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Efficient three-dimensional reconstruction of aquatic vegetation geometry: Estimating morphological parameters influencing hydrodynamic drag

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ABSTRACT

Aquatic vegetation can shelter coastlines from energetic waves and tidal currents, sometimes enabling accretion of fine sediments. Simulation of flow and sediment transport within submerged canopies requires quantification of vegetation geometry. However, field surveys used to determine vegetation geometry can be limited by the time required to obtain conventional caliper and ruler measurements. Building on recent progress in photogrammetry and computer vision, we present a method for reconstructing three-dimensional canopy geometry. The method was used to survey a dense canopy of aerial mangrove roots, called pneumatophores, in Vietnam's Mekong River Delta. Photogrammetric estimation of geometry required 1) taking numerous photographs at low tide from multiple viewpoints around 1 m^2 quadrats, 2) computing relative camera locations and orientations by triangulation of key features present in multiple images and reconstructing a dense 3D point cloud, and 3) extracting pneumatophore locations and diameters from the point cloud data. Step 3) was accomplished by a new 'sector-slice' algorithm, yielding geometric parameters every 5 mm along a vertical profile. Photogrammetric analysis was compared with manual caliper measurements. In all 5 quadrats considered, agreement was found between manual and photogrammetric estimates of stem number, and of number × mean diameter, which is a key parameter appearing in hydrodynamic models. In two quadrats, pneumatophores were encrusted with numerous barnacles, generating a complex geometry not resolved by hand measurements. In remaining cases, moderate agreement between manual and photogrammetric estimates of stem diameter and solid volume fraction was found. By substantially reducing measurement time in the field while capturing in greater detail the 3D structure, photogrammetry has potential to improve input to hydrodynamic models, particularly for simulations of flow through large-scale, heterogenous canopies.

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1. Introduction

Regions of aquatic vegetation, such as seagrass beds, saltmarshes and mangrove forests, contribute to biodiversity (Greenberg et al., 2006) while providing ecosystem services (Brander et al., 2006) such as carbon sequestration (Siikamäki et al., 2012) and biogeochemical processing of terrestrial run-off (Gren, 1995). Marine vegetation can shelter coasts from energetic currents, waves (Jadhav et al., 2013) and tsunamis (Alongi, 2008), enhancing coastal stability (Kirwan and Murray, 2007; van Maanen et al., 2015) by reducing erosion (Gacia and Duarte, 2001) or enabling deposition of fine-grain sediments (Furukawa et al., 1997; Bouma et al., 2007). Growing interest in the ability of vegetation to reduce flooding and erosion (Temmerman et al., 2013; Feagin et al., 2015) is further motivated by sea level rise (Nicholls et al., 1999; Arkema et al., 2013), wetland destruction (Thu and Populus, 2007; Giri et al., 2011), and the growth of coastal population

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centers (Small and Nicholls, 2003). Dissipation of wave and current energy by vegetation canopies depends on plant morphology and density (Temmerman et al., 2005b; Nepf, 2012; Dalrymple et al., 1984). Therefore, morphology and density measurements are required to understand and model the sheltering effects of aquatic vegetation.

Several parameters quantifying canopy morphology are routinely used in models for hydrodynamic drag and associated wave dissipation (Mullarney and Henderson, 2016). One simple and important parameter is the number of plant stems per unit horizontal area of seabed, denoted here by N (units m^{-2}). Elevation-dependent N is defined as the number of stems reaching at least an elevation z above the bed. Another important parameter is the vegetation's mean stem diameter ($\overline{d}$), which can also be evaluated as a function of z. Models for steady flows through rigid vegetation (Nepf, 2012; Temmerman et al., 2005b; Guannel et al., 2015; Belcher et al., 2003) often represent the hydrodynamic drag force F_D per unit volume, which acts to dissipate currents, using the formula

$$F_D = N\overline{d}\,f_1(u,\rho) = a\,f_1(u,\rho), \tag{1}$$

where we have introduced the parameter $a = N\overline{d}$, and the function $f_1(u,\rho)$ represents the dependence of drag on the water velocity u and water density ρ [models typically set $f_1(u,\rho) = (C_D/2)\rho u^2$, where C_D is a dimensionless drag coefficient, often order-one]. It can be shown that a is the cross-sectional area of stems, normal to the water flow direction, per unit volume of canopy (units m^{-1}, Finnigan, 2000). To account for rapid flow accelerations under waves, a widely-used generalization of Eq. (1) is the "Morison equation" $F_D = a\,f_1(u,\rho) + \varphi\,f_2(\partial u/\partial t,\rho)$ (Sumer and Fredsøe, 1997), where φ is the proportion of volume occupied by the solid canopy (for uniform, round stems, $\varphi = N\pi\overline{d}^2/4$, Mullarney and Henderson, 2016), and the function $f_2(\partial u/\partial t,\rho)$ represents the dependence of drag on Eulerian water acceleration $\partial u/\partial t$ and density ($f_2 = C_M\rho\partial u/\partial t$, where t = time and C_M is a dimensionless coefficient, often order-one). Therefore, both a and φ are required by common models for drag under rapidly accelerating flows. However, when calculating wave dissipation for rigid vegetation, it can be shown (e.g. Mullarney and Henderson, 2016) that contributions from the term involving φ average to nearly zero. Therefore, a is a particularly important parameter for modeling both slowly varying currents and higher frequency waves. For flexible vegetation, wave dissipation can be reduced as stems move back and forth with surrounding water (Utter and Denny, 1996; Méndez et al., 1999; Riffe et al., 2011). Models simulating stem motion require knowledge of hydrodynamic parameters and the geometric parameters such as N and $\overline{d}$ considered here, as well as plant material properties, such as the Young's modulus, which are beyond the scope of this paper (Mullarney and Henderson, 2010; Zeller et al., 2014).

Surveys of vegetation geometry have focused on subsamples of the full canopy, with measurements confined to a few small (often 0.1–1 m^2) quadrats (Temmerman et al., 2005b; Lightbody and Nepf, 2006; Riffe et al., 2011; Feagin et al., 2011; Paul and Amos, 2011). Subsampling is necessary because of the very large number of stems present in natural canopies (e.g. millions of stems in 100 × 100 m regions of natural sedge or Spartina saltmarsh, Jadhav et al., 2013; Riffe et al., 2011). For hydrodynamic modeling, subsampling should resolve the vertical variability in canopy geometry. Accurate modeling may also require sampling of lateral variability on scales ranging from meters to kilometers, because such heterogeneity can generate leading-order variability in water flows (Lightbody et al., 2008). Seasonal variability is also observed (Paul and Amos, 2011; Möller, 2006), but is not easily measured by sampling schemes that require the removal of vegetation from the field site (e.g. Lightbody and Nepf, 2006; Feagin et al., 2011; Temmerman et al., 2005a). Unfortunately, logistical constraints on time and labor often preclude sampling of three-dimensional spatial variability in canopy geometry (and possible seasonal variability) using conventional rulers, calipers, and hand counts. Indeed, even sampling a single small quadrat can sometimes be challenging. For example, below we present cases where numerous barnacles growing on stems produced such rough, irregular stem geometry that even sampling a single square meter by caliper measurements would require many hours of fieldwork. To address the challenges resulting from complex geometry of individual stems, and from heterogeneity of larger-scale vegetation statistics, more efficient, automated, non-invasive methods for measuring vegetation geometry are needed.

Analysis of photographic images has been used to estimate morphological characteristics of aquatic vegetation. For one approach (Möller, 2006; Neumeier, 2005; Lemein et al., 2015), a small (e.g. 0.2-m-wide) region of saltmarsh vegetation is isolated while exposed at low tide, a vertical backing board is placed behind the vegetation, and photographs of the horizontal view of the vegetation are analyzed. The percent of the backing board obscured by vegetation, here denoted B, has been related to biomass Neumeier (2005); Möller (2006); Lemein et al. (2015). Within a sedge canopy, a strong correlation has also been found between B and $N\overline{d}h$ (Lemein et al., 2015), where h = stem length (for a uniform-height canopy with depth-independent $\overline{d}$, $N\overline{d}h$ is the depth-integral of a). Vegetation height has been estimated from depth-dependence of B (Möller, 2006; Lemein et al., 2015). Depth-dependence of a has not been inferred directly from photographs, although a profiles have been estimated by combining photogrammetric estimates of stem length with an empirical relationship between stem length and diameter (Lemein et al., 2015, such relationships likely depend on species and seasonality).

This study is motivated by the idea that richer morphological information can be gleaned if multiple photographs, taken from varying angles and locations, are combined using modern photogrammetry techniques. When several 2D photographs are combined, the 3D structure of objects can be determined by triangulation (Hartley and Zisserman, 2004). This approach, often applied to mapping landscapes (Lane et al., 2000; Lejot et al., 2007) and archaeological sites (Brutto and Meli, 2012), has become steadily more efficient with improvements in computational power and computer vision algorithms (Hartley and Zisserman, 2004; Yastikli, 2007; Westoby et al., 2012). Modern automated photogrammetry software (e.g. VisualSfM) allows reconstruction of complex objects from hundreds, or even thousands of photographs. Although vegetation canopies are often more complex and irregular than archaeological artifacts and simple landscapes, recent analyses have demonstrated that photogrammetry can be used to reconstruct complex tree crowns (Gatziolis et al., 2015; Liénard et al., 2016). In the context of aquatic vegetation, reconstructions obtained by combining multiple photographs have been used to determine the stem number density N near the seabed in a pneumatophore canopy (Zhang et al., 2015). However, to our knowledge, the potential of photogrammetry to resolve the full vertical profile of aquatic vegetation geometry has not previously been exploited. Here, multiple photographs taken in the mangrove forests of the Mekong Delta, Vietnam are used to reconstruct the three-dimensional geometry of dense nearbed vegetation.

The major steps in the analysis are summarized in Fig. 1. First, photographs of vegetation were taken in the field from numerous points of view, with substantial overlap (Section 2). Then, a standard photogrammetric approach was used to build a 3D point cloud representing the scene (Section 3). Finally, a geometrical model of the canopy was computed and used to evaluate parameters

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