surface were collected, their holdfasts then were removed and they were stored in tanks filled with seawater. Seaweeds were transported to the University of Aberdeen and placed into a special storage container within 8 h after collection. The storage container was a 125 l tank filled with seawater and equipped with a custom-made aeration system. The seawater in the container was changed every 3–4 days according to the standard practice for seaweed storage in tanks with no recirculating flow (Frithjof Kuepper, University of Aberdeen, pers. comm., September 2014). The tank was kept outdoor so that water temperature was as close to the ambient temperature as possible and seaweeds were exposed to natural light conditions (i.e. 8 h:16 h day:night cycle). Seaweeds were visually monitored on a daily basis to assess their condition. The blades that showed visible signs of deterioration were discarded. All seaweeds were used within 14 days after collection.

### 2.2. Morphological assessment

At a first step, the stipe was detached from the seaweed sample. Then, the seaweed blade was carefully dried with paper towels and weighed using a digital scale (OHAUS GT 2100 or Mettler P161, Mettler Toledo, Columbus, USA). Photos of the sample were taken with a digital camera (Fujifilm Finepix S1000fd, Fujifilm, Tokyo,