

## **Dynamics of Tropical Deltas DRI: Hydrodynamics and Morphodynamics of Mangrove Swamps in the Mekong Delta, Vietnam**

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### **LONG-TERM GOALS**

The long-term goal is to examine the interactions between vegetation, hydrodynamics, and morphology in aquatic vegetation, with particular emphasis on the mangrove swamps of Vietnam's Mekong Delta.

### **OBJECTIVES**

Primary objectives focus on three areas:

1. The role of the mangrove pneumatophore (root) and small-scale structures in damping flows and creating turbulence. We will also examine how the spatial heterogeneity of the vegetated regions directly affects the hydrodynamics.
2. The role of winds, pressure gradients, and waves in forcing flows within and adjacent to mangrove regions.
3. The interactions between hydrodynamics, vegetation, sediment transport, and geomorphology in mangrove regions.

### **APPROACH**

As planned, this work was undertaken in close collaboration with the University of Waikato (PIs J. Mullarney and K. Bryan) and many results here are shared.

The approach is based on unique field observations of turbulence, waves, and currents across the fringing region of the mangrove swamp. High-resolution hydrodynamic and environmental measurements were made over a variety of short-term (1-3 days) deployments at the seaward edge of Cù Lao Dung Island in the Mekong Delta, Vietnam. Instrument deployments were grouped into arrays to analyze current and water density structure over a variety of spatial scales, ranging from very fine (mm-scale), through moderate scales (centimeters to meters), and up to cross-shore distances of 200 m. The frequent redeployment of instruments through the mudflat, fringe and forest over the course of the experiments allowed for a broad range of environmental conditions to be captured and for the resolution of the evolution of vegetation-induced turbulent flows, and wave dissipation over larger

scales. The fieldwork also provided detailed quantification of vegetation density through extensive photogrammetric surveys (>100 quadrats, each 1 m<sup>2</sup>).

Energetic waves were observed among the mangroves during February 2016, with a surfzone sometimes present at the mangrove fringe. This spurred interest in possible wave forcing of currents within vegetation canopies. Perturbation expansion theory, resembling that used to derive models for wave forcing of currents on beaches, has been used to examine such forcing, and will be tested against observed waves and currents.

We intend to work closely with the other investigators involved in the tropical deltas DRI to provide a more complete understanding of the dynamics of the larger-scale system.

## **WORK COMPLETED**

Major fieldwork has been successfully completed. High-resolution measurements of currents, waves, pressure, temperature, and salinity were made during two major field deployments in the fringing mangrove forest of southern Cù Lao Dung Island, one in September-October 2014 (wet season, SW winds) and the other in February-March 2015 (dry, windy and wavy conditions). Each deployment lasted approximately two weeks (see Figure 1) and covered two distinct geomorphological environments, one on the southwestern edge of the island (rapidly accreting, low slope, relatively sandy), and the other on the north eastern corner (erosional, steep, and muddy). In addition to the hydrodynamic observations, sediment samples were collected and photogrammetric surveying of the vegetation was conducted at each site (focused on instrument locations) and in the surrounding area.

The data have undergone initial quality control and are available for use by other DRI investigators. A document summarizing the deployment locations, configurations and data processing is accessible on the shared the dropbox folder, in addition to the smaller data files (from the weather station, Acoustic Doppler Velocimeter on the transect line and pressure sensor data). The large data files from the high-resolution arrays are also available on request (see Figure 2 for example short-term deployment). A number of preliminary but intriguing findings have arisen from our initial data analysis and these are detailed below.

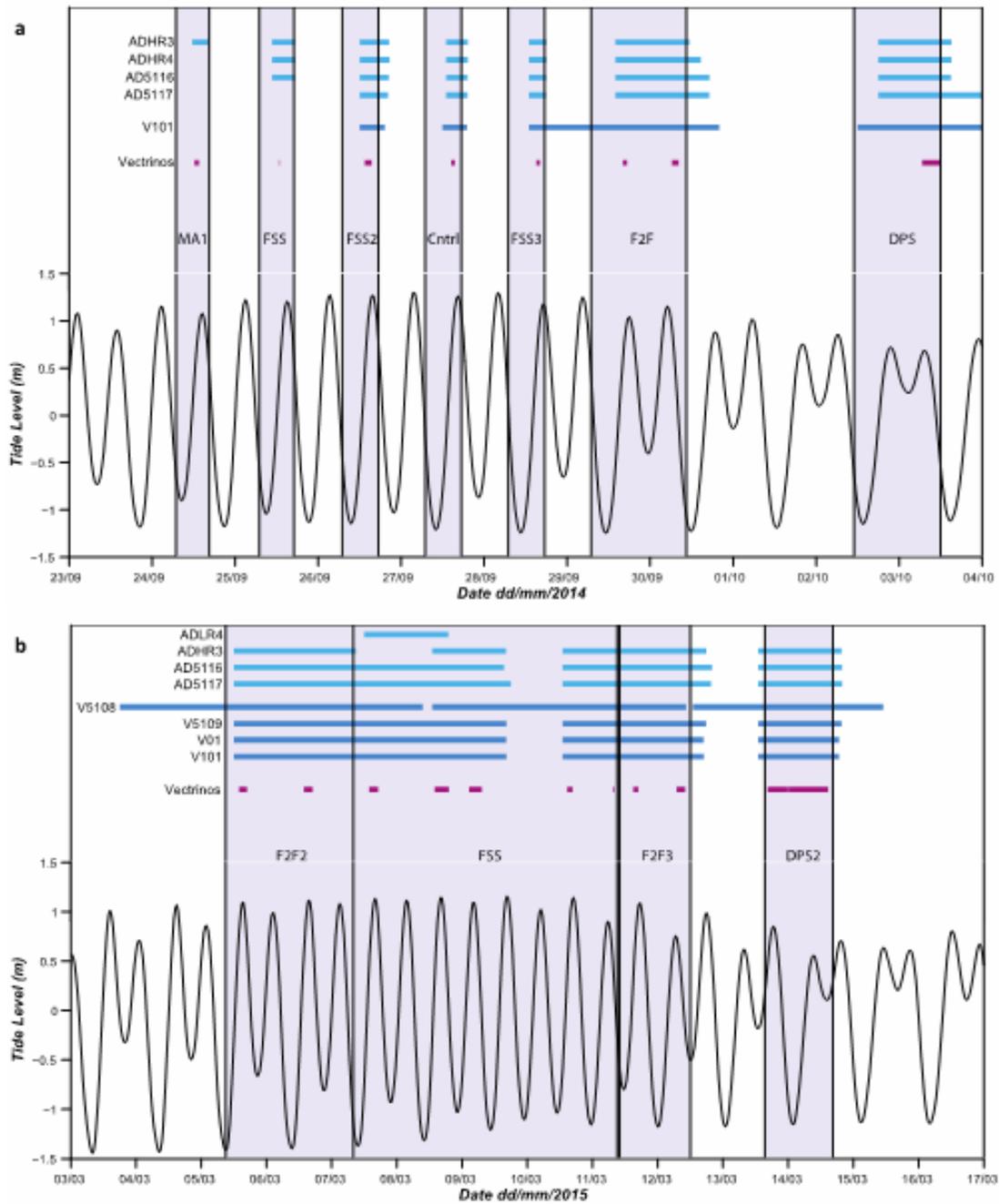
The perturbation theory for wave forcing of mean currents in vegetation canopies has been completed, and a manuscript presenting the theory is in preparation. This is the first depth-resolving theory for wave forcing of currents through vegetation, and both rigid and flexible stems have been considered.

## **RESULTS**

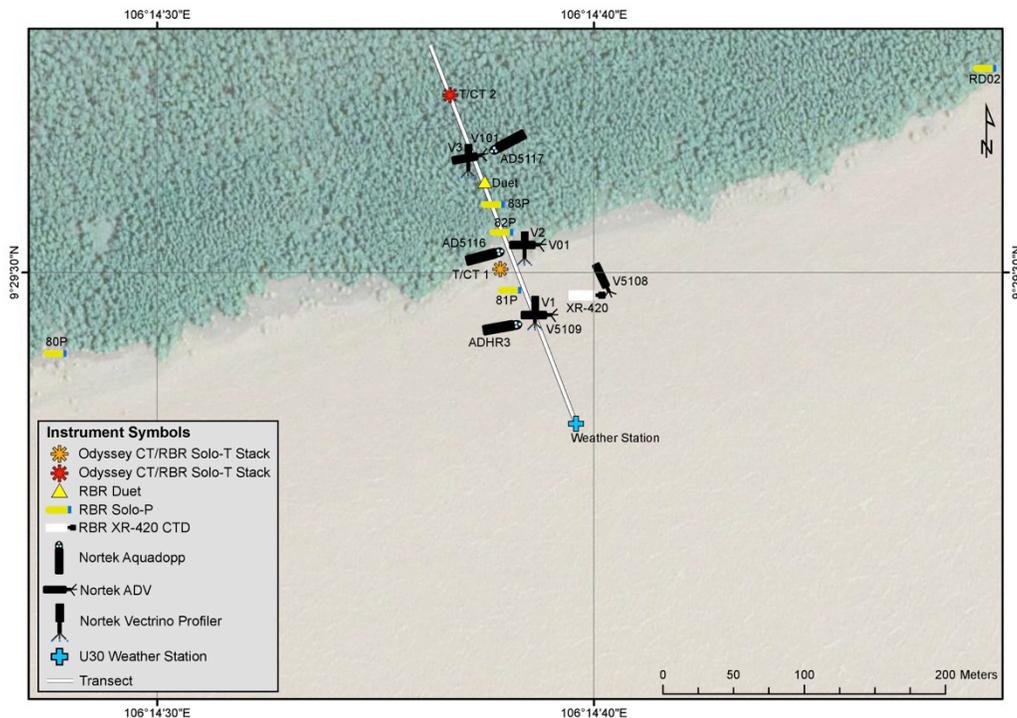
To-date, the major focus has been on fieldwork and data reduction. Several notable early findings are outlined below.

### *Observations of fine-scale turbulence within pneumatophore canopies*

Unique, millimeter-scale, 50 Hz velocity profiles were obtained using Nortek Vectrino Profilers within the pneumatophore canopy. In addition to providing high quality observations of wind-waves and currents, these profilers allow us to quantify the influence of pneumatophores on within-canopy turbulence. Turbulence was intensified within the canopy, particularly within a few cm of large pneumatophores (Figure 3). Synoptic measurements from across the differing environments from



**Figure 1: Data records for acoustic instruments obtained in (a) fall 2014 and (b) winter 2015. Color bars designate the instrument's reported length of deployment from the header file (light blue bars are Nortek Aquadopp ADCPs, dark blue are Nortek Vector ADVs and purple bars are Nortek Vectrino Profilers). Shaded regions designate the length of each experiment and letters correspond to the array name. Black lines are the tidal predictions from Dinh An.**



**Figure 2: Example of short-term deployment ‘F2F’, flats to forest, array. Three main groupings of instruments were deployed adjacent to the transect line encompassing the mudflat, fringe, and forest environments.**

mudflat to forest interior (over horizontal distances of ~200 m) reveal significant enhancement of turbulence at the forest fringe (dissipation elevated by 1-2 orders of magnitude) compared to the bare mudflat and forest interior. Given the importance of turbulence to sediment entrainment and suspension, these observations likely have importance to marsh geomorphology.

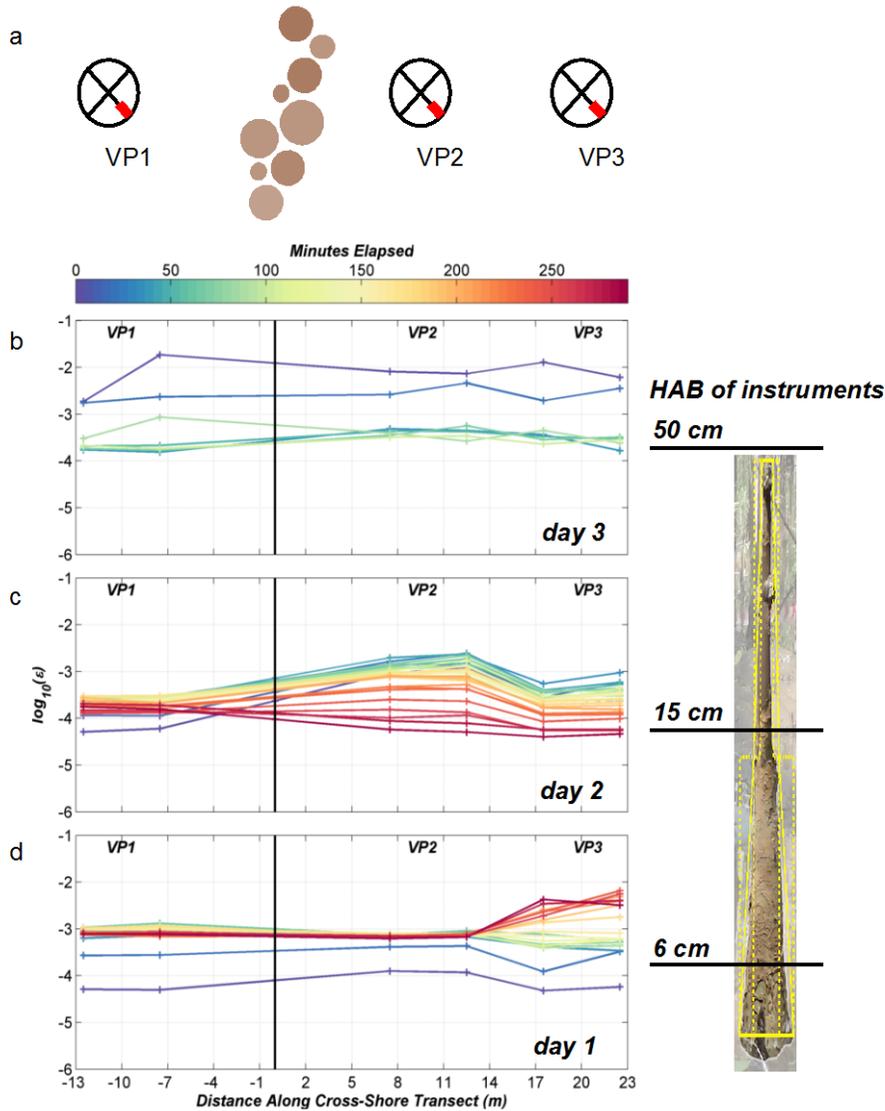
#### *Observations of sediment movement and fine-scale turbulence within pneumatophore canopies*

Changes in bed characteristics were observed during the experiment, indicating significant sediment movement. During a large wave event in March, wave breaking was observed up to 100 m inside the forest, with an intense surfzone at the forest edge. After the wave event, scour was observed around regions of dense pneumatophores, while sandy sediment mounds developed within the gaps between pneumatophores, and finer sediments were deposited on the mudflat outside the forest. These sedimentation patterns are opposite those observed in a modeling study of salt marshes by Temmerman *et al.* (2005), who found that sediments are rapidly trapped at the edge of the salt marsh with less decreasing inside the marsh and either reduced sedimentation or erosion in the gaps between the vegetation.

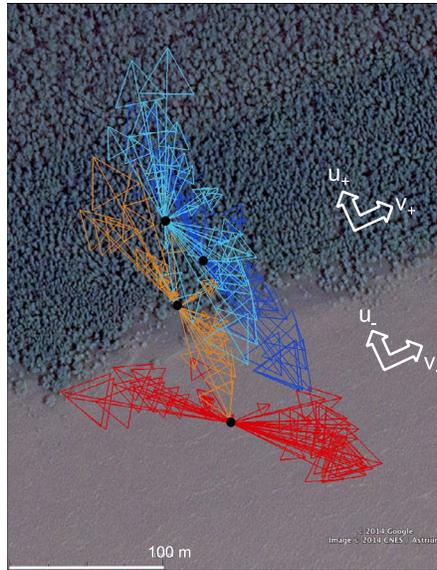
#### *Observations of tidal current rotation across the fringe*

Preliminary observations indicate that both surface waves and tidal currents contributed to total water velocity, which reached  $> 0.2 \text{ ms}^{-1}$  during the more quiescent September experiment and  $> 0.4 \text{ ms}^{-1}$  during the March experiment. Strong horizontal variability in wave-averaged flows was sometimes observed near the mangrove fringe over 10-m scales. Data from the fall 2014 experiment indicate that

the mean flows rotated into an orientation perpendicular to the vegetation fringe (Figure 4). Similar rotation has previously been explained by a corresponding rotation in tidal pressure gradients (e.g. Kobashi & Mazda, 2005; Mazda *et al.*, 2005; Horstman *et al.*, 2013). However, in our case, strong shore-parallel winds may have played a role, driving alongshore flows outside the forest, but not inside where wind stresses were reduced by two orders of magnitude. Simple models have been developed to test whether rotation is predominantly caused by rotating pressure gradients, or changes in wind stress.



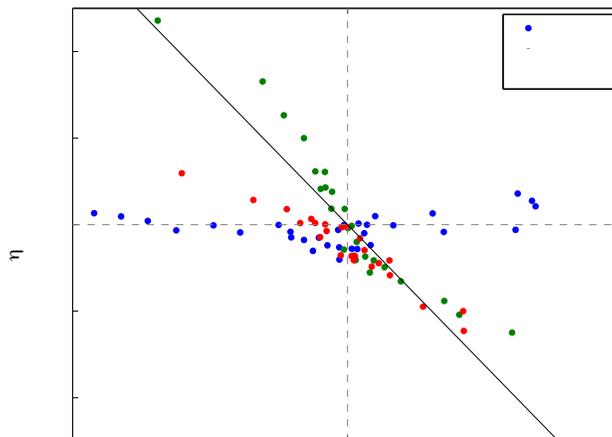
**Figure 3: Evolution of dissipation rate of TKE with time (colorscale) for the set up shown in Panel a. A series of Vectrino Profilers (VP) were placed in a line approximately parallel to the direction of wave propagation (left to right in figure) with one instrument in front of a line of pneumatophores roughly perpendicular to the instrumentation and two instruments behind the obstacles. Instruments were placed ~6, 15 and 50 cm above the bed on days 1, 2 and 3, respectively, corresponding to near the bottom, mid height and just above the pneumatophores. The colour scale indicates the minutes elapsed from when the instruments were covered with water, so the same colour corresponds to slightly later in the tide on later days. Each line represents a 10-minute time series. Very high values for  $\epsilon$  in panel b (blue lines) are likely owing to wave breaking.**



**Figure 4: Depth and burst-averaged horizontal velocities for a single tidal cycle showing strong flow rotation to an orientation approximately perpendicular to the forest fringe**

*Bulk momentum balance, and mean canopy drag*

Using buried, high-accuracy pressure gauges, we have examined the wave-averaged momentum balance, thereby quantifying the bulk drag exerted by the mangrove canopy. Preliminary observations indicate that outside of the mangroves, pressure gradients and drag were unmeasurably small (blue dots, Figure 5). However, at the marsh edge, where pneumatophores were most dense, drag was resolved and found to be much stronger than plausible bottom drag (conventional bottom drag parameterizations would require  $C_d \approx 0.033$ , 10 to 30 times greater than usual values). This drag appears particularly important near the start and end of flooding cycles (when currents and sediment suspension are elevated).



**Figure 5: Drag forces and pressure gradients over 10 minute averages for a single tidal cycle. The observed slope of the best fit line is equal to the drag coefficient  $C_D$ .**

## *Photogrammetric reconstructions of pneumatophore canopies*

Parameters quantifying canopy morphology such as the number of plant stems per unit horizontal area of seabed,  $N$ , and frontal area density  $a$  (Nepf, 2012) are routinely used in models for hydrodynamic drag and associated wave dissipation in vegetated environments (Mullarney and Henderson, 2015). Traditionally, these parameters have been estimated by surveys of vegetation geometry focused on subsamples of the full canopy, with measurements confined to a few small (often 0.1 to 1 m<sup>2</sup>) quadrats (e.g. Temmerman *et al.*, 2005; Feagin *et al.*, 2011, Paul and Amos, 2011; Riffe *et al.*, 2011). Unfortunately, owing to logistical constraints on time and labor, surveys using conventional rulers, calipers, and hand counts often preclude sampling of three-dimensional spatial variability in canopy geometry. However, for hydrodynamic modeling, subsampling should resolve the vertical variability in canopy geometry and lateral variability on scales ranging from meters to kilometers, because such heterogeneity can generate leading-order variability in water flows (Lightbody *et al.*, 2008).

In collaboration with Dr.s Jean Liegard and Nik Strigul (Washington State University), we developed and applied a novel photogrammetric method to resolve the vertical profile of vegetation geometry from our field surveys (Figure 6 shows details of nearbed vegetation). To our knowledge, this is the first time the 3D-rendering capabilities of photogrammetry have been applied to aquatic vegetation, and a manuscript demonstrating success of the method (shown by results in Figure 7) has been submitted to *Estuarine, Coastal and Shelf Science*. The unique and extensive surveys of vegetation geometry we obtained (5mm vertical resolution within pneumatophore canopy, obtained with few gaps along a 100 m transect into the forest) will permit more rigorous testing of momentum balances and wave dissipation models than has been possible using previous measurement techniques.

### **IMPACT/APPLICATIONS**

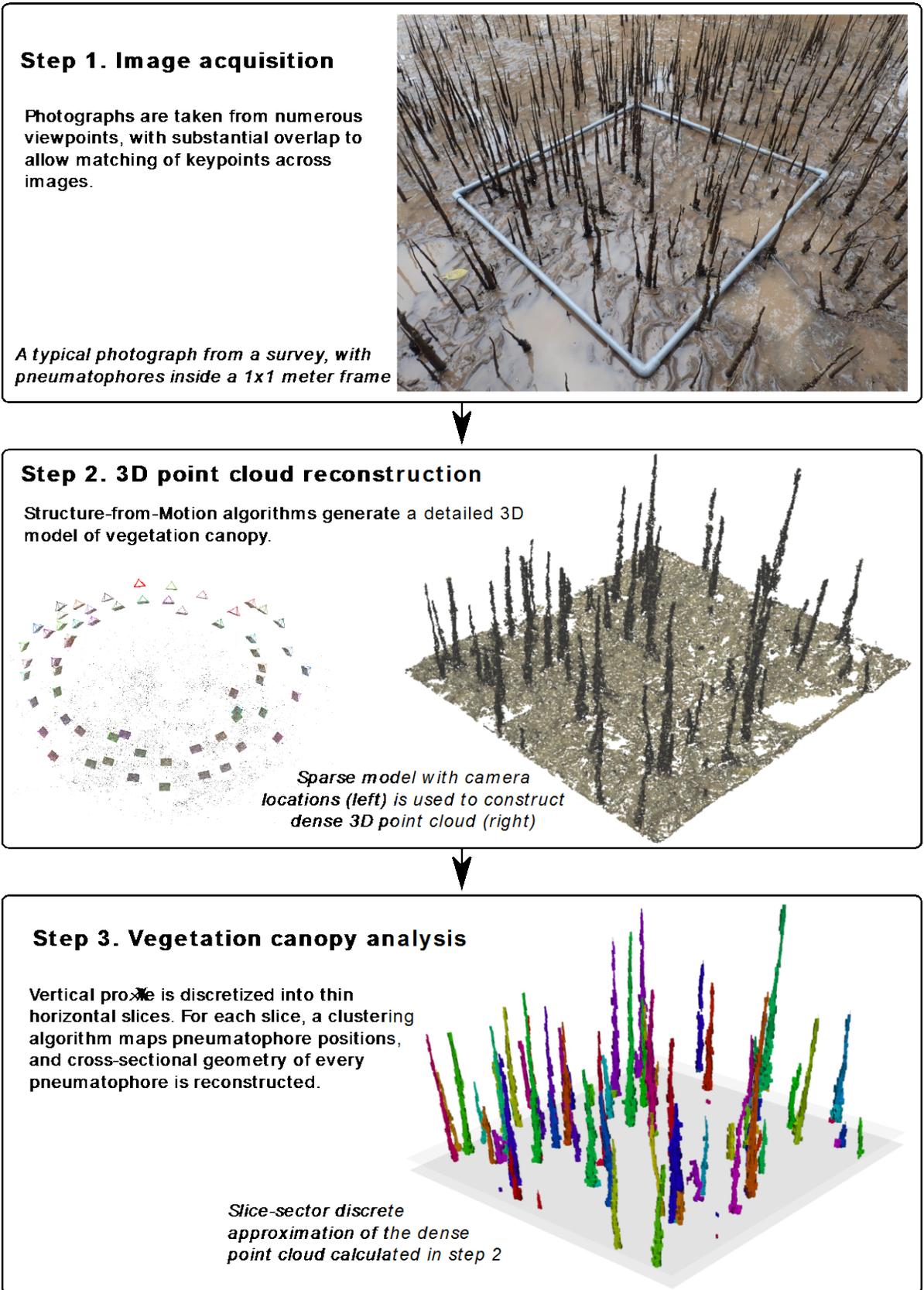
Given the importance of turbulence to bed stresses, sediment entrainment, and sediment suspension, improved understanding of turbulence within canopies will be useful in the development of improved models for sediment transport through marshes.

Observations of tidal currents, momentum balances, and wave attenuation will help in the development of improved hydrodynamic models. The ability to rapidly survey canopy geometry by photogrammetry will also help constrain hydrodynamic models. The high-resolution geometries obtained in this study will be of significant use to DRI participant Steven Jachec for his high-resolution numerical simulations of flows around pneumatophores.

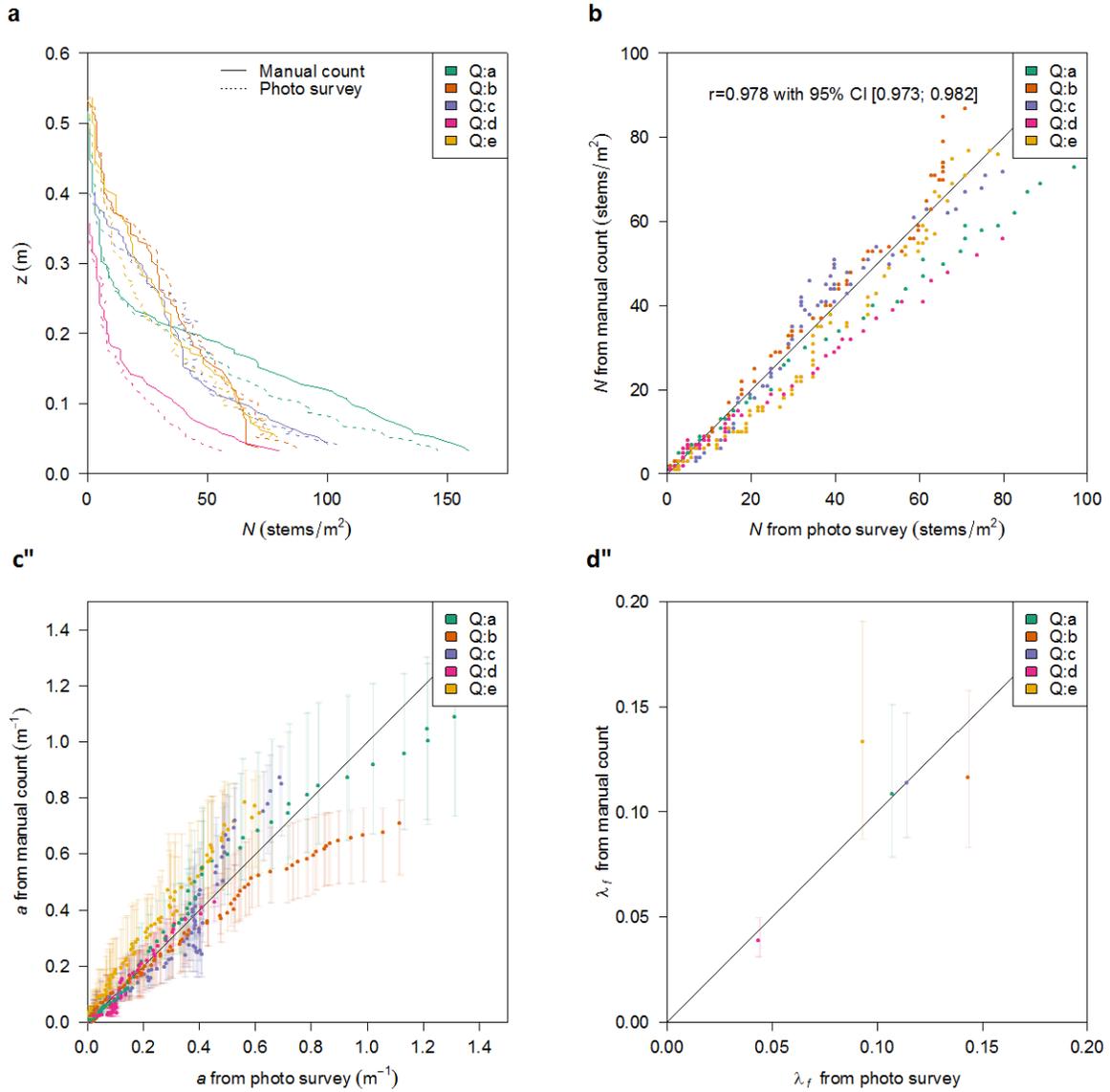
Interactions have been strengthened by Washington State University and scientists in Vietnam and New Zealand (collaborations ongoing).

### **RELATED PROJECTS**

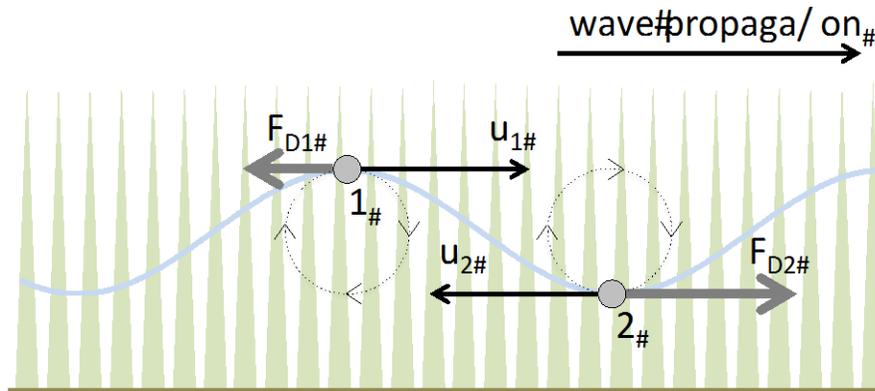
Bryan and Mullarney have recently received funding (as co-PIs) from the Royal Society of New Zealand Marsden fund to undertake related work within New Zealand mangroves (2015-2017). S. Henderson is an associated investigator, with funds for collaboration. New Zealand mangrove swamps also encapsulate muddy and sandy substrates but the native species *Avicennia* are much smaller and denser than the *Sonneratia* in the Mekong Delta, which will provide an intriguing point of comparison with the ONR funded work.



**Figure 6: Overview of photogrammetry approach used to obtain pneumatophore characteristics.**



**Figure 7: Comparisons between results determined from photogrammetry and those from hand counts and caliper measurements. a, stem counts as a function of height, b scatterplot of  $N$ , c, frontal area density, and d, the depth integrated frontal area per unit bed area  $\lambda_f$ . In b and c, each dot represents a 5 mm depth slice.**



**Figure 8: Mechanism for wave forcing of mean currents in rigid vegetation.** Wavy blue line marks a material surface distorted by a passing wave, and variable density near-bed pneumatophore canopy is represented schematically by tapered stems (light green triangles). Filled grey circles labeled 1 and 2 mark water particles, while the thin back dotted circles mark corresponding orbital motions. Particles displaced upward into low density vegetation (labeled 1) experience relatively weak friction ( $F_{D1}$ ) as they flow with velocity  $u_1$  in the wave propagation direction. Downward displacement into dense vegetation (2) leads to higher resistance to return flow ( $|F_{D2}| > |F_{D1}|$ ). Remarkably, detailed perturbation analysis shows that the resulting mean frictional force is represented in the Eulerian-mean momentum balance by Radiation Stress convergence.

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## PUBLICATIONS

- Lienard, J., Lynn, K. Strigul, N., Norris, B. K, Gatzliolis, D. Mullarney, J. C., Bryan, K. R. and Henderson, S.M., Efficient Three-Dimensional Reconstruction of Aquatic Vegetation Geometry: Estimating Morphological Parameters Influencing Hydrodynamic Drag, *submitted to Estuarine, Coastal and Shelf Science*.

### Abstracts

- J. C. Mullarney, B. K. Norris, S. M. Henderson and K. R. Bryan, Turbulence, hydrodynamics and morphodynamics within a fringing coastal mangrove forest, Abstract #191, *9<sup>th</sup> Symposium on River, Coastal and Estuarine Morphodynamics*, 30<sup>th</sup> August to 3<sup>rd</sup> September 2015, Iquitos Peru.