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# Large-scale 3-D experiments of wave and current interaction with real vegetation. Part 1: Guidelines for physical modeling

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ABSTRACT

The growing interest in incorporating nature-based solutions and ecosystem services as part of coastal protection schemes has recently increased in the literature and focused on the understanding and modeling of wave and current interactions with natural coastal landforms, such as salt marshes. With this purpose, using flumes or basins has been one of the preferred options in experimental modeling under controlled conditions. However, due to the inherent complexities associated with this approach, most of the previously published experiments are based on wave-flume experiments using vegetation mimics. The current demand for understanding the relevant processes requires a step forward, which includes experimental modeling with real vegetation on both a relevant large scale and at a sufficiently large water depth. In response to foreseen needs, this study provides useful guidance based on the experience gained from a unique set of experiments conducted in a large wave basin, including wave and current interaction with real salt marsh vegetation. This study reports on plant collection and growing strategies, plant properties, physical set-up, instrumentation, and experimental strategy and dismantling, providing guidelines aimed at being helpful for future experimental efforts at the interface of engineering and ecology.



## 1. Introduction

In the present era of global change, sustainable coastal protection is of growing importance. Hence, knowledge regarding the mitigation of flooding and erosion hazards with low environmental impact structures is of great interest (Duarte et al., 2013; Möller et al., 2014; Temmerman et al., 2013). Coastal vegetation, such as salt marshes, can play an important role in dissipating energy from waves and currents. They provide services with a high ecological and economical value (Costanza et al., 1997), which is partly related to their capacity to dissipate hydrodynamic energy (Millennium Ecosystem Assessment; United Nations, 2005; Nagelkerken, 2000; Valentine and Heck, 1999). Ecosystem services (ES) is the term applied to describe the benefits human populations obtain from ecosystem functions (Millennium Ecosystem Assessment, 2005). An increasingly recognized but not fully understood service provided by coastal ecosystems is their ability to contribute to coastal protection by attenuating waves, stabilizing shorelines and reducing flood-surge propagation (Bouma et al., 2014). All of these abilities will be relevant in the coming decades due to the potential of increasing storminess and rising sea levels (FitzGerald et al., 2008; Gedan et al., 2010).

The ability of tidal salt marshes to attenuate wave energy has been broadly studied (Asano and Setoguchi, 1996; Barbier et al., 2008; Knutson et al., 1982; Koch et al., 2009; Möller, 2006; Wayne, 1976), and this ability has been shown to have great importance for coastal defense (Barbier et al., 2008; Koch et al., 2009; Leggett and Dixon, 1994; Möller et al., 1999; Yang et al., 2008). Attenuating hydrodynamic energy is also essential for tidal marshes to follow the rising sea levels by accreting sediment (Leonard and Reed, 2002; Bouma et al., 2005a; Wang et al., 2006; Yang et al., 2008). Hence, from the perspective of both coastal defense and nature conservation, an in-depth understanding of the way wave and current energy is attenuated by salt marshes is necessary. Although a large number of studies in the literature analyze currents in tidal wetlands (e.g., Leonard and Luther, 1995; Leonard and Reed, 2002; Shi et al., 1995; Allen, 2000; Christiansen et al., 2000; Neumeier and Ciavola, 2004; Bouma et al., 2005b; and references therein) or characterize wave attenuation (Knutson et al., 1982; Möller et al., 1996; Wayne, 1976; Yang et al., 2008), only a few have focused on studying the attenuation that combines the action of waves and currents (Li and Yan, 2007; Maza et al., 2015; Ota et al., 2004; Paul et al., 2012).

Although most works in the literature have focused on addressing the energy damped by salt marshes, it is difficult to draw generalizations due to the difficulty of reproducing realistic hydrodynamic conditions in laboratory facilities for waves and currents acting together.

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Moreover, a realistic representation of the mechanical behavior and geometric characteristics of plants by means of mimics is difficult to accomplish. In the field, vegetation characteristics and hydrodynamic conditions cannot be properly controlled (Yang et al., 2008; Ysebaert et al., 2011). The results are affected by local conditions, and it is difficult to draw generalizations. Moreover, seasonal biomass changes are highly relevant, particularly in tidal salt marshes located in the temperate NE Atlantic zone, where the aboveground plant biomass is partly or completely lost during winter, which clearly affects plants' efficiency to dissipate energy from waves and currents. In contrast, flume experiments have led to generalizations by showing that wave damping by salt marshes is strongly affected by plant traits, such as rigidity, and by vegetation characteristics, such as vegetation density and standing biomass (e.g., Bouma et al., 2005a, 2010). Similarly, for submerged aquatic vegetation, biomass is a dominant factor in explaining vegetation wave-attenuating capacity (e.g., Penning et al., 2009, for macrophyte species). In addition, a recent study on seagrass surrogates showed that imposing currents on top of waves strongly reduces the wave-attenuating capacity of vegetation and that the magnitude of this effect depends on shoot stiffness (Paul et al., 2012). However, the vegetation structure, plant biomass and traits that determine shoot stiffness differ strongly among coastal plant communities (pioneer zone, lower and upper salt marsh). Wave attenuation is therefore expected to vary across communities and plants (Bouma et al., 2005a, 2010).

Consequently, the role of vegetation structure in terms of wave attenuation remains relatively poorly understood, and modelers lack sufficient experimental data to validate their models across vegetation types. It seems essential to use real vegetation to obtain realistic results to enhance the current understanding of the ecological trade-offs associated with plant-growth strategies. The use of mimics (based on plastic or flexible materials) or idealized vegetation (cylinders) is present in the literature (Anderson and Smith, 2014; Augustin et al., 2009), but this strategy falls well short of providing realistic results. Although scaling laws to preserve plants' mechanical conditions are used (Ghisalberti and Nepf, 2002), it is difficult to find materials to represent both geometrical (shoot-and-leave structure) and mechanical (bending and stiffness) properties, in accordance with a hydraulic scaling. Open questions regarding the use of surrogates in laboratory experiments arise, such as the geometrical representation of the plants (constant or variable height, width and thickness), the spatial distribution of the plants (regular and/or random arrangements) or a plant-fixing system to the bed (reproduction of the root characteristics: rigid or flexible). Moreover, the number of experiments using real vegetation under controlled flow conditions in a laboratory is low, primarily due to the difficulty of using and/or obtaining plants. Collecting seed, growing plants, keeping plants alive and monitoring plants' properties during the experiments are not easy tasks to solve.

The present contribution demonstrates a methodology to perform the eco-hydraulic modeling of salt marshes using real vegetation to determine the efficiency of plants in dissipating energy from waves and currents. The novelty of the experimental work presented here is the study of three-dimensional wave and current interactions with real salt marshes, using both collinear and non-collinear waves and currents. Two different salt marsh species are considered due to their different biomechanical properties and standing biomass, and they both can act as pioneer species in estuaries (Bouma et al., 2010): *Spartina anglica* and *Puccinellia maritima*. The methodology proposed for conducting experiments with living plants in a basin covers different steps, from the collection and growth of the plants to performance of the experiments. Although guides are already available in the literature that note the more important factors to consider (e.g., Frostick et al., 2014), the present work is also a case study in which the methodology is successfully applied. The main objective is to provide a general methodology to run experiments with living plants, and it considers both waves and current conditions, with the aim of extending understanding from both ecological and engineering perspectives.

This study is organized as follows. Section two is devoted to the identification of the experimental needs to perform experiments with real vegetation. Section three focuses on detailing the methodology, covering both practical and technical issues for the experiments presented here. The physical set-up, including the details regarding the flow conditions and the measurements, is introduced in section four. Section five presents a proposed set of recommendations based on the experience gained from the experiments. Finally, conclusions are drawn in the last section.

## 2. General considerations for the use of real plants in wave-basin experiments

When planning wave-basin experiments with living plants, a series of initial considerations must be made in order to analyze the feasibility and the quality of the data obtained from experiments. In the present study, the conceptual aim of the experiments was to analyze the wave-damping and flow alterations due to wave and current interactions with salt marsh vegetation patches/meadows considering the effect of different hydrodynamics, plant traits and meadow characteristics. Large-scale basin experiments using real vegetation were the preferred option to: 1) consider the collinear and non-collinear waves and currents, 2) avoid possible scale effects and 3) overcome the well-known limitations inherent to the use of mimics (Frostick et al., 2014). When addressing our overall objective, a number of important relevant questions arose:

- the selection of the most appropriate species for the experiments,
- the source, amount and survivability of the selected plants,
- the suitability of the substrate to host a meadow,
- the definition of the experimental set-up to simulate close-to-nature conditions,
- the plant degradation throughout the development of the hydraulic experiment,
- the hydraulic characteristics to be tested during the experiments (water depth, waves and currents),
- the plant response to hydraulic loading,
- the information to be collected from the experiments relative to the plants (physical and mechanical variables),
- the hydrodynamic variables to be collected and the measuring techniques and recoding equipment to be used to slightly interfere with hydrodynamics and plant behavior, and
- the logistics and operation to conduct a large-scale experiment using real vegetation.

It is difficult to summarize all of the different open questions presented during the experiments because options may vary according to the species tested, the characteristics of the facility and the previous experience. However, the set of issues found to be the most relevant are addressed in this section. Although some of them have been treated in Frostick et al. (2014), in the current study, general guidance is given for application to a real case.

### 2.1. Growing or collecting

After the plant species have been selected, the question of whether plants should be grown on site or collected from nature is likely the first question to answer (see sketch in Fig. 1). Both possibilities possess advantages and disadvantages, and the expenses should not be underestimated. Therefore, the choice for the planned experiment may vary by case.

#### 2.1.1. Growing

To develop a growing scheme, a number of steps needs to be followed to answer the questions of where, when and how to conduct

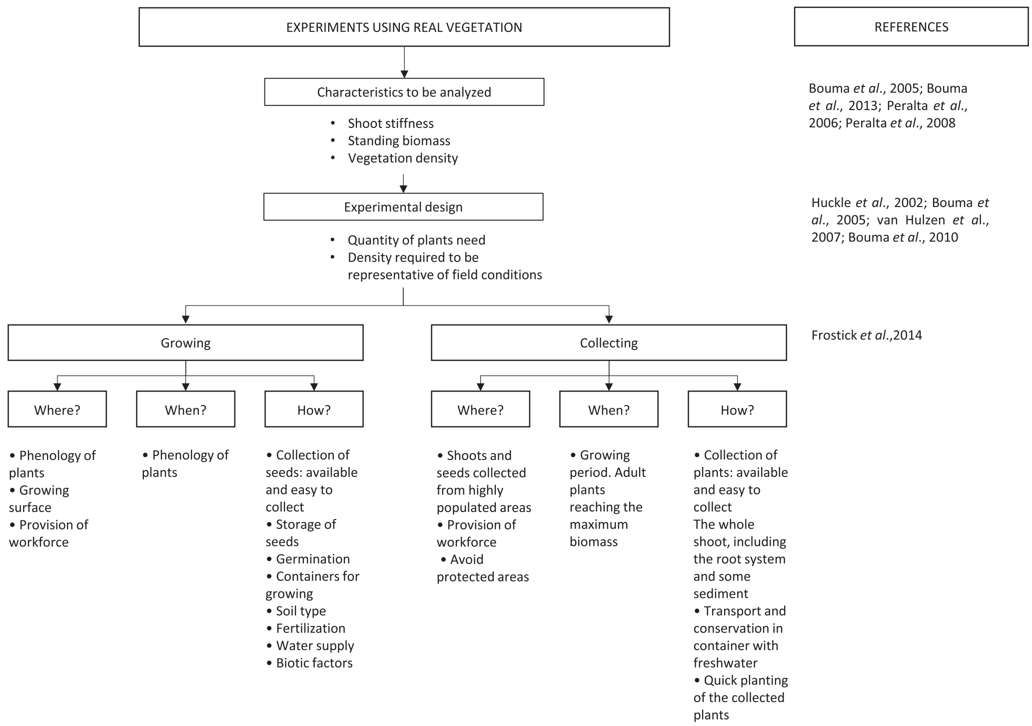


**Fig. 1.** Flow chart: initial questions regarding collecting or planting strategy for using plants in a lab experiment.

the growing. Good knowledge of the ecology and phenology of the target plants is fundamental. It must be decided whether to use an outdoor growing area or a climate room based on the environmental restrictions of the species, the required quantity of plants and the available facilities. In addition, it must be taken into account that most abiotic influences are two sided; there will be not only a minimum but also a maximum level of the factor that limits plant growth. Light intensity, for example, can be too low to assure good growth. However, excessively high light levels may also damage plants (Barber and Andersson, 1992). The usage of a climate room allows for the growth of a broader range of species and throughout the year, but it also restricts the amount of plants that can grow and may be more cost intensive. Whenever outdoor climate conditions are adequate, it is preferable to grow plants outdoors to mimic the natural conditions as much as possible. A lack of exposure to hydrodynamic forces from tidal currents and/or waves might cause plants to be less stiff, but this is not necessarily the case; mechanical properties might be driven by factors other than hydrodynamic exposure (La Nafie et al, 2012).

It is advisable to plan to grow a larger number of plants than the actual number required for the experiments. It is advisable to check the onset and end of the vegetation growing period (temperature, day length, rainfall) before planning the time schedule of the experiment. Additionally, small-scale variation of climatic factors should be taken into account, such as the proximity of buildings that can influence the wind intensity, insolation or precipitation reaching the growing area.

An important factor for time and financial planning is the availability of seeds. It is possible to buy seeds for some plants, but in many cases, it is necessary to collect seeds from the field. To do so, it is necessary to check whether official permission is required due to environmental restrictions. Depending on the species and quantity, collecting and preparing seeds can be a time-intensive task. The seeds need to be separated from remains of the inflorescence to prevent molding. The storage of the seeds in a dark and, in most cases, cool place is required to avoid germination impulses (e.g., lightproof boxes in a refrigerator; Bewley, 1997; Koller, 1972). In addition, the amount and frequency of irrigation should be determined. It is sometimes advisable to germinate seeds on petri dishes in a warm, moist and light room prior to planting; this can enhance germination success, and plants can be spaced more evenly. In many cases, germination impulses can enhance germination success. The type of germination impulse can vary across species, depending on their natural climatic conditions. Many species react positively in considerably higher temperatures, e.g., at 35 °C.

The optimal container in which to grow the plants should be selected based on the rooting system depth of the species and the feasibility of transporting and placing the plants into the experimental area. A good drainage system should be ensured, for example, by making drainage holes in the containers and filling them with cotton wool to avoid soil loss. This approach avoids anoxic conditions in the soil, which damage the plants either by toxins, desiccation due to reduced water uptake by the roots or nutrient deficiency (Drew and Lynch, 1980).

Another important aspect is the selection of the soil in which to grow the plants. The selection of the correct soil type is based on the plant's requirements and availability and the technical constraints in the flume or basin. The soil type, or, in other words, the grain-size distribution, defines not only the rooting ability but also the water-holding capacity and the retention of nutrients (Scheffer et al., 2002). It is important for soil to be permeable and to be mixed with clay. A sandy soil will absorb water well, but it will drain it just as easily. More sand makes it easier for the roots to grow (faster), but it also requires more fertilizer. That is, sand contains few nutrients, and the available nutrients are easily washed out, causing a low nutrient retention. Soils high in clay, in contrast, show a low infiltration rate but also low drainage. The water is held longer in the soil but is less available for plant roots due to high capillary forces in the soil pores. Silty loam shows the highest level of water available to plants (Scheffer et al., 2002).

In most cases, fertilization is advisable. Note that nutrients, although necessary for plant growth in a certain concentration, can also be harmful at high concentrations (Hernandez-Soriano, 2012; Kronzucker, 2013). Using a slow-release fertilizer will lower the risk of over-fertilizing and assure a more continuous nutrient supply. Depending on the soil selection, the addition of nutrients to the soil will be higher or lower. In sandy soils, nutrients are washed out faster, and a higher additional supply is needed (Scheffer et al., 2002). These nutrients can be added by fertilizers. Nutrient availability also depends on the pH and organic matter content (Osman, 2013). A lack or excess of different nutrients can be recognized by certain changes in the plants' appearance (e.g., yellow leaves for N-shortage; purplish veins and stems for P-shortage), and previous studies have described these changes (e.g., Snowball and Robson, 1991).

An appropriate water supply is crucial for adequate plant growth, particularly in the seedling phase, when plants have very small roots. At that initial stage, regular and well-distributed irrigation is very important. The use of sprinklers is also recommended to assure a good distribution of water. To plan the irrigation times, the hazard of the plants being burned while being wet during full sunshine should be considered. The loss of water due to temperature, wind and insolation must also be considered to preserve the most optimal conditions for plant growth.

In addition to the abiotic requirements of the plants, such as irrigation, nutrient supply and insolation, biotic factors can influence plant growth. Competition with other species should be avoided by removing those (weed) plants. Pests in the form of viruses, bacteria, fungi, insects, or slugs can cause considerable damage and should be taken into account when trying to identify the cause of possible damage or reduced growth. Microbial pests in particular are not easy to identify for the non-experienced, so consulting a professional maybe necessary. Some halophytic plants will grow better under the application of saline water. If it is sprayed on the leaves, water can also act as a repellent (albeit a weak one) against some pests. However, saltwater should not be sprayed when the sun is shining strongly because it may cause the osmotic 'burning' of the leaves.

Depending on the aim of the study, different sets of vegetation measurements are required. Density, height and biomass can serve as good measures to characterize the entire patch of vegetation. Plant height can be highly variable, and therefore, it is recommended to take sufficient replicates. Vegetation biomass is usually measured as dry mass/area. Density can also vary by location. Sufficient randomly selected samples should be taken to account for such spatial variability to quantify the density of 15 monitoring boxes. Morphological traits, such as the plant height, the weight (dry or fresh) of the different plant organs (stem, leaves, roots), the number, length, and onset of the leaves, and the stiffness of the stem and leaves can be used to characterize plant behavior under hydrodynamic stress. These traits should always be measured on a representative subset because there can be a noticeable intraspecific variation in a trait (Albert et al., 2011; Violle et al., 2012). Measurements should be taken at different stages of the growing period to monitor plant growth. This rule applies for all biological measures.

#### 2.1.2. Collecting

An alternative to growing plants from seeds is collecting them directly from the field. In most countries, permission is necessary to extract plants or collect seeds. The ease or difficulty of obtaining permission depends on the protection status of the target species and the protection status of the area in which it is growing. In general, because collecting plants presents a considerably stronger disturbance to the ecosystem, it can be expected to be harder to obtain permission to collect plants than to collect seeds. Furthermore, apart from the question of whether permission is required and likely to be obtained, it is advisable to conduct one's own assessment of the effect of the disturbance on the ecosystem. There are also logistical constraints that should be considered when collecting a large number of plants, such as the availability of machines able to access the terrain or the storage area.

To permit the resettlement of the plants after transplantation, the root system should be damaged as little as possible. For experimental or transport reasons, root systems may need to be cleaned of soil; this process can be difficult and time consuming, and it must be performed carefully. Plants with cleaned root systems can be stored for some time in water. Every act of disturbance, such as collection from the field, the cleaning of root systems, storage, transportation, and replanting, is a stressor to the plant and can reduce its performance (in terms of re-rooting, growth and survival) after being transplanted. Therefore, it is advisable to keep every disturbance as small as possible. When transplanting vegetation from the field, it should be considered that not all individuals will survive or continue growing in the long term. Transplanting with sufficient time ahead of the experiment will allow for root regrowth and plant stability but also carries some uncertainty regarding survival.

The most recent example of a field collection strategy can be found in Möller et al. (2014), where large-scale flume experiments were conducted using vegetated marsh blocks directly cut from a natural marsh.

### 2.2. Dismantling

Species selection can be performed attending to many different aspects, such as biomechanical properties, the growing time and success or attenuation capacity, which can lead to the selection of species that are not native to the area where the experiments are conducted. When no native species are used, it must be assured that no seeds, flowers, rhizomes or living plants leave the facility and thus have the chance to propagate. Special attention should be paid to the sediment that must be cleaned of any parts of clonal growth organs.

## 3. Plant growing and collection in the present experiments

Two different salt marsh species, both present in North European estuaries, were considered in the present experiments: *Puccinellia maritima* and *Spartina anglica*. They pioneer different habitat locations in estuaries. *P. maritima* can be found in middle and lower marshlands, whereas *S. anglica* occurs in lower marsh, i.e., the pioneer zone (Bouma et al., 2010). Moreover, they are characterized by different biomechanical behavior. *P. maritima* can be considered a flexible plant with a high degree of bending and waving behavior due to flow action. On the contrary, *S. anglica* is a stiff plant with a limited degree of bending. This difference in stiffness yields different abilities to trap sediment or dissipate wave energy in natural environments, as shown in Bouma et al. (2010). The plants' morphologies are also different. The aforementioned features of the two selected species allow for studying the influence of key plant traits in the attenuation capacity. Furthermore, their growing time is short; four months is enough time for seeds to mature into plants.

### 3.1. Growing

For both species, the seeds were collected at the Scheldt Estuary (The Netherlands) to be later planted and grown in a laboratory in Santander (northern Spain). Seeds of *S. anglica* were shipped in dormancy, protected from the light, in plastic containers filled with salty water. The containers were stored at 4 °C in the dark until germination. *P. maritima* seeds were also shipped in dormancy, protected from light and moisture in paper bags. The seeds were stored at 4 °C.

The vegetated area needed for the experiments was a circle with a 6-m diameter selected based on the basin's central pit dimensions (described in detail in section four). The plants were grown in plastic boxes that were later used in the experimental setup. To fill the 6-m-diameter circle with the highest number of boxes, 92 large boxes (0.60 m long, 0.40 m wide and 0.27 m high) and 18 small boxes (0.30 m x 0.40 m x 0.27 m) were required for each species of vegetation. Nevertheless, in order to have extra boxes available, 100 large and 25 small boxes were planted for each setup.

The number of seeds needed for the required vegetated area depended on the species. The survival rate of *S. anglica* seeds was estimated to be 5%. To cover the experimental area (28 $m^2$), 6,000 seedlings were necessary (approximately 220 seedlings per square meter).

Accordingly, 120,000 seeds were germinated. The germination was performed on 15-cm diameter petri dishes (70 seeds/dish) containing permanently moist paper. To increase success, the germination was performed in a warm and moist room (±25–30 °C) with natural light (left panel in Fig. 2). The two germination batches of *S. anglica* were affected by the fungus *Periconia* sp., which is known to be pathogenic to grasses. The estimated germination rate of the seeds of *P. maritima* was 100%. However, it was discovered that the roots of *P. maritima* seedlings are very fragile, and transplantation damaged the plants. Consequently, the seeds of *P. maritima* were directly sown in the containers. To address possible eventualities, a higher number of seeds than were required for the experiment were sown for the two species.

The boxes were placed outdoors in 5 double rows (right panel in Fig. 2). For an easier subsequent transportation to the flume and to help drainage water run below the planting area, boxes were placed over pallets. A major problem in this type of facility is the accumulation of water below the boxes, which may help algae and fungus grow.

To minimize the effect of box edges on the flow, which could induce additional and unrealistic roughness, the boxes were filled to the top with sediment. The soil for growing consisted of washed silica sand with a grain size of 200 μm (89 % sand, 9 % silt and 2 % clay), and 29 $m^3$ of sediment was used (1500 kg /$m^3$). Two layers of slow-release fertilizer (4.5 g /$dm^3$ of soil) were mixed with the sand in the filling process (upper and bottom half). To prevent algal blooms, no fertilizer was added to the top layer of sediment. Through the growing process, additional foliar fertilizers were applied to plants limited by phosphorous (purple leaves) or nitrogen (yellow leaves). One reason for poor plant growth is related to a change in soil pH due to fertilizer addition. Thus, the pH was constantly measured.

Although the two target species have a wide range of tolerance to salinity that allows them to colonize areas where other species cannot be established, their growth and photosynthetic capacity is enhanced by freshwater conditions. Although the plants were predominantly watered with freshwater, they were occasionally given saltwater to ensure normal plant development by preventing excessively fast growth, which may cause unnaturally weak plants. This is a widely used approach both when using plants grown from seed (e.g., Bouma et al., 2005a,b, 2010, 2013a,b) and when using field-transplanted vegetation that has to be kept alive over a prolonged period of time (e.g., Möller et al., 2014). Both species used in our experiment normally inhabit the regular inundated pioneer zone of the salt marsh (Bouma et al., 2010, 2013a,b), so we expect them to have a similar salt tolerance and thus to require a similar amount of saltwater flooding to ensure normal growth. Accordingly, freshwater was used for irrigation. A drip irrigation system with 4 lines of pipes in large boxes and 3 lines in small ones was designed (Fig. 3). The total hose length was approximately 900 m. The watering was set to start every 15 minutes, although it was adapted to the weather and stage of growth. Moreover, on hot days, young plants were moistened by sprinklers early in the morning. To prevent the accumulation of water, two holes were created at the lower part of the boxes and filled with plastic pillow stuffing (synthetic cotton wool) for drainage. The presence of slugs and worms was avoided by adding half-strong saltwater (17.5 g of salt /l) twice a week. Moreover, ecological pesticides were applied once a week after sunset to treat aphids (2 ml of piretrine and 1 ml of neem per liter of water) over three months.

The plants were grown outdoors from June to September, 2012. The growth rate is highly related to air temperature. Based on the temperature range registered in Santander between 2006 and 2011 and the time required for stems to grow 30–40 cm long (Bouma et al., 2013a), four months was considered sufficient time to achieve the required plant size.

Once they reached a height of 1.5–2 cm, the seedlings of *S. anglica* were planted individually in holes 10 cm deep (40 seedlings/large boxes; 20 seedlings/small boxes). To compare the success rate of different seeding techniques, which is important when one needs to obtain large quantities of plants, *P. maritima* was sown with dry and wet seeds. Dry seeds were sown directly, whereas wet seeds were maintained in freshwater some days before sowing. It should be noted that none of the dry seeds germinated. The sowing density ranged from 1.5 g/$m^2$ to 1.9 g/$m^2$. The seeds were weighted by mixing with sand, scattered homogeneously on the boxes and covered with a thin layer of dry sand on top. In the early germination stage, seedlings of *P. maritima* are extremely vulnerable to drought and light. Thus, to prevent plants from burning, the seedlings were covered with a coconut net when bright sunlight occurred. Additionally, a greenhouse-like coverage with mosquito net was built to protect the seedlings from birds.

The growth rate was directly monitored with measures and indirectly with pictures taken weekly (Fig. 3). The growth was highly irregular, and differences in the density and leaf length were observed for both species. Two weeks before the beginning of the experiments, the average shoot lengths reached within the small and large boxes were 28.4 ± 2.66 and 13 ± 1.89 cm, respectively. In most boxes, neither the length (the expected length was 30 cm) nor the density was sufficient to perform the experiments. Consequently, one shipment of *S. anglica* plants directly collected from the Scheldt estuary was planted in between the seedlings (see 3.2), which yielded the desired density (see 3.3). The differences observed in the boxes of *P. maritima* were highly related to the density of the seeds sown. The boxes sown with a density of 1.9 g/$m^2$ reached a maximum shoot height of 100 cm and the plants grew extremely dense; some of them blossomed. Boxes sown with 1.5 g/$m^2$ did not attain sufficient growth and they did not reach the required density. To homogenize the length and density of the boxes, some shoots from the dense boxes were transplanted into sparse boxes. Although some of the roots broke during the process, the transplantation worked well in achieving the desired density (see 3.3).

**Fig. 2.** *S. anglica* seedlings in the climate room (left) and outdoor plantation area (right).

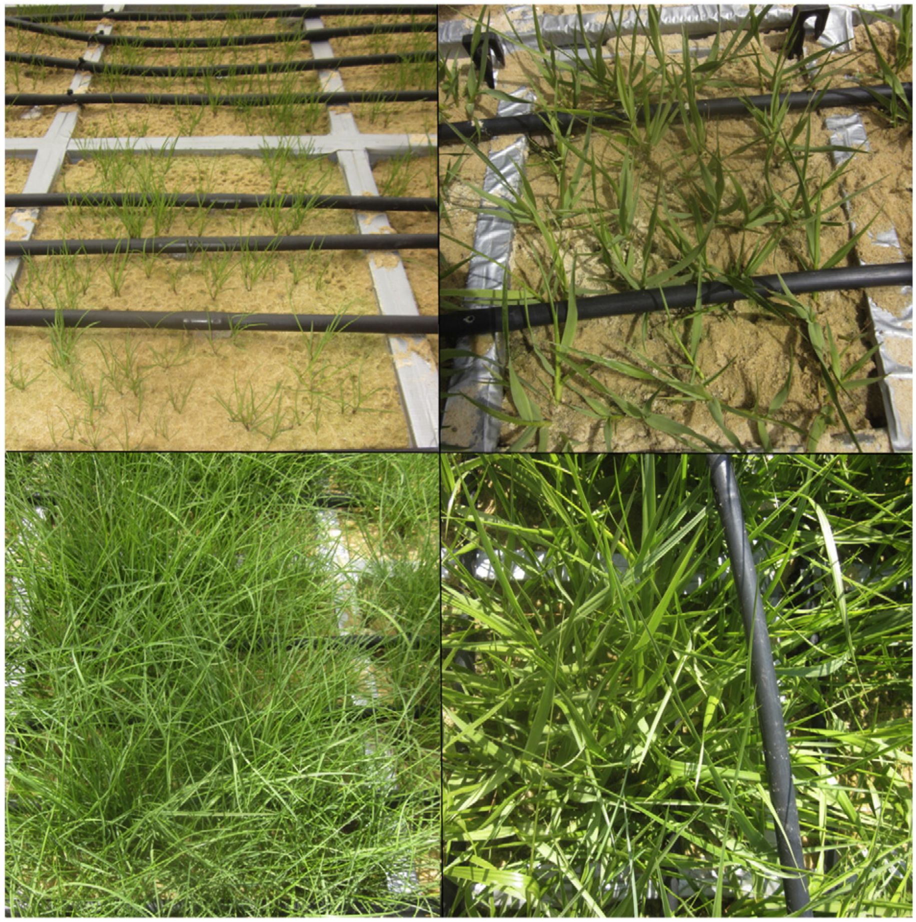

**Fig. 3.** *P. maritima* (left) and *S. anglica* (right) growth. The start of the growing process is shown in the top panels; the end, in the lower panels.

*3.2. Collecting*

The growing of *S. anglica* was not as successful as expected. The growth was sparse, and the density was lower than expected. Consequently, two weeks before starting the hydraulic experiments, approximately 6,000 plants were collected from the Eastern Scheldt Estuary. To minimize the damage to the above- and below-ground organs, the plants were excavated with their root systems. For transportation, the root systems were cleaned of sediment so that the weight was low and the packing space was small. The cleaned plants were stored in open plastic boxes with filtered seawater.

Plants were shipped two weeks before the experiments began and stored outdoors in open boxes with natural light, filtered seawater and fertilizer. Shoots were planted in the boxes 3 days before the tests started. The length of the plants varied between 30 and 60 cm. To prevent the loss of shoots with water movement, the plants were planted 27 cm deep (bottom of the boxes), and the top of the sediment was covered with pebbles. The number of shoots planted in each box depended on the initial density, considering a desired final averaged density of approximately 700 shoots/m$^2$.

*3.3. Plant property measurements*

The density, standing biomass, plant traits and plant stiffness, including stems and leaves, were determined to characterize the plants. The average dry mass of the standing biomass (g DW m$^{-2}$) and dry mass per shoot (both dried for 48 h at 70 °C) were measured on representative subsamples at the end of the experiments. Subsamples for standing biomass were obtained by harvesting 15 boxes (10% of the total boxes). Dry mass per shoot was obtained by weighing 81 and 87 shoots of *S. anglica* and *P. maritima*, respectively, randomly selected and representative for the size distribution of the vegetation. Shoot density was obtained by dividing the standing biomass by the average shoot dry weight.

The meadow density ultimately used was 2436 shoots/m$^2$ for *P. maritima* and 729 shoots/m$^2$ for *S. anglica*. The meadow density was reduced in two sequential steps, obtaining approximately 66% and 33% of the original density for *P. maritima*, and only one step was needed for *S. anglica,* achieving 66% of the initial density in that case. The 100% densities were representative of field conditions, and the lower densities (66% and 33%) were used to study the influence of this parameter in energy attenuation. With these density reductions, we targeted having similar biomass levels for both species to be able to compare wave attenuation. As shown in Table 1, the biomass for the 66% density for *P. maritima* is very similar to the 100% density measured for *S. anglica*. The same occurred for the 33% density for *P. maritima* and the 66% density for *S. anglica*. These density reductions were performed via snorkeling over the meadow to avoid stepping on and damaging the plants. The density reduction of the entire meadow was performed in

**Table 1**
Vegetation conditions.

| Case | Species | Target density (shoots/m$^2$) | Achieved density (shoots/m$^2$) | Biomass (g/m$^2$) |
|---|---|---|---|---|
| P100 | *P. maritima* | 2436 (100%) | | 443 |
| P66 | *P. maritima* | 1608 (66%) | 1389 (57%) | 254 |
| P33 | *P. maritima* | 804 (33%) | 877 (36%) | 146 |
| S100 | *S. anglica* | 729 (100%) | | 290 |
| S66 | *S. anglica* | 481 (66%) | 430 (59%) | 171 |

one day. Table 1 contains the target density obtained when the plant density was reduced by removing plants and the one obtained after the evaluation of the measurement in the meadow. The vegetation densities used in the experiment fit within normal densities, as observed for *S. anglica* on sandy sediments (van Hulzen et al., 2007 and Widdows et al., 2008) and with local field counts for *P. maritima* (Bouma et al., 2013a,b). The 100% densities were representative of field conditions, and the lower densities (66 and 33%) were used to study the influence of this parameter in energy attenuation, which may be expected to occasionally occur under poor growing conditions. Biomass was measured for both species at the beginning and at the end of the experiments of each density tested. *S. anglica* biomass changed 6 % from the beginning to the end of the tests. A loss of 11 % was calculated for *P. maritima*. The loss of biomass was estimated for the different densities tested throughout the experiments. For *S. anglica,* the average shoot biomass for the 100% density test was 0.55 ± 0.33 DW/shoot (using 37 samples). For the case with 66% density, a biomass of 0.51 ± 0.34 DW/shoot (using 44 samples) was estimated, revealing a small deviation in the standing biomass. The values for *P. maritima* showed the same behavior, with a biomass of 0.74 ± 0.48 DW/shoot (using 32 samples) for a 66% density and 0.85 ± 0.58 DW/shoot (using 26 samples) for 33%. The standing biomass was also determined for each configuration, as shown in Table 1.

Leaf traits were measured in the subsamples of the 15 boxes selected for monitoring (2 shoots/box of *P. maritima* and 3 shoots/box of *S. anglica*). The mean height, mean leaf width and mean number of leaves per shoot were evaluated via a statistical analysis conducted on the randomly chosen samples. Table 2 shows the results obtained from the analysis of the mentioned properties, and Fig. 4 shows an example of one plant for the two species.

Vegetation stiffness was measured via a tensile strength test for both stems and leaves. The tests were performed in the Laboratorio de la División de Ciencia e Ingeniería de los Materiales (LADICIM) at the University of Cantabria using plants from both species with 100% density (Fig. 5). To preserve the biomechanical properties of the plants, tensile strength tests were conducted immediately upon harvesting the plants from the nursery areas. The results for the Young's modulus of the stem and leaf elasticity of both species are specified in Table 3. Although it is well known that the biomechanical properties of plants (stiffness and elasticity) are degraded during the performance of experiments (Puijalon et al., 2005, 2008), this degradation was minimized by lowering the water level from the basin at the end of the day and keeping the plants exposed to natural light during the experiments. It was desirable but not possible to repeat tensile strength tests throughout different stages of the experiments. In addition, the number of broken plants throughout the experiments was evaluated, revealing the stable structural integrity and healthy physiology of the plants.

The values obtained from the tensile strength test were found to be in agreement with those found for *S. anglica* by Chatagnier (2012), who reported a modulus of elasticity equal to 159.8 MPa. We are not aware of tensile strength test results for *P. maritima* to compare with the ones obtained here.

### 3.4. Dismantling

*S. anglica* is the result of chromosome doubling by *Spartina x townsendii,* the sterile hybrid between the cord-grass *Spartina maritima* and the introduced North American smooth cord-grass *Spartina alterniflora* (Nehring and Adsersen, 2006). This species has been shown to be highly invasive in many parts of the world. As of now, *S. anglica* has not been cited in Spain, but *S. alterniflora* is cataloged as an invasive alien species (Sanz Elorza et al., 2004). Because of the high potential for the natural dispersal of introduced aquatic species, precautionary measures were taken in the dismantling of the experimental setup. The main pathways of dispersal were whole plants, fragments of rhizomes or seeds to be introduced in sanitation systems or to leave the facility. To reduce the dispersal risk, the plants were collected from the containers by hand, and the sediments were sieved. The plant remains were treated with herbicides, stored in dark conditions until dehydrated and calcined (500 °C, 24 h). Because *P. maritima* is native to northern Spain, its disposal was less critical. However, the management of the plants and seeds was the same as for *S. anglica.*

**Table 2**
The mean and standard deviation (in brackets) for plant dimensions of both species.

| Species | Averaged height (cm) | Averaged leaf width (cm) | Averaged number of leaves per shoot |
|---|---|---|---|
| *P. maritima* | 47.29 (8.65) | 0.30 (0.10) | 5.5 (2.57) |
| *S. anglica* | 28.40 (2.66) | 0.62 (0.20) | 5 (1.24) |

## 4. Physical set-up

The experiments were performed in the CCOB (Coastal and Ocean Basin) laboratory at the Environmental and Hydraulic Institute “IH Cantabria” in Santander, Spain. The basin was 44 m wide, 30 m long and 4.75 m deep, and it was able to generate multidirectional waves and omnidirectional currents simultaneously, covering the objectives of the present work. Waves were generated using a segmented-type system formed by 64 independent wave paddles able to generate multidirectional short- and long-crested waves. Although wave makers are capable of both piston- and flap-type motion, only the piston type was used in the experiments to better represent waves in shallow-water conditions. Currents were created using 12 thrusters (900 mm in diameter) placed on the floor level below the basin bed. Water was pumped from the lower level and flowed up through a set of gates opened at the basin-bottom level. Gates were disposed in two rows along the width of the whole basin, one close to the wave-makers and another close to the opposite basin wall. Operating the thrusters accordingly, the current was generated in the same or in opposite direction of the waves (Fig. 7). Although the wave generation device was equipped with an active absorption system, it was not used during the experiments. A wave-maker correction to absorb waves was not applied to ensure the same wave input signals for wave generation, even when the current was activated. In addition, several tests were performed to ensure that the energy dissipated by the passive absorbers (made of multi-layers of perforated screens) placed around the full basin perimeter was lower than 5% and consequently did not affect the experiments.

Vegetation was placed taking advantage of a 6 m-diameter central pit located at the center of the wave basin, which could be lowered beneath the basin bottom up to 8 m. The pit was far enough from the gates to allow the current to develop a uniform profile prior to reaching the meadow. Several tests were developed to confirm the uniformity of profiles by means of ADV measurements at different points in the water column before placing the vegetation on site. The level of the pit was lowered, and the boxes containing the plants were placed inside, approximately 27 cm below the basin bottom. Groups of 4 plastic boxes containing plants were mounted over a pallet and moved with forklift inside the pit. The upper soil level of the boxes was set at the same level as the basin bottom. This allowed for the saving of time and effort to ensure a smooth transition from the basin bottom to the vegetation patch. The other way to place the boxes in the basin is to build a transition slope long enough to ensure that velocity profiles affecting the vegetation respond to the target and that they are uniform (Luhar and Nepf, 2011). Moreover, waves and currents were affected by a uniform bottom roughness across the test area corresponding to the basin's concrete bed. To prevent sediment from washing up from the boxes due to flow action, small gravel was placed on the soil contained in the boxes filled up to the same level of the basin bed. Because the meadow was constructed using rectangular boxes and the pit was

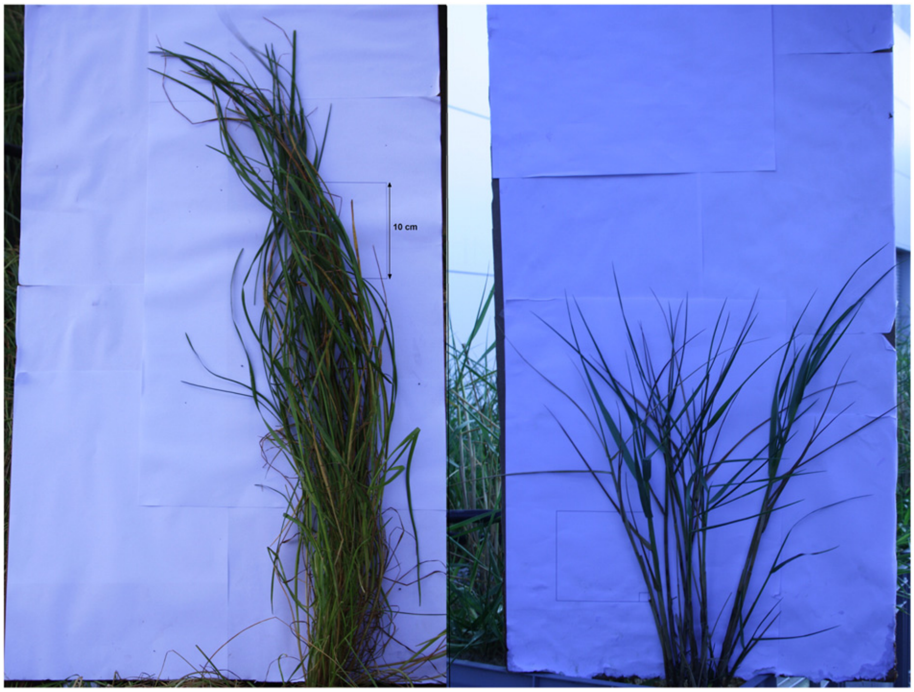


**Fig. 4.** Mature *P. maritima* and *S. anglica* plants.

circular, a platform made of wood was designed to cover the remaining space. Fig. 6 shows the box setup procedure, and Fig. 7 shows the details of the box distribution. To keep the plants healthy, the water level was lowered after the tests at the end of the day, keeping plants out of the water for almost 12 h per day. Although the basin was inside a building with a black roof, windows were kept open during the experiments to allow natural light to reach the plants to keep the conditions as natural as possible. Furthermore, the experimental timetable enabled continuous work to reduce the total number of days that plants spent inside the basin.

Free surface and flow velocities were measured during the experiments. Furthermore, a submerged camera was placed to record plant movements, and a top-side camera was used to record the tests. *P. maritima* tests were performed using 20 capacity free surface gauges and 3 ADVs to record the flow velocity. *S. anglica* tests were conducted using the same devices but included 8 extra free surface gauges (numbered in Fig. 7 from 21 to 28). The position of the free surface gauges and the velocity ADVs is displayed in Fig. 7. Crosses represent the location of the free surface gauges. The ADV locations are plotted in the figure with triangles.

**Fig. 5.** Tensile strength test for *S. anglica* stem.

A group of five gauges was placed close to the wave-makers to calculate directional reflection (see gauges 16, 17, 18, 19 and 20 in Fig. 7) using a Bayesian directional method. Two gauges were placed seaward (gauge 1) and leeward (gauge 9) in the meadow to measure incident waves from the wave-makers and transmitted waves from the meadow. The rest of the wave gauges were placed both inside (15 gauges) and outside (7 gauges) the meadow to record the spatial distribution of the free surface. Gauges located inside were set following three alignments, along the diameter and at two lateral profiles, to measure spanwise free-surface oscillations.

Velocity measurements were recorded using three 3-D Acoustic Doppler Velocimeters (ADVs): two Vectrinos and one Nortek device. The Nortek ADV was located seaward in the meadow to evaluate incident flow conditions. The two Vectrinos were placed inside the meadow, at the center of the pit and halfway between the center and the leeward end. Velocity measurements were taken at a single elevation, 30 cm from the bed. The measurements were synchronized using an external trigger to initialize both velocity and free surface measurements to easily relate the free-surface and velocity measurements. Both the free surface and velocity were sampled at 120 Hz.

To prevent plant leaves from entering the ADV measurement control volume, a special structure was designed (see Fig. 8). It was made of plastic wires and installed at the ADV arm, protecting the ADV measuring sensor and keeping the measurement area free of plants. This system prevents a decrease in the number of shoots to be removed to create a clean area (cf. Luhar et al., 2010), minimizing the effect on the

**Table 3**
Young's modulus of elasticity for the stems and leaves of each vegetation species.

| Species | Stem (MPa) | Leaf (MPa) |
|---|---|---|
| *Puccinellia* | 13 | 7.8 |
| *Spartina* | 164.2 | 77.6 |

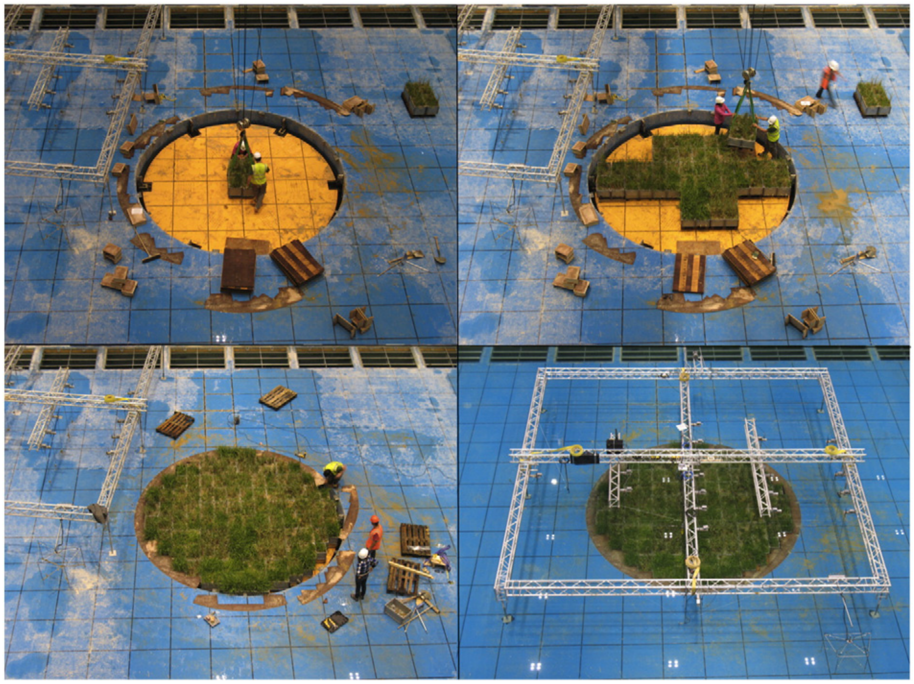

**Fig. 6.** Box disposition in the lowered pit of the basin.

field density and consequently allowing measurements to be taken under more realistic conditions.

*P. maritima* and *S. anglica* grow in middle and upper tidal marshes and are permanently submerged only during flooding events. Because the current research was focused on the wave-attenuation capacity of the plants during extreme events, four different water depths (h) were considered during the experiments, 0.40, 0.60, 0.80 and 1 m, to be representative of flooding conditions. Five regular and one irregular wave cases were tested. Wave heights and wave periods were selected based on the wave conditions presented in estuarine zones and under extreme events. The locations of *P. maritima* and *S. anglica* in the estuary correspond to areas sheltered from large waves; consequently, wave conditions are representative of average natural conditions on a prototype scale. Details of the wave characteristics are presented in Table 4. Regular wave conditions were generated using non-linear wave generation. Wave energy was distributed for irregular wave tests according to a JONSWAP-type spectrum with a 3.3-enhancement factor. Only one current velocity (Uc = 0.3 m/s, depth averaged value) was considered, acting collinearly in the same direction as wave propagation and also in the opposite direction. The value of the current velocity was selected

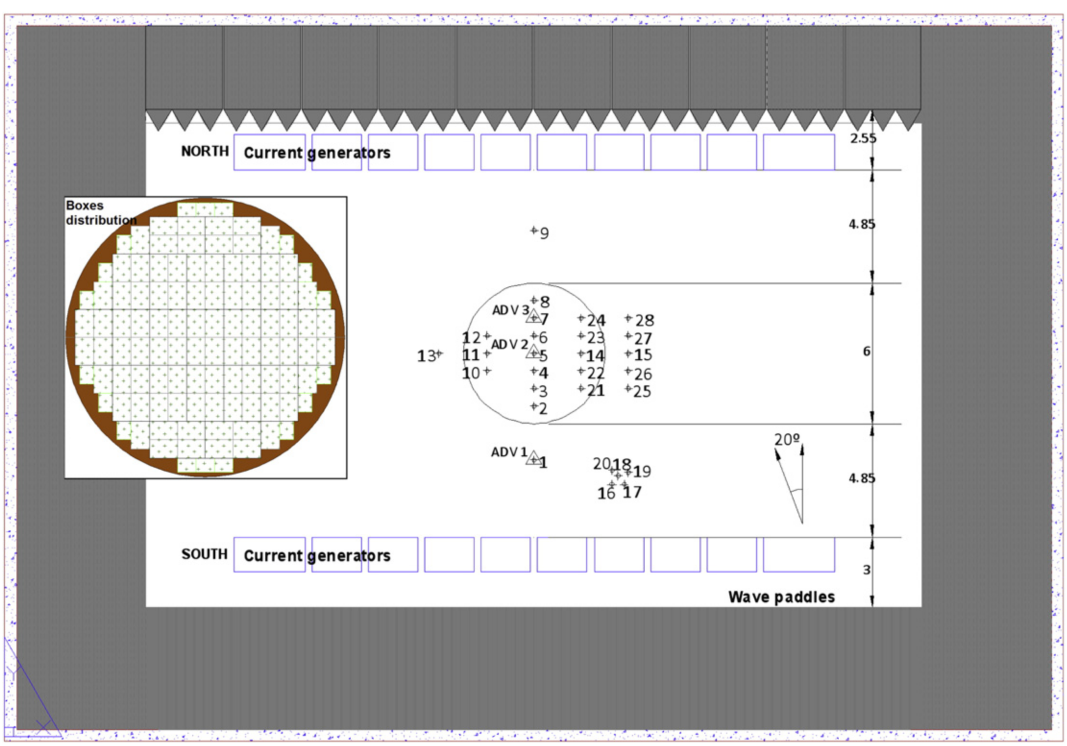


**Fig. 7.** Free surface gauges and ADV location sketch in the Cantabria Coastal and Ocean Basin. Details of the boxes' distribution in the pit are shown.

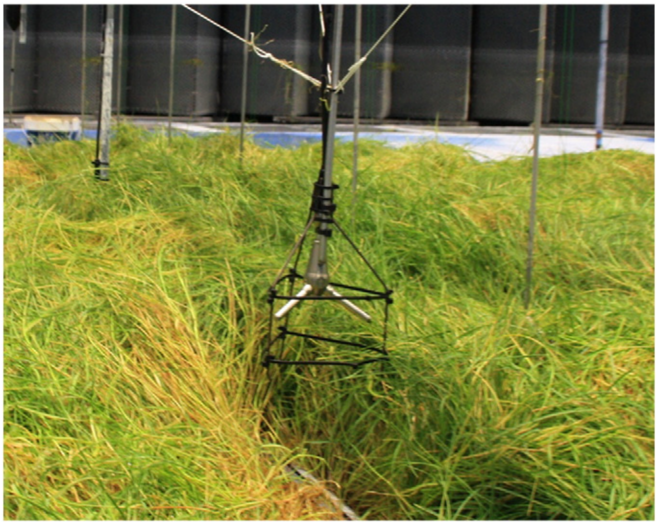

**Fig. 8.** Special structure built around the ADV.

according to the values presented in Bouma et al. (2013a,b) to reproduce conditions similar to natural environments. Additional tests were performed with an obliqueness of 20° between the waves and the current. For all cases, 200 waves were measured. When waves and currents were tested simultaneously, waves were activated first to allow the wave train to develop. The current was activated next, leaving an extra time of 200 s to allow the current to reach a steady stage before recording started.

In summary, the wave conditions specified in Table 4 were tested combined with the two current conditions for the two species with a 100% density and water depths of 0.40 and 0.60 m. R1 and R3 wave conditions combined with currents were also tested for 0.80 and 1.00 m water depths. Vegetation with a lowered density was tested under R1, R3 and IR wave conditions combined with currents for 0.40 and 0.60 m water depths. Only R1 and R3 were considered for $h = 0.80$ and 1.00 m. R1, R3 and IR were tested with a 20° angle with respect to the current direction for both current conditions and $h = 0.40$ and 0.60 m. The total number of experimental runs was 186, as summarized in Table 5.

Regarding the timetable to perform the experiments, one day was needed to introduce the boxes in the basin for each species, and one day was spent for each meadow density change. Six days were used to perform the tests considering 100% density for both species, and four days were needed to test the density-reduction cases. This led to one month of experiments without interruption because the tests were performed continuously to diminish the total time the plants were inside the basin and prevent their alteration.

## 5. Experimental operation and logistics: recommendations

Based on the experience gained from the set of experiments described in this work, a group of methodological recommendations is formulated as a good practice guide when live vegetation is used in hydraulic engineering experiments. Although the final objective of future experiments could vary from the one in the present work, the list of actions presented here could help foresee problems when performing experiments with real vegetation.

**Table 4**
Wave conditions.

| Wave Conditions | Type | H(m)\|Hs(m) | T(s)\|Tp(s) |
|---|---|---|---|
| R1 | Regular | 0.15 | 2 |
| R2 | Regular | 0.20 | 2 |
| R3 | Regular | 0.20 | 1.2 |
| R4 | Regular | 0.20 | 1.7 |
| R5 | Regular | 0.20 | 2.2 |
| IR | Irregular | 0.12 | 1.7 |

**Table 5**
Performed tests. +C is the current in the same direction as wave propagation; –C is the current in the opposite direction.

| Vegetation | Wave conditions | Water depth (m) | Current |
|---|---|---|---|
| P100, S100 | R1, R2, R3, R4, R5, IR | 0.40, 0.60 | +C, −C |
| P100, S100 | R1, R3 | 0.80, 1.00 | +C, −C |
| P66, P33, S66 | R1, R3, IR | 0.40, 0.60 | +C, −C |
| P66, P33, S66 | R1, R3 | 0.80, 1.00 | +C, −C |
| All | R1,R3,IR $\theta = 20°$ | 0.40, 0.60 | +C, −C |

Methodological recommendations are classified under different aspects and are presented in the following sections. The first section covers the choice of the experimental facility. The next group of recommendations, summarized in Fig. 9, is devoted to the performance of the experiments themselves. They are categorized under four different aspects: the selection of the facility, the selection of vegetation species, the experimental set-up and the selection of hydrodynamic conditions. The accomplishment of the four aspects leads to a list of recommendations for each experimental step that aims to be helpful for future experimental efforts developed at the interface between engineering and ecology.

### 5.1. Selection of the facility

The first and most important step is the choice of the experimental facilities in which to develop the experiments. Because ecohydraulic experiments are multidisciplinary work that involves engineering, ecological and environmental scientists, a hydraulic experimental facility is needed, as is access to a hydrobiological and mechanical laboratory. The biological plant characteristics, such as the size, morphology and biomass, must be determined throughout the development of the experiments, particularly during plants' growing period, if that option is followed. In addition, the mechanical properties of the plants (bending and stiffness) should be determined via tensile strength tests throughout the experiments as one indirect way to evaluate the plants' health. Increasing the number of analyzed parameters, including flow, biological and mechanical aspects, will provide better insight into the phenomena.

Regarding the hydraulic facility, it is crucial to know the characteristics, potentials and limitations of the facility to fulfill the objectives of the experiments. The use of a large-scale facility is desirable to reproduce conditions similar to nature. Most facilities have not been designed to perform experiments with real plants, and some of them do not fulfill the requirements pursued. Although saltwater is present in coastal and estuarine ecosystems, most hydraulic facilities, including wave flumes and basins, work with freshwater to prevent the mechanical systems from rusting. This aspect is relevant for preserving the health and strength of plants during the execution of the experiments, particularly for halophytic species, as noted below. The capacity of the experimental facility to reproduce hydrodynamic conditions similar to nature, including waves and/or currents, is also important. Although the number of facilities able to simulate waves and currents has increased in the last decade, they were mostly designed for testing coastal or marine engineering designs and fall short of meeting ecohydraulic demands. The use of measuring equipment could also be linked to the use of the facility. Another important aspect, also covered later more in detail, is the availability of an annex facility to grow or store plants. Special requirements, such as water supply, natural light, and temperature conditions, are necessary. Using an area close to the hydraulic facility saves time and effort.

Regarding the use of a hydrobiological laboratory to perform biological analysis, the availability of facilities and the instrumentation to perform sediment analysis (i.e., particle size, texture or sediment

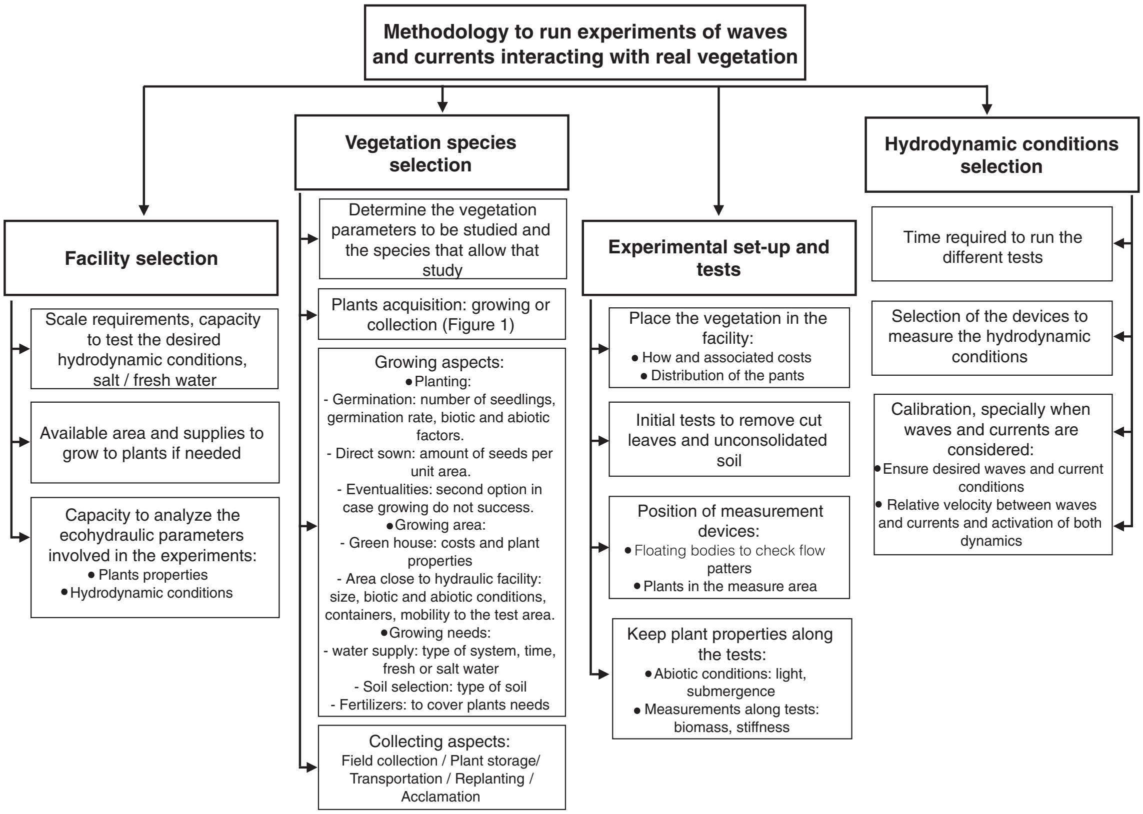


**Fig. 9.** Recommendations to design and perform experiments for the study of waves and current interactions with real vegetation.

characterization) and biological analysis (i.e., precision scales, muffle oven, stoves, heated room, refrigerator or freezers) is desirable. Special attention should be paid to the quality of the analysis performed. In the context of experimental research, it is important for laboratory methodologies to be based on standards and standardized procedures supported under national or international accreditation entities.

A mechanical analysis of the plants is highly recommended. Plant degradation can be important, particularly throughout the development of the experiments. As a consequence, energy-damping capability could be strongly influenced, yielding wrong predictions. Tensile strength tests can help determine plant degradation. Depending on the plant morphology, different tests should be performed, including those on leaves and stems. Because botanical samples need to be tested a short time after being harvested to preserve their mechanical properties, it is preferable to have the mechanical laboratory and the hydraulic facilities be close to one another.

### 5.2. Selection of vegetation species

Vegetation species must be collected in accordance with the capabilities of the experimental facility and the plants' feasibility to be grown or collected. Adequate knowledge of the ecology and phenology of the target plants is required. First, it is essential to know whether seeds are available from the field and consequently can be grown or if only collecting can be done (see Section 2 for further details). Collecting is a valuable option if the expected time for growing plants is very long, demanding considerable effort to obtain suitable plants for testing. Second, it is needed to estimate if the stress suffered by the plants during the experiments will induce large plants' degradation or even mortality. Because the latter is relevant but poorly documented in the literature, it is very difficult to determine in advance.

If growing is chosen, aspects such as seeds' availability, germination, places to grow plants, soil selection, water supply, and the use of fertilizer and pesticides need to be carefully considered. If collecting is chosen, aspects such as minimizing the damage during collection, plant storage, transportation and replanting are relevant. Previous aspects are described next in greater detail.

#### 5.2.1. Growing

The first step to follow when growing is chosen is to determine the size of the containers to be used during the process. Container size is an important parameter because the containers will be heavy when filled with soil and plants, and they need to be later placed inside the flume or basin. Although large experimental facilities have overhead cranes with a large capacity, they must be analyzed. Based on our experience, it is more convenient to use small boxes than large containers. Meadows can be easily built by gathering small boxes in a desired shape. If single boxes present poor plant development and they cannot be finally accepted for the experiments, only a small area of plants is lost. In addition, small boxes are easier to handle and to place inside the wave flume/basin.

Germination is very relevant in the process, and it could act as a bottleneck. Particular attention should be paid when planning and performing the experiments. Many different factors must be controlled to achieve the total number of seedlings needed for the experiments. For example, in the present experiments, two germination batches of *S. anglica* seeds were carried out following the same procedure and using seeds collected in the same area but in different years. The germination rate for the second batch was much lower than that for the first batch, which highlights the importance of testing seed batches for viability. Additional factors, such as the emergence of fungus in the petri dishes or on the seeds and a change in the room moisture percentage or temperature, affect the germination success. The use of gloves is advisable to prevent the presence and spread of fungus. *P. maritima* was sown with dry and wet seeds. Dry seeds were sown directly, whereas wet seeds were maintained in freshwater some days before planting. It was observed that none of the dry seeds grew. Having a second (back-up) option to obtain plants is advisable, and the associated time and efforts should be considered. In our experiments, the growing of *S. anglica* was not as successful as expected, and 6000 plants were collected in the Eastern Scheldt Estuary. In total, the collection and cleaning of 6000 plants took approximately 100 working hours.

Growing can be performed in a greenhouse. However, the construction and the associated costs should be taken into account. When it is most convenient to grow the plants close to the hydraulic experimental facility, some aspects should be considered. An area large enough to ensure adequate climatic conditions, such as insolation hours or low wind intensity, is needed. Furthermore, plants should be protected from birds, bugs and fungus. In our experiments, a greenhouse-like coverage with a mosquito net was built, and half-strong saltwater was added twice a week. Furthermore, ecological pesticides were applied once a week to treat aphids and fungus over three months. To avoid sunlight degradation, it is advisable to apply pesticides after sunset.

Soil selection is a key factor, and the type chosen depends on the species and its water needs. It defines not only the rooting ability but also the water-holding capacity and retention of nutrients. It is important for soil to be permeable and mixed with clay.

The water supply must be designed according to climatic conditions and plant necessities. A drip irrigation system covering the plantation area is advisable to avoid wasting water. Our experience with two species of salt marshes confirms that using freshwater with periodical salt supplementation is good practice. It should be noted that some halophytic plants grow better under the application of full saline water.

A common practice is to add fertilizers to soil to enhance plant growth. In our experiments, two layers of slow-release fertilizers were added, and additional foliar fertilizers were added depending on the leaves' color. It is advisable to take into account this aspect because leaves' color is an indicator of plants' needs. For example, purple leaves may indicate they are limited by phosphorous, whereas yellow leaves may indicate nitrogen limitations. Moreover, plant death can be related to pH changes because of the fertilizer added. Then, soil pH measurements are advisable.

In addition, it is extremely important to avoid the introduction of an invasive species in the local environment when foreign species are used in an experiment. Therefore, this aspect should be considered from the beginning. If an invasive species is (for good reasons) the topic of the study, precautionary measures must be taken. In our experiments, *S. anglica* was known to be an invasive species. Hence, it was first ascertained that the growing area did not increase the risk of spreading. Moreover, at the end of the experiment, plants were collected by hand, and sediments were sieved to treat them with herbicides. The remaining plants were stored in dark conditions until they were dehydrated and calcined.

#### 5.2.2. Collecting

When collecting is chosen, it is advised to extract plants with their root systems to minimize the damage to above- and below-ground organs. For transportation, cleaning the plant roots of sediment and storing them in distilled water was very successful in our case, but successful collection highly depends on the target species. Because of the lack of previous studies, it is advised to conduct preliminary tests before completing the full collecting campaign, particularly for large meadows. Replanting is relevant and necessary to later place plants in a flume or basin. Some time is needed to allow plants to acclimate to the soil to establish a sufficiently strong rooting system that will resist hydrodynamic loading. In our case, the plants were planted in boxes 3 days before the tests were started, with very successful results. The sediment was covered with cobbles to improve the stability.

Finally, it is important to note that collecting could be a good option when time is required for growing. In our experiments, we decided to start growing plants because we expected to obtain adult plants in three months due to the natural conditions (e.g., insolation, humidity, and hours of natural light). However, if it is not possible because the latitude of the site, the growing season, or the high cost of using or building a greenhouse, among other factors, collecting is presented as the only alternative to obtain live plants for experiments.

### 5.3. Experimental set-up

The experimental set-up starts with considering how the plants will be set and disposed of inside the wave and/or current flume or basin. The best vegetation placement option inside the basin should be studied because that determines the time and effort needed and the influence on the generated flow conditions. In our case, the capability of lowering the tap of the basin pit was used to avoid building a platform and ensure a smooth transition from basin floor to the vegetated area. Plants grew in boxes grouped in pallets, which were used later to easily lift them and place them in the basin. After placing the vegetation in the facility, it is advisable to run a short-wave train test to remove cut leaves or unconsolidated sediment from the facility and be ready to start the tests. It is preferable to wash away any dust present on the plant leaves or any soil that has been deposited during growing and is contained in the boxes. By doing so, plant visualization will be improved, particularly when submerged video cameras are used.

An aspect that should be considered when using real vegetation is the uniformity of the meadow. Plants characteristics may vary along the meadow when grown in boxes or even when being transplanted from the field. For that reason, the different elements that comprise the meadow should be disposed to minimize heterogeneity in terms of the density, plant morphology or standing biomass, among others. Large heterogeneity creates preference flow paths, inducing particular hydrodynamics and local effects on the flow.

When density cuts are desirable to reduce meadow density for additional tests, they should be performed without damaging the plants. That could be a challenging task, depending on the size of the meadow. When plants cannot be reached from the meadow edge, one option is to move the boxes, when possible, to have access to all of them. Another alternative is to build a walkway over the meadow to have access to the plants. The first alternative is very time consuming and risky because soil and plant conditions can be altered significantly, and test repeatability can be lost. The latter demands an external infrastructure particular to each single test. In our experiments, plant cutting was performed by snorkeling with an amount of water sufficient to cover the plants. Two divers were able to cut the whole meadow without disturbing the plants. This practice was faster, particularly with plants that cannot stay upright in the absence of water, as in our case for *P. maritime*, a very flexible plant.

In addition, it is important to maintain the plants' characteristics throughout the experiments. The combination of biomass measurements and tensile strength tests can complement visual inspections to provide valuable information on plant degradation throughout the execution of the experiments. Checking plant health and quantifying stress due to flow action is necessary because it is directly related to plants' attenuation capability. Additional actions can be taken to mitigate degradation, such as exposing plants to natural light during experiments or lowering the water level at the end of the day. Those actions were revealed to be very effective in our experiments.

### 5.4. Selection of hydrodynamic conditions

Hydrodynamic conditions are chosen according to the target species (e.g., habitat, ecosystem) and the facility capabilities. The first determines the natural hydrodynamic conditions to be expected to be reproduced in the laboratory, and the second establishes the possibility of reproducing such conditions. An agreement of the two is necessary.

It is desirable to run experiments before placing the vegetation in the basin to evaluate the damping induced by flume/basin bottom friction. This allows for quantifying with higher accuracy the damping capacity of the meadow.

Before running the tests, the wave-gauge typology to be used for monitoring the experiments should be selected. When hydrodynamic conditions need to be measured inside the meadow, some problems could arise. Resistive free-surface gauges are not a good option because the interference of the plant leaves with the metallic sensor wires can lead to incorrect measurements. Capacitive gauges are more stable than resistive sensors, and daily calibration is not needed. This will save time during the performance of the tests. Therefore, capacitive gauges are more advisable. They were used during our experiments with very successful results. Regarding velocity measurements, ADVs performed well in our tests. However, acoustic beam interference with plant leaves and stems needs to be avoided. One option to do so is to remove shoots to create an area free of plants. This can be a good alternative for sparse meadows, but it is not recommended for dense meadows because it could alter the local meadow density, inducing undesired flow patterns. In our experiments, a special structure was built using plastic wires that was able to keep the measurement area free of plants.

It is advisable to calibrate hydrodynamic conditions before starting the experiments, even before placing the vegetation inside the flume/basin, particularly when waves and currents are tested simultaneously. In that case, both hydrodynamic conditions should be calibrated separately to ensure the desired conditions because when both waves and currents flow simultaneously, they interact nonlinearly. That interaction strongly depends on the relative velocity magnitudes for waves and currents. Furthermore, that parameter can lead to different behaviors when the current is activated before or after the waves. In our tests, waves were activated prior to the current. Conversely, the current velocity did not allow the waves to develop and to propagate towards the meadow.

The use of floating bodies can be useful to rapidly identify the developed flow patterns all along the basin and to select the best positions for the different sensors used to measure flow characteristics. In the present experiments, oranges were used as tracers to check flow patterns under wave and current conditions.

## 6. Conclusions

Working with real vegetation in physical experiments housed in large-scale facilities provides a unique way to reproduce the natural field environment under controlled conditions. The successful application of this experimental approach is not exempted from complexity. Using real plants or other living organisms introduces new challenges for conventional hydraulic facilities in the planning, operation and overall logistics of the experiments, which can be addressed only with a cross-disciplinary approach at the interface of ecology and hydraulic engineering. Although the removal or collection of living plants in the field can have severe consequences for the environment and hence may be limited by environmental restrictions, growing plants may require logistically demanding conditions and considerable expertise, limiting the number of facilities where such experiments can be carried out. Moreover, the high sensitivity of plants to housing and experimental conditions and their variations over time introduce new variables that are not usually considered in conventional hydraulic engineering but are essential hurdles to jump to advance current understanding.

Although mimicking live plants with different materials and similar stiffnesses at different scales has been the most extensive approach to understanding their hydrodynamics and transport processes, it is clear that scientific progress is linked to increasing field work and controlled experiments with real vegetation without scaling. Notwithstanding the important contributions made so far in the standardization of the current knowledge of physical modeling in ecohydraulics (Frostick et al., 2014), experience with wave basins and real vegetation for coastal applications, particularly on large scales, is very limited. The present experiment and recommendations may contribute to accelerating the practice of using live vegetation in hydraulic engineering experiments.

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