Chapter 1

Flows Within Marine Vegetation Canopies

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This chapter reviews the interaction of flows with marine vegetation. We discuss the influence of vegetation on coastal and estuarine hydrodynamics, including both unidirectional and oscillatory flows. The presence of vegetation introduces considerable spatial heterogeneity to flow regimes and we highlight the change in key length scales. Recent drag parameterizations and corresponding estimates for energy dissipation from a mixture of laboratory, field and observational studies are reviewed. The broad range of model predictions and contradictory dependencies on key variables emphasize both the difficulty of measuring vegetation characteristics and the challenge of finding a parameterization for vegetative drag suitable for use across a wide range of species. Particular attention is focused on how to incorporate the effects of flexibility of vegetation into drag coefficients and how the associated vegetation movement changes the ability to dissipate wave energy.

The changes in hydrodynamic conditions induced by vegetation have significant consequences for sediment transport. In many cases, vegetation has been observed to enhance sediment deposition, but in some cases vegetation has been found to enhance erosion. These results highlight the importance of continuing research into hydrodynamics within spatially variable canopies. We briefly note the dependence of geomorphological evolution on the above complex biophysical interactions and conclude by identifying some of the key research challenges within the extrapolation to large spatial and longer time scales.

1. Introduction

The world’s shorelines are constantly being reshaped by the combined hydrodynamic forces of waves, tides and storm surges. These dynamic areas have great ecological importance, providing a home to numerous benthic and pelagic flora and fauna (Greenberg et al., 2006; Zedler et al., 2001), and the economic value of this natural capital is receiving increasing recognition.
(Barbier et al., 2008; Costanza et al., 1997). Shallow coastal waters are characterized by a wide variety of substrates, from salt marshes, wetlands and sandy beaches to mangrove forests and rocky shores.

In addition to the ecological and economic values of nearshore areas, attention in recent years has focused on the ability of marine vegetation to provide coastal protection (Arkema et al., 2013; Temmerman et al., 2013), buffering shorelines against damage even during extreme events. Salt marshes can effectively dissipate waves during large wave events and high water levels (Möller et al., 2014), while mangrove forests have sometimes provided shelter from tsunamis (Alongi, 2008; Danielsen et al., 2005; Wolanski, 2007) and hurricanes (Krauss et al., 2009).

The use of coastal vegetation as a “soft” engineering solution to reduce the effect of storms has been advocated as a cost-effective alternative to more traditional “hard” engineering solutions which typically involve the construction of solid structures such as seawalls (Broekx et al., 2011; Fengin et al., 2015). Hard solutions have sometimes been accompanied by erosion (Plant and Griggs, 1992) and negative habitat changes (Airoldi et al., 2005; Martin et al., 2005). Bulkheads have been shown to fragment habitats and thus reduce ecological connectivity and environmental sustainability (Peterson and Lowe, 2009). Conversely, soft solutions might enhance resilience while providing co-benefits such as enriched habitat, improved water quality and nutrient recycling (Jones et al., 2012).

Although much less extensive than some terrestrial regions of carbon burial such as peatlands, vegetated marine environments can be locations of extremely intense carbon burial. In particular, mangrove forests are responsible for about 10% of all marine carbon burial (Breithaupt et al., 2012; Donato et al., 2011; Nellemann et al., 2009), with additional storage in seagrass (Fourqurean et al., 2012) and macroalgae beds (Duarte and Cebrian, 1996). The intensity of mangrove carbon burial may make mangrove preservation an economically attractive method for emission reduction (Siikamäki et al., 2012).

1.1. Coastlines under threat

Coastlines globally are becoming more vulnerable in the face of climate change and sea-level rise. Some regions are expected to encounter more frequent flooding (Nicholls et al., 1999; Sallenger et al., 2012), while other areas may experience stronger extreme storm events (Emanuel, 2005; Knutson et al., 2010; O’Gorman, 2010; Webster et al., 2005). These effects are coupled with unprecedented pressures from an ever-increasing population
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living in coastal regions (Small and Nicholls, 2003). Dam and reservoir construction has changed sediment transport pathways (Day et al., 2007), and deltas have subsided as a consequence of oil withdrawal (Syvitski et al., 2009). Resource requirements have led to destruction of much salt marsh and mangrove habitat (e.g. Nguyen et al., 2013; Thu and Populus, 2007). The rate of the habitat destruction is accelerating, leading to projections that 30–40% of current coastal wetlands could be lost within the next 100 years (IPCC, 2007). Mangrove forests are particularly threatened, with half the global mangrove coverage lost since pre-industrial times (Giri et al., 2011) and coverage currently disappearing at a rate of 1–2% a year (Duke et al., 2007). Since initial observations began in 1879, 29% of the known area of seagrass has also disappeared (Orth et al., 2006; Waycott et al., 2009). Such alarming loss rates are greater than or comparable to those of tropical forests (Achard et al., 2002).

1.2. Overview

In recent decades, much progress has been made in understanding water flows through vegetation canopies. This understanding has proven valuable in refining models for wetland morphodynamics, and has the potential to guide coastal management decisions. This chapter focuses on research into the dynamics of waves and currents flowing through wetlands, and complements excellent reviews by Nepf (2012a, 2012b). In the present work, in addition to including some more recent literature, we focus more closely on flexible vegetation and wave flows. We briefly discuss the quantification of vegetation geometry (Section 2), before considering in turn the relatively steady currents such as tides and storm surges (Section 3) and the more rapidly oscillating flows under waves (Section 4). We then discuss links between the hydrodynamics and sedimentation (Section 5) and briefly relate the previous sections to the long-term timescales and marsh-scale evolution (Section 6). Finally, we summarize the current state of knowledge and conclude with a discussion of some of the many remaining challenges to be explored (Section 7).

2. Canopy Geometry

The intricate geometry of many vegetation canopies presents a challenge to scientific understanding, and the number of stems influencing flows on 100–1,000 m scales can range from less than a hundred to many millions. Therefore, statistics summarizing canopy geometry are needed to capture overall vegetation characteristics on a marsh scale. Throughout this chapter,
we define the vegetation height as $\ell$ and water depth as $h$. One important statistic, denoted $\phi$, is the proportion of volume occupied by the solid canopy (sometimes also denoted $\lambda_p$; Britter and Hanna, 2003; Lowe et al., 2005). Given $n$ cylindrical stems per square meter, each with diameter $d$, $\phi = n\pi d^2/4$. Since a typical distance between stems is $\Delta S = n^{-1/2}$, this can be rewritten as $\phi = (\pi/4)(d/\Delta S)^2$ (Figure 1). For many (but not all) canopies, the stem spacing is substantially greater than the stem diameter, so $\phi \ll 1$, i.e. the proportion of volume occupied by the solid canopy is often small. A very wide range of canopies is found in the coastal ocean, but Table 1 lists $\phi$ values for a few typical cases. However, even within a particular vegetation class, a wide range of geometries may be encountered so, for example, the values for any given mangrove or seagrass species may depart significantly from the values given in Table 1.

When evaluating the drag exerted by a canopy on the water flow, a particularly important statistic is the frontal area density $a$ (units m$^{-1}$), i.e. the plant area in the plane perpendicular to the flow, per unit volume. For

![Figure 1. Definition of canopy variables. The example shown here is the case of an idealized canopy of equally-spaced uniform vegetation of height $l$, diameter $d$ and spacing $\Delta S = 0.25$ m. (a) Side view, (b) plan view. Here, $n = 16$ m$^{-2}$ and $A_s = l \times d$ is the frontal area of each individual stem, so $\lambda_f = al = nld = 16A_s$.](image)
Table 1. Summary of typical geometric parameters for common plant types: marsh grasses (Lightbody and Nepf, 2006; Valiela et al., 1978), mangroves (Krauss et al., 2003; Mazda et al., 1997b; Norris et al., 2017), and seagrasses (here given for Posidonia oceanica, Luhar et al., 2013).

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Blade or trunk widths d (mm)</th>
<th>Solid volume fraction φ</th>
<th>Frontal area per canopy volume a (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marsh grasses</td>
<td>1–10</td>
<td>0.001–0.01</td>
<td>1–7</td>
</tr>
<tr>
<td>Mangroves (trunks only)</td>
<td>60–90</td>
<td>0.003–0.005</td>
<td>0.06–0.07</td>
</tr>
<tr>
<td>Mangroves (prop roots only)</td>
<td>~36</td>
<td>0.073–0.13</td>
<td>2.6–4.5</td>
</tr>
<tr>
<td>Mangroves (pneumatophores)</td>
<td>6–33</td>
<td>0.0003–0.038</td>
<td>0.1–6.2</td>
</tr>
<tr>
<td>Seagrasses</td>
<td>26</td>
<td>0.008</td>
<td>16</td>
</tr>
</tbody>
</table>

Note: For mangroves, prop roots and trunk measurements were undertaken for the species Rhizophora stylosa and pneumatophore measurements are given for Sonneratia alba; values are expected to vary considerably for other species (particularly those with pneumatophore roots). For seagrass, stem width exceeds stem thickness by more than an order of magnitude, so stems were treated as rectangular, with thickness 0.5 mm.

vertical cylindrical stems, a is

\[
a = nd = \frac{d}{\Delta S^2}. \tag{1}
\]

If one looks horizontally through a canopy of randomly spaced stems, the probability of seeing a distance \( x \), without the view being blocked by a stem, is \( e^{-ax} \). Therefore, if stems are arranged randomly, an order-of-magnitude estimate of \( a^{-1} \) can be determined by visual inspection. For the canopies listed in Table 1, \( a \) varies from 0.06 to 16 m$^{-1}$.

The depth-integrated frontal area blocking flow, per unit bed area, is

\[
\lambda_f = \int_{z=0}^{z=\ell} a dz. \tag{2}
\]

For vertically uniform vegetation, this dimensionless parameter simply equals \( a \ell \) (Figure 1). However, in many natural canopies, stems are far from uniform, and \( n, d, \phi \) and \( a \) all vary with elevation. For example, \( n \) often decreases with increasing elevation, owing to natural variations in stem height, although increases can also occur in branching canopies. If canopies are measured manually using rulers and calipers, obtaining stable statistics that accurately represent natural vertical and horizontal variability can be extremely labor intensive. The use of cameras and automated optical image analysis techniques (Lemein et al., 2015; Liénard et al., 2016) has the potential to significantly improve the description of natural canopy geometry, thereby improving the rigor of field tests of hydrodynamics models.
In many cases, hydrodynamic drag will prove to be proportional to $a$ (Section 3.2). Furthermore, high stem densities are often observed when stems are thin i.e. large $n$ is often associated with small $d$. Therefore, an interesting question is whether thin- or thick-stem canopies will tend to have higher $a = nd$. Alongi (2008) (Figure 2) notes $n \sim (10d)^{-2}$ for terrestrial vegetation, which appears consistent with limited data from mangrove forests (here “$\sim$” denotes an order-of-magnitude relationship). This relationship suggests $\Delta S \sim 10d$, $\phi \sim 0.01$, and $a \sim (100d)^{-1}$. With the exception of seagrass, the vegetation of Table 1 fits this relationship to within an order-of-magnitude. For emergent vegetation, these estimates suggest a rule-of-thumb that thin-stems canopies will often be most effective in blocking flows. However, the variety of natural canopies suggests that exceptions to this very approximate trend may be common.

Figure 2. Schematic showing the change in velocity profiles (black lines) and length scales associated with the presence of vegetation (a) emergent canopies, (b)–(d) deeply submerged canopies with varying densities, sparse with $\lambda_f$ below about 0.04 (b), transitional (c), and dense (d), with $\lambda_f$ exceeding about 0.23. In all cases, stem diameter scale turbulence is introduced within the canopy (circles). For the denser vegetation, shear at the top of the canopy induces monami (or waving) and canopy scale turbulence (ovals in (c) and (d)) which penetrates a distance $\delta \sim (C_D a)^{-1}$ downwards into the canopy. Figure redrafted from Nepf (2004, 2012a).
3. Unidirectional Flows

We first review the primary length scales in vegetated flows, as well as factors controlling vegetation drag and the associated reduction of water velocities in steady flows. Oscillating flows will be considered in Section 4.

3.1. Key length scales of flows within vegetation canopies

The presence of vegetation introduces significant spatial variation to flow. In particular, within a plant canopy, the key length scales change from the flow depth (associated with unobstructed flows) or flow depth and channel width (for bathymetrically constrained flows) to scales defined by the stem diameter, stem length, stem spacing and \( a^{-1} \). These change of scales alters the velocity profiles and results in damping of larger scale motions, but introduces turbulence (through vortex shedding and wake generation) at smaller stem scales. The behavior of flows is also governed by the level of submergence defined as the ratio of plant height to water depth, with \( \ell/h = 1 \) corresponding to emergent flows, \( \ell/h < 0.1 \) corresponding to deeply submerged flows and \( 0.1 < \ell/h < 1 \) defining a transitional regime (Nepf, 2004) (Figure 2).

3.2. Characterizing drag in rigid vegetation

The drag force on a single isolated stem \( F_d \), per unit stem length, can be expressed as

\[
F_d = \frac{1}{2} \rho d C_D |u|^2 \text{,} \tag{3}
\]

where \( \rho \) and \( u \) are water density and velocity. The drag coefficient \( C_D \) depends on the Reynolds number \( \text{Re} = \frac{ud}{\nu} \), where \( \nu \) is the molecular viscosity of water (Batchelor, 2000). For \( \text{Re} \gtrsim 200 \), the wake formed by a cylindrical obstruction is turbulent (Williamson, 1992), and for \( \text{Re} \) above this value, \( C_D \) becomes about 1. For lower \( \text{Re} \), \( C_D \) increases, reaching about 2.5 for \( \text{Re} \approx 10 \), and continuing to increase with further reduction in \( \text{Re} \) (Clift et al., 1978). Even under relatively slow flows (0.1 \( \text{ms}^{-1} \)), the stem Reynolds numbers for the stems in Table 1 range from \( \text{Re} = 100 \) to 9,000, indicating that within canopies, flow around stems is often turbulent.

When multiple stems are present at sufficiently high density, drag coefficients are changed, although reported dependencies on stem density are often contradictory in that \( C_D \) has been seen to both increase (Koch and Ladd, 1997) and decrease with increasing \( \phi \) (Nepf, 1999). The conflicting
results are discussed in Tanino and Nepf (2008) who conclude that for low energy flows (Re < 1,000), the drag coefficient increases with the increasing density of stems. Drag coefficients have also been shown to decrease with increasing Reynolds number as found in several laboratory experiments with mimics of rigid vegetation (Nepf, 1999; Stone and Shen, 2002). Sheltering effects in which wake generation by upstream stems reduces water velocities and lowers the drag on downstream stems likely become important when stem spacing ΔS is not much larger than stem diameter d. Sheltering effects have been found to be significant for arrays with φ > 0.24, but are usually considered to be small for arrays with φ < 0.08 (Raupach, 1992) (we have re-expressed results originally stated in terms of ad using \(ad = 4\phi/\pi\)). For many (but not all) natural canopies, φ is less than 0.08 (Table 1), suggesting that it may often be valid to neglect the interactions between stems. In this case, simply summing Eq. (3) over all stems in a canopy, and noting \(a = nd\), yields a total canopy drag

\[ F_c = \frac{1}{2} \rho a C_D |u| u, \]  

per unit volume.

### 3.3. Characterizing drag in flexible vegetation

Drag becomes more complex in flexible vegetation, which has a tendency to bend over sufficiently fast flows. This bending of the stems and/or leaves can change the drag, and development of drag parameterizations for these cases remains an active area of research (see Statzner et al., 2006, and references therein). Bending of a thin stem is minimal if the dimensionless Cauchy number \(Ca = \rho du^2/\ell (EI) \ll 1\), where \(E =\) Young’s modulus and \(I =\) the “second moment of stem area” representing the influence of the stem’s cross-sectional geometry on stem bending (Alben et al., 2002). For circular and rectangular stems, \(I = \pi r^4/4\) and \(bd^3/12\), respectively, where \(b\) and \(d\) are stem widths in across- and along-flow directions. Even if stem elasticity is insufficient to prevent bending, stem buoyancy will prevent bending if \(B \gg Ca\), where \(B = (\rho - \rho_v)gbd^3/(EI)\), and \(\rho_v =\) density of solid vegetation (kg m\(^{-3}\)) (Luhar and Nepf, 2011).

In cases where vegetation bending is substantial, the drag force is often related to the velocity as \(F_d \propto U^{2+\gamma}\), where γ is referred to as the Vogel exponent (Vogel, 1994). In plants for which elasticity is the restoring force balancing the drag, an analytic model gives a value of \(\gamma = -2/3\) (Alben et al., 2002), consistent with measurements of −0.7 and −0.5, observed for simulated aquatic vegetation (Albayrak et al., 2012). However, if buoyancy
is the dominant restoring force, Luhar and Nepf (2011) have proposed a model which incorporates the change in posture, and they find values of $\gamma < -1$.

### 3.4. Scaling for depth-uniform flow

We next compare the magnitude of canopy drag with other influences on the flow. For simplicity, we assume vegetation extending over most of the depth, and $\phi \ll 1$. For more general analysis, see Lowe et al. (2005). Consider the shallow water momentum equation

$$
\rho \frac{\partial u}{\partial t} + \rho \left( \frac{\partial u^2}{\partial x} + \frac{\partial uw}{\partial y} + \frac{\partial uw}{\partial z} \right) + \rho g \frac{\partial \eta}{\partial x} + \frac{\rho C_B u^2}{\ell} + \frac{1}{2} \frac{\rho a C_D u^2}{L} = \text{turbulent mixing},
$$

(5)

where $u$, $v$, and $w$ are velocity in the $x$, $y$, and $z$ directions and $\eta$ is the sea surface elevation. Here, the momentum fluxes, in parentheses, may be important for laterally non-uniform flow. The next term on the left represents pressure-gradient forcing. The following term represents bottom friction, where the bottom drag coefficient $C_B \approx 2 \times 10^{-3}$, to within about a factor of 2. Vegetation drag is the last term on the left. To assess the relative magnitudes of the terms in Eq. (5), let $T$ and $L$ be temporal and horizontal length scales of flow variability, and consider the dimensionless variables

$$
R_B = \text{bottom drag/vegetation drag} \sim 4 \times 10^{-3} / (a\ell),
$$

(6)

$$
R_T = \text{time dependence/vegetation drag} \sim 4\pi / (auT),
$$

(7)

$$
R_M = \text{momentum flux convergence/vegetation drag} \sim 2 / (aL).
$$

(8)

where we have taken $C_D \sim 1$. For the canopies listed in Table 1, $R_B \ll 1$, indicating that vegetation drag often dominates over bottom friction.

Next we consider time-variability. Throughout this section, we discuss long-period motions with $T \gg 4\pi / (au)$, so $R_T \ll 1$ and time dependence has little effect on the momentum balance (for the opposite limit $R_T \gg 1$, discussed in Section 4, drag has little effect within a single period). For the canopies listed in Table 1, the transition $R_T \sim 1$ occurs for periods of 4 s to 35 min (for $u \sim 0.1$–0.2 m s$^{-1}$). Therefore (given vegetation extending over much of the depth), time dependence likely has little effect on the momentum balance for tides and storm surges, whereas tsunamis are sometimes a transitional case.
Finally, we consider momentum fluxes (this analysis is similar to that shown in Belcher et al., 2003; Chen et al., 2012). For large horizontal scales, \( L \gg 2/a, R_M \ll 1 \) and flow is in equilibrium with local conditions. Conversely, at small scales \( L \ll 2/a, R_M \gg 1 \), and water may be advected through small-scale variability before adjusting to local conditions. For the canopies listed in Table 1, setting \( R_M \sim 1 \) yields a transition scale in the range of 0.13–33 m. A similar analysis, comparing momentum fluxes with bottom friction, suggests that horizontal scales for frictional adjustment are a factor \( R_B^{-1} \) larger in the absence of vegetation. Given the heterogeneity and small \( R_B \) of many canopies, vegetation is expected to introduce relatively small-scale flow variability (this argument neglects flow variability caused by order-one depth variability over small horizontal scales).

### 3.5. Large-scale, depth-integrated flows

An important practical application of flow modeling is the simulation of long-duration, large-scale inundation of emergent marshes associated with tides and storm surges. Storm surges in particular have generated much interest, motivated by the potential of aquatic vegetation to protect onshore regions from flooding. Using a thoroughly validated numerical model based on the full shallow water equations, Zhang et al. (2012) found that many kilometers (7–8 km) of mangroves were required to substantially reduce the slow-moving storm surge heights associated with the category three hurricane Wilma. Surges associated with slower-moving simulated storms propagated farther inland through the marsh. Another numerical study investigating the storm surge reduction capacity of salt marsh vegetation showed a substantial variation of energy dissipation rates depending on storm duration, intensity, speed, wetland characteristics and local topography (Wamsley et al., 2010).

By examining an idealized scaling of tidal and surge inundation, we note that for most tides and surges, \( R_B, R_T \) and \( R_M \) are all small, so vegetation drag balances pressure gradient forcing and vertical turbulent mixing:

\[
\frac{1}{2} \rho a C_D |u| u = -\rho g \frac{\partial \eta}{\partial x} + \text{turbulent mixing},
\]

(9)

Turbulent mixing is likely negligible if this balance is depth-averaged (because \( R_B \) is small). The remaining simple balance between pressure gradients and vegetation drag is also relevant to many laboratory studies (Nepf, 1999). Neglecting vertical flow variability, solving Eq. (9) for \( u \), together with an analogous equation for the perpendicular horizontal velocity \( v \), and substituting into the shallow water mass conservation equation.
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(e.g. Kundu and Cohen, 2010) yields

\[
\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial \eta}{\partial x} \right) + \frac{\partial}{\partial y} \left( D \frac{\partial \eta}{\partial y} \right),
\]

where

\[
D = (\eta - \eta_b) \sqrt{\frac{2g}{a C_D |\nabla \eta|}},
\]

\(\eta_b\) is the bed elevation, and \(|\nabla \eta| = [(\partial \eta/\partial x)^2 + (\partial \eta/\partial y)^2]^{1/2}\). Equation (10) is the zero-bed-slope case of the diffusion wave equation, which has been used by hydrologists to model flow in river channels and over floodplains (Bedient and Huber, 1992). A similar equation has been suggested for friction-dominated propagation of tides in estuaries LeBlond (1978) and Jackson (1984) found an analogous limit for baroclinic flows through kelp forests. Scaling of Eqs. (10) and (11) suggests that tides and storm surges can propagate inland across a flat-bed wetland a distance of order

\[
L = \left( \frac{2gT^2 \eta_0}{a} \right)^{1/3},
\]

where \(\eta_0\) and \(T\) are tide or surge height and duration. Therefore, marsh widths much greater than \(L\) are expected to attenuate surges very effectively. In contrast, for marsh widths much less than \(L\), this scaling predicts nearly uniform sea level across the marsh.

As an example, for mangroves with \(a = 0.035\) m\(^{-1}\), significant attenuation of a fast-moving storm surge with \(T = 2.8\) h and \(\eta_0 = 5\) m would require on the order of 6.5 km of marsh width. Although this estimate is highly simplified, numbers are in fair agreement with the scale over which storm surge was halved in the sophisticated numerical simulations of Zhang et al. (2012) [their case 425R35, with \(a\) estimated from Figure 3(a) of Ward et al. (2006) and \(T\) set to \(2 \times (maximum\ wind\ radius)/(storm\ propagation\ speed)\)]. For tides in a dense sedge canopy with \(a = 3\) m\(^{-1}\), taking \(\eta_0 = 1\) m and \(T = 4\) h gives an attenuation scale of 1 km.

3.6. **Vertical and horizontal flow variability**

Numerous laboratory, observational and numerical studies have examined the reduction of currents by vegetation. Early laboratory flume experiments by Fonseca et al. (1982) and Gambi et al. (1990) found reduced currents behind a patch of the seagrass *Zostera marina*. Within-canopy velocities were reduced by a factor of 2–10, depending on plant densities. Turbulence
intensity was also reduced, but exhibited no clear dependence on stem density. Shi et al. (1995) observed a non-logarithmic velocity profile within a canopy of the salt marsh plant *Spartina anglica*. These laboratory findings have been supported by field observations (Figure 3). Measurements of flow speeds above and within salt marshes revealed that both the mean flow speed and turbulence intensities varied inversely with stem density and also decreased with distance into the marsh (Leonard and Luther, 1995). Reductions in total kinetic energy were observed, ranging from one order of magnitude for sparse canopies to 2–3 orders of magnitude for denser canopies. Rosman et al. (2007) found reduced currents within a kelp forest, and a positive correlation between turbulent energy dissipation and surface canopy coverage.

For deeply submerged canopies with $\lambda_f$ exceeding about 0.3, many studies have highlighted the occurrence of three flow zones in the vertical (Figure 2(d)), a logarithmic layer above the canopy, a low shear zone with a reduction in turbulence intensity inside the canopy (the “longitudinal exchange zone”), and a high shear, high turbulence zone near the top of

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Figure 3. Schematic of profiles of vegetation densities (a), (d) and corresponding velocity (b), (e) and turbulent kinetic energy (c) and (f) profiles for emergent (a)–(c) and submerged vegetation (d)–(e). Figure redrawn and adapted from measurements by Leonard and Croft (2006). (b) indicates the presence of three local velocity maxima within the canopy and for submerged vegetation (e), there is a global velocity maximum above the canopy and a smaller maximum within the canopy.
the canopy (the “vertical exchange zone”) (Lefebvre et al., 2010; Nepf and Vivoni, 2000). For smaller $\lambda_f$, the sheltered longitudinal exchange zone may be absent, in which case the bed may be exposed to high levels of turbulence generated by canopy drag (Nepf, 2012a). For flexible canopies, coherent waving structures or “monami” can be generated, centered on the high shear layer, which enhance the vertical transport of momentum or particulate matter into the canopy (Ghisalberti and Nepf, 2002). Some laboratory (Shi et al., 1995) and field measurements (Leonard and Croft, 2006) have found secondary flow maxima in the lower layer within the canopy. The location of such maxima is controlled by the vegetation morphology and is just below the main branching depth for branching vegetation (Figure 3). However, flow maxima are not always observed within a canopy. For example, Lefebvre et al. (2010) used a lab experiment with real seagrass to demonstrate relatively uniform reductions within a seagrass canopy and no dependence on shoot density for small patches, while Neumeier and Amos (2006) rarely saw a secondary maximum in natural salt marshes, attributing its absence to the relatively uniform canopy structure. The relatively fast above-canopy flow is sometimes called a “skimming flow”, to which the canopy simply appears as an enhanced bottom roughness element.

In addition to the vertical variability discussed above, observations sometimes show strong within-canopy horizontal flow variability. Both vertical and horizontal variability often lead to the development of preferential flow paths. Even in a constructed wetland of salt marsh plants which exhibited much less horizontal and vertical heterogeneity than in natural systems, Lightbody et al. (2008) still observed “short-circuiting” flow paths. Furukawa et al. (1997) found that vegetation-induced friction in dense mangrove forest in Australia resulted in complicated circulation patterns with jets, eddies and stagnation zones. They estimated a Manning friction coefficient of $n = 0.1$, a value four times higher than in the adjacent tidal creeks and the canonical values used in estuaries.

Heterogeneity associated with incised creeks promotes tidal asymmetry in mangrove forests, with in-creek ebb dominance proportional to the density of surrounding mangroves (Mazda et al., 1997b). Two flow regimes were distinguished by Horstman et al. (2013) through field measurements within mangrove forests. One regime, designated creek flow, was characterized by large velocities and water predominantly enters the mangroves via over flow from the creeks with minimal exchange across the forest edge. The second regime was sheet flow, with direct water exchange across the forest edge. Rotation of the flow occurs with creek parallel flow at the edges of the marsh transitioning to creek perpendicular slow flow farther into the forest. Two distinct flow regimes have also been observed inside salt marshes by
Temmerman et al. (2005a). Temmerman et al. (2005b) used Delft3D to develop the corresponding numerical model. They found creek flow was present when water levels were lower than the top of the vegetation (i.e. emergent conditions), whereby the vegetated area flooded perpendicularly from marsh edges, and sheet flow when water levels exceeded vegetation heights. The vegetation density was found to exhibit the strongest control on the flow routing, with small-scale topography within the forest having little effect.

4. Oscillatory Flow Inside Canopies

Aquatic vegetation is commonly exposed to waves. Much attention has therefore focused on wave interactions with vegetation and the parameterization and modelling of dissipation under oscillatory flows (Chen et al., 2018).

4.1. Drag and dissipation in oscillating flows

Drag is often modeled using the Morison equation (Sumer and Fredsøe, 1997)

\[ F_d = \frac{1}{2} \rho d C_D |u| u + \frac{\pi d^2}{4} \rho C_M \frac{\partial u}{\partial t}, \]

(13)

where the first term resembles steady drag of Eq. (3), and \( C_M \) is an inertia coefficient (usually order-one), representing additional forces exerted in an accelerating flow. The ratio between the acceleration term and the more standard drag term is of order \((2\pi^2)KC^{-1}\) where \( KC = uT/d \) (we have assumed \( C_M/C_D = 2 \)). The parameter \( KC \), called the the Keulegan–Carpenter number, equals \( 2\pi \times \) (wave-induced displacement of water particles)/\( d \). For thin stems (e.g. sedges, grasses and mangrove pneumatophores), \( KC \) is often large, in which case the last term of Eq. (13) is small and drag forces resemble those found in steady flows. However, for thick stems (e.g. the trunks of mangroves), \( KC \) can be small, indicating significant acceleration-induced forces. The coefficients \( C_D \) and \( C_M \) depend on \( KC \) and \( Re \) (Sumer and Fredsøe, 1997).

If vegetation is not too dense (\( \phi \ll 1 \), summing over individual stems gives the total canopy drag

\[ F_c = \frac{1}{2} \rho a C_D |u| u + \rho \phi C_M \frac{\partial u}{\partial t}. \]

(14)

The wave dissipation rate at a fixed elevation is the mean rate of working by this drag on the flow

\[ \overline{F_c u} = \frac{1}{2} \rho a C_D |u|^3, \]

(15)
where the overbar denotes the average over a wave period, and for rigid vegetation, the last term of (14) does not contribute because \( u \frac{\partial u}{\partial t} \approx 0 \).

### 4.2. Modeling wave attenuation

Using Eq. (15), Dalrymple et al. (1984) calculated the depth-integrated dissipation \( \epsilon = \int F_c u \, dz \) for waves propagating through a uniform canopy of cylindrical stems, which yielded the dissipation estimate for waves of root-mean-squared height \( H \),

\[
\epsilon = \frac{1}{4} \rho g c_g f(\omega, h, \alpha) H^3, 
\]

where \( \omega \) is wave angular frequency in radians s\(^{-1} \), \( c_g \) is the group velocity, and \( \alpha \) is a submergence parameter (\( = \ell/h \) for submerged vegetation and 1 for emergent plants). The effects of depth-dependent velocity and canopy height are represented by

\[
f(\omega, h, \alpha) = \frac{g^2}{3\pi c^3 c_g} \left( \frac{a}{k} \right) C_D \frac{\sinh^3 k ah + 3 \sinh k ah}{3 \cosh^3 k h},
\]

in which \( k \) is the wave number and \( c \) is the phase speed. Here, \( f \), \( k \) and \( c_g \) are calculated from linear wave theory (Phillips, 1977). It may seem odd to use linear wave theory, which neglects drag, to estimate within-canopy velocities. Indeed, in very dense seagrass canopies, a modest but clearly observable reduction in water velocity from linear theory predictions has been measured (Luhar et al., 2010; Luhar and Nepf, 2013). Nevertheless, non-dissipative linear theory provides a useful first approximation in many canopies, because drag often has only a small effect within a single wave period (i.e. \( R_T \gg 1 \), Section 3.4; for behavior in very dense canopies, see Henderson et al., 2017; Lowe et al., 2005). Even for \( R_T \gg 1 \), substantial wave attenuation can occur as waves propagate for many periods into a marsh, as described by the wave energy balance

\[
\frac{\partial E c_g}{\partial x} = -\epsilon,
\]

where \( E = 1/8 \rho g H^2 \) is the wave energy, and \( x \) is the direction of wave propagation. Given a horizontally uniform canopy and depth, Eqs. (16) and (18) can be written in the form \( \partial H^2/\partial x = -2f H^3 \), which has the solution

\[
H = \frac{H_0}{\frac{1}{1 + x/x_0}},
\]
where $x_0$ is the wave attenuation scale (i.e. the distance waves propagate before their initial amplitude is halved), given by

$$x_0 = (fH_0)^{-1}, \quad (20)$$

and $H_0$ is the wave height at $x = 0$. Although the attenuation predicted by Eq. (19) is consistent with standard drag laws, dissipation can also be approximated by exponential decay of the form

$$H = H_0 \exp(-k_D x), \quad (21)$$

where $k_D$ is the decay coefficient (Kobayashi et al., 1993, using a linearized function of velocity to represent the drag force).

### 4.3. Observed attenuation in rigid vegetation

Using $k_D$ to compare between attenuation in a salt marsh and over a nearby sand flat, Möller et al. (1999) found that the marsh dissipated waves at a rate of almost three times the rate of the sand flat, with a more uniform dissipation across frequency range. Many observations of wave dissipation have focused on marshes with flexible vegetation, to be discussed in the following section. However, mangroves provide a clear case of rigid vegetation which has been shown to substantially dissipate wave energy (Bao, 2011; Henderson et al., 2017; Massel et al., 1999) with a 5–7.5 times reduction in wave height observed by Quartel et al. (2007) and a maximum rate of 44%/100 m observed by Horstman et al. (2014). Accurately quantifying vegetation densities within mangrove forests can be particularly labor intensive owing to the presence of both roots (pneumatophores) and trunks. Mazda et al. (1997a) used the age of trees as a proxy for vegetation cover and Vo-Luong and Massel (2008) found that most attenuation occurred owing to wave trunk interaction in comparison with breaking (although the importance of breaking increased in sparse forests). For a forest composed of *Sonneratia* sp., Mazda et al. (2006) found an initial reduction in wave attenuation with water depth (consistent with Horstman et al., 2014) as the roots became more deeply submerged; however, the rate of attenuation rose again once the water level was sufficient to reach the branches and leaves of the main trees.

As waves propagate through vegetation, different frequencies may be attenuated at different rates. In mangroves, short wind waves were observed to be more rapidly attenuated than longer period swell (Horstman et al., 2014). According to linear wave theory, attenuation of energy at each frequency is expected to obey a model resembling Eqs. (18)–(20) (slightly modified since the $|u|$ term in Eq. (14) should be a value representative
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of the entire spectrum). The predicted attenuation scale $x_0$ is frequency-independent for shallow water waves, but for intermediate- or deep-water waves in depth-uniform emergent vegetation higher frequencies are attenuated more rapidly. In a dense (high $\phi$) canopy, predictions diverge from the model of Dalrymple et al. (1984), and high-frequency shallow water waves are dissipated preferentially (Lowe et al., 2007). Mendez and Losada (2004) refined the model of Dalrymple et al. (1984) to include wave breaking and non-uniform bathymetry and found reasonable agreement with observed wave damping against laboratory observations.

4.4. Dissipation in flexible vegetation: Parameterizations based on Reynolds or Keulegan–Carpenter numbers

When flexible canopies are deformed by water flows, it may be best to interpret $u$ in Eqs. (13)–(15) as the water velocity relative to the moving vegetation. Therefore, the plant motion itself becomes an important factor influencing drag and wave dissipation. To represent the resulting dynamics simply, an empirical relationship between the effective drag coefficient and Reynolds number was suggested by Kobayashi et al. (1993) with the form

$$\hat{C}_D = \alpha + \left(\frac{\beta}{Re}\right)^\gamma.$$  \hspace{1cm} (22)

This form provided a good fit to data from experiments with artificial kelp conducted by Asano et al. (1993). Here, $\hat{C}_D$ is the drag coefficient required to yield the correct predictions if vegetation motion is neglected when evaluating equations such as Eqs. (13)–(15). This effective drag coefficient parameterizes the complex dynamics of plant motion, and may be quite different from the drag coefficient that would apply if vegetation motion were accounted for in Eqs. (13)–(15). This approach has since been used in many studies to characterize drag for a variety of vegetation and wave conditions (see Table 2 and Figure 4). Some of these parameterizations use the water motion relative to vegetation in the calculation of Reynolds number (Bradley and Houser, 2009). Several authors have found that a better parameterization can be obtained using the Keulegan–Carpenter number (Augustin et al., 2009; Mendez and Losada, 2004), although in one low-energy case Bradley and Houser (2009) did not find that such parameterization outperformed a Reynolds number-based parameterization. Plants in natural canopies often have a wide variety of shapes, sizes and flexibility. Blackmar et al. (2014) evaluated wave attenuation over mixed vegetation (two types) and found that a linear combination of the
Table 2. Summary of fitted coefficients for a drag coefficient of the form in Eq. (22) from a variety of studies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>Plants</th>
<th>Real or mimics</th>
<th>Type of study</th>
<th>Comments</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kobayashi et al. (1993)</td>
<td>0.08</td>
<td>2200</td>
<td>2.4</td>
<td>Kelp</td>
<td>Mimics</td>
<td>L</td>
<td>Data from Asano et al. (1993)</td>
<td>Black solid</td>
</tr>
<tr>
<td>Méndez et al. (1999)</td>
<td>0.08</td>
<td>2200</td>
<td>2.2</td>
<td>Single stem</td>
<td>A</td>
<td>Motionless plants</td>
<td>Black dashed</td>
<td></td>
</tr>
<tr>
<td>Méndez et al. (1999)</td>
<td>0.4</td>
<td>4600</td>
<td>2.9</td>
<td>Single stem</td>
<td>A</td>
<td>Swaying plants</td>
<td>Black dash-dot</td>
<td></td>
</tr>
<tr>
<td>Bradley and Houser (2009)</td>
<td>0.1</td>
<td>925</td>
<td>−3.16</td>
<td>Seagrass Thalassia testudinum, and Halodule wrightii</td>
<td>Real</td>
<td>F</td>
<td>Re from water velocity</td>
<td>Black dot</td>
</tr>
<tr>
<td>Bradley and Houser (2009)</td>
<td>0.1</td>
<td>925</td>
<td>−3.52</td>
<td></td>
<td>Real</td>
<td>F</td>
<td>Re from relative velocity of seagrass blades</td>
<td>Blue solid</td>
</tr>
<tr>
<td>Paul and Amos (2011)</td>
<td>0.06</td>
<td>153</td>
<td>1.45</td>
<td>Seagrass Zostera noltii</td>
<td>Real</td>
<td>F</td>
<td>Restricted to $H_S \geq 0.1$ m</td>
<td>Blue dashed</td>
</tr>
<tr>
<td>Jadhav and Chen (2012)</td>
<td>0.36</td>
<td>2600</td>
<td>1</td>
<td>Salt marsh Spartina alterniflora</td>
<td>Real</td>
<td>F</td>
<td>Observations during tropical cyclone</td>
<td>Blue-dot-dash</td>
</tr>
<tr>
<td>Maza et al. (2013)</td>
<td>0.87</td>
<td>2200</td>
<td>0.88</td>
<td>Submerged plants</td>
<td>N</td>
<td>No vegetation movement</td>
<td>Blue dot</td>
<td></td>
</tr>
<tr>
<td>Maza et al. (2013)</td>
<td>1.61</td>
<td>4600</td>
<td>1.9</td>
<td>Submerged plants</td>
<td>N</td>
<td>Submerged and emergent vegetation</td>
<td>Red solid</td>
<td></td>
</tr>
<tr>
<td>Koftis et al. (2013)</td>
<td>0</td>
<td>2400</td>
<td>0.77</td>
<td>Seagrass Posidonia oceanica</td>
<td>Real</td>
<td>L</td>
<td>Irregular waves</td>
<td>Red dashed</td>
</tr>
<tr>
<td>Anderson and Smith (2014)</td>
<td>0.76</td>
<td>744.2</td>
<td>1.27</td>
<td>Salt marsh Spartina alterniflora</td>
<td>Mimics</td>
<td>L</td>
<td>Submerged and emergent vegetation</td>
<td>Red dot-dash</td>
</tr>
</tbody>
</table>

Notes: The type of study is given by: L — laboratory flume study, F — field observational study, A — analytical and N — numerical modeling. The corresponding curves for the range of Reynolds number considered in each study are shown in Figure 4.
Multiple studies have considered frequency-dependent dissipation. Anderson and Smith (2014) found preferential dissipation of higher frequencies, and dissipation increased at frequencies above the spectral peak, consistent with Bradley and Houser (2009) and Zeller et al. (2014). However, Manca et al. (2012) found wave attenuation was greatest at the peak frequency. Jadhav et al. (2013) used the model of Chen et al. (2012) to examine field measurements of wave heights and velocities across a salt marsh in storm conditions. They found significant dissipation across the leading section with the dominant energy loss close to the spectral peak, while lower frequencies (<0.16 Hz) were not substantially dissipated. The spectral model resulted in an improved fit of the frequency-dependent curve for velocity attenuation $u_{\text{veg}}/u_{\text{no veg}}$.

For storm events, inspection of Eq. (20) suggests more rapid wave attenuation, given constant depth, than for cases with smaller waves. However, Eq. (22) suggests that effective drag coefficients may be reduced during storms. Furthermore, for submerged canopies, if a storm surge increases the depth by an amount that is not much less than a wavelength, then Eq. (17) suggests that depth attenuation reduces dissipation $|\sinh(kh)/\cosh(kh)|$.

Figure 4. Drag coefficient as a function of Reynolds number for an equation of the form of Eq. (22). Results from multiple authors over the range of Reynolds numbers considered in each case. See Table 2 for authors and line styles and the coefficients $\alpha$, $\beta$ and $\gamma$. 

attenuation coefficients formed a reasonable estimate of dissipation in these cases.
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is reduced]. A laboratory study found that a constructed salt marsh retained its ability to dissipate waves under simulated storm wave and surge conditions (Möller et al., 2014). Field observations during intense storm conditions (Jadhav et al., 2013) found substantial vegetation-induced dissipation, in addition to dissipation by breaking near the marsh edge.

The parameterizations described in this section were fit to particular vegetation types, and finding an accurate drag parameterization which can be applied to a variety of vegetation types and hydrodynamic conditions remains a substantial challenge (Pinsky et al., 2013). Figure 4 demonstrates that fitted drag coefficients between studies can vary over three orders of magnitude for small ranges of Reynolds numbers. Indeed, even intra-annual seasonal variations have been shown to change the wave attenuation characteristics of vegetation (Paul and Amos, 2011). A wide variety of intriguing trends have been observed. For example Sanchez-Gonzalez et al. (2011) found reduced dissipation of steeper waves. Augustin et al. (2009) and Anderson and Smith (2014) found substantially increased attenuation during emergent conditions. Anderson and Smith (2014) found trends in fitted drag coefficient with frequency, and opposite dependencies on wave period between the submerged and emergent cases, while Bradley and Houser (2009) found the ability to dissipate waves decreases for higher wave heights or as the conditions became more turbulent.

4.5. Dissipation in flexible vegetation: The role of vegetation stiffness

Vegetation flexibility depends on properties such as stem length \( l \), the stem’s Young’s modulus \( E \), which measures a material’s resistance to deformation, and the density of the solid plant material \( \rho_s \) (in kg m\(^{-3}\)), which influences a plant’s buoyancy. Such properties are not included in Re- or KC-based parameterizations, a fact that may contribute to the wide range of results that have been obtained (Figure 4). In this section, models that incorporate the properties controlling vegetation flexibility are discussed, starting with models emphasizing vegetation stiffness, and then proceeding in Section 4.6 to models for buoyant vegetation.

As with unidirectional flows (Section 3.3), drag can be reduced when stems bend to align with the flow, as noted in the context of seagrass by Bradley and Houser (2009) and Luhar et al. (2010). Chapman et al. (2014) used torque sensors placed on individual shoots to demonstrate that flexible vegetation experiences lower wave drag than equivalent rigid vegetation. In addition to streamlining, oscillatory flow introduces a new mechanism
for drag reduction: if the wave orbital excursion does not exceed the stem length, then very flexible stems can ‘go with the flow’, so that water and stem velocities are almost equal. Since it is the difference between water and stem velocities that appears in Eqs. (13)–(15), this can greatly reduce drag forces and dissipation (Denny and Gaylord, 2002; Koehl, 1984). This mechanism for drag reduction is not possible for steady flows, in which particle displacements are unbounded. Zeller et al. (2014) called the ratio between water and stem displacements a modified Keulegan–Carpenter number, and found that drag reduction (relative to rigid vegetation) for simulated stems was strongly correlated with this ratio. The simulations of Zeller et al. (2014) were conducted using a numerical model that represented stem dynamics, including stem inertia and forces of drag, lift, stiffness and buoyancy. Laboratory experiments were conducted in a wave flume using flexible artificial stems resembling seagrass, and good agreement was found between simulations and measurements.

For many stems, it may be possible to simplify the full equations governing stem motion. In most cases where stems bend, the Keulegan–Carpenter number is large, often justifying neglect of stem inertia and the last term in Eq. (13), which reduces the stem dynamics to a balance of forces. If wave-induced oscillations in stem tilt are small, as is often true for sedges and giant kelp, but sometimes is not true for seagrasses or short kelp, then the differential equation for bending of non-buoyant stems (the “Euler–Bernoulli equation”) becomes linear. Mullarney and Henderson (2010) developed an analytic model for this case, assuming a balance between elastic restoring forces and bending by drag forces (neglecting buoyancy). Solutions were governed by one key parameter \( S \), termed the “dimensionless stiffness”, incorporating both wave and vegetation characteristics

\[
S = \frac{\pi Ed^2 t_0}{4\rho C_D \ell^4 u} \tag{23}
\]

where \( u \) here represents horizontal wave velocities and \( t_0 \) is the wave period. Short, thick stems, small waves, or long wave periods produce large \( S \). In the rigid limit \( S \gg 1 \), stem motions are much smaller than water motions, whereas for \( S \ll 1 \) vegetation moves almost with the surrounding water. The model was tested by video tracking of an intermediate stiffness sedge in a natural salt marsh. The model was forced using vertical profiles of water velocity, estimated using linear wave theory and a nearbed current meter, and good model-data agreement was obtained (Figure 5). The model indicated that flexibility reduced wave dissipation by 70%, a prediction broadly supported by larger scale measurements and modeling of wave...
Figure 5. Amplitude (a), (b), (e) and (f) and phase (c), (d), (g) and (h) of transfer functions between stem motion and surface water motion for two sedge stems ((a)–(d): stem 1, ℓ = 0.81 m, (e)–(h): stem 2, ℓ = 0.45 m) computed from observations (a), (c), (e) and (g), together with corresponding theoretical transfer functions for a tapered stem (b), (d), (f) and (h) obtained from the theory of Mullarney and Henderson (2010). Observed amplitudes and phases are shown only when the squared coherency was > 0.3 (this region is marked by the white outline in (b), (c), (e) and (f). Black contour lines indicate amplitudes of 0, 0.4, 0.8 and 1.2 and phases of 0°, 30°, 60° and 90°. The observed wave period was ∼2 s.
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Figure 6. Relative reduction in dissipation owing to vegetation motion as predicted by Mullarney and Henderson (2010). Dissipation of each wave frequency is simulated using a model for vegetation motion. The line indicates the ratio between dissipation in flexible vegetation and dissipation in rigid vegetation with equivalent stem geometry. Summing over all frequencies indicates that dissipation is \( \sim 30\% \) of that for equivalent rigid stems. The thin vertical dashed line indicates the peak forcing frequency.

attenuation in the same marsh, which found a 50% reduction in dissipation owing to flexibility (Riffe et al., 2011).

For general depth-dependent flows, the Mullarney and Henderson (2010) model requires projection of velocity profiles onto the normal modes of stem motion. Complex behavior can result, and in some cases vegetation can act as a band-pass filter, preferentially damping both high and low frequencies (Figure 6). However, if \( S \ll 1 \) predictions reduce to a simple, easily evaluated formula. Given small stem tilt, highly flexible, non-buoyant, stems move with surrounding water except in a nearbed region of thickness \( S^{1/4} \ell \). Consequently, predicted dissipation in such stems is equal to \( 1.23 S^{1/4} \epsilon_r \), where \( \epsilon_r = (1/2) \rho_a C_D |u_b|^3 \) is the dissipation expected if the stem were rigid, and \( u_b \) is the nearbed water velocity. This scaling was emphasized by Luhar and Nepf (2016) who found it to be in good agreement with wave dissipation observed in the laboratory across a range of \( S \) values.

4.6. Dissipation in flexible stems: The role of buoyancy

Large marine algae grow to tens of meters, a height comparable to terrestrial trees. If these macroalgae were rigid, then 2 ms\(^{-1}\) flows, as occur under
large waves, would exert a force comparable to that felt by a tree in a 200 km h\(^{-1}\) wind. Macroalgae are not subjected to such high forces because they are highly flexible, relying for support on buoyancy rather than rigidity. The force reduction resulting from flexibility can reduce stem breakage (Denny and Gaylord, 2002; Koehl, 1984). In field investigations, morphological differences have been observed to correspond to physical stressors (e.g. Armstrong (1987) observed differences in the morphology of *Hedophyllum sessile*, and Hurd *et al.* (1996) found differences amongst the blades of *Macrocystis integrifolia* between sites with different wave exposure). Additionally, deformation and motion of the kelp blades can alter boundary layers and nutrient uptake (Hurd and Pilditch, 2011; Hurd *et al.*, 1997).

Alongshore currents can be reduced by a factor of three or more in large kelp stands (Jackson and Winant, 1983; Jackson, 1997). A particularly extensive array revealed spatial variability on the scale of a patch of the giant kelp *Macrosystis pyrifera* a few hundred meters across (Gaylord *et al.*, 2007). In contrast to the effectiveness of kelp in reducing tidal and other long period currents, the ability of kelp to damp waves is less clear. Elwany *et al.* (1995) and Rosman *et al.* (2007) carried out field experiments and found little dissipation of swell waves by large *Macrocystis pyrifera* kelp beds in California. Further field observations have indicated that forces experienced depend on position along the stipe with even flexible kelp species found not to move with the surrounding water close to the sea bed (Stevens *et al.*, 2001, 2002), raising the possibility of enhanced nearbed dissipation owing the presence of kelp. In the laboratory, detailed within-canopy measurements have revealed a reduction in wave orbital velocities within a synthetic kelp canopy (Rosman *et al.*, 2013).

A numerical model for kelp motion was developed by Utter and Denny (1996). This model represented a kelp blade as a mass on the end of a massless elastic cord. The acceleration of the mass was calculated, accounting for added mass and the forces of drag, buoyancy, tension and pressure gradients associated with water motion. Simulated maximum stem tensions over multi-day deployments were compared with measured maximum tension on *in situ* stems, with fair agreement reported.

Recent work by Mullarney and Pilditch (2017) has examined the possibility that kelp may non-uniformly dissipate energy at different frequencies and across different depths. They conducted a field experiment to examine the movement of a single kelp at varying heights along the stipe. The kelp specimen was instrumented with accelerometers and placed slightly outside the kelp forest to exclude sheltering effects. The response was found to be depth-dependent and dominated by tilt, but the kelp responded very
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Figure 7. Power spectral densities of accelerations (sum of all three axes $S_{g_x}+S_{g_y}+S_{g_z}$) from sensors on kelp at different heights above the holdfast (indicated by colors). Each data record was 48 minutes long, and the spectra have 29 degrees of freedom. Responses at (a) infragravity and (b) swell frequencies showing larger tilts toward the surface at the infragravity frequency and conversely larger tilts closer to the bottom at the swell frequencies. Note the change in $y$-axis scale between (a) and (b) demonstrating responses were dominated by the lower frequency motions. Insets: the corresponding shape of the kelp at the different frequencies.

...differently between the swell and infragravity frequencies. At the infragravity frequencies, more tilting (corresponding to larger "accelerations" recorded by the sensors) was observed at the top of the stipe relative to the bottom, whereas at the swell frequencies the opposite was observed (Figure 7). The results were attributed to the differences in frond lengths along the stem. At the top of the kelp, fronds were longer than the horizontal particle motion at the swell frequencies but shorter than the displacements at infragravity frequencies, whereas close to the bottom the shorter fronds were stretched out (and exerting forces on the stipe) at all frequencies.

4.7. Wave-induced streaming through vegetation

Waves induce a mean flux of momentum, often called the radiation stress, whose convergence sometimes acts to generate mean currents. One
well-known example is the forcing of mean alongshore currents by waves breaking on a beach (Longuet-Higgins and Stewart, 1964). Luhar et al. (2010) showed that friction associated with a nearbed vegetation canopy can lead to a nearbed convergence in the wave-induced vertical flux of horizontal momentum, which is expected to force a nearbed mean current in the direction of wave propagation. Observations in natural (Luhar and Nepf, 2013) and artificial (Luhar et al., 2010) nearbed canopies confirm the existence of mean currents, scaling with $u^2/c$ as expected if the currents are wave-forced. Only one set of field observations has been obtained, laboratory observations of mean currents in canopies that extend over much of the water column exhibit some unexplained trends (Pujol et al., 2013), and a vertically resolved theory for wave-forced currents in vegetation has not yet been established. However, the currents observed in the sole existing field observations were striking, being almost as large as the wave-induced velocity fluctuations, and substantially larger than the Stokes drift. Such currents are easily large enough to have a major effect on many transport processes, suggesting that further research into wave forcing of currents within vegetation may prove fruitful.

5. Sedimentation Within Vegetation Canopies

The damping of mean flows and oscillatory currents caused by marine vegetation has consequences for sediment transport in coastal regions, with significant changes in patterns of erosion and accretion. The tendency for vegetation to slow currents and dissipate waves can create sheltered regions of low flow, where sediments can deposit. Most early studies focused on this enhanced deposition in vegetated regions relative to nearby unvegetated areas (e.g. Fonseca et al., 1983, found higher topography within meadows of the seagrass *Zostera marina*), or reduced suspended particulate matter (SPM) inside seagrass beds (Ward et al., 1984). Consequently, fluvial wetlands can act as short-term sediment sinks and longer-term sediment storage (Phillips, 1989), emphasizing their usefulness in retaining and removing nutrients (Gribsholt et al., 2007). Vegetation also induces spatial variability and changes in bed shear stress. Numerical simulations of Lopez and Garcia (1998), found that under constant forcing (i.e. constant $dp/dx$) the presence of simulated vegetation reduced momentum at bed and for $\lambda_f = 0.3$, the bed stress was reduced to 20% of bare bed values. However, for smaller $\lambda_f$, vegetation may increase nearbed turbulence (Nepf, 2012a; Norris et al., 2017). Furthermore, geotechnical studies have also found that salt marsh vegetation in high salinity regions can increase the soil shear
strength (and consequently marsh-scale resilience) owing to binding by root networks (Howes et al., 2010).

Many authors have emphasized the distinction between the enhancement of deposition (e.g. by leaves trapping the sediment particles) and the suppression of resuspension preventing particles from being removed once settled (e.g. Garcia and Duarte, 2001). However, there is still much to be determined regarding the interaction of vegetation and sedimentation as conflicting results are often obtained. For example, on occasion, the presence of vegetation has been observed to coincide with higher suspended sediment concentrations (SSCs) relative to unvegetated areas. Koch (1999) observed higher values of SSC for short sections of the tidal cycle, and attributed this result to intensification of the speed close to the bottom and the earlier trapping of fine materials, allowing for resuspension at a lower velocity. The interactions of flow with vegetation at the marsh edge is also an active area of research, with a variety of results reported owing to the competing processes of sediment trapping due to energy reduction and the enhanced turbulence generation. The transition from unvegetated to vegetated areas has sometimes been observed to correlate with erosion and local topographic depression owing to the rapid generation of turbulence by the fast (as yet unslowed) flow interacting with obstacles (e.g. Widdows et al., 2008a, who observed a topographic depression at the edges of a mudflat populated with Spartina anglica). Similarly, high sedimentation rates but erosion at the front and side of high-density patches, was observed by Bouma et al. (2007) in their 2-year long field study. Conversely, low patches showed only small-scale erosion around different elements. The transition between these regimes is not clearly distinguished, and their hydrodynamic model could not reproduce the erosion at the upstream edge of the patch.

The dependence of patch dynamics on patch size, density and spacing is still unclear. For the range of complex geometries observed in natural wetlands, many spatially variable deposition patterns have been observed. In a flume study, Zong and Nepf (2010) explored flow in and around a patch of vegetation and described three separate zones of variable deposition. In front of the patch, deposition was observed, owing to flow blockage inducing lateral divergence and deceleration (similar to observations of accretion at a salt marsh edge by Pratolongo et al., 2010). Within the patch, deposition was almost laterally uniform, and deposition decreased with distance from the leading edge, except for a region of diminished deposition at the sheared region between the open channel flow and patch. Similarly Rominger et al. (2010) found erosion at lateral edges stopped lateral expansion of vegetation patches in streams. A laterally uniform
deposition region among emergent vegetation was characterized by Zong and Nepf (2011) as occurring for distances less than the longitudinal advection length scale \( x_a = u h / w_s \), where \( w_s \) is the settling velocity, (so \( h / w_s = T_S \) is a settling timescale). For distances further than \( x_a \), net deposition was largest near the flow parallel edge and decreased into the patch. In their experiments with glass beads, the advection length scales \( x_a \) ranged from 1.2 to 4.2 m for dense arrays (\( \phi = 0.1 \)) and from 7.2 to 19.6 m for sparse patches (\( \phi = 0.02 \)) over varying flow speeds (\( u \) ranging from 0.05 to 0.12 ms\(^{-1} \)).

Chen et al. (2012) considered a circular patch composed of rigid cylinders and concluded that the flow was controlled by the ratio between the patch width \( D \) and the blockage length scale \( (C_D a)^{-1} \). When \( D \gg (C_D a)^{-1} \), scaling of flow deep inside the patch transitions to dependence on \( \phi \). They found two regions with peaks in turbulence intensity, in which deposition is inhibited; one directly behind the patch (owing to its small size) and a second peak at the length defined by the von Karman vortex behind the patch.

Despite these differences in observed sedimentation between studies, it is generally acknowledged that the 3D structure of the vegetation is an important factor influencing sedimentation patterns within many wetlands. In a numerical study, Temmerman et al. (2005b) conclude that relatively spatially homogenous deposition occurs during sheet flow (water levels higher than the vegetation); however, for lower water levels they found at the edge of the salt marsh, sediments are rapidly deposited, with the amount of deposition decreasing with distance into the marsh. They found that in the gaps between the vegetation, faster flow velocities result in less sedimentation or erosion. Conversely, recent field observations from within the fringing region of a mangrove forest (consisting of pneumatophores and sparsely spaced trees) in the Mekong Delta, Vietnam revealed scouring around individual roots and tree trunks and mounding and deposition of sand within the gaps between obstacles after a large wave event (Figure 8) (Mularney et al., 2017).

The influence of vegetation on sediment dynamics may vary greatly with grain size. Van Katwijk et al. (2010) found that at a wave-exposed sandy site, dense vegetation induced muddification, but appeared to have no effect at sparse sites. Conversely, at sheltered muddy sites the presence of sparse vegetation led to sandification (removal of fine sediments and organic materials), whereas the dense vegetation had no effect on the bed composition. The balance between the dominant processes of energy reduction and turbulence generation shifted with plant density, with high densities promoting muddification and stabilization of the sediment.
Figure 8. Photos from the mangrove fringe at the Southern end of Cu Lao Dung Island in the Mekong Delta, Vietnam after a large wave event. Scouring around (a) individual pneumatophore roots, (b) individual tree trunks and deposition of sand in the gaps between the lines of roots (c). After this event, observations reveal that mud was deposited further outside the forest on the intertidal mudflat (Photo credits: Julia Mullarney and Benjamin Norris).

Although the above discussion has focused on the physical aspects of sedimentation, transport and deposition can be strongly modulated by biological processes such as bioturbation and biostabilization. In a flume study with seagrass beds of different densities, Widdows et al. (2008b) found that, despite enhanced turbulent kinetic energy and bed stress within a high-density seagrass bed in a sandy substrate, the sediment was stabilized (shown by an increase in critical erosion threshold). This stabilization was attributed to an increase in the abundance of microphytobenthos, which increases binding and cohesiveness through production and excretion of...
extracellular polymeric substances (EPS). Sedimentation patterns in rivers have also been shown to depend on the changes in macrophyte coverage associated with different growing seasons (Cotton et al., 2006).

6. The Prediction of the Long-Term Evolution of Vegetated Shorelines

The discussion above focused on time scales not exceeding a tidal period. Over longer time scales, vegetation canopies grow and bathymetry evolves. A rich variety of interactions may develop between hydrodynamics, sediment fluxes, morphological evolution and vegetation growth, all potentially modified by human activities (Figure 9). The current state of research into longer term evolution of salt marshes and tidal networks has been addressed in comprehensive recent reviews by Coco et al. (2013) and Fagherazzi et al. (2012), so we only discuss a few key results here.

Figure 9. Schematic depicting the range of possible biophysical interactions over multiple temporal and spatial scales which control the long-term evolution of our vegetated coastlines. Figure adapted from Coco et al. (2013).
Tidal networks exhibit great diversity of form and, unlike some fluvial networks, are not scale invariant (Feola et al., 2005; Rinaldo et al., 1999). By the standard of landscape formation processes, evolution of tidal wetlands occurs relatively quickly (D’Alpaos et al., 2005). Nevertheless, time scales are sufficiently long to make measurements of interactions between vegetation and morphology challenging. However, the merging of two vegetation patches has been observed in a flume experiment by Vandenbruwaene et al. (2011). Morphodynamics have been simulated using models that incorporate two-way coupling between hydrodynamics and plant growth, with growth often parameterized as a nonlinear function of hydrodynamic regimes and depth. Such models have been found to produce complex tidal networks (D’Alpaos et al., 2005), with vegetation playing a key role (Mariotti and Fagherazzi, 2013). A modeling study by van Maanen et al. (2015) found that mangroves enhance simulated initiation and branching of tidal channels. Similarly, Temmerman et al. (2007) found that simulated flow is concentrated between patches of dense marsh vegetation, leading to scouring and channelization. Development of salt marshes decreased the width-to-depth ratio of simulated channels (D’Alpaos et al., 2006), whereas reductions in tidal prism were not found to have a significant effect (Vandenbruwaene et al., 2013). Simulated coupled evolution of vegetation and morphology may be sensitive to the choice of sediment transport formulation, as has been found to be the case in cases without vegetation (Dissanayake et al., 2009).

A common feature of many models is the existence of multiple equilibria (Marani et al., 2007), with transitions between states exhibiting hysteresis (D’Alpaos et al., 2007; Marani et al., 2010). Permanent loss of simulated wetland was seen to occur after even temporary changes in vegetation coverage (Kirwan et al., 2008), or under some sea-level rise and lower sediment supply scenarios (Kirwan and Murray, 2007). Coupling between the hydrodynamics and ecology is also crucial, with morphological regimes differing between single species regions and areas colonized by multiple species (D’Alpaos et al., 2007).

7. Conclusions and Future Challenges

In recent years, flows through vegetated canopies have received growing attention, as the importance of vegetated environments has become more widely recognized, particularly in light of recent work demonstrating that salt marshes are sensitive to climatic change and sea-level rise (Fagherazzi et al., 2012). Research is progressing rapidly, and observations have revealed a rich variety of flow patterns, many resulting from the heterogeneity of
natural canopies. A very broad variety of canopies exist, and only a few have yet been extensively studied (Bouma et al., 2014). Similarly, few field studies have been undertaken during “extreme” conditions, during which large amounts of sediments can be moved and shorelines substantially altered.

Estimation of mean drag and wave dissipation in flexible canopies remains a significant challenge. Recent progress on the mechanics and scaling of stem bending may have the potential to aid in the development of broadly applicable models under steady flows. Under waves, empirical models have success when tuned for a particular species, but must be returned for each new species considered. Research into the coupled solid–fluid dynamics underlying vegetation bending is in progress, partly motivated by the hope that this approach may yield more broadly applicable parameterizations.

As modeling of flows through vegetation becomes more sophisticated, the need for accurate parameterizations of sediment transport processes is likely to grow. The balance between processes of erosion and scouring, and the feedback effects on plant growth and vegetation patch development, remain unclear. Additionally, little work has focused on the process of flocculation of sediments within canopies. Although some of these important research questions are challenging, the ecological importance and vulnerability of vegetated environments provide sufficient motivation for further work, and the numerous yet-unstudied environments provide ample opportunities for continued rapid progress in this field.

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References


Flows Within Marine Vegetation Canopies


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