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Article title: A Review of Plant-Flow Interactions on Salt Marshes: The Importance of Vegetation Structure and Plant Mechanical Characteristics

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Abstract

Observations of plant-flow interactions on salt marshes have revealed a highly complex process dominated by the tightly coupled effects of plant characteristics and hydrodynamic conditions. This paper highlights the importance of vegetation structures such as plant density and height, as well as their spatial variability and mechanical properties including flexibility, upon energy dissipation and flow modification. Many field, laboratory and modelling studies which attempt to predict flow dissipation or improve our understanding of plant-flow interactions use simplified structural measures of salt marsh vegetation or artificial representations. These simplifications neglect important plant and canopy elements and are unlikely to be truly representative of their natural counterparts. Such approaches limit our understanding of plant-flow interactions and potentially compromise the predictive accuracy and application of numerical flow models. It is important therefore that improved techniques to measure vegetation structure are adopted in order to better define the key relationships between measurable plant characteristics and drag-relevant plant properties.

Introduction

Flow modification in the presence of salt marsh vegetation is pervasive and thought to influence many intertidal ecosystem functions and services.¹ When tidal currents and/or waves interact with vegetation, the physical structure of the plant modifies flow, typically resulting in reduced velocities and dampening of turbulence across marsh surfaces.²⁻⁴

Quantifying plant-flow interactions is very important for flood-risk assessment as salt marshes contribute significantly towards flood and erosion protection by dissipating high-energy waves⁵⁻⁷ and tidal flows.^{1,8} Landform evolution processes including sediment erosion, entrainment, transport pathways, and deposition are influenced by plant-flow interactions affecting flow velocities, directions and turbulence.⁹⁻¹¹ Such dynamics need to be seen in the context of both climate change (accelerating rates of sea-level rise and changes in storminess) impacts at the coast and the role of vegetated intertidal surfaces in sea defence projects.¹² Finally, there is significant ecological and environmental interest in mechanisms and processes involved in plant-flow interactions as these can affect seed¹³ and larvae dispersal as well as sediment mobilisation and contaminant trapping.¹⁴

The importance of plant-flow interactions has encouraged both empirical investigations and the development of numerical models which estimate flow modifications across various spatial and temporal scales.^{9,10} Field and laboratory (flume) based studies conducted with natural vegetation have revealed the complexity of plant-flow interactions as a result of varying hydrodynamic conditions and plant characteristics.^{15,16} However, our limited understanding of this complex process, combined with the difficulties in measuring hydrodynamically relevant plant characteristics, has led many laboratory and modelling studies to adopt simplified and reductionist approaches when predicting plant-flow interactions.^{17,18} Studies which utilise simplified approaches may have questionable validity and relevance within natural salt marsh environments. In addition, numerical models are also likely to suffer from relatively large predictive uncertainties which then require additional calibration and validation procedures.^{12,19} Therefore the aim of this paper is to investigate the plant characteristics and hydrodynamics involved in wave and tidal flow dissipation, particularly the role of vegetation structure and flexibility. In addition, we review the limitations and validity of the assumptions made when these characteristics are quantified within laboratory studies and incorporated into numerical models.

FLOW MODIFICATION OF TIDAL AND WAVE CURRENTS AT THE MARSH SCALE

A growing body of evidence highlights the capability of many types of salt marsh vegetation in reducing velocity and turbulence generation under a range of wave and tidal current flow conditions.^{1,5,7,20} Observations of wave heights in vegetated marsh against bare mudflats², or tidal current velocities in creek channels against adjacent marsh platforms⁴, have generally found that mean flow speed and energy is inversely related with distance from the salt marsh margin in the direction of wave/current flow.⁸

Tidal Flows

Tidal flooding of the marsh can occur via creek channels or in the form of sheet flow from the marsh edge; the latter being responsible for a greater proportion of marsh flooding as water levels rise.^{10, 21, 22} Field evidence has shown that as waters flood the marsh surface, i.e. flow from an unvegetated into a vegetated zone, they do so in fully turbulent form.⁸ At the vegetated interface there is sudden and initial increase in turbulent kinetic energy (TKE) and in certain circumstances velocity, as flow is constrained by the vegetation and turbulent wakes form behind vegetation.^{23, 24} However within a short distance (<5m) flow velocities and TKE are significantly reduced with some studies reporting a 50%⁸ reduction in flow velocities whilst others report a 250-300% reduction when compared to unimpeded flows.²⁰ Mean flow velocity and TKE generally decrease logarithmically as flow penetrates further into the canopy and momentum is extracted from the fluid.^{4, 8, 25}

It is apparent from the literature that there is considerable variation in the reduction of mean flow velocities and energy with varying vegetation types, flow depths and speed. Zones of relatively higher turbulent intensities and velocities have been observed in areas of marsh which exhibit a spatially abrupt decline in plant densities.⁸ Other empirical evidence includes isolated salt marsh plants and canopies which can often be seen with localised scour surrounding the plant (see Figure 1) where increased turbulence and velocities have led to erosion.^{15, 26, 27}

Contradictory reports regarding flow modifications in the vertical dimension as plants become submerged are also common within the literature. When plants are in an emergent state (plant height > water depth) a linear increase between both turbulence and velocity with depth is generally observed^{8, 24}, although some studies have reported a notable absence of any trend in turbulence.²³ When a canopy becomes submerged (plant height < water depth), a faster moving, turbulent layer is observed near the top of the canopy, called skimming flow, whilst the layer below is characterised by a relatively constant velocity and lower turbulence, except for a small layer adjacent to the bed.^{20, 24, 28} Some variation in observations in the vertical velocity profile have been reported with some authors^{1, 25, 29} observing a second velocity maximum near the bed as opposed to a logarithmic profile^{23, 24} or even a constant vertical profile.²⁰ The observed second velocity maximum near the bed has also been observed in riparian vegetation and is often associated with the relatively lower canopy densities where flow is diverted and thus concentrated within this lower region.^{1, 25, 29-31}

Waves

Under more complex and typically higher energy oscillatory (wave) flow forms, energy dissipation over salt marshes generally occurs over much longer distances (see Table 1). Empirical datasets from the literature illustrate that these relatively complex flow types also exhibit significant reductions in energy⁷, which generally decay exponentially with distance across the salt marsh.^{3, 32, 38} Similar to tidal currents, the presence of vegetation has an immediate effect upon the wave energy spectra with Möller and Spencer⁷ reporting a 2.12% per metre reduction within the first 10 metres of vegetated marsh surface. Waves propagating through salt marshes lose energy through drag forces, leading to a reduction of wave height.³⁹⁻⁴¹ Waves may also break due to shoaling as a result of reduced water depth and thus dissipate energy in the process.¹⁵

Due to the complex circulatory flow under waves²⁴ published results on energy dissipation are highly variable. Thus for example, a 63% mean reduction in wave height over 180m⁶ was observed from a

North Norfolk marsh (U.K.), whilst at a site in Essex (U.K.) a 92% mean reduction over 310m was recorded.⁷ Table 1 compares the mean energy reductions and, assuming exponential decays are observed throughout all studies, the calculated decay constants (shown in Table 1). Both values highlight the variability of dissipation reported throughout the literature but especially amongst different saltmarsh species and mixed plant communities. The presence and abundance of species at a particular location within a salt marsh varies according to ecological (including intra and interspecific species competition) and environmental (such as salinity, soil water content) factors.⁴² Therefore canopy composition and density are likely to exhibit spatial dependence at scales of 10s of metres across the marsh.⁴² This could suggest that flow dissipation exhibits some form of spatial correlation and could account for the highly non-linear response of wave dissipation across marsh surfaces. There is very little information correlating observations of flow attenuation with spatial distribution of species at the scale of 10s meters because many studies record the structural characteristics of only one species with simplified measures and over relatively small areas in comparison to the size of the marsh (e.g. 4m²).³

The characteristics of incident waves must also be considered as a cause of the variability in reports of saltmarsh wave energy dissipation. Water depths relative to plant height are important in determining the nature and degree of energy dissipation over the vegetated marsh surface. Tschirky, Hall⁴³ observed greater dissipation under larger incident waves which was also found in the large wave flume experiment of Möller, Kudella⁵, although beyond a certain wave height, dissipation did not continue to increase. Bradley and Houser⁴⁴ observed a general decrease in wave attenuation under increased wave heights but highlight the importance of wave period which was also supported by findings by Möller, Kudella⁵ but not by Tschirky, Hall⁴³ or Möller, Spencer² where no correlation between wave dissipation and larger wave periods were observed.³² This relationship is likely to be strongly influenced by plant flexibility which will be discussed further in the following section.

Finally it is important to acknowledge a temporal dependence of plant-flow interactions occurring on different scales reflecting seasonal variations in wave climate and plant cycles or shorter timescales such as tidal cycles and changing wave periods.¹⁵ At long timescales, weather systems (storms) produce higher energy and/or higher frequency waves which often coincide with a seasonal decline in vegetation density for typical salt marsh plant species.^{24, 36, 45} Investigations into the seasonal variances of wave dissipation across salt marshes have been conducted^{7, 36, 46} but establishing a statistically significant seasonal trend remains a challenge, given the number of co-varying controls on wave dissipation.

THE INFLUENCE OF VEGETATION STRUCTURE AND PLANT MECHANICAL PROPERTIES ON PLANT-FLOW INTERACTIONS

Salt marsh vegetation, like many other vegetation types, exhibits differences in shape, dimensions and architecture both within species and between species as a consequence of genetics and environmental factors. Variations in type, size and density of plant elements often exhibit some form of vertical dependence contributing to the characteristic shape and the total surface area of the plant.¹² In general, field and laboratory studies have reported reductions in flow velocities when the

canopy exhibits a greater surface area of plant material, typically indicated through increased stem or shoot counts/densities.^{3, 38, 44}

Plant Shape, Height and Density

Plant elements such as stems, shoots, leaves and inflorescences contribute significantly to the total surface area (herein referred to as vegetation density) and standing biomass. The flow resistance generated by a plant as a whole thus creates a greater obstacle to flow than the plant stem alone.^{1, 3, 47, 48} Mean flow velocities and TKE initiated by tidal currents generally decline with increases in plant biomass and stem density exposed in the water column.⁸ Similarly, increases in wave attenuation are linked to those plants with greater vegetation densities and standing biomass, although the relationship with biomass is not direct or straightforward, as biomass varies greatly for a given plant volume between and within species.^{36, 49} There is also evidence to suggest that these plant characteristics are more influential in effecting drag forces than mechanical properties such as flexibility.³ Bouma, Vries³⁸ observed strong correlations between shoot densities and standing biomass with wave attenuation amongst two salt marsh species (*Spartina anglica* and *Puccinellia maritima*) despite differences in stem flexibility, highlighting the importance of these plant characteristics. Finally, there is growing evidence to support the spatial dependence of vegetation density. Small-scale laboratory experiments have shown that dissipation rates and the extent of flow modification are sensitive to the spatial configuration or positioning of artificial stems.^{14, 50-52}

Leonard and Reed²⁰ observed greater spatial variations in vertical velocity and turbulence profiles in those salt marsh plants which exhibited a relatively complex structure. In contrast, *Spartina alterniflora* exhibited a relatively predictable curved flow profile where velocities reduce in the mid section^{1, 4, 8} due to the species-characteristic branching pattern, increased foliage and thus vegetation density at this height.²⁸ Skimming flow is associated with higher velocities and turbulence when vegetation is submerged and exposed to tidal currents.⁸ The vertical position of skimming flow can strongly influence the proportion of flow that is dissipated, and the turbulence generated, within the canopy. The vertical position of this flow type has been found to correspond with 85-90% of the cumulative vertical canopy biomass.^{20, 23, 28, 30, 45} Mechanical properties such as buoyancy may also be important in modifying the vertical distribution of plant elements. Relatively buoyant elements of *Atriplex portulacoides* for example have been observed to shift position within the canopy, with plants lifting in the water column as flooding proceeds.²⁰

Under oscillatory flows, canopies which consist of taller vegetation types (such as *Spartina* species) are often associated with areas of greater wave dissipation^{3, 15, 24}, as wave orbitals exhibit higher velocities in the upper, forward-directed, orbital flow section of the wave.^{3, 28, 37, 48} Möller³⁶ observed that taller 15-26cm *Spartina* spp. canopies have a significantly greater influence on wave attenuation when compared with smaller (6cm) *Salicornia* dominated canopies, despite exhibiting similar biomass values. Yang, Shi³⁷ found that the ratio of plant height to water depth was inversely related to wave dissipation and therefore relatively taller salt marsh plants such as *S. alterniflora* (~100cm) were more efficient dissipaters of wave energy than *S. maritima* (~50cm). However the influence of water depth on wave dissipation when plants are fully submerged is unclear. Möller, Kudella⁵ found that even when vegetation was submerged to depths of 2m, plant-flow interactions clearly affected wave propagation while Yang, Shi³⁷ observed only limited interactions where water depth greatly exceeded plant height (by a factor of 1.5-2).

Incident Hydrodynamics and Flexural Rigidity of Plant Elements

During certain flow conditions, flexible plants are able to reconfigure their shape and become more streamlined, thereby reducing the forces exerted upon them.^{47, 53} The complex and potentially non-linear nature of this coupled process depends not only upon incident hydrodynamics but also the flexibility of the plant or plant element. Under uniform flow conditions, theoretical descriptions of flow modification suggest that as incident velocity increases, the drag forces exerted by vegetation increase in a quadratic trend.^{54, 55} However where vegetation exhibits some form of flexibility, a linear or 1.5 power relationship is observed (Eq. 1).⁴⁷

Under oscillatory flows, the hydrodynamics of incident flow conditions become increasingly important as wave period and frequency can often force the plant to flex in or out of phase with the incoming wave (dynamic reconfiguration).^{44, 54} The plant can, therefore, move passively with the wave or alternatively generate resistance by moving more slowly or in the opposing direction to the wave.⁵⁶ Bouma, De Vries⁴⁸ observed that a stiff salt marsh grass was 3 times more effective at dissipating waves than a relatively flexible seagrass. Möller, Kudella⁵ also found that greater movement of *Puccinellia* sp. occurred under larger waves with stronger currents whereby increases in wave energy corresponded with no further increases in wave dissipation. These findings could be interpreted as showing that the dynamic response of *Puccinellia* led to the forward-flowing wave-driven current becoming relatively unimpeded by the plants.

Several flume and numerical modelling studies have also investigated the effects of flexibility on flow resistance using artificial vegetation with varying degrees of flexibility.^{48, 57} However reported results appear variable; some report a limited influence of flexibility on flow resistance⁵⁷, while others report a twofold increase in flow velocity over flexible compared to rigid vegetation.⁵⁸ Inconsistent observations are undoubtedly linked to the complexity of the flow dissipation process, including the variable influence of other plant characteristics which distort the true effect of flexibility. These plant mechanical properties include buoyant plant elements which may aid the restoration of plant shape⁵⁰ even during relatively strong flows.

Unfortunately, without more data regarding the mechanical properties of salt marsh vegetation, it is unclear how artificial representations relate to their natural counterparts⁵⁹ and it is thus difficult to translate the results of these studies using artificial vegetation to natural salt marsh vegetation.¹² Despite the clear relevance of flexibility, there are only a few datasets documenting this property and then only for a limited number of salt marsh plants, usually *Spartina* spp.^{16, 49} Furthermore, these datasets also indicate very high variability both within and between species which are thought to be a result of plant traits, difference in life cycle stages, as well as plant health due to environmental stress.^{48, 49, 60} Without further flexibility data, it is difficult to determine the importance of this particular plant characteristic in influencing flow dissipation.

MODELLING PLANT-FLOW INTERACTIONS

Due to the influence of plant flow interactions within many important processes such as water and energy conveyance as well as sediment transport, the hydrodynamics of plant flow interactions are

often incorporated into numerical models. All models employ simplified assumptions to quantify the removal of momentum of a moving fluid despite the complex nature of plant-flow interactions. In its most simplistic form, the resistance generated by vegetation is commonly described through an extra bed-friction term such as Manning coefficient or Darcy-Weisbach friction factors.^{2, 57} Due to their simplicity, these friction factors are popular^{52, 61, 62} However, as noted by Wamsley, Cialone⁶³ these extra bed friction terms may not be appropriate as they do not explicitly account for vegetated drag, especially when the plant is in an emergent state. Therefore, whilst these approaches may be suitable for 1D considerations of flow modification, generally these coefficients do not allow for complex and/or detailed examinations of flow.^{64, 65}

Another widely used empirical based model to describe plant-flow interactions is the drag force equation^{18, 32, 66} where the total horizontal drag force (F_D) can be expressed as:

$$F_D = 0.5\rho C_D A_p U^2 \quad (1)$$

where the mass density of fluid is ρ , A_p , is the frontal area, C_d is the drag coefficient and U is the mean horizontal fluid velocity.^{32, 48, 64, 67} Similar equations have also been used to describe flow dissipation under oscillatory flow conditions using the Morrison type equation.^{39, 40, 68} Swaying of vegetation in response to oscillatory flows is sometimes incorporated through an additional drag coefficient³⁴ or by modifying the approach velocity.⁴¹ These empirically derived models have also been incorporated into more complex 2D/3D numerical modelling software such as SWAN-VEG and DELFT-3D.^{10, 56, 69, 70}

Whilst numerical models are generally able to accurately quantify energy and momentum losses they are heavily dependent on the correct assignment of key parameters, most notably the drag coefficient. The dependence upon accurately assigning and calibrating these parameters is problematic especially when considering the variability of such values combined with the lack of available datasets. Furthermore model simplifications and assumptions create difficulties when assigning parameters.

Model Assumptions and Limitations

Complex plant shapes are often simplified to a single effective element, with a clear and easily defined shape such as a cylinder.^{19, 65, 71-73} This allows easy quantification of the frontal projected area (the projected area of the cylinder perpendicular to the flow direction) through simplified structural measures including mean height, width and density of cylinders (expressed either per m or m²).¹² Spatial averaging techniques⁷⁴ remove spatial variation in both the size and spacing of cylinders which is important when quantifying mean velocities and turbulence.^{52, 72} Also, neglecting flexibility and assuming cylindrical elements are rigid along their entire length ensures the frontal area remains unchanged and independent of velocity.⁷⁵ In addition, the assumption of cylindrical elements allows the theoretical and empirical understanding of drag, which derives from experiments conducted on rigid, uniform cylinders or piles³⁹, to be applied with relative ease. Using the well-established cylinder Reynolds number, which is a function of the approach velocity, the diameter of the cylinder and the kinematic viscosity,^{39, 76} the drag coefficient can be assigned to an isolated cylinder.⁷⁶

Rigid cylinders are unlikely to provide an adequate representation of plant or plant elements in terms of both geometry⁴⁵ and mechanical characteristics.⁷⁷ However, this approach can arguably be applied to salt marsh vegetation by selecting only cylindrically shaped plant elements, such as stems or shoots which are only exhibited by a limited number of salt marsh species.^{52, 78} Many studies report stem or shoot metrics of *Spartina* spp. (see Table 2). However, to assume that a salt marsh canopy consists solely of uniformly shaped, rigid stems while neglecting other plant elements such as flowers and inflorescences, is a major simplification of reality.^{17, 36, 48} These elements can contribute a significant proportion of the above ground biomass exhibited by a plant and thus represent additional resistance to flow.^{36, 45} Few studies have attempted to incorporate leaves¹¹ but where this has been undertaken these elements are also assumed to conform to the rigid cylinder analogy, an assumption that must be questioned when considering their actual appearance (see Figure 2). Even those plant elements with apparently simple geometry, such as cylindrical stems, may exhibit significant vertical variability between the basal and stem terminus³⁷ which may lead to variations in vertical flow structure.^{25, 45} Neglecting the horizontal and vertical variation in plant structure may thus lead to incorrect predictions of flow modification at plant and canopy scales. Finally, representing temporal variations through cylinder or stem metrics are poor indicators of seasonal change⁴⁵ as significant annual changes in plant structure can be attributed to the presence, absence, and attributes of other plant elements such as flowers, leaves and litter layer characteristics.³⁶

At the marsh scale those vegetation types deemed cylindrical in form may only constitute a small proportion of the vegetation present throughout the entire marsh. Furthermore those species that approximate cylindrical form, such as *Spartina*, are likely to vary in abundance and density at the canopy and marsh scales according to locally varying environmental and ecological conditions.⁷⁹ The spatial variability of simplified plant metrics is highlighted in Table 2 and strongly suggests that plant variables should not be assigned values on the basis of species information alone but must be assigned values according to location within a particular marsh.

Limited evidence suggests that plants exhibit significant variations in flexibility both within^{16, 49} and between species³⁸, despite some studies still assuming complete rigidity of stems or plant elements.^{80, 81} Although some studies account for swaying of plant elements through modified parameters such as relative approach velocity⁴¹, it is unclear how these parameters are defined.⁴⁴ Many laboratory flume studies have replaced rigid cylinders with artificial, flexible vegetation (surrogates) to investigate the role of flexibility within plant-flow interactions.¹⁶ Such studies have also generated new empirical relationships with Reynolds numbers to define the bulk drag coefficient for flexible vegetation types.⁵⁷ However there are concerns that surrogates are chosen based upon visual representation of their natural counterparts rather than accurately replicating their mechanical properties (see Table 3) and do not include the structural heterogeneity displayed by natural marsh canopies.^{12, 49, 50, 77} Although some studies are now comparing mechanical measures of both artificial and natural salt marsh vegetation^{16, 57} the lack of data is still limiting any assessment of the degree to which artificial materials accurately represent real plant matter.

Bulk Drag Coefficients from Natural Salt Marsh Vegetation

When cylinders are positioned in an array, the drag coefficient of a single cylinder may vary, even if all cylinders are of the same size and equally spaced.⁹⁰ The effect, best described as 'sheltering',

describes the situation where cylinders positioned to the rear of an array have a relatively lower drag potential. This results from the lower incident velocities, and increased turbulence, generated by those cylinders positioned in front of them.^{14, 90} Therefore an average or bulked drag coefficient is typically assigned to all cylinders within the array using the relationship with the cylinder Reynolds number empirically derived from studies conducted with similar cylinder densities.^{75, 76}

Calibrating or empirically deriving bulk drag coefficients using measurements of flow dissipation in natural salt marsh vegetation is often required to take into account these neglected plant characteristics that are important when quantifying flow modification.^{16, 41, 91} This approach may be suitable for experimental field and laboratory studies^{5, 52} but not for those requiring a predictive estimation of drag or flow dissipation. Therefore the bulk drag coefficient is typically assigned using empirical relationships with the Reynolds or Keulegan-Carpenter number reported from other studies.^{41, 44, 92} However, this approach is unlikely to provide an accurate calibration and assignment of the drag coefficient given the varying and complex structural properties exhibited by plants, combined with the poor assumptions associated with the parameterisation of vegetation structure. Furthermore the variability in the observed relationship between empirically derived bulk drag coefficients and stem Reynolds numbers for salt marsh vegetation have been highlighted by Houser, Trimble⁵⁶ and Pinsky, Guannel⁹³, even for the same species.¹⁶ This provides further evidence that that reported bulk drag coefficients determined in this way are highly location (marsh type and hydrodynamic condition) specific⁹³, probably as a result of the variability and site specific nature of plant characteristics.

The discussion above highlights that the rather arbitrary assignment of the drag coefficient with simplistic and/or unrepresentative vegetation measures is insufficient to reliably and efficiently model plant-flow interactions.¹⁹ This has led some authors to call for a new approach that could assign values of drag *a priori* in natural systems using more accurate and representative measures of relevant physical plant properties.^{5, 12} This approach could be realised if we further our understanding into possible relationships between measurable plant characteristics and drag-relevant plant structure/flexibility. However we must also adopt and develop new techniques which quantify plant structure more accurately, and move away from unrepresentative and inefficient methods such as those relying on simplified stem measures (stem density, diameter).

NEW METHODS TO OBTAIN VEGETATION CHARACTERISTICS AND PARAMETERISATION TECHNIQUES

Attempts to improve data acquisition of plant structural characteristics have resulted in the development of numerous instruments and techniques. These include the horizontal point frame (similar to a point transect)^{94, 95}; photodiode probe⁶⁰; and photographic methods that can estimate vegetation density including vertical variations in the canopy.^{36, 45, 96} The horizontal point frame method, which is highly labour intensive and time consuming, has nonetheless been successfully applied in fluvial environments to estimate vegetation density.⁹⁴ Other apparatus including the photoframe have been widely adopted across many different salt marshes to deliver reliable estimates of vegetation density.³⁶ This apparatus delivers a more efficient estimation of vegetation density relative to the point frame. However both pieces of apparatus provide limited spatial coverage, especially given the variability of marsh vegetation and the typical scale of salt marshes

themselves. Whilst such apparatus may provide an improved approach to the estimation of vegetation density, as opposed to traditional stem frequency counts, it is still unclear precisely how these measures could be incorporated into a new or modified model to predict flow dissipation.

Plant metrics such as Leaf Area Index (LAI; the one-sided leaf area per ground area^{66,97}), have been used to estimate vegetation density for many years⁹⁸ but have only recently been incorporated into flow dissipation models. First proposed by Järvelä⁹⁹, this plant metric represents a physically based parameter that could potentially account for all structural plant properties (vegetation density)^{19,66} but may not be adequate for describing the spatial (vertical and horizontal) distribution of vegetation elements within a canopy.¹⁰⁰ In addition, with respect to leaf density as projected onto a vertical plane, this plant metric has, to the authors' knowledge, only been applied in models parameterising tree growth form elements.^{19,66,97,99} Despite potential application problems in relatively low-growing salt marsh canopies¹⁰¹⁻¹⁰³, recent improvements in airborne and terrestrial laser scanning, as well as image post-processing techniques have enabled a more detailed parameterisation of marsh canopy complexity. These novel techniques include utilising airborne lidar combined with multispectral imagery from satellites and ground-referencing measures to obtain estimations of canopy properties such as height and density.¹⁰⁴⁻¹⁰⁶ Developing these remote sensing techniques, including those utilised via unmanned aerial vehicles, may ultimately allow for relatively cheap and efficient site-specific data regarding structural plant measures. Repeat imaging could also permit the incorporation of important seasonal changes exhibited by the vegetation into marsh-scale assessments of canopy characteristics.¹⁰³

Finally, measures of flexibility (as indicated through Young's modulus of elasticity⁴⁹) have recently been incorporated into models via the Cauchy number and/or buoyancy parameter.¹⁰⁷ These parameters have successfully captured the resistance produced by stiffness and buoyancy of seagrass although it is unclear whether the approach would be applicable to vegetation types with more complex, part-woody structural properties.^{56,107} The incorporation of measureable properties such as flexibility is an advance but now requires further research to fully understand the role of this characteristic in flow dissipation. Part of this research must include more extensive datasets on plant flexibility across a wider range of salt marsh species and associated growth forms.

Conclusion

Quantifying plant-flow interactions is an important but under-researched field in environmental monitoring. At the coast, these interactions play an important role in buffering wave and tidal flow energy and thus act as an 'environmental filter', influencing, over inter-annual to decadal time scales, landscape scale geomorphology. While our understanding of plant-flow interactions across estuarine environments is slowly improving, the complexity of the process is being revealed through variable and often contradictory observations of flow attenuation. Numerous plant and hydrodynamic characteristics may affect the dissipation of energy and the structure of flow resulting from its interaction with salt marsh vegetation. Evidence from the wider literature suggests vegetation structure, particularly the vertical and horizontal distribution of biomass, to be a critical canopy characteristic controlling flow properties through, and over, the vegetation layer. The role of flexibility and buoyancy of plants in affecting flow is difficult to determine and studies have yielded

contradicting results, which could indicate a stronger dependence of flow dissipation upon plant structure and canopy geometry than previously realised.

Representing salt marsh vegetation as simplified, artificial objects (cylinders) in flume experiments is unlikely to adequately replicate structural and mechanical plant characteristics. The current approaches are limiting understanding in regards to the importance of particular plant structures and mechanical properties within flow dissipation, as well as reducing the capability and predictive reliability of numerical flow models. New methods and techniques are gradually improving our ability to quantify and spatially define all vegetation structures. New remote sensing techniques offer the potential of more accurate and efficient data collection. However these approaches require further development in order to improve their application across different salt marsh vegetation types.

Finally, the reliance of current models upon an empirically defined bulk drag coefficient are unlikely to deliver accurate results due to the variability (location-specificity) of the coefficient and the spatially and temporally varied mechanical and structural properties of vegetation. If current approaches to empirically define and calibrate flow/wave dissipation factors are to be replaced by *a priori* quantifications of drag we need to improve our understanding of plant-flow interactions and include more accurate and meaningful physical vegetation properties within models.

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Figure captions

Figure 1. Scour around an isolated *Salicornia* sp. plant.

Figure 2. *Spartina anglica* canopy during late growing season consisting of a single stem and many blade shaped leaves.

Tables

Table 1. Average wave height and energy reduction results from field observations. Data collated from Anderson ³² and Möller ¹⁵.

Source	Transect Length (m)	Dominant species	Average wave height reduction over transect length	Exponential Decay Constant (m ⁻¹)
Wayne ³³	20	<i>Spartina alterniflora</i>	71%	0.063
Knutson, Brochu ³⁴	10	<i>Spartina alterniflora</i>	65%	0.105
	20	<i>Spartina alterniflora</i>	87%	0.102
	30	<i>Spartina alterniflora</i>	94%	0.094
Möller, Spencer ²	180	Mixed salt marsh community (<i>Limonium vulgare</i> , <i>Aster Tripolium</i> , <i>Atriplex portulacoides</i> , <i>Salicornia sp.</i> , <i>Spartina sp.</i> , <i>Suaeda maritima</i> , <i>Plantago maritima</i> , <i>Puccinellia maritima</i>)	61%	0.005
Möller and Spencer ⁷	163	<i>Aster</i> , <i>Suaeda</i> , <i>Puccinellia</i> , <i>Salicornia</i> , <i>Limonium sp.</i>	65%	0.00005
	10	<i>Aster</i> , <i>Suaeda</i> , <i>Puccinellia</i> , <i>Salicornia</i> , <i>Limonium sp.</i>	25%	0.0004
Cooper ³⁵	300	<i>Puccinellia</i> , <i>Salicornia</i>	90%	0.008
	250	<i>Atriplex</i> , <i>Spartina</i>	65%	0.004
	110	<i>Atriplex</i> , <i>Salicornia</i>	78%	0.014
Möller ³⁶	10	<i>Spartina anglica</i> , <i>Salicornia sp.</i>	15-20%	0.016 – 0.022
	10	<i>Spartina anglica</i> , <i>Salicornia sp.</i>	11-17%	0.012 – 0.019
	10	<i>Salicornia sp.</i>	10-12%	0.011 – 0.013
Ysebaert, Yang ³	>50	<i>Spartina alterniflora</i> and <i>Spartina maritima</i>	80%	0.032
Yang, Shi ³⁷	51	<i>Spartina alterniflora</i>	79%	0.031

Table 2. Structural plant and canopy characteristics recorded in the literature.

Source	Species	Stem Density (stems/m ²)	Mean plant height (m)	Mean stem diameter (m)	Study site
Ellison ¹⁰⁸	<i>Salicornia europaea</i>	>10,000	0.1	0.0001	Rhode Island, U.S.A
Leonard and Luther ¹	<i>S. alterniflora</i> (Dominant)	176-370	0.5 +/- 0.08	-	Louisiana, U.S.A
Shi, Pethick ²⁵	<i>S. anglica</i>	133-350	0.31-0.34	0.004	Humber Estuary, U.K.
Christiansen, Wiberg ⁴	<i>S. alterniflora</i>	88-204	0.45-1.1	0.005-0.011	Virginia, U.S.A
Neumeier and Amos ²⁴	<i>S. anglica</i>	560-1290	0.19-0.34	0.003-0.006	West Sussex, U.K.
	<i>S. maritima</i>	2340-3030	0.24-0.25	0.003-0.006	Portugal
	<i>S. anglica</i>	1450-1850	0.32-0.47	0.003-0.006	Lincolnshire, U.K.
Ysebaert, Yang ³	<i>S. alterniflora</i>	334+/- 12	0.84 +/- 0.63	0.0052 +/- 0.0017	Yangtze estuary, China
Yang, Shi ³⁷	<i>S. alterniflora</i>	508	0.97	0.0039 +/- 0.0003	Yangtze estuary, China
Jadhav, Chen ⁸¹	<i>S. alterniflora</i>	422	0.22	0.008	Louisiana, U.S.A

Table 3. Types of materials used to as surrogates to represent natural vegetation in laboratory flume studies. Adapted from Anderson and Smith¹⁶.

Source	Material of Surrogate	Species Imitated
Dubi ⁸²	Moulded Plastic	<i>L. hyperborea</i>
Dunn, Lopez ⁸³	Drinking straws	Not specified
Wu, Shen ⁸⁴	Horsehair mattress	Brushes and shrubs
Løvås and Tørum ⁸⁵	Moulded plastic	<i>L. hyperborea</i>
Lima ⁸⁶	Nylon rope	<i>Brachiaria subquadripata</i>
Augustin, Irish ⁵⁷	Wooden dowels and polyethylene foam tubing	<i>S. alterniflora</i>
Mei, Chan ⁸⁷	Perspex cylinders	Not specified
Manca, Cáceres ⁸⁸	Polypropylene stripes	<i>P. oceanica</i>
Koftis, Prinos ⁸⁹	Polypropylene stripes	<i>Posidonia oceanica</i>
Anderson and Smith ¹⁶	Polyolefin tubing	<i>S. alterniflora</i>