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**Comparison of drag and velocity in model mangrove forests with
random and in-line tree distributions**

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Abstract:

This study examined the role of tree arrangement (random versus aligned) on the drag forces and velocity inside a 1/12th-scale model mangrove forest over a range of tree density (trees m⁻²). Each model tree included an aerial root system geometrically similar to *Rhizophora*, with maximum root height HR_{max} and water depth $H > HR_{max}$. The non-dimensional root density was defined as $a_r HR_{max}$, with root zone frontal area per volume, a_r . For both random and aligned low-density forests, $a_r HR_{max} < 0.1$, the vertical profile of velocity followed a boundary layer shape. Within both random and aligned high-density forests, $a_r HR_{max} > 0.1$, the velocity was diminished in the root zone ($z < HR_{max}$) and enhanced above the root zone, relative to the boundary layer profile. For all forest arrangements, the force on the roots dominated the force on the entire tree, even in cases with diminished velocity within the root zone. Compared with a tree at the leading edge, a tree inside a randomly distributed forest could experience either a greater or lesser force, and the variation in drag force increased with tree density. In contrast, for an aligned distribution of trees the force on an individual tree within the forest was always diminished relative to a tree at the leading edge. A drag coefficient was defined using a quadratic drag law. The forest-average drag coefficient, defined using the channel-average velocity, was up to 30 percent higher for random tree arrangements, compared to in-line tree arrangements.

Keywords: Mangrove forest; Random tree distribution; Drag force; Velocity; Drag coefficient

1 Introduction

Mangroves grow in the intertidal areas of tropical coastlines and provide coastal protection by attenuating the energy of tsunamis, cyclones and storm surge and by reducing velocity on channel floodplains (Tanaka et al., 2007; Alongi 2008; Osti et al. 2009; Struve et al. 2003; Liu et al. 2013). Field studies report that coastal areas with mangroves are less damaged from tsunami-induced waves than non-vegetated areas (Danielsen et al., 2005). Similarly, mangrove forests have been noted to protect property and human life during tsunamis and cyclones (Harada and Imamura 2005; Das and Vincent 2009; Bayas et al. 2011; Strusinska-Correia et al. 2013). For example, the maximal tsunami flow pressure behind a 100-meter-wide dense forest was reduced by 90% relative to the pressure at the coastal edge of the forest (Hiraishi and Harada 2003). Because mangrove forests efficiently provide natural protection against tsunamis and storm surges, people are encouraged to live behind mangrove forests and to maintain the integrity of the forests (Kathiresan and Rajendran, 2005).

Mangroves also protect the banks of tidal channels (Stuve et al. 2003), and mitigate coastal erosion by trapping sediment, especially for coasts with a rich sediment supply from rivers (Phan et al. 2015). The flood plain vegetation can diminish local velocity by 20 to 44% compared to the main channel, which leads to reduced erosion and enhanced sediment retention (Struve et al. 2003, Liu et al. 2013). Specifically, both numerical simulations (Gelfenbaum et al. 2007, Willemsen et al. 2016) and field observations (Schwarzer et al. 2016) have shown enhanced sedimentation within a mangrove forest, relative to regions without forest.

Planting and maintaining mangrove forests is frequently cited as a solution for coastal and channel protection (e.g., Alongi 2008, Albers and Schmitt 2015). Mangrove trees are also important in the restoration of degraded coastal wetlands (e.g., Gedan et al. 2011; Jaramillo et al. 2018). The assessment of mangrove protection and the design of mangrove restoration is significantly aided by numerical models, within which the forest is typically represented by a distributed drag characterized by a tree drag or bed friction coefficient (e.g. Yanagisawa et al. 2010, Kaiser et al. 2011, Willemsem, 2016). A lack of understanding of how tree drag coefficients vary with tree morphology, density, and arrangement is a major source of uncertainty within the models (e.g., Marois and Mitch 2015). This is the motivation of the present study, which determines the impact of the tree arrangement, specifically random versus aligned trees, on tree drag over a range of tree density. The paper specifically considers the mangrove species *Rhizophora*, which is one of the most popular species for mangrove planting and comprises approximately 90% of the world's mangrove species (Ohira et al. 2013). *Rhizophora* features a complex aerial root system (Mazda et al. 1997; Kathiresan 2003). Model mangrove trees, constructed to mimic the complex aerial root system of *Rhizophora*, have been used in laboratory experiments (Zhang et al. 2015; Maza et al. 2017). The model forests have a high-drag region associated with the roots and a low-drag region above the roots, resulting in diminished velocity within the root zone (Maza et al., 2017).

Previous studies have investigated the longitudinal evolution of velocity and force exerted on individual mangrove trees in an aligned forest under both tsunami (e.g., Strusinska-Correia et

al. 2013; Maza et al. 2015) and unidirectional flow conditions (e.g., Zhang et al. 2015; Maza et al., 2017). For an in-line distribution, trees within the forest are positioned directly in the wake of upstream trees, and thus experience diminished velocity and diminished drag, such that the maximum force on an individual tree occurs in the first row, i.e. at the forest leading edge (Strusinska-Correia et al. 2013, Maza et al. 2017). While in-line configurations are typically used during replanting, natural and mature forests are more likely to have a random distribution of trees. For a random distribution of circular cylinders, numerical simulations indicate that the maximal force exerted on an individual cylinder occurs inside the array rather than at the leading edge (Maza et al. 2015). Building on previous studies (Zhang et al. 2015, Maza et al. 2017), in which drag and velocity were studied within arrays of in-line tree models, the present study explores the difference in individual tree force, local velocity and forest-scale drag coefficient between random and aligned tree arrangements over a wide range of tree density (trees m⁻²) and uses model trees that are geometrically similar to *Rhizophora*.

2 Model mangrove forest

The model mangrove forests were built at a 1:12 scale, based on the morphology of mature *Rhizophora* reported in Ohira et al. (2013), and similar to the models used in Maza et al. (2017). The mangrove trunks were constructed using acrylic tubes with a diameter $D_{trunk} = 1.6$ cm. The roots were constructed using brass rods with a diameter $D_{root} = 3.175$ mm, which were bent to the specific geometry outlined in Ohira et al. (2013). The acrylic tubes were drilled at specific

heights, following the details reported by Ohira et al. (2013), and the rods were affixed in the holes to form a three-dimensional tree model, as shown in Figure 1. Each model tree contained 20 roots with a maximum root height $HR_{max} = 16$ cm. At full scale this corresponds to $D_{trunk} = 19.2$ cm and $HR_{max} = 192$ cm, which is consistent with measured values from real *Rhizophora* reported in Figure 7 of Ohira et al. (2013). Similarly, the number of model tree roots (20) falls within the range of root counts for real *Rhizophora* with $D_{trunk} = 19.2$ cm, as shown in Figure 8 in Ohira et al. (2013). The materials used for the trunks and roots were rigid, and the absence of deflection with flow was representative of the stiffness of an actual mangrove tree, based on the values of stiffness reported by Zhang et al. (2015). Two types of model mangrove were constructed: full trees, with one trunk and 20 roots; and half trees, with one trunk and 13 roots. The half trees were created to allow tree placement along the channel wall.

The model velocity was $U_m = 9.9$ cm/s, which satisfied Froude number similarity with real field scale tidal flow and storm surge, $U_r = 20$ to 50 cm/s (e.g., Kathiresan 2003; Roeber et al. 2015). Specifically, based on the ratio of the model length-scale (L_m) to the real length-scale (L_r), $L_m/L_r = 1/12$, the model velocity corresponded to a field velocity of $U_r = (L_r/L_m)^{1/2} U_m = 3.4U_m = 34$ cm/s. In addition, the Reynolds numbers for the model trunk and roots ($Re_{trunk} = \frac{U_m D_{trunk}}{\nu} = 1583$ and $Re_{root} = \frac{U_m D_{root}}{\nu} = 314$, with ν the kinematic viscosity) were both in the turbulent wake range, which is consistent with field conditions. Specifically, turbulence generation by tree elements occurs for $Re > 120$ (Liu and Nepf 2016).

Plastic baseboards (0.68 cm thick) were placed on the bottom of the flume. The baseboards contained holes in a staggered arrangement. Tapered flanges were used to securely hold the model trees in the baseboards in the upright position and flush with the bed. The mangrove forest was placed within a test section that was 1-m long and 1-m wide and was located 5-m downstream of the flume inlet (Figure 2). The length of the model forest was chosen based on previous studies in the same channel. First, using a similar model *Rhizophora*, Maza et al. (2017) reported that flow adjustment length at the leading edge of the canopy was 0.85 m. Second, Chen et al. (2013) showed that the flow adjustment length has no dependence on the overall length of the model forest. Together, these ensured that force and velocity measured at the target tree, located at the end of the 1-m forest (red tree in Figure 2), represented fully-developed flow conditions within the forest.

The individual model trees were arranged in either a random distribution (RD, Figure 2a) or an in-line distribution (IL, Figure 2b) at five different tree densities $n = 2, 6, 10, 14$ or 18 trees/m^2 , corresponding to 139, 417, 694, 972 or 1250 trees/ha at the field scale, respectively, which included densities recorded in real mangrove forests ($n = 525 \pm 95$ and $704 \pm 242 \text{ trees/ha}$), as reported in Ward et al. (2006) and McCoy et al. (1996), respectively. For the in-line distribution, the trunks were aligned in rows in the streamwise direction, and adjacent rows were staggered. The holes on the baseboard were used to determine each tree position. The streamwise, lateral and vertical directions were assigned to x , y and z coordinates, respectively. The origin was located at the right-hand wall at the leading edge of the forest test section (full). The forest test

section ($1 \text{ m} \times 1 \text{ m}$) included 67 holes in the y direction and 57 holes in the x direction. Thus, the model forest area was set up as a 57×67 grid of holes, with hole coordinates (n_x, n_y) , in which $57 \geq n_x \geq 1$, and $67 \geq n_y \geq 1$ (Figure 3). Looking downstream, the right-most hole at the upstream edge of the test section corresponded to $(n_x, n_y) = (1, 1)$. In all cases, the target tree, for which drag was measured, was fixed at the center of the downstream edge of the test section, corresponding to $(n_x, n_y) = (57, 34)$, which is denoted by the red tree in Figure 2. The locations of trees in a random distribution were determined using the random number generator in MATLAB. The minimum allowed distance between adjacent trunk surfaces was specified as $D_{trunk} = 1.6 \text{ cm}$, and the smallest surface-to-surface distance between two adjacent holes was 0.6 cm. Therefore, once a tree was placed in a hole, the six adjacent holes around that tree were excluded from being chosen for a tree. For each tree density, $N = 10$ realizations (different random distributions) were created. Photos of one realization for $n = 18$ and for 6 trees/ m^2 are shown in Figure 4. All ten distributions for $n = 18$ and for 6 trees/ m^2 are shown in Figures S1 and S2, respectively, in the Supporting Information. The convergence of the mean and standard deviation of the ensemble was used to verify that $N = 10$ was sufficient to obtain an accurate ensemble mean drag force and drag coefficient. This is described in more detail in the next section.

Digital images were used to measure the tree frontal area within each 1-cm vertical slice, $dA(z)$, with units of cm^2 per cm vertical slice, or simply cm (Figure 1). Digital images were converted to black and white binary images using the MATLAB image processing toolbox, with black denoting the mangrove trunks and roots. The image pixels were converted to real distances

based on the maximum root height in the vertical direction and the trunk diameter in the horizontal direction. To assess the frontal area variability (horizontal bars in Figure 1), the images were collected with four different tree rotations. In the root zone, the frontal area gradually decreased with distance from the bed (z), until the maximum root height HR_{max} ($= 16$ cm). The uniform frontal area between the top of the roots ($z = HR_{max}$) and the water surface ($z = H$) reflected the uniform trunks. The total frontal area of a single tree (A) was estimated from the integral of $dA(z)$ over the flow depth. Specifically, $A = \int_0^H dA(z)dz = 0.015 \text{ m}^2$ for flow depth $H = 25$ cm.

The root zone ($z < HR_{max}$) was associated with distinctly higher flow blockage than the zone above the roots (Figure 1), such that it was reasonable to assign this region a distinct non-dimensional density, as defined by Nepf (2012). The non-dimensional density of the root zone was defined as the product of a_r , the frontal area per unit volume in the root zone, and HR_{max} , i.e., $a_r HR_{max} = n \int_0^{HR_{max}} dA(z)dz$. We anticipated that below a threshold value of $a_r HR_{max}$ (likely to be close to 0.1, based on studies in submerged meadows) the vertical distribution of mean velocity would not be affected by the roots and would follow a boundary layer profile. Further, above the threshold value of $a_r HR_{max}$, the root drag was expected to be greater than the bed drag, such that the velocity will be diminished within the root zone, relative to the boundary layer profile. In our study, the forests produced $a_r HR_{max} = 0.01$ to 0.25 (Table 1). The measured velocity profiles were used to determine the value of $a_r HR_{max}$ at the transition between low- and high-density forests.

173

174 **3 Flume experiments**

175 The experiments were performed in a 12-m long and 1.2-m wide recirculating flume with a
176 horizontal bed. A variable-speed pump drove the flow from the tail tank to the head tank. The
177 tailgate at the end of the channel controlled the flow depth. A flow discharge of 24.75 L/s and a
178 flow depth $H = 25$ cm were used in all cases. With this flow depth, the mangrove roots were
179 submerged, $H > HR_{max}$. The width of the test section was narrowed to 1 m by constructing acrylic
180 walls on the right side of the flume. A schematic is shown in Figure 2. The channel-average
181 velocity upstream of the forest was $U_0 = 9.9 \pm 0.1$ cm/s. Only unidirectional flow was considered
182 in these experiments, representing flow through mangroves situated on the floodplains of tidal
183 channels. It also reasonably represents storm surge, for which the flow velocity varies over the
184 time scale of hours, which can be considered a quasi-steady flow within a forest. Finally, because
185 a tsunami typical has a time-scale of flow unsteadiness that is long compared to the time-scale for
186 advection around a single tree (high Keulegan-Carpenter number), the drag coefficients relevant
187 to tsunami propagation should be similar to those for uni-directional flow (Keulegan and
188 Carpenter, 1958). Velocity and force measurements were made for a single tree in isolation
189 (called the single tree case), for in-line tree distributions at four densities ($n = 6, 10, 14$ and 18
190 trees/m²), and for ten random distributions at each of five densities ($n = 2, 6, 10, 14$ and 18
191 trees/m²).

Vertical profiles of velocity were measured using a Vectrino Acoustic Doppler Velocimeter (ADV) with a side-looking probe, which was mounted to a vertical rod that moved vertically. The velocity profile was measured at the position of the target tree, but with the tree removed. Velocity was measured at $z = 1, 4, 7, 10, 13, 16, 19$ and 22 cm. Velocity in the x, y and z directions were recorded over a period of 30 s at a sampling rate of 200 Hz. The raw data were de-spiked using the method of Goring and Nikora (2002) and averaged to define the time-averaged velocities (u, v , and w) corresponding to x, y and z , respectively. The 30 s record was compared to a 5 min record, and the difference between mean velocities was less than 0.6% . Thus, the 30 -second record was sufficient to obtain stable mean statistics. The ensemble-averaged, streamwise velocity profile, $\langle u \rangle(z) (= \frac{1}{N} \sum_{i=1}^N u(z))$, was obtained by averaging the velocity profiles from $N (=10)$ realizations. For the i^{th} random distribution (with $i = 1$ to 10 for each tree density), the local depth-averaged velocity at the target tree (U_i) was obtained by integrating the vertical velocity profile (i.e., $U_i = \frac{1}{H} \int_0^H u(z) dz$). Similarly, U_{IL} represented the local depth-averaged velocity at the target tree for the in-line distribution.

Forces were measured using a Futek LSB200 100-g-capacity load cell (Figure 5). The load cell was calibrated weekly using weights of known mass, which consistently produced a linear relationship between the recorded strain and the force. The target tree was fixed on one side of a pivoting arm, and the load cell was connected to the other side (Figure 5). The distance from the pivot point to the channel bed was $L_b = 32.5$ cm, and the distance from the pivot point to the load cell was $L_{lc} = 17.0$ cm. After mounting the target tree to the arm, the position of the tree was

checked to confirm that the target tree was not touching any other trees or the bed. The gap between the roots of the target tree and the bed was less than 5 mm. In each case the force was measured with $U_0 = 9.9$ cm/s and in still water. The still water condition provided the baseline force with no hydrodynamic drag. Force measurements were collected over a period of 60 s at a sampling rate of 2000 Hz and were used to calculate the time-mean force on the load cell, F_{lc} .

The hydrodynamic drag force exerted on the tree (F_d) can be described with a quadratic drag law:

$$F_d = \int_0^H \frac{1}{2} \rho C_d dA(z) u(z)^2 dz \quad (1)$$

in which ρ is the water density and C_d is the drag coefficient. This force exerted a torque around the pivot, $F_d L_d$, with L_d the distance from the centroid of tree drag force to the pivot (Figure 5).

The torque produced by the tree drag force balanced the torque provided by the load cell, $F_{lc} L_{lc}$, such that

$$F_d = \frac{F_{lc} L_{lc}}{L_d} \quad (2)$$

The distance L_d from the pivot to the centroid of the drag force is defined by equating two expressions of torque around the pivot, $\int_0^H (L_b - z) \frac{1}{2} \rho C_d dA u^2 dz = F_d L_d$, which leads to

$$L_d = L_b - \frac{\int_0^H \frac{1}{2} \rho C_d dA u^2 z dz}{\int_0^H \frac{1}{2} \rho C_d dA u^2 dz} = L_B - \frac{\sum_{j=0}^H dA(j) u^2(j) z(j) \Delta z(j)}{\sum_{j=0}^H dA(j) u^2(j) \Delta z(j)} \quad (3)$$

with the right-most expression the discretized version used with the data. Here, $\Delta z(j)$ the vertical interval included in bin j of the integral approximation. Following previous studies (e.g., Dalrymple et al. 1984; Kobayashi et al. 1993; Mendez and Losada, 1999; Losada et al. 2016), the

drag coefficient, C_d , was assumed to be constant along the vertical, such that it was cancelled from the right-most term in (3), which allowed L_d to be estimated without a priori knowledge of C_d . Based on the positions of the velocity measurements, the sums in the right-most term in (3) were evaluated using vertical bins of $\Delta z = 3$ cm centered at $z = 4, 7, 10, 13, 16, 19$ and 22 cm. The velocity near the water surface ($25 \text{ cm} > z > 22 \text{ cm}$) could not be accessed by the ADV, so that the value of $u^2(j) dA(j)$ at the centroid of the top interval ($z = 24.25$ cm) was assumed to be the same as that at $z = 22$ cm, and the interval of $\Delta z = 1.5$ cm was used for this topmost interval. Finally, for the position nearest the bed, the velocity measured at $z = 1$ cm was assumed to be representative of the interval $z = 0$ to 2.5 cm.

Equations (2) and (3) were used to estimate the drag force on the target tree in each configuration, defined as $F_{d(s)}$ for the single tree case, $F_{d(i)}$ for the i^{th} realization of a random distribution, and $F_{d(IL)}$ for in-line distributions. In each case, three replicate force measurements were made to determine the uncertainty for that measurement. For the random distributions, each with $N = 10$ realizations, the ensemble mean drag force, $\langle F_d \rangle$, was calculated as:

$$\langle F_d \rangle = \frac{1}{N} \sum_{i=1}^N F_{d(i)} \quad (4)$$

Drag coefficients were estimated in two ways; using the channel-average velocity, U_0 , and the local depth-averaged velocity, U_i , measured at the position of the target tree. The two estimators were considered to explore the role of local flow adjustment on the drag coefficient defined for individual trees. For the in-line distributions,

$$C_{d(IL)} = \frac{2F_{d(IL)}}{\rho A U_i^2} \quad \text{using local velocity} \quad (5a)$$

$$C_{d(IL-mean)} = \frac{2F_{d(IL)}}{\rho AU_0^2} \quad \text{using channel-mean velocity} \quad (5b)$$

The uncertainty in each drag coefficient, $\delta C_{d(IL)}$ and $\delta C_{d(IL-mean)}$, was estimated by propagating the uncertainty in the force and velocity measurements (Taylor, 1998). A similar analysis was used for the single tree case, yielding the drag coefficient, $C_{d(S)}$.

Similarly, two drag coefficients were estimated for each of the 10 realizations for each tree density in a random distribution:

$$C_{d(i)} = \frac{2F_{d(i)}}{\rho AU_{(i)}^2} \quad \text{using local velocity} \quad (6a)$$

$$C_{d(mean)} = \frac{2F_{d(i)}}{\rho AU_0^2} \quad \text{using channel-mean velocity} \quad (6b)$$

The ensemble mean drag coefficients were then denoted as $\langle C_d \rangle$ and $\langle C_{d(mean)} \rangle$, respectively.

Note that to simplify later discussions, in both (5a) and (6a) C_d was estimated using the depth-averaged velocity, $U_{(i)}$, rather than the full integral of the velocity profile shown in Eq. (1).

This simplification was justified, because estimates of C_d made using the integral of the velocity

profile, $C_d = \frac{2F_d}{\rho \sum_{j=0}^H dA(j) u^2(j) \Delta z(j)}$, differed by a maximum of 6% from the estimates made with

the depth-averaged velocity (Eqs. (5) and (6)). Finally, an additional case was performed with $n =$

10 trees/m² to examine the influence of trees located downstream from the target tree. Five

additional trees were randomly placed in the 0.5 m long and 1 m wide section directly

downstream of the test section. The force exerted on the target tree was measured with and

without the five downstream trees. There was at most a 6% difference between the forces

measured with and without the five trees, indicating that the influence of these trees on the force measurement was negligible.

For a random distribution, the standard deviation for N realizations is defined as:

$$\sigma = \sqrt{\frac{1}{N-1} \sum (X_{(i)} - \langle X \rangle)^2} \quad (7)$$

in which $X_{(i)}$ and $\langle X \rangle$ represent either the force ($F_{d(i)}$ and $\langle F_d \rangle$) or drag coefficients ($C_{d(i)}$ and $\langle C_d \rangle$, or $C_{d(mean)}$ and $\langle C_{d(mean)} \rangle$). The uncertainty in an ensemble average ($\delta \langle X \rangle$) is the

standard error $\delta \langle X \rangle = \frac{\sigma}{\sqrt{N}}$, and the uncertainty in the standard deviation is $\delta \sigma = \frac{\sigma}{\sqrt{2(N-1)}}$ (Taylor

1998). To assess the convergence of the mean and standard deviation, the ensemble-average drag

force, $\langle F_d \rangle$, and the normalized standard deviation of the force measurements, $\frac{\sigma}{\langle F_d \rangle}$, were

estimated using progressively larger ensembles, *i.e.*, increasing from $N = 1$ to 10. An example for

$n = 6$ trees/m² is shown in Figure 6, in which the standard deviation and ensemble-mean drag

force reached constant values for $N \geq 6$. The same trend was observed across all tree densities.

Based on this, ten realizations were deemed to be sufficient to characterize the random

distribution cases.

4 Results and discussion

4.1 Velocities

The vertical profiles of ensemble-averaged, streamwise velocity measured in random

distributions, with $n = 2$ to 18 trees/m² (dimensionless density $a_r HR_{max} = 0.03$ to 0.25,

respectively), are shown in Figure 7. For $n = 2$ and 6 trees/m² ($a_r HR_{max} = 0.03$ and 0.08, black

symbols in Fig. 7), the velocity profiles followed a boundary layer profile similar to that measured upstream of the forest (blue triangles), indicating that the forest did not create significant vertical re-distribution of the velocity. In contrast, for $n = 10$ to 18 trees/m² ($a_r HR_{max} = 0.14$ to 0.25 , red symbols in Figure 7), the ensemble-averaged velocity in the root zone ($z < HR_{max}$) was diminished, and the vertical profile no longer followed the boundary layer profile, suggesting that the transition between low- and high-density forests was between $a_r HR_{max} = 0.08$ and 0.14 . This was consistent with the expected transition number ($= 0.1$) defined for submerged canopies (e.g. Nepf, 2012). Based on the transition number ($a_r HR_{max} = 0.1$), forests were classified into low-density forests, with $n = 2$ and 6 trees/m² ($a_r HR_{max} = 0.03$ and 0.08 , respectively), and high-density forests, with $n = 10$, 14 and 18 trees/m² ($a_r HR_{max} = 0.14$, 0.20 and 0.25 , respectively).

The vertical profile of streamwise velocity measured in each random distribution and the in-line distribution, with $n = 6$ trees/m² ($a_r HR_{max} = 0.08$, low-density) and $n = 18$ trees/m² ($a_r HR_{max} = 0.25$, high-density), are presented in Figure 8. The horizontal dashed line indicates the maximum root height ($HR_{max} = 16$ cm). For the low-density forest (Figure 8a), the velocity profile in both the random (black circles) and in-line distribution (red squares) was not significantly affected by the trees, and both the random ensemble-average and in-line velocity profiles matched the upstream velocity profile (blue triangles) to within 0.5%. For the random distributions, a small degree of lateral flow distribution was observed (not shown), with the local variation in depth-averaged velocity limited to 5% among the 10 realizations (red circles in

Figure 9). In contrast, for the high-density forest (Figure 8b), the shape of both the ensemble-average velocity profile (black circles) and the in-line profile (red squares) were altered relative to the upstream velocity profile (blue triangles). For the random distribution (black circles), velocity in the root zone ($z < HR_{max}$, below dashed line in Figure 8) was decreased by $6 \pm 3\%$, and the velocity above the root zone ($z > HR_{max}$) was enhanced by $8.5 \pm 0.6\%$, compared to the upstream profile. This is similar to a submerged dense canopy, in which velocity is diminished (Nepf 2012; Cheng et al. 2012). The velocity profile was more significantly altered for the dense in-line forest (red squares in Figure 8b), with a reduction in depth-averaged velocity of $12.2 \pm 0.1\%$ relative to the upstream profile, consistent with previous studies of in-line configurations (Maza et al. 2017). For the in-line distribution, the trees were arranged in straight lines, and the trees in front deflected the flow in the lateral direction, creating a shelter for the target tree, which sat in the wake of the upstream, in-line trees and, thus, experienced diminished velocity, relative to the channel-average velocity.

The local, depth-averaged velocity depended on both the forest density and the tree distribution. This is illustrated in Figure 9, which shows the normalized depth-averaged velocity for individual random distributions ($\frac{U_i}{U_0}$, red circles) and for in-line distributions ($\frac{U_{IL}}{U_0}$, black squares) at different tree density, n . As expected, $\frac{U_i}{U_0} = 1$ for the single, insulated tree, which, for convenience, was plotted at $n = 1$ trees/m² (blue diamond). For the in-line cases, as tree density increased, the streamwise distance between the in-line trunks was reduced, producing greater sheltering, and a smaller local depth-averaged velocity (black squares in Figure 9). For example,

for $n = 6$ trees/m², the streamwise distance between trunks was 50 cm, and $\frac{U_{IL}}{U_0} = 0.98 \pm 0.04$. In contrast, for $n = 14$ trees/m², the streamwise distance between trunks decreased to 22 cm, and $\frac{U_{IL}}{U_0} = 0.87 \pm 0.03$. For the two highest forest densities ($n = 14$ and 18 trees/m²), the in-line velocity (black squares) appeared to have reached a minimum of $\frac{U_{IL}}{U_0} = 0.88 \pm 0.05$. However, this may arise because the trunk-to-trunk spacing was the same (22 cm) for both in-line $n = 14$ and 18 trees/m². For cases with random distributions, the variability in local velocity increased with increasing forest density (red circles in Figure 9). In other words, the spatial variance in the local velocity increased with increasing forest density. This is consistent with Tanino and Nepf (2008), who showed that for random arrays of circular cylinders, the spatial variance in velocity increased with array density (Figure 9 in Tanino and Nepf, 2008). It is important to note that the individual random distributions produced significantly higher local velocity than occurred in the in-line cases (Figure 9). For example, for $n = 18$ trees m⁻², the peak local velocity measured in a random distribution was 32% higher than the in-line local velocity. In addition, even the ensemble average local velocity was higher by 12%, compared to the in-line arrangement.

4.2 Drag forces

The force exerted on an individual tree was proportional to the frontal area and local velocity, i.e., $dA(z)u(z)^2$ (e.g. Eq. (1)). In both the in-line and random distributions, the profile of $dA(z)u(z)^2$ (Figure 10) was more similar to $dA(z)$ (Figure 1) than to $u(z)$ (Figure 8), indicating the dominant

role of mangrove geometry in drag distribution. That is, the vertical profile of drag was determined predominantly by the vertical distribution of frontal area, with little compensation from the redistribution of flow toward the region of lower frontal area. As a result, the root zone consistently contributed a greater fraction of the drag, emphasizing the need to represent the root zone accurately in scaled-models. To emphasize this point, the drag on the root zone was estimated as:

$$F_{d(root)} = \frac{1}{2} \rho C_d \int_0^{HR_{max}} dA(z) u(z)^2 dz \quad (8)$$

and compared to the force on the entire tree (Eq. (1)). $F_{d(root)}$ was calculated for each realization, and the ensemble mean was denoted $\langle F_{d(root)} \rangle$. As shown in Figure 11, $\frac{\langle F_{d(root)} \rangle}{\langle F_d \rangle}$ was not a function of tree density, and approximately a constant ($= 0.85 \pm 0.01$, dashed line). Note that the distribution of force between the root zone and trunk zone will also depend on the flow depth H . For the water depth considered here $\frac{HR_{max}}{H} = 0.64$, and the root zone frontal area ($\int_0^{HR_{max}} dA(z) dz = 0.014 \text{ m}^2$) contributed 93% to the total frontal area, $A = 0.015 \text{ m}^2$.

The force exerted on an individual tree within a random distribution is compared to the drag measured on a single, isolated tree in Figure 12. The force on a tree inside the forest, $F_{d(i)}$, (red circles), was both diminished and enhanced relative to the force on the single tree, $F_{d(s)}$ (black dashed line). Specifically, the force was elevated in 26% of the measurements and by up to 13%, and the force was diminished in 72% of the measurements and by up to 28%, relative to the force on the single tree. This suggested that a fraction of trees within the forest have a greater chance of damage or breakage than a single, isolated tree. In contrast, for in-line tree arrangements, the

368 upstream, in-line neighbors provided shelter for the trees within the forest. As a result, the force
369 on a tree within an in-line forest was diminished, relative to the force on a single tree (Figure 12).
370 For in-line arrangements with $n = 6$ and 10 trees/m², the streamwise distance between trunks was
371 50-cm, and the force, $F_{d(IL)}$ (black squares), was $10 \pm 2\%$ smaller than the force on a single tree
372 (black dashed line, $F_{d(S)}$). For the higher density forests (specifically, $n = 14$ and 18 trees/m²), the
373 distance between in-line trunks decreased to 22 cm, and the force was $27 \pm 3\%$ smaller than the
374 force on the single tree.

375 The force on an isolated tree is also representative of the force exerted on a tree at the
376 leading edge of the forest; thus, the measurements reported in Figure 12 can also be interpreted as
377 the difference expected between the leading edge of a forest (here, the single tree) and the interior
378 of the forest. For the in-line distribution, the drag on a tree within the forest was significantly
379 reduced relative to a tree at the leading edge, which was consistent with Thuy et al. (2012), who
380 reported that trees at the leading edge of a forest have a higher probability of being damaged by
381 tsunami forces than trees in other locations in a uniformly distributed forest. Similarly, the force
382 was maximal for trees in the first row of uniformly distributed forests in both flume experiments
383 (e.g., Strusinska-Correia et al. 2013) and in numerical simulations (e.g., Maza et al. 2015). In
384 contrast, the forces on individual trees within a randomly distributed forest might be higher, or
385 lower, than the leading edge (Figure 12). Similarly, Maza et al. (2015) reported higher forces on
386 rigid, emergent cylinders within a random array, relative to the array leading edge.

The variation in individual tree force measured in the random distributions is characterized by the standard deviation, specifically $\pm 2\sigma$ captures 95% of the expected variation. The maximum force expected for a tree would be $\langle F_d \rangle + 2\sigma$, with 95% confidence. The maximum force across all densities was $10 \pm 3\%$ greater than the force on the leading edge (Figure 13a), indicating that a tree inside both low- and high-density forests could have a higher chance of damage than a tree at the leading edge. The normalized force variation range, $\frac{2\sigma}{\langle F_d \rangle}$, increased with increasing tree density up to $n = 14$ trees/m², and then decreased at the highest density of $n = 18$ trees/m² (Figure 13b). The increasing trend was consistent with observations in Tanino and Nepf (2008), who reported that the velocity spatial variance, to which force is correlated ($F_d \sim U^2$) increased with increasing solid volume fraction, but leveled off at high solid volume fractions (see Figure 9 in Tanino and Nepf 2008). White and Nepf (2003) derived a theoretical expression for the velocity spatial variance in a random cylinder array, showing that velocity spatial variance increased with the square root of array density, which explains why the spatial variance in velocity, and thus tree force, tends to level off at higher array density.

With an increase in velocity spatial variance, regions of both elevated and diminished velocity (relative to the channel average) are created. With regard to tree damage, there is a particular interest in regions of elevated velocity. As shown in Figure 9, 40% of the velocity measurements within randomly distributed forests were elevated above the channel mean velocity, such that the force was enhanced relative to an isolated tree, as shown in Figure 12. Similarly, using a hydrodynamic simulation of a randomly distributed array of cylinders, Maza et al. (2015)

showed that the maximum force associated with the passage of a tsunami wave was not at the leading edge, but occurred within the forest (Figure 21 in Maza et al. 2015). That is, in a randomly distributed forest, tree damage may not be constrained to the forest edge.

4.3 Drag coefficients

The drag coefficients calculated using the mean channel velocity, are plotted against tree density in Figure 14. For random distributions (red circles), the ensemble average drag coefficient, $\langle C_{d(mean)} \rangle$, was constant across the stem densities, $n = 2$ to 18 trees/m², and approximately 90% of the drag coefficient for the single tree (horizontal dashed line in Figure 14). As expected, there was a more significant reduction in drag coefficient for the dense in-line distributions ($n = 14$ and 18 trees/m², black squares), for which the values of $C_{d(IL-mean)}$ were approximately 70% of the drag coefficient for the single tree. In contrast, the drag coefficients estimated using the local, depth-averaged velocity ($\langle C_d \rangle$ and $C_{d(IL)}$) were not a function of forest density or arrangement and agreed with the drag coefficient for single tree within 7 ± 4 (SD) % (Figure 15). Across all densities, the mean drag coefficient was 0.80 ± 0.05 (SD), which was the same as the single tree value of 0.83 ± 0.03 , within uncertainty, and this was true for both random and in-line distributions. Maza et al. (2017) reported a similar result only for in-line distributed forests.

Many numerical models use a distributed drag to represent the hydrodynamic drag of a mangrove forest, for which the ensemble mean drag coefficient determined in this study ($\langle C_{d(mean)} \rangle$ or $C_{d(IL-mean)}$) would be appropriate. Importantly, the ensemble mean drag

coefficients are smaller than those derived from measurements on individual tree models, which only represent the drag at the leading edge of the forest. Maza et al. (2017) showed that the flow adjustment at the leading edge of a forest is completed by the fifth tree row. So, for forests of spatial extent much greater than five trees, the within-forest drag coefficient reported here would be a good estimator over the majority of the forest. Finally, if the local, depth-average velocity can be resolved within a numerical model, e.g. when using a point-drag representation for the trees, the drag coefficient necessary to represent the tree is a constant (0.80 ± 0.05) and equal to that for a single tree, $C_{d(S)} = 0.83 \pm 0.03$, and the present study has shown this condition is met in both random and in-line tree distributions and across a range of tree density (Figure 15).

Summary

Using a 1/12th scale model of a mangrove forest, this study characterized the drag forces on individual trees and the velocity distribution within forests with random and in-line distributions of trees, with tree densities of 2 to 18 trees/m², which correspond to 139 to 1280 trees/ha at full scale. Each model mangrove included a prop root system, constructed based on the geometry of *Rhizophora* observed in the field by Ohira et al. (2013). For both randomly distributed trees and in-line trees within a low-density forest ($a_r HR_{max} < 0.1$), the ensemble-average velocity profile was unchanged from the boundary layer profile measured upstream of the forest. For randomly-distributed, high-density forests ($a_r HR_{max} > 0.1$), the velocity profile was altered from the upstream profile, with the ensemble-averaged velocity reduced in the root zone ($z < HR_{max}$)

and enhanced above the root zone ($z > HR_{max}$), relative to the upstream profile. The randomly distributed forests included greater velocity spatial variance, which translated into a greater variability in force on individual trees, compared to the in-line forests, and within a random forest, the spatial velocity variance and peak force both increased with tree density. The force on an individual tree within a random forest ranged from 13% higher to 28% lower than the force on the leading edge tree. However, the ensemble average force and thus the ensemble average drag coefficient $\langle C_{d(mean)} \rangle$ was consistently diminished by 10% from the leading edge across all random forest densities. For in-line forests the individual tree force as well as the drag coefficient based on the channel-average velocity ($C_{d(IL-mean)}$) was always diminished from the leading edge and by up to 27%. In contrast, the drag coefficients calculated for the local depth-averaged velocity, $\langle C_d \rangle$ and $C_{d(IL)}$, were not a function of local velocity or forest area density, with mean value 0.80 ± 0.05 .

When simulating flow through a mangrove forest, the tree distribution is often unknown and the drag on individual trees varies with both tree distribution and density. Our study defines the range of drag force and drag coefficients for individual trees inside randomly distributed forests across different densities, which can be used to define the contribution of drag coefficient variability to the uncertainty in numerical simulations. Specifically, the local variation in drag was shown to be up to 24% of the forest-scale ensemble mean drag force.

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Notation

A	=	Total mangrove frontal area, $A = \int_0^H dA(z)dz$;
a_r	=	Frontal area per unit volume of root zone, $a_r = \frac{n}{HR_{max}} \int_0^{HR_{max}} dA(z)dz$;
$dA(z)$	=	Frontal area per cm in vertical direction;
$C_{d(IL)}$	=	Drag coefficient defined using local depth-averaged velocity within the in-line distribution, Eq. (5a);
$C_{d(IL-mean)}$	=	Drag coefficient defined using channel mean velocity within the in-line pattern case, Eq. (5b);
$C_{d(i)}$	=	Drag coefficient defined using local depth-averaged velocity for the i^{th} random distribution, Eq. (6a);
$\langle C_d \rangle$	=	Ensemble mean drag coefficient of $C_{d(i)}$ for N realizations;
$C_{d(S)}$	=	Drag coefficient for the single tree;
$C_{d(mean)}$	=	Drag coefficient defined using channel mean velocity, Eq. (6b);
$\langle C_{d(mean)} \rangle$	=	Ensemble mean drag coefficient of $C_{d(mean)}$ for N realizations;
D_{root}	=	Diameter of mangrove roots;
D_{trunk}	=	Diameter of mangrove trunk;
F_d	=	Hydrodynamic drag force exerted on the tree, Eq. (1);
$F_{d(i)}$	=	Drag force on the target tree for the i^{th} realization of a random distribution;
$F_{d(S)}$	=	Drag force on the single tree;
$\langle F_d \rangle$	=	Ensemble mean drag force for N random distributions, Eq. (4);

$F_{d(IL)}$	=	Drag force on the target tree in the in-line distribution;
$F_{d(root)}$	=	Force exerted within the root zone ($z < HR_{max}$), Eq. (8)
$\langle F_{d(root)} \rangle$	=	Ensemble mean force exerted on the root zone only;
F_{lc}	=	Time-mean force on the load cell;
H	=	Flow depth;
HR_{max}	=	The maximum root height, $HR_{max} = 16$ cm;
L_b	=	The distance from the pivot point to the channel bed, $L_b = 32.5$ cm;
L_d	=	The distance from the centroid of tree drag to the pivot;
L_{lc}	=	The distance from the pivot point to the load cell, $L_{lc} = 17.0$ cm;
N	=	Number of realizations considered for a given tree density, $N \geq 1$;
n	=	Tree density in trees per m^2 ;
n_x, n_y	=	Hole coordinate system, Figure 3.
Re_{root}	=	The Reynolds number based on the root diameter, $Re_{root} = \frac{U_m D_{root}}{\nu}$;
Re_{trunk}	=	The Reynolds number based on the trunk diameter, $Re_{trunk} = \frac{U_m D_{trunk}}{\nu}$;
U_i	=	Local depth-averaged velocity measured at the target tree within the i^{th} realization;
U_{IL}	=	Local depth-averaged velocity at the target tree for the in-line distribution;
U_m	=	Model velocity;
U_r	=	Full scale velocity;
U_0	=	Channel-average velocity upstream of the forest;
u, v, w	=	Time-averaged velocity in the streamwise, lateral and vertical directions, respectively;
x, y, z	=	Streamwise, lateral and vertical directions, respectively;
$\Delta z(j)$	=	Vertical interval included in bin j;
ρ	=	Water density;
ν	=	Kinematic viscosity;

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Table 1. Summary of experimental arrangements and results ^a

n (trees/m ²)	Case arrangements	$a_r HR_{max}$	$\langle F_d \rangle$ (N)	2σ (N)	$F_{d(IL)}$ (N)	$\langle C_d \rangle$	$\langle C_{d(mean)} \rangle$	$C_{d(IL)}$	$C_{d(IL-mean)}$	U_i (cm/s)	U_{IL} (cm/s)
Single tree	10 replicates	0.01	0.0607 ± 0.0023 ^b	-	-	0.83 ± 0.03 ^c	0.83 ± 0.03 ^c	-	-	9.9 ± 0.3	-
2	10 RD	0.03	0.0578 ± 0.0028	0.0082	-	0.77 ± 0.04	0.78 ± 0.04	-	-	$9.3-10.4$ ^d	-
6	10 RD and 1 IL	0.08	0.0551 ± 0.0029	0.0093	0.0536 ± 0.0028	0.74 ± 0.04	0.74 ± 0.05	0.76 ± 0.04	0.72 ± 0.04	$9.3-10.8$ ^d	9.7 ± 0.4
10	10 RD and 1 IL	0.14	0.0546 ± 0.0032	0.0123	0.0560 ± 0.0036	0.84 ± 0.04	0.73 ± 0.04	0.91 ± 0.06	0.78 ± 0.06	$8.6-10.9$ ^d	9.2 ± 0.4
14	10 RD and 1 IL	0.20	0.0567 ± 0.0033	0.0134	0.0460 ± 0.0019	0.79 ± 0.04	0.75 ± 0.05	0.83 ± 0.04	0.62 ± 0.04	$8.0-12.0$ ^d	8.6 ± 0.3
18	10 RD and 1 IL	0.25	0.0574 ± 0.0029	0.0097	0.0426 ± 0.0018	0.78 ± 0.03	0.76 ± 0.04	0.74 ± 0.03	0.58 ± 0.03	$8.5-11.6$ ^d	8.8 ± 0.4

^a n is the mean tree density per m² bed area; 10 replicates were performed for the single tree; RD indicates random distribution cases, and 10 RD indicates 10 realizations with different tree distributions; IL indicates cases with in-line tree arrangement; the non-dimensional density is $a_r HR_{max} = n \int_0^{HR_{max}} dA(z)dz$, in which a_r is the frontal area in the root zone per unit volume of the forest; HR_{max} is the maximum root height; $\langle F_d \rangle$ is the ensemble mean drag force (Eq. (4)); σ is the standard deviation of the ensemble mean (Eq. (7)); $F_{d(IL)}$ is the drag force on a tree inside the in-line forest; $\langle C_d \rangle$ is the ensemble mean drag coefficient for N realizations of the random distribution, using local velocity; $\langle C_{d(mean)} \rangle$ is the ensemble mean drag coefficient for N realizations of random distributions, using mean channel velocity, $U_0 = 9.9 \pm 0.1$ cm/s; $C_{d(IL)}$ is the drag coefficient calculated using the local depth-averaged velocity with the in-line distribution (Eq. (5a)); $C_{d(IL-mean)}$ is the drag coefficient calculated using the channel mean velocity, U_0 , within the in-line distribution (Eq. (5b)); U_i is the local depth-averaged velocity at the target tree for the i^{th} random distribution; U_{IL} is the local depth-averaged velocity at the target tree in the in-line distribution.

^b The drag force measured for the single tree, $F_{d(S)}$.

^c The drag coefficient for the single tree, $C_{d(S)}$.

^d The uncertainty for U_i in each realization is less than 0.4 cm/s.

Figure 1. The left-hand figure shows the vertical profile of frontal area per cm, $dA(z)$ (cm), for a single tree, estimated from digital images (such as right-hand figure). The vertical distance above of the bed, z , is normalized by the maximum root height $HR_{max} = 16$ cm. H is the flow depth. The horizontal bars indicate the variability associated with four tree rotations.

Figure 2. Top view of the flume and model mangrove trees for (a) the staggered, in-line tree distribution for $n = 10$ trees/m², (b) one realization of a random distribution for $n = 10$ trees/m², (c) one realization of a random distribution for $n = 2$ trees/m². The test section was 1 m long and 1 m wide. The drag was measured on the target tree (red tree), which was kept at the same position for all cases. The velocity at the target tree position was measured with the tree removed.

Figure 3. Schematic of the hole distribution in the baseboard. The model forest was set up within a 57×67 grid of holes, with the hole coordinate system (n_x, n_y) , in which $57 \geq n_x \geq 1$, and $67 \geq n_y \geq 1$. For each density, the tree positions for 10 random distributions were determined using the random number generator in Matlab. The target tree (red tree in Figure 2) was fixed at the downstream edge of the forest at the center of the flume, with $(n_x, n_y) = (57, 34)$.

Figure 4 Examples of random tree distributions, (a) Realization (1) for $n = 6$ trees/m², (b) Realization (1) for $n = 18$ trees/m². Realizations 1 to 10 are presented in Figures S1 and S2 in Supporting Information. The two dashed red lines indicate the extent of the test section (1 m $\times$ 1 m). At the right side of each photo the white tree highlighted by a red arrow was used to indicate the position of the target tree. Flow was from the left to right.

Figure 5. Schematic of force transducer attached to the target tree. L_{lc} is the distance from the pivot point to the load cell. L_b is the distance from the pivot point to the bed. L_d is the distance from the centroid of tree drag force to the pivot. HR_{max} is the maximum root height. The roots of the target tree made no contact with the bed, and the gap between the roots and the bed was less than 5 mm.

Figure 6. Relationship between the ensemble mean drag force $\langle F_d \rangle$ (red squares and right-hand axis) and the normalized drag standard deviation, $\frac{\sigma}{\langle F_d \rangle}$, (black circles, left-hand axis), for an ensemble of N drag measurements with $n = 6$ trees/m². For $N \geq 6$ both $\frac{\sigma}{\langle F_d \rangle}$ and $\langle F_d \rangle$ become constant within uncertainty. The vertical bar indicates uncertainties.

Figure 7 Vertical profiles of the streamwise, time-averaged velocity. The upstream velocity profile (blue solid triangles) followed a boundary layer profile. All other profiles represent ensemble-averages, $\langle u \rangle(z)$, measured at the target tree position in ten random distributions with $n = 2$ trees/m² ($a_r HR_{max} = 0.03$, black circles), 6 trees/m² ($a_r HR_{max} = 0.08$, black squares), 10 trees/m² ($a_r HR_{max} = 0.14$, red diamonds), 14 trees/m² ($a_r HR_{max} = 0.20$, red hexagons) and 18 trees/m² ($a_r HR_{max} = 0.25$, red inverse triangles). Horizontal bars indicate the uncertainty estimated by propagating the measurement uncertainty and the standard error of ensemble-average velocity. In some cases the uncertainty is smaller than the symbol.

Figure 8. Vertical profiles of the streamwise, time-averaged velocity measured for two tree densities (a) $n = 6$ trees/m² (low-density case, $a_r HR_{max} = 0.08$), and (b) $n = 18$ trees/m² (high-density case, $a_r HR_{max} = 0.25$). The blue triangles are the velocity profile upstream of the forest, $u(z)$, which is the same in both subplots. The black circles are the ensemble-average streamwise velocity, $\langle u \rangle(z)$, of ten random distributions, with horizontal bars indicating the uncertainty estimated by propagating the measurement uncertainty and the standard error of ensemble-average velocity. The red squares are the case with in-line tree distribution. HR_{max} ($= 16.0$ cm) was the maximum root height.

Figure 9. Local depth-averaged velocity measured at the target tree location normalized by the channel-average velocity versus tree density. The blue diamond $\frac{U_i}{U_0}$ ($= 1$) corresponds to the single tree case. The red circles show $\frac{U_i}{U_0}$, and correspond to individual random distributions. The black solid squares show $\frac{U_{IL}}{U_0}$, and correspond to the in-line distribution. Uncertainties in $\frac{U_i}{U_0}$ and $\frac{U_{IL}}{U_0}$ are smaller than 0.05.

Figure 10. Vertical profile of $dA(z) u(z)^2$ for $n = 18$ trees/m². Red squares indicate the staggered, in-line distribution. Blue circles indicate the ensemble mean of 10 random distributions. The dashed line indicates the maximum root height HR_{max} ($= 16.0$ cm).

Figure 11. The ensemble mean drag force exerted on the tree (roots and trunk) within the root zone ($z < HR_{max}$), denoted by $\langle F_{d(\text{root})} \rangle$, normalized by the ensemble mean force exerted on the entire tree $\langle F_d \rangle$, as a function of tree density (n). The uncertainty is less than the symbol size. The blue diamond indicates the value of a single, isolated tree. The horizontal dashed line indicates the mean value across all cases ($= 0.85 \pm 0.01$).

Figure 12. Drag force, normalized by the drag force on the single tree, $F_{d(s)}$, versus tree density. The blue diamond ($= 1$) corresponds to the single tree case. Red circles show $\frac{F_{d(i)}}{F_{d(s)}}$ for individual random distributions. Black squares show $\frac{F_{d(IL)}}{F_{d(s)}}$, corresponding to the in-line distributions.

Uncertainties in $\frac{F_{d(i)}}{F_{d(s)}}$ and $\frac{F_{d(IL)}}{F_{d(s)}}$ are smaller than 0.07.

Figure 13. (a) The maximal force exerted on an individual tree inside the forest, normalized by the force on an isolated, single tree, $\frac{\langle F_d \rangle + 2\sigma}{F_{d(s)}}$, versus tree density n ; (b) Variability in forces on individual trees within random distributions, defined by the twice the standard deviation of the ensemble, and normalized by the ensemble average force, $\frac{2\sigma}{\langle F_d \rangle}$, plotted against the tree density n .

Figure 14. Drag coefficients estimated using the channel-average velocity, versus tree density. The drag coefficients for in-line distributions, $C_{d(IL-mean)}$, are shown with black squares. The ensemble means for ten random distributions, $\langle C_{d(mean)} \rangle$, are shown with red circles. The horizontal dashed line indicates the drag coefficient for a single, isolated tree ($C_{d(s)} = 0.83 \pm 0.03$).

Figure 15. Drag coefficients estimated using the local, depth-averaged velocity measured at the target tree as a function of tree density. The drag coefficients for in-line distributions, $C_{d(IL)}$, are shown with black squares. The ensemble-mean drag coefficients for ten random distributions, $\langle C_d \rangle$, are shown with red circles. The horizontal dashed line indicates the drag coefficient for a single, isolated tree ($C_{d(S)} = 0.83 \pm 0.03$).