DRAG FORCES ON SUBTROPICAL TREES WITH SCLEROPHYLLOUS FOLIAGE TOWED THROUGH STILL WATER

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ABSTRACT

Hydraulic models used to simulate floods through riparian forests along rivers need to account for flow resistance caused by tree drag. Tree drag formulations have been developed for this purpose in previous studies, using drag force measurements on several broad-leaved, temperate species at tree scale to calibrate model parameters. However, tree reconfiguration and reduction in drag force in response to increased flow velocity are still not fully understood, particularly for subtropical tree species with sclerophyllous foliage. An established towing tank method was adapted to a field setting using a motorboat to tow submerged sheoak and tea trees through still water. Drag coefficients for both genera decreased with increasing velocity due to stem and foliage reconfiguration, except for the lowest velocity measurements on some sheoak trees, indicating the

emergence of a rigid regime. The rigid regime has also been observed in previous studies and is important for flood modeling, because drag forces could otherwise be overestimated at low velocities. Therefore, a new Cauchy number has been formulated and tested to predict regime transition for sheoak trees.

INTRODUCTION

Simulating floods along rivers using 1D and depth-averaged 2D hydraulic models is common practice in flood risk management studies. Where floodplains are forested, these models need to be capable of simulating the interaction between trees and floodwaters. Hydrodynamic drag forces exerted by floodwater on trees absorb flow momentum. This leads to an increase in flow resistance, which can raise water levels and reduce velocities over the forested floodplain. Flow resistance through vegetation is usually represented in hydraulic models with increased boundary resistance factors which can be obtained from lookup tables (e.g., [Chow 1959](#)). Numerous studies have investigated drag forces through arrays of rigid cylinders or rectangular prisms as a basis for developing process-based methods for computing flow resistance through vegetation ([Li and Shen 1973](#); [James et al. 2004](#); [Ben Meftah and Mossa 2013](#); [Stone et al. 2013](#); [Guillén-Ludeña et al. 2020](#))), and various process-based methods that use a description of the vegetation's drag coefficient have been developed (e.g., [Baptist et al. 2007](#); [Cheng 2011](#); [Huthoff et al. 2007](#); [Järvelä 2004](#); [Klopstra et al. 1997](#); [López and García 2001](#); [Petryk and Bosmajian 1975](#); [Wu et al. 1999](#)). Many of these process-based methods were developed using the classic drag force formula shown in Eq. 1, where F_D is the drag force, C_D is an empirical drag coefficient, ρ is the water density, A is a reference area of the object (frontal area is used in the present study), and U is the flow velocity.

$$F_D = \frac{1}{2}\rho C_D A U^2 \quad (1)$$

Eq. 1 assumes no geometric deformation in response to the drag force exerted on the object ([Schlichting and Gersten 2016](#)). For this rigid condition, C_D is generally related to the object's Reynolds number, $Re = UL/\nu$, where L is a characteristic dimension (such as the diameter for

cylinders) and ν is the water kinematic viscosity. C_D is uniform with increasing Re when flow in the boundary layer is laminar and wake is turbulent (the subcritical regime) but decreases abruptly when flow in the boundary layer switches from laminar to turbulent (drag crisis) and recovers to a uniform value in the transcritical regime. For example, C_D for drag on a smooth cylinder is roughly 1.0 to 1.2 for $1 \times 10^3 < Re < 2.0 \times 10^5$, then drops to a value of 0.3 when $Re \sim 3.8 \times 10^5$, and subsequently recovers to a value of 0.8 as Re increases (Nakayama 2018). Given that tree stems are relatively rough and foliage blockage and movement will induce turbulence through the canopy, it seems unlikely that a laminar wake would be encountered for flow through full scale trees. Nevertheless, C_D measurements on real vegetation are dependent on velocity (and by extension, Re), but this is due to geometric deformation (e.g., Fathi-Maghadam and Kouwen 1997; Vollsinger et al. 2005). When drag forces are large enough to bend an object, the reference area is, in effect, reduced by the increased angle between the streamline and the object's surface area. In the case of vegetation, this geometric deformation is known as stem and foliage reconfiguration for which Vogel (1984) observed a power drag-velocity law, $F_D \propto U^{2+\chi}$, instead of the quadratic drag-velocity law implied by Eq. 1. The empirical Vogel exponent, χ , represents the reconfiguration propensity and simulates the reduction in momentum absorbing area and increasing inclination angle with increasing velocity. An alternative solution is to develop a bending model and simulate the geometric distortion (Leclercq and De Langre 2016; Stone et al. 2013; Marjoribanks et al. 2014; Chen et al. 2014). However, the simple empirical solution using a Vogel exponent is more practical for application to complex structures like trees and has been successful in predicting drag forces on woody vegetation (Jalonen and Järvelä 2014; Järvelä 2004; Whittaker et al. 2015; Västilä et al. 2013) and applied to flow resistance through forests at field scale (Wang and Zhang 2019; Dalledonne et al. 2019).

For drag on a simple flexible structure, like an upright cylindrical cantilever beam inserted into flowing water, the structure remains undistorted in a rigid regime until drag forces are large enough to induce bending (Leclercq and De Langre 2016). The drag-velocity relationship is quadratic in the rigid regime (Eq. 1) and switches to the Vogel power law following transition into the

reconfiguration regime. A Cauchy number, which is a dimensionless number defined as the ratio between inertia and elastic forces, is often used to study fluid–structure interactions such as this (De Langre 2008). For modeling drag forces, the Cauchy number can be defined as shown in Eq. 2 (e.g., Gosselin et al. 2010; Hassani et al. 2016; Luhar and Nepf 2011; Leclercq and De Langre 2016; Luhar and Nepf 2013).

$$\text{Cauchy number} = \frac{\text{rigid drag force}}{\text{unbent elastic restoring force}} \quad (2)$$

An undisturbed, rigid state is used for reference. Therefore, the Cauchy number provides an indication of the degree of distortion and theoretically equates to unity when the rigid drag force (from Eq. 1) is the same as the elastic restoring force of the unbent structure and is less than unity in the rigid regime and greater than unity in the reconfiguration regime.

Since trees are heterogeneous, compound structures with a mix of components, the rigid and reconfiguration regime concept becomes more complex. Highly flexible foliage may bend at the slightest flow velocity and exhibit little or no rigid regime. Thicker stems, especially those with little foliage and secondary stems, may require some forcing before bending occurs and exhibit a relatively broad rigid regime. Stem bending depends on the characteristics of attached foliage and lower order stems, because the drag forces on these secondary elements will apply a bending moment on the supporting stem (Västilä and Järvelä 2014). Thus, a distinct transition between rigid and reconfiguration regimes may not always occur at the tree scale and may occur at different velocities for different tree species. Nevertheless, Xavier (2009) observed the presence of two regimes for the case of drag on full-scale trees. For practicality with regards to flume studies, many of the published drag experiments use tree off-cuts or juvenile plants that bend readily and are less likely to expose a rigid regime that may manifest with larger trees (e.g., Fathi-Maghadam and Kouwen 1997; Armanini et al. 2005; Wilson et al. 2008; Wunder et al. 2011; Västilä et al. 2013). Thus, the topic of rigid and reconfiguration regimes for drag on full-scale trees remains poorly understood, and is important for simulating flow resistance through mature forests where the moments of drag forces are not large enough to induce reconfiguration due to relatively shallow flow

(partial submergence) and/or low velocity. A new Cauchy number formulation has been developed in the present study to improve the prediction of regime transition for the subject trees.

Drag force and flexibility measurements on full-scale trees are needed to calibrate the drag coefficients and Vogel exponents used in tree drag models. Measurements of hydrodynamic drag forces on full-scale trees are limited to deciduous, broad-leaved species growing in temperate climates in the northern hemisphere, such as willow, birch, alder and poplar (Xavier 2009; Jalonon and Järvelä 2014). Drag forces have been measured on coniferous species, but only for small saplings (Fathi-Maghadam and Kouwen 1997). Here, drag forces are measured on sclerophyllous species found in riparian forests along the subtropical east coast of Australia. The specific species tested were river and swamp sheoak (*Casuarina cunninghamiana* and *C. glauca*) and river tea-tree (*Melaleuca bracteata*). Sheoak are common pioneer species often forming monodominant patches of forest on floodplain and channel bars (Erskine et al. 2009; Woolfrey and Ladd 2001). The leaves are reduced to small scales surrounding the stems, which have developed into cladodes giving the appearance of long, needle-like leaves. A third sheoak species, not tested here (*C. equisetifolia*), has a similar morphology and is distributed closer to saline environments with a range that extends to Southeast Asia. These three species are invasive in other parts of the world, including Florida, USA, where they are also known as Australian Pine (Wheeler et al. 2011). River tea trees have bushy foliage with small, spiky leaves. Given the different leaf morphology compared to northern hemisphere species that have been investigated previously, drag force behavior and model parameters may differ. These drag model parameters are needed to apply the process-based methods for estimating flow resistance through riparian forests along subtropical rivers on the Australian east coast. Uprooting of trees during floods has also been observed in these forests, and a tree drag model is needed to improve on methods used in previous studies to investigate tree stability during large floods (e.g., Tanaka and Yagisawa 2009).

Due to flume size limitations, several researchers have measured drag forces on full-scale trees by towing trees through still water at a uniform velocity in a ship laboratory towing tank (Oplatka 1998; Xavier 2009; Jalonon and Järvelä 2014). Here, an alternative method has been developed.

The towing method forces a uniform vertical velocity profile that does not self-regulate in response to flow resistance created by the drag force. Vertical velocity profiles through vegetation are often assumed linear in studies that use uniform vegetation models (e.g., Baptist et al. 2007; James et al. 2004; Huthoff et al. 2007). In the case of real trees, the vertical velocity profile will adjust according to vertical variations of drag on the trees. Further research will be needed to determine the implications of the uniform vertical velocity assumption for real trees.

In summary, this paper has three objectives. Firstly, to fill a gap in the literature by measuring drag forces on subtropical trees with sclerophyllous foliage at the tree scale. Secondly, to test an inexpensive alternative to large scale experiments in ship laboratories by towing trees across a reservoir with a boat moving at a uniform velocity. Thirdly, to use the measurements to test two existing tree drag formulations and a new Cauchy number formulation developed in the present study.

METHODS

Drag Models

Eq. 1 can be manipulated into a form that expresses the Vogel exponent relationship, $F_D \propto U^{2+\chi}$, by scaling the drag coefficient as shown in Eq. 3, where the reconfiguration term, ϕ , is dimensionless and $\phi = f(U)$.

$$C_D = C_{D\chi} \phi^\chi \quad (3)$$

$C_{D\chi}$ is a reference drag coefficient and equivalent to C_D when $\phi = 1$. Eq. 3 is a power function. Therefore, $C_{D\chi}$ and χ can be obtained by fitting a power regression to a plot of the measured C_D versus ϕ . The rigid regime is implemented by limiting ϕ to a minimum value of unity as shown in Eq. 4.

$$C_D = \begin{cases} C_{D\chi}, & \text{if } \phi \leq 1 \\ C_{D\chi} \phi^\chi, & \text{if } \phi > 1 \end{cases} \quad (4)$$

With this limitation, $C_{D\chi}$ is essentially the rigid regime drag coefficient. Järvelä (2004) applied this concept, without consideration of a rigid regime, to a tree drag model using a dimensionless velocity term as shown below.

$$C_D = C_{D\chi} \phi_u^\chi \quad \text{and} \quad \phi_u = \frac{U}{U_\chi} \quad (5)$$

In the ϕ_u model, U_χ is a reference velocity needed for dimensional homogeneity. The lowest velocity in the set of drag force measurements is usually selected for U_χ . Järvelä (2004) adopted leaf area for the reference area (A), as spatial variations in leaf area can be determined at field scale from indices commonly used in the environmental sciences (Antonarakis et al. 2010; Aberle and Järvelä 2013). Tree frontal area can also be selected for A (Västilä et al. 2013) and has been adopted in the present study with a view to estimate tree frontal areas in the field from a combination of airborne laser scanning surveys and allometric equations derived from high-resolution surveys.

Aiming to develop a tree drag model based more on measurable tree characteristics, Whittaker et al. (2015) proposed a Cauchy number-based formulation with $\phi_a = Ca^{1/2}$, where Ca is their proposed Cauchy number. The Whittaker et al. (2015) formulation is shown in Eq. 6 and Ca is determined from Eq. 7, where H is the tree height and EI is a reference rigidity for the tree.

$$C_D = C_{D0} \phi_a^\chi \quad \text{and} \quad \phi_a = \sqrt{Ca} \quad (6)$$

$$Ca = \frac{\rho A U^2 H^2}{EI} \quad (7)$$

Instead of the reference drag coefficient, $C_{D\chi}$, Eq. 7 uses C_{D0} which is determined by solving C_D in Eq. 1 with the lowest measured U and F_D pair. The ϕ_a model assumes that C_{D0} provides an approximation of the coefficient in the power relationship between C_D and ϕ_a ; i.e., $C_{D0} \equiv C_{D\chi}$ in Eq. 3. This assumption is based on the idea that C_D becomes relatively uniform when $Ca \leq 1$ and has worked reasonably for some data sets (Whittaker et al. 2015). However, since the numerator in Eq. 7 is not scaled by half the drag coefficient, Ca does not fully express the drag force, hence

does not quantify the balance between the drag and restoring forces and should not be expected to conform to the theoretical regime transition at $Ca = 1$ (Chen and Chen 2017). If the lowest measured U and F_D pair occur at a Ca that is significantly greater than unity, or a Ca less than unity and no rigid regime occurs, C_{D0} will produce a poor estimate of $C_{D\chi}$ and prediction of F_D . Eq. 7 also assumes that the drag resultant is exerted at the top of the tree. However, vertical variations in tree morphology, bio-mechanical, and hydrodynamic properties will dictate the position of the drag resultant and magnitude of the bending moment along the trunk.

Since the tree flexibility problem is one of bending, an alternative Cauchy number formulation is to use the ratio of the applied moment created by the drag loading and the elastic restoring moment due to bending. The applied moment (M_D) is the product of the drag force resultant and the height of the resultant above the base of the tree (H_r), i.e., $M_D = F_D H_r$. Approximating H_r as the height of the frontal area centroid, then $H_r = Z/A$, where Z is the projected first moment of area of the tree, and $Z = \int_0^H h dA$ where dA is the change in tree frontal area at height h from the tree base. The applied moment can be formulated by replacing the projected area term (A) in the classic drag force formula from Eq. 1 as $M_D = \frac{1}{2} \rho C_{D\chi} Z U^2$, where $C_{D\chi}$ is used since $C_{D\chi} \equiv C_D$ in the rigid regime. The elastic restoring moment is, $M_e = EI/r$, where r is the radius of curvature of bending and is equivalent to H for the rigid reference condition. Thus, the Cauchy number, C_y , can be formulated as shown in Eq. 8 and applied as shown in Eq. 9.

$$C_y = \frac{\rho C_{D\chi} Z U^2 H}{2EI} \quad (8)$$

$$C_D = C_{D\chi} \phi_y^\chi \quad \text{and} \quad \phi_y = \sqrt{C_y} \quad (9)$$

ϕ_y can be written in the U/U_χ form, like the ϕ_u model, by equating Eq. 5 and 9. Then, U_χ is interpreted as the transition velocity and determined from Eq. 10.

$$U_\chi = \sqrt{\frac{2EI}{\rho C_{D\chi} Z H}} \quad (10)$$

The Cauchy number formulation in Eq. 8 is an improvement on Eq. 7, as the assumption that the drag force resultant is located at the top of the tree crown has been removed and the drag coefficient has been included. The drag force resultant is now applied at the centroid of the frontal area, which accounts for the influence of vertical variations in tree morphology on the vertical drag loading and associated bending moment. A problem remains regarding the determination of EI . Whittaker et al. (2015) used trunk rigidities measured at a quarter (EI_{25}) and half (EI_{50}) the tree height from the base of the tree. Jalonen and Järvelä (2014) also measured EI_{50} on trees that were towed across a towing tank to measure drag forces. In the present study, trunk flexibility has been measured at a third of the tree height (EI_{33}) and used to determine the elastic modulus (E) of the lower trunk. EI at various locations on the trunk could then be interpolated from several trunk diameter measurements. Measured trunk EI values were compared to EI values obtained from Eq. 10 and transition velocities interpolated from measured drag forces. To determine $C_{D\chi}$ in Eq. 9 the rigidity number, R , is defined as the measured C_D (rearranging Eq. 1) divided by the reference drag coefficient; i.e., R is $C_D/C_{D\chi}$ for the ϕ_u and ϕ_y models and C_D/C_{D0} for the ϕ_a model. Then, Eq. 5, 6, and 9 can be written in terms of rigidity numbers as follows,

$$R_u = \phi_u^\chi, \quad R_a = \phi_a^\chi \quad \text{and} \quad R_y = \phi_y^\chi \quad (11)$$

R_y and ϕ_y were solved iteratively using estimates of $C_{D\chi}$ to seek a power regression with a coefficient of unity from the plot of R_y versus ϕ_y . After $C_{D\chi}$ had been determined, U_χ for each tree was computed from Eq. 10 and averaged for each genus. The genus averaged U_χ values were used to prescribe U_χ values for the ϕ_u model (i.e. for Eq. 5). This way, the plotting positions from the ϕ_y model were carried forward to the ϕ_u model, which is not necessary in theory as any uniform velocity can be adopted. However, keeping the plotting position consistent was useful for comparing plots of R_y versus ϕ_y with plots of R_u versus ϕ_u . The $C_{D\chi}$ and χ parameters in Eq. 5 were obtained from the coefficient and exponent of a power regression fitted to a plot of C_D versus ϕ_u . For all three models, the power regressions were only fitted to the measured data where $\phi > 1$. This was done to avoid any tendency towards a more rigid regime which would distort the Vogel

exponent.

Drag Experiments

A drag resistance frame was designed and constructed to measure the drag forces on trees fixed off the side of a motorboat and towed through still water on a reservoir (Fig. 1). The front and rear vertical chords of the aluminum frame were connected by two horizontal internal members with integrated load cells. All joints, except the fixed upper front chord joint, were pin joints. The tree specimen was attached below the lower joint on the rear chord, such that the drag force on the tree creates a cantilever loading that is resisted by the frame. The resistance forces were measured using 200 kg capacity S-type load cells, which can measure both tension and compression forces. The data logger recorded force readings averaged over one second intervals. The drag force was computed using the measured forces and a force balance $F_D + F_U + F_L = 0$, where F_U and F_L are the force recorded by the upper and lower load cell (F_L was typically 40% larger than F_U).

The experiments were carried out in a narrow bay (~ 150 m wide) on a freshwater reservoir at Hinze Dam, 70 km south of Brisbane, Australia. Powered boats are not usually permitted on the reservoir as it is used for water supply. Thus, there were no issues with wake interference from other boats. A series of steady-state boat runs were undertaken incrementing the boat speed after each run. Each boat run covered a distance of approximately 100-200 m over a period of approximately 1-2 minutes (see Figs. S2-S3 in the Supplemental Materials). The measured drag forces were relatively steady during each boat run, with a standard deviation of 2% on average and no more than 7%. The boat velocity was measured using the bottom track velocity captured from a SonTek ADCP and verified by the on-board GPS heading. The water was assumed to be still in the top few meters in which the trees were towed. This was confirmed by observing ADCP velocity measurements and the absence of foliage motion while the boat was still. Further details on the setup of the experiment are provided in [Sharpe et al. \(2019\)](#), in which drag measurements on aluminum poles were used to validate the method. The measurements on aluminum poles were repeated on the reservoir at Hinze Dam and the results suggest that the method produces a measurement accuracy of 94–95% on average (see Fig. S1).

Specimen Characterization

Five sheoak trees ranging between 2 m and 4 m in height and three tea trees approximately 2 m in height were acquired from a riparian forest on a small Australian east coast river (Fig. 2). Dimensional properties of the trees are listed in Table 1. Two species of sheoak trees were collected, including one river sheoak (*Casuarina cunninghamiana*) and four swamp sheoak (*C. glauca*). The two sheoak species exhibit differences in the color and texture of the bark. River sheoak bark was brown and slightly rougher, whereas swamp sheoak bark was gray with a scaly appearance. Otherwise, the tree morphology, with needle-like foliage, is identical (Fig. 2(a)). The sheoak specimens exhibited two distinct canopy forms. Two specimens (CC01 and CG04) had pyramidal forms with a low frontal area centroid (at 40% of the tree height) as is characteristic of these species when they form the forest's primary story. The remaining three specimens had narrower, columnar canopies starting higher up the trunk and spreading towards the crown with a higher frontal area centroid (at 60% of the tree height). These three specimens were harvested from the forest understory where competition for light may be a factor in the deviation from the canopy form found in the primary story.

A LiDAR survey of the trees was undertaken using a Leica ScanStation C10 terrestrial laser scanner (TLS). The trees were placed far from background objects to minimize ghost points in the point cloud data and no statistical filtering routines were deemed necessary. The scans were transformed into 2D raster grids sampled on a 3 mm grid. Raster pixel values were set to the population of coincident points from the point cloud. The 3 mm sample size was selected after trial and error to obtain the finest raster resolution that could be achieved given the point cloud resolution, i.e., to keep solid surfaces contiguous in the raster image. Raster pixels with a value greater than zero were counted to estimate the projected area of the trees. The results are shown in Table 1.

Trunk rigidity (EI_{33}) was measured at a third height from the base of each tree (H_{33}). For specimen CC01, this was done before the tree had been harvested while the tree was still rooted *in-situ*. For the other specimens, the flexibility test was done two days after the trees had been harvested

by fixing the base of the trees to a post in an upright position. The measurement procedure involved fixing a cord to the tree at one end, threading the cord through a slot in a board, and attaching a luggage scale at the other as shown in Fig. 3. The scale was pulled incrementally while recording the deflection distance and pulling force. The deflection distance was measured by recording the change in distance from the board with an ultrasonic sensor. The ultrasonic sensor and scale were wired to the same microprocessor for simultaneous logging of data. The measured pulling force (F_p) was plotted against the deflection distance (δ), and the slopes from linear regressions of these plots were used to estimate EI_{33} with Eq. 12.

$$EI_{33} = \frac{F_p}{\delta} \frac{H_{33}^3}{3} \quad (12)$$

The second moment of area of a circle ($I = \pi D^4/64$) was used to determine the elastic modulus of the trunks (E) assuming the lower third of the trunks were linearly tapered cylinders (a reasonable assumption based on several trunk diameter measurements) with an average diameter of $(D_0 + D_{33})/2$ where D_0 is the trunk diameter at the trunk base and D_{33} the trunk diameter at H_{33} .

RESULTS

Drag Forces

Drag forces have been compared against a quadratic and power drag-velocity relationship in Fig. 4. The lower velocity measurements fit the quadratic relationship but deviate from this for velocities of over 1 m/s where reconfiguration is more pronounced and the power relationship provides a better fit. The measurements appear to cross into the rigid regime at low velocity (< 1 m/s) for sheoak specimens CG03 and CG04 (Fig. 4(a)). The shortest sheoak (CG03), follows the quadratic drag-velocity relationship across a broader velocity range than CG04. This is likely due to lower bending moments on the short tree caused by a smaller first moment of area. While the lowest velocity measurement for the tea tree (MB03) may fall in the rigid regime, the regime transition is less clear for the tea tree specimens which fit the power relationship well across the full range

of velocities (Fig. 4(b)). Should a rigid regime exist for this species, lower velocity measurements would be required to confirm the transition position.

Tree Rigidity

A plot of measured C_D versus U is shown in Fig. 5(a) for three of the sheoak specimens where a rigid regime is apparent for the lowest velocity measurement. The trend lines shown in Fig. 5 are power regressions fitted to the plots of measured C_D versus U , excluding the slowest velocity, or 'rigid', measurement. For CG03, which is the smallest sheoak specimen at 2.0 m tall, velocities of greater than 3 m/s (i.e., the two largest velocity measurements) were excluded from the power regression fitting because the measured C_D values appear to converge towards a constant value at high velocity (the plant's capacity to reconfigure appears to become exhausted). The power regression errors range between $0\pm4\%$ for CG04, $0\pm3\%$ for CG01, and $0\pm3\%$ for CG03, using standard deviation to represent departure from the mean. Measurements of C_D for the slowest velocity measurements are 26% for CG04, 8% for CG01, and 15% for CG03 lower than that predicted by the power regressions. These deviations are substantial compared to the power regression error ranges and indicate a deviation from the reconfiguration trend into a more rigid regime at lower velocity. Of the five sheoak trees, the tallest tree (CG04 at 4.1 m) showed the strongest transition into a rigid regime at low velocity and two of the specimens (CC01 and CG02) showed no rigid regime transition, as indicated by an insignificant departure ($<1\%$) from power regression models at the slowest velocity measurement. Velocities at the intersection between the 'rigid' C_D measurements and the power regressions in Fig. 5(a) have been used to interpolate transition velocities, U_χ , of 0.52 m/s for CG04, 0.89 m/s for CG03, and 0.69 m/s for CG01. Using these U_χ values in Eq. 10 yields EI values of 327 MPa for CG04, 33 MPa for CG03, and 88 MPa for CG01. Fig. 5(b) compares these EI values with trunk rigidities measured at the tree base (EI_0). A power regression was fitted to measured EI_0 values (Eq. 13) and is shown in Fig. 5(b).

$$EI_0 = 2.44H^{3.67} \quad (13)$$

The EI values inferred from the drag measurements are 3% lower for CG01, 5% greater for CG03, and 26% lower for CG04 than that determined from Eq. 13. Given the close relationship between EI inferred from the drag experiments and EI_0 for the sheoak trees, EI_0 has been used as the reference EI for the sheoak trees. A similar analysis could not be undertaken for the tea tree specimens, as there was no clear deviation from the reconfiguration trend.

Drag Modeling

Fig. 6 shows measured rigidity numbers (R) plotted against the reconfiguration terms (ϕ) for the Järvelä (2004) model with reconfiguration term, ϕ_u , the Whittaker et al. (2015) model with reconfiguration term, ϕ_a , and the model developed in the present study with reconfiguration term, ϕ_y . Fig. 6 is split into three separate figures, with one figure for each data source in the Supplemental Materials (Figs. S4–S5) to illustrate these relationships for individual tree species. These plots include data collected from Xavier (2009), which is also used in Whittaker et al. (2015), and Jalonen and Järvelä (2014). For the Xavier (2009) data, Z was estimated from species-averaged models of the vertical frontal area profiles and EI_0 from the measured EI_{25} , D_{25} , and D_0 . There were insufficient data provided in Jalonen and Järvelä (2014) to compute EI_0 and Z . Therefore, EI_0 was estimated as 2.4 times greater than EI_{50} (based on averaged EI_0/EI_{50} measurements from Xavier (2009) and the present study) and the height of the area's centroid was assumed to be half the tree height. The reference area used by Jalonen and Järvelä (2014) was the total leaf area added to the frontal area of the stems. This differs from the frontal area used in the present study and by Xavier (2009), and has resulted in substantially smaller drag coefficients (see Table 2). The Vogel exponents presented in Table 2 differ slightly to that presented in Whittaker et al. (2015) and Jalonen and Järvelä (2014) because only the data where $\phi > 1$ were used in the regression fitting. A flattening of the data from the power regression trend with decreasing ϕ_y in Fig. 6(c) indicates the emergence of a rigid regime. In theory, R_y should converge towards a constant value of unity when $\phi < 1$. However, the data does not support this theoretical treatment, as R_y continues to increase with decreasing $\phi < 1$. This is especially so for the Jalonen and Järvelä (2014) data on foliated trees, which shows no distinct regime change (their data for defoliated trees does display a

rigid regime with Vogel exponents closer to zero in the lower velocity range). The [Xavier \(2009\)](#) data and data collected in the present study indicates a transition into a more rigid regime with a flattening of the $R_a-\phi_a$ trends near a ϕ_a of 0.8 for alder and poplar, 1 for willow, 6 for sheoak and 4 for tea tree (see Fig. S5). For the ϕ_y model, these transition points are near 0.2 for alder and poplar, 0.5 for willow, 1 for sheoak and 0.8 for tea tree (see Fig. S4). Fig. 6(b) displays more scatter than Fig. 6(a) and (c). This is because the ϕ_a model uses C_{D0} instead of the regression coefficient $C_{D\chi}$, and there is a large difference between C_{D0} and $C_{D\chi}$ for some data (see Table 2).

The accuracy of the three models, ignoring the $\phi < 1$ limit (Eq. 4), is shown in Fig. 6(d) and is 14% for ϕ_u , 43% for ϕ_a , and 20% for the ϕ_y model, on average. The accuracy of the ϕ_a model is distorted by the poor prediction of the sheoak and tea tree drag forces. The reason for this inaccuracy is that the lowest measured F_D-U pairs for these data are not proximate to a Ca of unity. Thus, $C_{D0} \ll C_{D\chi}$ (see Table 2) and the predicted drag forces are 76% lower than measured on average for the data measured in the present study. For the ϕ_u and ϕ_y models, the average error in predicting drag forces for the sheoak is 17% and 15%, and for the tea tree is 9% and 10%, on average. Using the ϕ_y model, the error for the lowest velocity measurement on sheoak specimen CG04 is 129%, which reduces to 41% if ϕ_y is limited according to Eq. 4.

DISCUSSION

Legislation preventing destruction of native forest in Australia limited the number of tests that could be run, but the experiment setup worked well for the trees that were tested. An interesting outcome from this research was the appearance of two regimes for the sheoak trees. The rigid regime has also been observed in drag forces measured on alder, poplar and willow trees ([Xavier 2009](#); [Whittaker et al. 2013](#)), where the rigid regime extended across a velocity range of ~0.1-0.5 m/s, and appears to become more prominent when trees are defoliated ([Jalonen and Järvelä 2014](#)). The rigid regime may be important in many applications. For example, shallow and/or slow floodwater flowing through forests with large trees may not induce significant reconfiguration of the stem network. Drag measurements within the rigid regime are limited in the present study, due to the relatively high minimum speed that could be achieved with the boat of approximately 0.5

m/s depending on the tree size. Therefore, more data is needed to confirm the position of regime transition and whether a uniform C_D occurs throughout the rigid regime. A smaller boat engine may enable a broader low-end velocity range to be measured. The use of larger trees, which will slow the boat due to the higher drag, and investigations into partial submergence, which will induce a wider rigid regime velocity range due to reduced drag forces and bending moments on the trunk, would also aid this objective.

Sheoak foliage was observed to bend at the slightest movement in the water, and it was surprising that a rigid regime is apparent in the measurements. Also, the transition between regimes was expected to be more gradual than the abrupt transition observed in the data and dictated by the theoretical treatment, because trees are compound structures with components that span a broad range of dimensions and stiffnesses. The observed drag behavior may be due to rapid reconfiguration of foliage in the low velocity range (< 0.5 m/s), which was not measured in this study. Västilä et al. (2013) observed more rapid reconfiguration in the 0.1–0.5 m/s velocity range than at higher velocity. The needle-like foliage of the sheoak trees appear to fully reconfigure, aligning with the direction of flow, at very low velocity. The rigid regime appears to represent a stage where the initial reconfiguration of foliage has been exhausted and there is little reconfiguration of the larger network of stems. Then, the transition to reconfiguration observed in the drag force measurements from the present study is caused by bending of the larger stem network rather than the foliage. This idea is supported by the coincidence of the EI values inferred from measured drag force transition positions and EI_0 at the trunk base, noting that greatest bending occurred at the trunk base. Jalonen and Järvelä (2014) found that trunk rigidity measured midway along the trunk increases at an increasing rate with tree height for trees taller than 2 m, which is similar to the EI_0 model and observations in this study. However, the number of measurements in this study is limited to five for sheoak, with heights of 2 m to 4 m. A wider range of rigidity measurements is needed, particularly for taller trees, since the intended application of this work is to estimate flow resistance through mature forests. This line of thinking also raises the question of whether the contribution of foliage and stems to drag should be lumped together, as was done in the present study. The measures

of A and Z do not distinguish between foliage and stems; all components were treated as having equal contribution to drag. Västilä and Järvelä (2014) adapted the Järvelä (2004) model (ϕ_u) to treat foliage and stem drag separately. However, this decoupling is complex because bending (or reconfiguration) of stems is influenced by drag forces on attached foliage and the associated bending moments. Thus, foliated stems reconfigure more readily than defoliated stems (Jalonen and Järvelä 2014). The drag model developed in this paper performed reasonably without the complexity of attempting to decouple foliage and stem drag.

The ϕ_a model developed by Whittaker et al. (2015) produced poor drag force predictions for the sheoak and tea trees. This is because the ϕ_a model uses C_{D0} instead of the reference drag coefficient ($C_{D\chi}$). It is likely that replacing C_{D0} with $C_{D\chi}$ in the ϕ_a model will improve the drag force prediction. The Cauchy number, C_y , developed in the present study provides a fuller description of the bending processes than the Cauchy number, Ca , suggested by Whittaker et al. (2015). However, regime transition for the different genera did not consistently occur near $C_y = 1$; only the sheoak, and possibly the tea tree, conformed to this concept. Thus, the C_y formulation has only been partially successful and a method to consistently predict regime transition across multiple genera is still needed. The position of regime transition for the Xavier (2009) data can be aligned to a ϕ_y value of unity if an EI value of $0.13EI_{25}$ for alder, $0.17EI_{25}$ for poplar, and $0.50EI_{25}$ for willow trees are assumed. Further research into reference rigidities and drag resultant heights may improve the Cauchy number formulation and positioning of regime transition. The ϕ_u model developed by Järvelä (2004), which uses a uniform normalizing velocity term (U_χ), predicted drag forces with greater accuracy than the Cauchy number-based models, on average. Also, given the simpler parameterization of the ϕ_u model, there is little added value from a Cauchy number-based model unless the measured data displays a rigid regime transition that can be predicted by the Cauchy number. The ϕ_u model can be adapted to implement a rigid regime if the U_χ term is redefined as a transition velocity and ϕ_u limited to a minimum of unity.

Drag coefficients measured on the sheoak and tea tree are compared to that measured for other genera using the ϕ_u model's parameters and defining the bulk ϕ_u coefficient as $C_u = C_{D\chi}/U_\chi^X$ (see

Table 2). The sheoak and tea tree C_u values of 0.08 and 0.12 are two to three times smaller than the values of 0.24 to 0.26 measured for alder, poplar and willow trees using the [Xavier \(2009\)](#) data. The C_u values from the [Jalonen and Järvelä \(2014\)](#) data are 0.05 on average, but not directly comparable as a different reference area was used. [Jalonen and Järvelä \(2014\)](#) measured C_u values of eight times greater on defoliated trees compared to foliated trees. Thus, the lower C_u measured on sheoak and tea tree may indicate a behavior similar to temperate, broad-leaf trees with more or bushier foliage. The Vogel coefficients for sheoak and tea tree, of -0.9, are larger in absolute value terms than that the -0.7 measured from the [Xavier \(2009\)](#) data and similar to that measured from the [Jalonen and Järvelä \(2014\)](#) data. A Vogel exponent of -1.11 has been measured on poplar off-cuts up to 30 cm long ([Västilä et al. 2013](#)), which is larger than that measured on full-scale poplar trees ([Whittaker et al. 2013](#)) and demonstrates that measurements on off-cuts may produce different results to full-scale trees. The average C_u for all data obtained from [Xavier \(2009\)](#) and the present study is 0.23, and the average Vogel exponent obtained from all the data is -0.83. The lower C_u measured in the present study suggests that sheoak and tea trees produce lower drag forces per unit area and the larger Vogel exponents suggest that sheoak and tea trees reconfigure more compared to the northern hemisphere species that have been measured at full scale. The greater reconfiguration propensity may be related to tree morphology. For instance, a bushier foliage concentrated towards the ends of stems could produce lower drag forces but greater bending moments, due to longer lever arms, than foliage distributed more evenly. The Vogel exponent for tea tree is 10% higher than for sheoak, which suggests that tea trees reconfigure more than sheoak. However, the tea tree trunks were not more flexible (see Table 1, comparing 2 m tall trees). The greater reconfiguration experienced by tea tree may be due to a higher foliage drag, which loads and bends the supporting stem network. In other words, the long and slender sheoak foliage reconfigures and streamlines more readily than tea tree foliage, leading to lower foliage drag and less bending of the supporting sheoak stems. This idea is supported by the generally higher drag forces and a 50% higher C_u , measured on the tea trees. Greater foliage drag on the tea trees could also explain why a rigid regime was not as apparent, because the foliage drag caused stem bending even at low velocity

creating a narrower rigid regime range. Sclerophyllous trees with long and slender foliage, such as the needle-like foliage of sheoak trees, appear to exhibit a wider rigid regime and lower stem reconfiguration propensity than those with short and bushy foliage.

In application of the drag force models to simulate forest flow resistance at field scale, larger trees and slow flow velocities that induce the rigid regime may be encountered. Furthermore, the likelihood of inducing the rigid regime is amplified when trees are only partially submerged. Thus, the two-regime problem is considered important for describing flow resistance through mature forests. One method to account for partially submerged conditions is to replace the height, area, and first moment of area with the flow depth, h , submerged frontal area, $A(h)$, and submerged first moment of area, $Z(h)$ (Whittaker et al. 2013). Then, the partially submerged ϕ_u model is shown in Eq. 14, which can be adapted to the ϕ_y model by using Eq. 15 to determine the transition velocity, U_χ .

$$F_D = \frac{1}{2} \rho C_{D\chi} A(h) U^2 \left(\frac{U}{U_\chi} \right)^\chi \quad (14)$$

$$U_\chi = \sqrt{\frac{2EI}{\rho C_{D\chi} Z(h) h}} \text{ and } U_\chi = \min(U, U_\chi) \quad (15)$$

EI has not been varied vertically due to its similarity with EI_0 (in the case of the sheoak trees) and the trunk base is the stiffest component of the tree. Since the influence of trunk bending, which draws more of the stems and foliage down into the water, is ignored, this approach may become inaccurate when $U \gg U_\chi$ and substantial bending of the trunk occurs. Eq. 14 and 15 has been applied to the tallest tree specimen (CG04) in Fig. 7, which shows how the regime transition varies with flow depth and energy slope assuming uniform flow conditions with a Manning's n ranging between 0.08 and 0.16. The tree becomes more rigid at lower depths and for flow depths of less than 1 m, abnormally high energy slopes are needed to induce reconfiguration. Further work is being undertaken to validate Eq. 14 and 15, using these equations to develop a forest flow resistance model for a monodominant sheoak forest. The forest resistance model is being tested in

a depth-averaged 2D hydraulic model by simulating a flood and comparing modeled and recorded flood levels. The drag force model is also being used to investigate the forces on trees that were dislodged during the flood.

CONCLUSION

The experiment successfully measured drag forces on submerged sheoak and tea trees towed through still water. Dragging trees in still water using a boat is a viable and inexpensive option for evaluating flow resistance of trees. Reconfiguration of the stems and foliage was observed in the data, as evidenced by the decline in classic drag coefficient with increasing velocity which generally followed a power trendline. The lowest velocity measurement for three of the five sheoak trees deviated from the power trendline, indicating the emergence of a rigid regime at low velocity. A similar transition was not noted in the tea tree drag forces for the velocity range used.

Three drag force models were tested using the results collected from the experiments. For the ϕ_y model developed in the present study, the prediction accuracy of drag forces and regime transition was reasonable, with errors of 15% for sheoak and 10% for tea tree, on average. For the ϕ_a model developed by Whittaker et al. (2015), the accuracy was poor with errors of 79% for sheoak and 71% for tea tree, on average. For the ϕ_u model developed by Järvelä (2004), predictions were reasonable with errors of 17% for sheoak and 9% for tea tree, on average. The ϕ_y model did not predict regime transition well for data collected in previous studies using EI_0 as the reference rigidity. Therefore, the limit of $\phi_y = 1$ (Eq. 4) was not imposed for predicting drag forces. The dimensionless velocity-based model (ϕ_u) predicted drag forces across all data sets with reasonable accuracy despite the fact that this formulation does not account for a rigid regime. Given the simpler parameterization of the ϕ_u model, this model may be preferred when drag is not influenced by a rigid regime, and the normalizing velocity term (U_χ) can be redefined or interpreted as a transition velocity and formulated from the ϕ_y model when regime transition is required.

Drag forces on the sclerophyllous trees tested in the present study were lower per unit area and Vogel exponents larger than that measured on broad-leaf, temperate trees at tree scale. The measured drag coefficients and Vogel exponents will assist with implementing process-based methods to

compute flow resistance through subtropical riparian forests where these tree species are distributed. The rigid regime is important for estimating flow resistance in forests when drag forces are not large enough to induce significant reconfiguration, due to low flow depth (i.e., partial submergence) and/or low velocity. Given the small number of measurements in the rigid regime in the present study, further research is needed to confirm the presence of this regime and to confirm that drag coefficients are indeed uniform across the range of velocities in this regime. In addition, further research is needed to measure drag forces, and test existing drag force models, on trees under partially submerged conditions.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies (<https://osf.io/kp4qv>, Sharpe 2021).

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NOTATION

The following symbols are used in this paper:

A	=	frontal area (m ²);
$A(h)$	=	frontal area at flow depth, h (m ²);
C_{D0}	=	drag coefficient for rigid object;
$C_{D\chi}$	=	species-specific drag coefficient;
C_y	=	Cauchy number developed in present study;
C_u	=	Bulk coefficient for the ϕ_u model;
Ca	=	Cauchy number from Whittaker et al. (2015);
D	=	trunk diameter (m);
D_0	=	trunk diameter at base (m);
D_{33}	=	trunk diameter at a third of the tree height (m);
$\bar{D}$	=	average trunk diameter (m);
E	=	elastic modulus of the trunk (MPa);
EI	=	tree reference rigidity (Nm ²);
EI_0	=	trunk rigidity at the tree base (Nm ²);
EI_{33}	=	trunk rigidity at a third of the tree height (Nm ²);
$\bar{EI}$	=	trunk rigidity based on average trunk diameter (Nm ²);
F_D	=	drag force (N);
F_L	=	force measured in lower load cell (N);
F_U	=	force measured in upper load cell (N);
F_p	=	pulling force (N);
H	=	tree height (m);
H_r	=	height of the drag resultant above the tree base (m);
H_{33}	=	third of tree height (m);
h	=	flow depth or a reference height up the tree (m);
I	=	second moment of area of trunk cross-section (m ⁴);
M_D	=	moment of the drag force about the tree base (Nm);
M_e	=	elastic restoring moment due to bending (Nm);

r = trunk's radius of curvature due to bending (m);
 R = rigidity number;
 R_a = rigidity number for ϕ_a model;
 R_u = rigidity number for ϕ_u model;
 R_y = rigidity number for ϕ_y model;
 U = velocity (m/s);
 U_χ = normalizing velocity or transition velocity (m/s);
 Z = first moment of frontal area (m³);
 $Z(h)$ = first moment of frontal area at flow depth, h (m³);
 δ = trunk deflection distance (m);
 ρ = density of water (kg/m³);
 ϕ = reconfiguration term; and
 ϕ_u = reconfiguration term for dimensionless velocity model; and
 ϕ_a = reconfiguration term for Cauchy number (Ca) model;
 ϕ_y = reconfiguration term for Cauchy number (C_y) model; and
 χ = Vogel exponent;

SUPPLEMENTAL MATERIALS

Figs. S1–S6 are available online in the ASCE Library (ascelibrary.org)

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List of Tables

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TABLE 1. Properties of the collected tree specimens. The prefix in tree ID denotes the following, *CC* for *Casuarina cunninghamiana*, *CG* for *C. glauca*, and *MB* for *Melaleuca bracteata*. The tree height (H), frontal area (A) and first moment of area (Z) were calculated from the TLS survey results. Flexural rigidity of the trunks (EI_{33}) was measured at a third of the tree height and used with trunk diameters measured at the trunk base (D_0) and a third of the tree height (D_{33}) to compute the elastic modulus (E). The average trunk diameters ($\bar{D}$) were calculated from measurements taken at least every 500 mm up the trunk to a point where the stem transitions from a woody appearance to foliage.

Species	Tree ID	H (m)	Trunk diameter (m)			EI_{33} (Nm ²)	E (MPa)	A (m ²)	Z (m ³)
			D_0	D_{33}	$\bar{D}$				
Sheoak	CC01	2.45	0.028	0.019	0.014	33	2,192	1.72	1.68
Sheoak	CG01	2.69	0.031	0.021	0.018	30	1,318	0.67	1.14
Sheoak	CG02	2.78	0.029	0.021	0.016	49	2,543	0.91	1.55
Sheoak	CG03	2.02	0.021	0.019	0.012	36	4,647	0.31	0.37
Sheoak	CG04	4.13	0.049	0.031	0.025	248	1,975	3.42	5.95
Tea tree	MB01	2.22	0.035	0.025	0.019	44	1,114	1.28	1.42
Tea tree	MB02	1.97	0.028	0.025	0.016	47	1,929	0.83	0.75
Tea tree	MB03	2.08	0.040	0.025	0.018	40	726	0.80	0.81

TABLE 2. Summary of reference drag coefficients ($C_{D\chi}$ and C_{D0}) and Vogel exponents (χ) for the Järvelä (2004) model (ϕ_a), Whittaker et al. (2015) model (ϕ_a), and the drag model developed in the present study (ϕ_y). The percentage difference between the two reference drag coefficients (i.e., $[C_{D0} - C_{D\chi}]/C_{D\chi}$) for the ϕ_a model is also listed (ΔC_D).

	ϕ_u			ϕ_a			ϕ_y	
	$C_{D\chi}/U_\chi^\chi$	χ	C_{D0}	$C_{D\chi}$	ΔC_D	χ	$C_{D\chi}$	χ
Sheoak	0.08	-0.88	0.12	0.60	-80%	-0.88	0.14 ⁽³⁾	-0.88
Tea tree	0.12	-0.94	0.23	0.83	-72%	-0.94	0.20	-0.94
Alder ⁽¹⁾	0.26	-0.70	0.96	0.71	35%	-0.70	0.24	-0.70
Poplar ⁽¹⁾	0.23	-0.68	0.76	0.58	32%	-0.63	0.32	-0.68
Willow ⁽¹⁾	0.24	-0.72	0.88	0.89	-1%	-0.72	0.40	-0.72
Alder ⁽²⁾	0.049	-0.91	0.42	0.32	30%	-0.91	0.04	-0.91
Birch ⁽²⁾	0.050	-0.86	0.34	0.31	9%	-0.86	0.04	-0.86

(1) data from [Xavier \(2009\)](#) with velocity and area ranging between 0.1–3.5 m/s and 0.2–1.2 m².

(2) data from [Jalonen and Järvelä \(2014\)](#) with velocity and area ranging between 0.1–2.5 m/s and 0.5–2.0 m².

(3) $C_{D\chi}$ changes to 0.12 when using Eq. 13 to specify EI .

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