

24 **Abstract**

25 Mangrove forests with complex root systems contribute to increased coastal protection through
26 drag effects. Previous flume studies proposed a predictive model of drag in *Rhizophora*
27 mangrove forests based on quadratic drag law. However, its general applicability on mangrove
28 forests in the field has not been tested. To fill this knowledge gap, this study quantified drag in
29 a 17-year-old planted *Rhizophora* mangrove forest using a comprehensive measurement of
30 hydrodynamics and vegetation morphology. The vegetation projected area density, a , showed
31 an approximate exponential increase towards the bed, mainly due to root branching. This
32 vertical variation led to enhanced vegetation drag per unit water volume relative to velocity
33 with decreasing water depth. Alternatively, the drag per vegetation projected area solely
34 depended on the square of velocity, indicating association with the quadratic drag law. The
35 derived drag coefficient (C_D) was 1.0 ± 0.2 for tide-driven currents, consistent with previous
36 flume studies. By using the mean value of derived C_D (1.0), it was confirmed that the quadratic
37 drag model expresses well the field-measured drag. We also presented a method for predicting
38 a value for a , another unknown parameter in the drag model, using an empirical *Rhizophora*
39 root model, and confirmed a successful prediction of a and drag. Therefore, the drag in a
40 *Rhizophora* mangrove forest can be accurately predicted only using the input parameters of the
41 *Rhizophora* root model – stem diameter and tree density. This provides insights into effectively
42 implementing the drag model in hydrodynamic models for better representation of mangroves'
43 coastal protection function.

44 **Plain Language Summary**

45 Mangrove forests with *Rhizophora* trees that have complex above-ground root systems
46 attenuate flow and wave energy and protect coasts from disasters such as storm surges and high

47 waves. This drag effect of mangrove forests has been previously examined by flume
48 experiments and characterized with two parameters – drag coefficient and vegetation frontal
49 area. However, field measurements of drag in mangrove forests are limited and it is still
50 unknown whether the insights obtained by flume experiments are applicable to mangrove
51 forests in the field. To fill this knowledge gap, this study quantified drag in a 17-year-old
52 planted *Rhizophora* mangrove forest based on field measurements. We showed that the value
53 of drag coefficient obtained in previous flume studies can be used for drag prediction in
54 mangrove forest examined in this study, suggesting the applicability of the insights from flume
55 experiments to the field. We also showed that the vegetation frontal area – another needed
56 information for drag prediction – can be predicted only using information on stem diameter
57 and tree density using an empirical model for *Rhizophora* root morphology. These results
58 provide a way for effectively predicting drag in *Rhizophora* mangrove forests in the field, thus
59 contributing a better understanding of mangroves’ coastal protection function.

60 Keywords: coastal vegetation; coastal protection; nature-based solution; drag coefficient; root
61 morphology

62 **1. Introduction**

63 Mangroves are one of the coastal vegetation ecosystems that grow in intertidal areas in
64 tropical and subtropical regions (Giri et al., 2011). They are characterized by complicated
65 patterns of above-ground root systems (Ezcurra et al., 2016; Tomlinson, 2016) that
66 substantially attenuate flow and wave energy and provide coastal protection (Furukawa et al.,
67 1997; Horstman et al., 2014; Menéndez et al., 2018, 2020). The significance of mangrove
68 forests in reducing damages by tsunami-induced waves and storm surges through their drag
69 effects has been noted by field, laboratory, and numerical modeling studies (Danielsen et al.,

70 2005; Krauss et al., 2009; Yanagisawa et al., 2010; Zhang et al., 2012; Strusińska-Correia et
71 al., 2013; Maza et al., 2019, 2021; Montgomery et al., 2019; Tomiczek et al., 2020). While the
72 risk of coastal flooding is expected to increase in the future due to increased occurrence of
73 more intense cyclones and sea-level rise (Woodruff et al., 2013), the coastal protection function
74 of mangrove forests is of great interest as a sustainable and cost-effective nature-based solution
75 (Temmerman et al., 2013; Gijssman et al., 2021).

76 Despite the valuable ecosystem services provided by mangroves, they have declined
77 globally predominantly due to deforestation (Friess et al., 2019). Although the perception of
78 mangroves ecosystem services has encouraged management actions such as protection and
79 restoration, deforestation is still ongoing especially in Southeast Asia (Friess et al., 2020).
80 Rigorous evaluation of the coastal protection function would help in better decision making for
81 facilitating management actions and implementation of nature-based solutions (Menéndez et
82 al., 2018; Gijssman et al., 2021). However, our understanding of the drag effects of mangrove
83 forests remains limited due to the complex architecture of root systems which makes it a
84 challenging task to quantify. Hence, this study aims to quantify mangroves drag from field
85 measurements and contribute to a better understanding of the mangroves' coastal protection
86 function. This study specifically focuses on the drag effects of *Rhizophora* genus which is
87 known to form complicated prop root systems (Ong et al., 2004). It is one of the most dominant
88 mangrove genera in the Asia-Pacific region and is often used for mangrove plantation
89 (Primavera and Esteban, 2008; Friess et al., 2019).

90 Recently, several studies have conducted flume experiments using model *Rhizophora*
91 trees to characterize the flow and drag in *Rhizophora* mangrove forests (Zhang et al., 2015;
92 Maza et al., 2017; Shan et al., 2019). They showed that the model based on the quadratic drag
93 law with the spatial average of streamwise depth-averaged velocity or channel mean velocity

94 (U , m s^{-1}) can well express the drag exerted by mangroves (vegetation drag). This can be
 95 written in a form of spatial average as (Nepf, 2012; Xu and Nepf, 2021)

$$96 \quad F_{veg,model} = \frac{1}{2} \frac{C_D}{1-\varphi} AU|U| \quad \text{where } A = \int_0^h a(z) dz \quad (1)$$

97 where $F_{veg,model}$ is the modeled vegetation drag per bed area ($\text{m}^2 \text{s}^{-2}$), C_D is the vegetation drag
 98 coefficient, φ is the solid volume fraction occupied by vegetation, and A is the vegetation
 99 projected area per bed area ($\text{m}^2 \text{m}^{-2}$), calculated by vertically integrating the vegetation
 100 projected area density a ($\text{m}^2 \text{m}^{-3}$) for water column with depth h (m). Here, C_D values around
 101 1 have been obtained in flows with Reynolds numbers (Re) high enough to ensure turbulent
 102 wakes.

103 The drag model, Eq. (1), with suggested C_D values may offer an accurate evaluation of
 104 the mangroves coastal protection function once it is implemented in coastal hydrodynamic
 105 models (Cao et al., 2021). However, actual mangrove forests in the field often have more
 106 complicated root systems than model mangroves examined in flume experiments; thus, the
 107 applicability of the drag model to field mangrove forests needs to be tested. To date, only a few
 108 studies have quantified vegetation drag in field mangrove forests. Mullarney et al. (2017) and
 109 Horstman et al. (2021) quantified the drag from pressure gradient by measuring water level
 110 differences along transects, however, C_D was not derived because the parameter a was not
 111 quantified. Only Mazda et al. (1997) obtained field estimates of C_D by putting additional efforts
 112 in measuring vegetation morphology for a . The derived C_D showed high variability ranging
 113 from 0.4 to more than 10 in tide-driven currents where turbulent wakes are usually expected,
 114 which contradicts the results of laboratory-based studies. However, their estimates of C_D were
 115 based on velocity measured at a single point while derivation of C_D requires velocity profiling
 116 as indicated in Eq. (1). Also, the measurement of vegetation morphology was rather limited in
 117 terms of sampling number to obtain the representative (or spatially averaged) value of a in
 118 more than 100-m long transects. Thus, the reliability of the derived C_D is questionable, and we

119 concluded that the drag model, Eq. (1), has not been adequately tested in field mangrove forests
120 yet.

121 The feasibility of the drag model, which is attributed to parameter a in Eq. (1), also
122 needs to be established. This parameter is labor-intensive to obtain in the field because it is
123 significantly influenced by tree density and individual tree morphology and could be highly
124 heterogeneous horizontally and vertically. Therefore, implementing the drag model in coastal
125 hydrodynamic models is challenging, especially in a forest-scale simulation (but see Horstman
126 et al., 2015 and Willemsen et al., 2016). In fact, numerical modeling studies often parameterize
127 mangrove drag effects in the bed roughness parameter without accounting for the spatial
128 heterogeneity of vegetation morphological structures (Li et al., 2012, 2014; Zhang et al., 2012;
129 Menéndez et al., 2019); this may result in an inaccurate representation of the coastal protection
130 function.

131 Here, we have set two specific objectives in this study. First, we aim to quantify the
132 drag and test the applicability of the drag model, Eq. (1), in a *Rhizophora* mangrove forest in
133 the field. Second, we propose a method to predict the parameter a in Eq. (1) to reasonably
134 predict the drag in mangrove forests. Such results would provide insights into implementing
135 the drag model in hydrodynamic models, thus, advancing our understanding of the mangroves
136 coastal protection function. A field survey was conducted in a planted *Rhizophora* mangrove
137 forest. A comprehensive data set on hydrodynamics and vegetation morphology needed for
138 testing the drag model were collected for the first time to fill the knowledge gap between the
139 model- and the field-mangrove forests. The spatially uniform distribution of trees with the same
140 age is characteristic of the relatively homogeneous vegetation morphological structures in the
141 selected forest. The transect established for the drag quantification was 30-m long; this is
142 shorter than in previous studies (Mazda et al., 1997; Mullarney et al., 2017; Horstman et al.,
143 2021). The homogeneous vegetation morphology and the short transect allowed us to estimate

144 a with high reliability from a relatively small number of morphological measurements. The
145 short transect also enabled us to confirm the unidirectional flow between the ends of the
146 transect during the tidal cycles. To accurately measure the small water level differences within
147 the 30-m long distance which cannot be achieved by usual pressure sensors, we applied a water
148 leveling method as described in this study. For the second objective, we applied a predictive
149 model of *Rhizophora* root morphological structures developed in Yoshikai et al. (2021a) for
150 the parameter a , and examined the predictability of drag in the forest using the drag model Eq.
151 (1) using the predicted values of a .

152 **2. Materials and Methods**

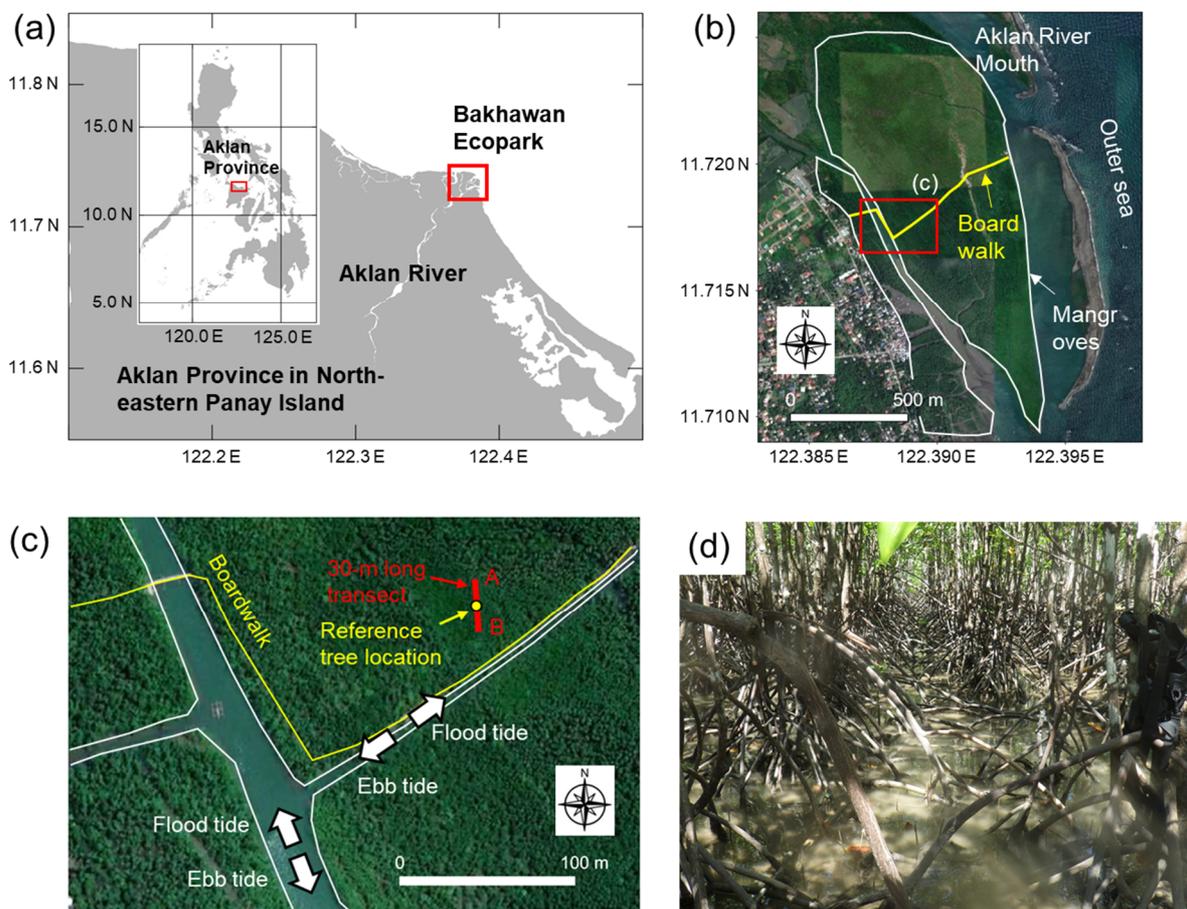
153 **2.1 Study site overview and transect setting**

154 This study was conducted in a planted mangrove forest (locally known as Bakhawan
155 Ecopark) found at the mouth of Aklan River in the province of Aklan, Panay Island, Philippines
156 (Fig. 1a, b). The plantation of *Rhizophora apiculata* started in a mudflat in the early 1990s
157 (Duncan et al., 2016). Subsequent plantations were conducted periodically, producing zones
158 characterized by *R. apiculata* stands with different ages (e.g., ~10 years old, ~20 years old, and
159 ~30 years old). The tide is semi-diurnal with the highest amplitude of 2.0 m. Except areas
160 facing the Aklan River mouth, the flows in the forest and creeks are basically tide-driven. The
161 forests and creeks are sheltered from waves by a sandbar (Fig. 1b).

162 A reconnaissance of the mangrove areas was conducted and 17-year-old (as of 2018)
163 *R. apiculata* stands were chosen as the drag measurement site (Fig. 1c, d). The site is
164 characterized by well-developed above-ground root systems, uniformly sized and evenly
165 distributed trees, and relatively energetic flows. Here, trees were planted following a 1.5 m ×
166 1.5 m spacing rule. The canopy is closed and sheltered from winds. This is also the site where

167 the morphological structures of above-ground roots were investigated in Yoshikai et al. (2021a)
 168 (referred to as site Bak1).

169 The transect for drag measurement was established on September 9, 2018, a day before
 170 the drag measurement was carried out. A reference tree was first identified and located at the
 171 center of the transect (Fig. 1c). A visual confirmation was then made such that the above-
 172 ground root structures of the reference tree do not deviate largely from those of the surrounding
 173 trees in terms of complexity. A 30-m long transect along the major flow direction (A–B; Fig.
 174 1c), which was determined visually, was set during the ebb tide. Afterwards, the x -coordinate
 175 was defined to align with the direction of mean flow during ebb tide (the major axis is shown
 176 in Fig. 2d), the y -coordinate oriented laterally, and the z -coordinate oriented vertically with $z =$
 177 0 m at the bed. The x -coordinates of A and B were defined as x_1 and x_2 , respectively.



178

179 Figure 1. Location of the study site – (a) Bakhawan Ecopark in Aklan province, Panay Island,
 180 Philippines; satellite images (Google Earth) of (b) the overview of Bakhawan Ecopark, (c)
 181 locations of transect A–B and the reference tree for drag measurement; and (d) photo of the
 182 drag measurement site taken near the reference tree. Shoreline data are from the Global Self-
 183 consistent, Hierarchical, High-resolution Shorelines (GSHHG) database.

184 2.2 Measurement of vegetation variables

185 To obtain the value of the spatially averaged vegetation projected area density, a (m^2
 186 m^{-3}), the morphological structures of above-ground roots and stems around the reference tree
 187 were extensively measured from September 13–18, 2018. Data on some trees, including the
 188 reference tree, are shown in Yoshikai et al. (2021a). Ten additional trees were compiled and
 189 added for a total of 23 trees for this study. The information on the locations of the measured
 190 trees are provided in Fig. 2a. Some information on the vegetation parameters is provided in
 191 Table 1. Here, the *R. apiculata* trees have multiple stems, where one tree has 3–7 stems. When
 192 the main stem of a tree could not be identified in the field, the diameter of the largest stem was
 193 used as DBH (diameter at breast height) of the tree.

194 Table 1. Vegetation and topography information in the study site.

Parameter	Unit	Value
Forest age	years	17
Tree density (n_{tree})	trees m^{-2}	0.36
Number of measured trees (N_{tree})	trees	23
Mean and standard deviation of DBH	m	0.066 ± 0.013
DBH range of measured trees	m	0.045–0.105
DBH of the reference tree	m	0.076
Mean root diameter	m	0.03
Scaling parameter (α in Eq. (9))	m^{-1}	$10^{-3.59}$
Scaling parameter (α_1 in Eq. (9))	–	-2.04
Scaling parameter (β in Eq. (9))	m	0.08
Scaling parameter (β_1 in Eq. (9))	–	15.38
Root angle of approximated root shape (θ in Eq. (11))	degree	-34.5
Ground level at A relative to near the reference tree	m	0.045

Ground level at B relative to near the reference tree m -0.049

195 As described in Yoshikai et al. (2021a, b), four parameters of root were measured; these
 196 are height (HR , m), horizontal distance (L , m), angle (θ , degree), and diameter (D_{root} , m). Then,
 197 following Ohira et al. (2013), the shape of each root projected from the mean flow direction
 198 was estimated from quadratic curve approximation as

$$199 \quad z = -\frac{HR+L \tan \theta}{L^2} \left(\frac{y}{\cos \psi} \right)^2 + (\tan \theta) \left(\frac{y}{\cos \psi} \right) + HR \quad (2)$$

200 where ψ is the azimuth angle of root to the mean flow direction; here, $y = 0$ at the location
 201 where a root emerges, i.e., the position of y -axis varies for each root. Because the azimuth root
 202 angles were not measured, a random number for ψ was given for each root in the range $0^\circ \leq \psi$
 203 $< 90^\circ$ using the random number generator in MATLAB. The projected area of one root can be
 204 estimated by multiplying D_{root} with the root length provided by Eq. (2). Similarly, root volume
 205 can be estimated from these parameters. By summing the projected areas of all roots in a tree
 206 per vertical height, dz (m), the whole-tree root projected area per dz , $a_{root,i}(z)$ (m tree^{-1} , here and
 207 hereafter; i denotes tree index), is obtained; a value 0.01 m was used for dz throughout this
 208 manuscript.

209 The stem diameter at 1.3 m height was also measured for the 23 trees. When the root
 210 in a tree exceeds the 1.3 m height, the diameters above the highest root were measured. Some
 211 stems branched from other stems, and in such cases, the height of the branching point was also
 212 measured. Then, the whole-tree stem projected area per dz , $a_{stem,i}(z)$ (m tree^{-1}), was estimated
 213 by approximating it as a patch of vertical cylinders whose stem density varies with height
 214 depending on the branching of the stems.

215 Three-dimensional point clouds of the measurement site were obtained using a hand-
 216 held GeoSLAM Horizon laser scanner (GeoSLAM Ltd., Nottingham, UK) for the purpose of

217 site visualization (Fig. 2a). From the point clouds, locations of trees were identified, and tree
 218 density of the site, n_{tree} (tree m^{-2}), was computed from the visualized tree locations (Table 1).

219 From the derived parameters $a_{root,i}$, $a_{stem,i}$, and n_{tree} , the vertical profile of the parameter
 220 a was calculated as

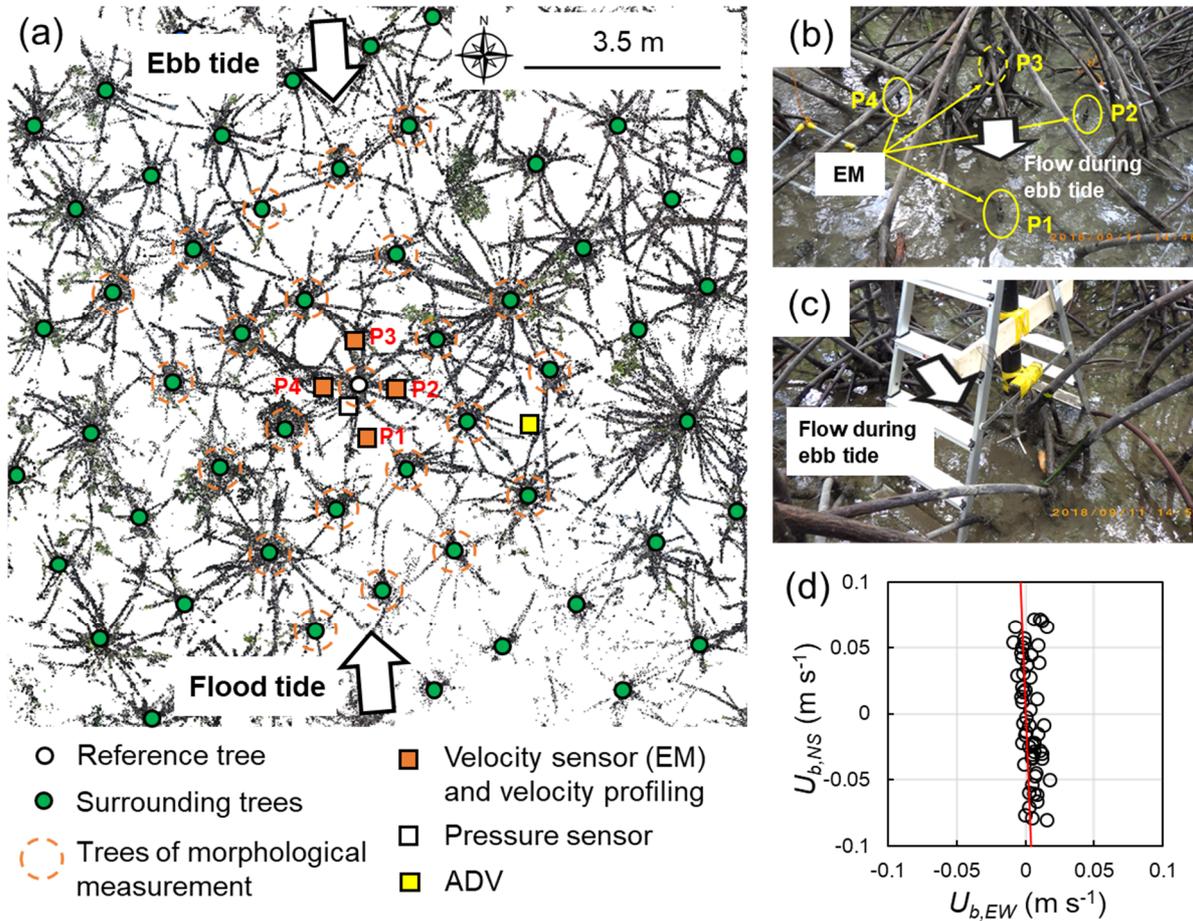
$$221 \quad a(z) = \frac{n_{tree} \sum_{i=1}^{N_{tree}} (a_{root,i}(z) + a_{stem,i}(z))}{N_{tree}} \quad (3)$$

222 where N_{tree} is the number of measured trees (Table 1). Here, due to the randomness in the
 223 azimuth angle in Eq. (2), the estimated value of a has some uncertainties. In this regard, the
 224 value of a was computed repeatedly for 20 times, and the median value was taken as the
 225 representative value of a in the area.

226 **2.3 Measurement of hydrodynamic variables**

227 The measurement of hydrodynamic variables for drag quantification was conducted on
 228 September 10 and 11, 2018, which were spring tide conditions. A pressure sensor (U20L-04,
 229 Onset Computer Corporation, USA), four electromagnetic velocity meters (EM; Infinity-EM,
 230 JFE Advantech, Japan), and one Acoustic Doppler Velocimeter (ADV; Nortek Vector,
 231 Norway) were deployed around the reference tree (Fig. 2a) for the two-days measurement. The
 232 EMs were deployed to measure the near-bed velocities behind (P1), in front (P3), and the sides
 233 (P2, P4) of the reference tree relative to the flow direction during the ebb tide (Fig. 2a, b). The
 234 body of EM was buried in the mud to position the probe at 5 cm above the bed as done in
 235 Schettini et al. (2020). The ADV was deployed around 3 m away from the reference tree in a
 236 downward-looking orientation (Fig. 2a, c), where the center of the sampling volume was placed
 237 at 5 cm above the bed for bed drag quantification (Pope et al., 2006). The ADV was set to
 238 collect data with 16 Hz for 1 minute (960 samples) every 10 minutes. The pressure sensor and

239 EMs were also set to collect data every 10 minutes. Using data from the deployed EMs, it was
 240 confirmed that the flows had a distinct axis and did not rotate during the tidal cycles (Fig. 2d).



241
 242 Figure 2. Visualization of the drag measurement set-up: (a) top view of point clouds around
 243 the reference tree with information on the locations of measured trees and deployed sensors
 244 (The point clouds shown were cropped at heights between 0.1–1.7 m for a better visualization
 245 of the root systems); photos of (b) velocity sensors (EM) deployed near the bed around the
 246 reference tree (P1–P4) and (c) deployed ADV; and (d) near-bed horizontal flow velocities of
 247 the eastern ($U_{b,EW}$) and northern ($U_{b,NS}$) components indicating the major axis (red line) during
 248 the measurement period (September 10–11, 2018) obtained by averaging the velocities from
 249 the four EMs.

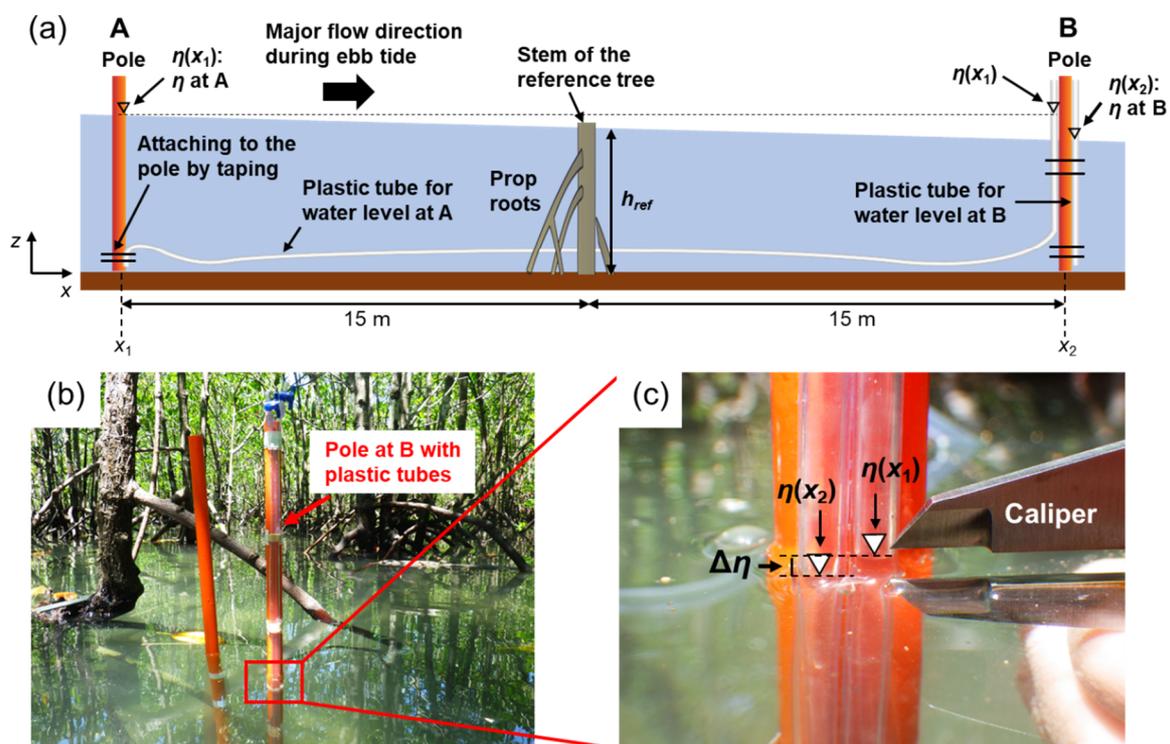
250 The water level differences between the transect ends A and B, $\Delta\eta$ (m), were measured
 251 during the ebb tides using the water leveling method. A schematic of the measurement setup is

252 shown in Fig. 3a. The method is based on the principle that the water level at both ends of a
253 conduit will equalize based on atmospheric pressure. Plastic poles were installed at the transect
254 ends A and B and a 35-m long plastic tube (inner and outer diameters: 6 and 8 mm,
255 respectively) spanned between the poles as illustrated in Fig. 3a. Also, a 1.5-m long plastic
256 tube with the same inner and outer diameters was placed onto pole B vertically (Fig. 3a, b).
257 When the ground was submerged during flood tide on a measurement day, the water
258 connectivity within the tubes was ascertained by removing any trapped air from the upward-
259 oriented tube end using a syringe. This made the water level inside the tube equalized at a
260 location where the downward-oriented tube end is placed, hence the water levels at A ($\eta(x_1)$)
261 and B ($\eta(x_2)$) were made visible at B (Fig. 3c). The downward orientation of the tube end was
262 to prevent the effects of pressure created by flows on the water level inside the tube. When the
263 water became still during high tides, the same level of $\eta(x_1)$ and $\eta(x_2)$ was confirmed. During
264 ebb tides, $\Delta\eta$ was measured using a caliper with 0.1 mm resolution every 10 minutes
265 synchronized to the timing of data collection by the deployed sensors (Fig. 3c). The $\Delta\eta$ was
266 recorded as 0 mm when the water level difference was too small to measure even though the
267 waters were flowing.

268 The water depths at A, B, and near the reference tree were measured manually when
269 the water was still at high tide. From these water depths, the ground levels at A and B relative
270 to the site near the reference tree were calculated (Table 1).

271 In conjunction with the sensor data collection and the water level difference
272 measurement, vertical profiling of flow velocity was conducted at the four locations around the
273 reference tree (P1–P4; Fig. 2). An electro-magnetic current meter equipped with a pressure
274 sensor (AEM213-DA, JFE Advantech) was used for the profiling. The sensor is connected to
275 a display unit with a cable and collects data at 1 Hz; one person stood on the root system of the
276 reference tree above the water surface and slowly moved the sensor down ($\sim 1.0 \text{ cm s}^{-1}$) from

277 the water surface to the bottom using a cable. When the water became shallower than around
 278 20 cm, a propeller velocimeter (CR-11, Cosmo Riken, Japan) was used for the profiling instead
 279 of the AEM213-DA. Its small propeller (~ 2 cm diameter) made it possible to measure velocity
 280 within a thin layer and is well-suited to profile shallow waters. In this case, the flow velocities
 281 along the transect (x -axis) at the surface, middle, and bottom layers were measured at the four
 282 locations around the reference tree.



283
 284 Figure 3. Water level difference measurement: (a) schematic diagram of setup; photos of (b)
 285 the pole set at B; and (c) a close view of the plastic tubes attached to the pole showing the water
 286 level difference ($\Delta\eta$) between A and B. The η is the water level (m), and h_{ref} is the water depth
 287 near the reference tree (m). Note that the schematics is not drawn to scale and the ground level
 288 slope is not depicted in the diagram.

289 2.4 Data processing and bed drag estimation

290 To obtain the streamwise mean flow velocity profile, the velocities along the x -axis,
 291 which were measured by the AEM213-DA, were binned using 0.05-m depth-width and

292 averaged in each bin. The channel mean velocity, U , was calculated by averaging the mean
 293 velocities in the bins (or layers, in the case of data from the propeller velocimeter) of the four
 294 locations (P1–P4), based on the assumption that the average of the four locations represents
 295 the spatial average in the area. To check the validity of this assumption, a particle tracking
 296 velocimetry (PTV) survey was conducted around the reference tree in March 2019. See Text
 297 S1 and Fig. S1 for the details.

298 The bed drag, F_{bed} ($\text{m}^2 \text{s}^{-2}$), was quantified from the measured Reynolds stress provided
 299 by the ADV data (see Text S2 for the details). A bed drag coefficient (C_{bed}) was then
 300 determined by fitting the measured F_{bed} and U in following equation of the quadratic drag law
 301 (Biron et al., 2004)

$$302 \quad F_{bed} = C_{bed}U|U| \quad (4)$$

303 where the value of C_{bed} was determined as 4.2×10^{-3} with $R^2 = 0.55$ (see Fig. Text S2 and Fig.
 304 S2). This equation was used to compute the bed drag in the subsequent analyses.

305 **2.5 Estimation of vegetation drag and drag coefficient**

306 Drag by vegetation was quantified from the depth-averaged momentum balance. The
 307 inertial terms were significantly small compared to the pressure gradient (more than 20 times
 308 smaller), and thus they were neglected as done in other works (Nepf, 1999; Mullarney et al.,
 309 2017; Monismith et al., 2019; Horstman et al., 2021). The momentum balance can be then
 310 reduced to

$$311 \quad g \frac{d\eta}{dx} = -\frac{F_{veg,obs}}{h} - \frac{F_{bed}}{h} \quad (5)$$

312 where g is the gravitational acceleration (m s^{-2}), h is the water depth (m), and $F_{veg,obs}$ is the
 313 vegetation drag ($\text{m}^2 \text{s}^{-2}$) quantified from field data. Here, we assumed that the water flux is
 314 conserved between the transect, $U(x, t)h(x, t) = U_{ref}(t)h_{ref}(t)$, where U_{ref} and h_{ref} are channel

315 mean velocity and water depth near the reference tree, respectively, and the bed slopes between
 316 A–reference tree and B–reference tree are constant. Then, following Lentz et al. (2017), Eq.
 317 (5) can be rearranged by horizontally integrating between x_1 and x_2 as

$$318 \langle F_{veg,obs} \rangle (x_2 - x_1) = -g\Delta\eta \int_{x_1}^{x_2} h dx - \langle F_{bed} \rangle (x_2 - x_1) \quad (6)$$

319 where the angle bracket denotes the spatial average between the transect ends A–B and

$$320 \langle F_{bed} \rangle (x_2 - x_1) = C_{bed} \int_{x_1}^{x_2} U|U| dx. \text{ This equation gives estimates of the mean vegetation}$$

321 drag between the transect, $\langle F_{veg,obs} \rangle$. Similarly, by assuming that value of C_D does not vary

322 between the ends of the transect, integration of the drag model Eq. (1) between x_1 and x_2 yields

$$323 \langle F_{veg,model} \rangle (x_2 - x_1) = \frac{1}{2} C_D \int_{x_1}^{x_2} \frac{AU|U|}{1-\phi} dx \quad (7)$$

324 The value of C_D was derived by equating Eqs. (6) and (7) for each measurement.

325 **2.6 Prediction of drag using a *Rhizophora* root model**

326 The *Rhizophora* root model developed in Yoshikai et al. (2021a) was applied as a
 327 predictor of a in the drag model, Eq. (1). This model basically predicts the vertical distribution
 328 of root density per tree and has successfully predicted the complex root morphological
 329 structures in various *Rhizophora* mangrove forests (Yoshikai et al., 2021a). The model assumes
 330 that the following equation applies for any root in root system of a tree

$$331 HR_k = HR_{max} S^{(k-1)} \quad (8)$$

332 where HR_k and HR_{max} are the root heights (m) of k^{th} highest and the highest root in a root system,

333 respectively, and S is a scaling factor. The parameters S and HR_{max} can be expressed as

334 functions of DBH, and thus, HR_k is a function of DBH as

$$335 HR_k = (\beta_1 DBH + \beta)(1 - \alpha DBH^{\alpha_1})^{(k-1)} \quad (9)$$

336 where β , β_1 and α , α_1 are the scaling parameters for HR_{max} and S , respectively. The values of

337 these parameters for our study site were derived in Yoshikai et al. (2021a) (Table 1). Similarly,

338 if the t^{th} highest root is the one with the minimum height in a root system, t is the largest integer
 339 number that satisfies

$$340 \quad HR_t = (\beta_1 DBH + \beta)(1 - \alpha DBH^{\alpha_1})^{(t-1)} \geq HR_{min} \quad (10)$$

341 where HR_{min} is the critical height (m) to be given as a model parameter. From Eqs. (9), (10),
 342 the vertical variation of root density per dz in a tree is modeled.

343 To compute the root projected area from the modeled root density, an empirical
 344 relationship of $n_{root,i}(z)$ and $a_{root0,i}(z)$ provided in Fig. S3 was used, where $n_{root,i}(z)$ is the number
 345 of roots per dz in tree i (root m^{-1} tree $^{-1}$), and $a_{root0,i}(z)$ is the root projected area per dz with zero
 346 azimuth angles (m tree $^{-1}$). The strong linear relationship between $n_{root,i}(z)$ and $a_{root0,i}(z)$ suggests
 347 that the individual roots can be approximated to a single linear shape assuming a uniform root
 348 diameter as

$$349 \quad z = (\tan \theta) \left(\frac{y}{\cos \psi} \right) + HR \quad (11)$$

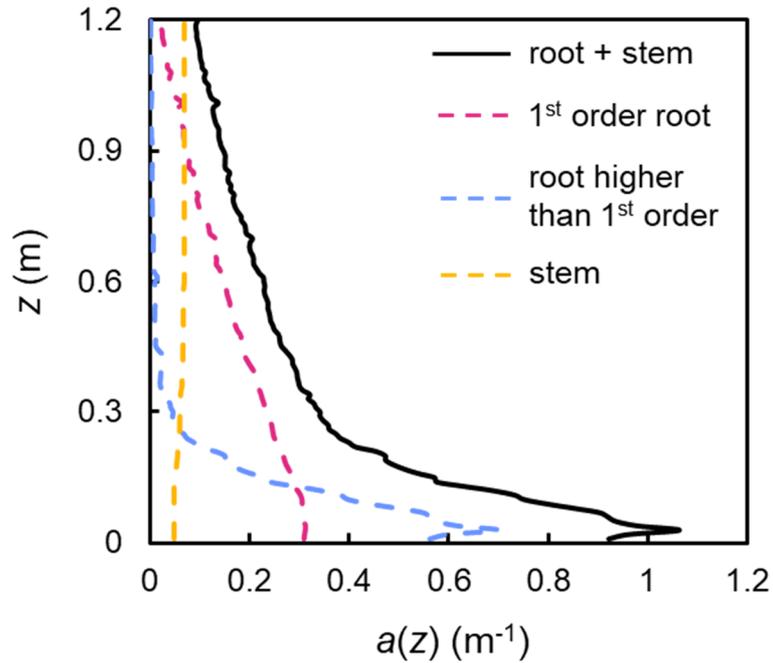
350 If Eq. (11) is applied, the slope of the $n_{root,i}(z)$ and $a_{root0,i}(z)$ relationship stands for $D_{root} dz / \sin(-$
 351 $\theta)$. By applying the average root diameter ($D_{root} = 0.03$ m; Table 1), the value of the root angle
 352 θ was determined as -34.5° for our study site (Fig. S3a; Table 1). As with the field data, random
 353 numbers were given to ψ in Eq. (11) for each root. The parameter a was then calculated from
 354 the modeled root projected area using Eq. (3) for 20 times, and the median value was taken as
 355 the representative value of model prediction; the observed value was used for $a_{stem,i}(z)$, which
 356 can be easily measured in the field.

357 Different parameter settings of HR_{min} were tested for predicting a by changing the
 358 values from 0.01 to 0.1 m with 0.01 m interval. The root angle ($\theta = -41.9^\circ$; Fig. S3b) determined
 359 for another mangrove forest (Fukido mangrove forest in Ishigaki Island, Japan; site Fuk in
 360 Yoshikai et al., 2021a) was also tested. The modeled a was then used in the drag model Eq. (1)
 361 for prediction of the drag exerted in the measurement site.

362 3. Results

363 3.1 Vegetation parameters

364 Figure 4 shows the vertical profile of the parameter a with component-specific
365 projected areas of the 1st order root, higher order root, and stem, where the root order indicates
366 the level of branching from the stem. The variations in a attributed to the random factor of root
367 azimuth angle (Eq. (2)) were negligibly small, less than 2% of the value shown in Fig. 4; thus
368 these variations were not considered in the subsequent results. The slightly lower projected
369 area of stems at the lower portion ($z < 0.3$ m) is attributed to the branching of stems. The
370 parameter a showed significant vertical variation and the root is clearly the dominant factor
371 affecting the value of a compared to the stem. While 1st order roots showed a moderate increase
372 in their projected area towards the bed, the higher order roots showed a drastic increase below
373 0.3 m height. Consequently, the value of a exhibited a nearly exponential increase with
374 decreasing height and reached 1.06 m^{-1} near the bed (black solid line in Fig. 4). Specifically,
375 the projected area of roots higher than 1st order was almost twice of the 1st order root near the
376 bed ($z < 0.1$ m), highlighting the importance of the presence of higher order roots in parameter
377 a . The vertical variations in the vegetation solid volume fraction, φ , was around 0.025 at the
378 highest near the bed (Fig. S4).



379

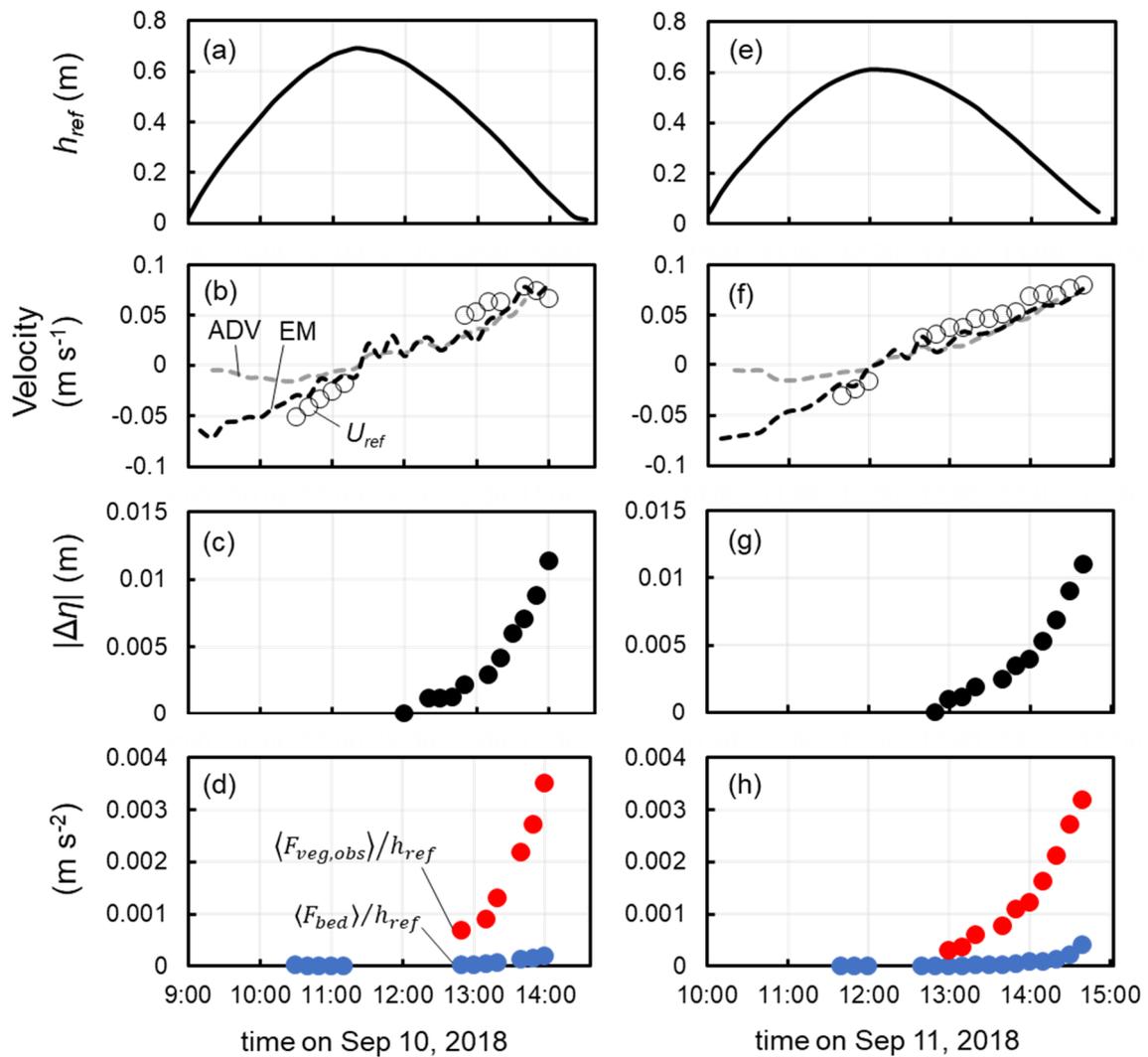
380 Figure 4. Vertical profile of spatially averaged vegetation projected area density (a , m^{-1}). The
 381 values of a were calculated with 0.01 m vertical resolution. The black solid line shows the
 382 median values of a from ensemble calculations ($N = 20$) while the red, blue, and yellow dashed
 383 lines show the contributions of 1st order root, higher order root, and stem to a , respectively.

384 3.2 Measured flow velocity and drag force

385 Figure 5 shows the time-series of measured hydrodynamic variables on September 10
 386 and 11, 2018. Note that some data on U_{ref} and $\Delta\eta$ are absent due to instrument problems and
 387 measurement setup maintenance, therefore the number of measured $\langle F_{veg,obs} \rangle$ is smaller than
 388 those of U_{ref} or $\Delta\eta$ (Fig. 5); also, $\langle F_{veg,obs} \rangle$ was not derived when the $\Delta\eta$ recorded was 0 mm.
 389 The U_{ref} was generally around 1.5 times larger than the velocities near the bed measured by
 390 EM sensors but became comparable when the water depth decreased ($h_{ref} < 0.2$ m). While these
 391 patterns were consistent during the two-days measurement, the U_{ref} on September 10, 14:00,
 392 was smaller than the velocity from EM sensors, possibly due to an unreliable measurement of
 393 U_{ref} using the propeller velocimeter (Fig. 5b). Velocity magnitude measured by ADV during

394 flood tide was significantly lower than EM-measured velocity or U_{ref} (Fig. 5b, f), probably due
 395 to local influence of nearby roots at the upstream side (Fig. 2c).

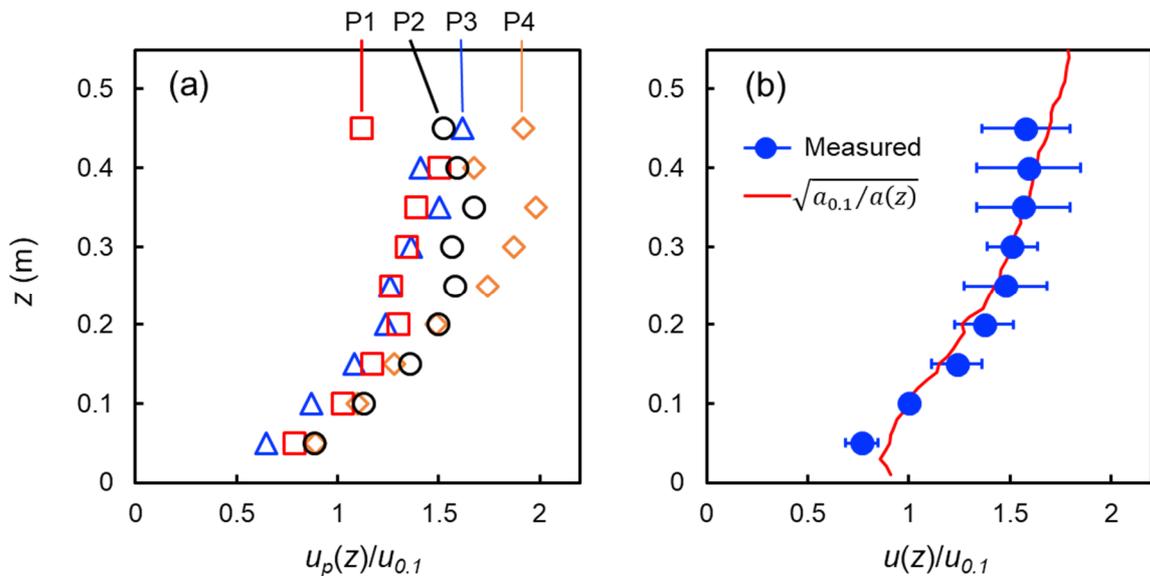
396 The variations of the measured $\Delta\eta$ were 1.2–11.4 mm (Fig. 5c, g). The $\Delta\eta$ increased as
 397 water depth decreased. Accordingly, the vegetation drag per water volume $\langle F_{veg,obs} \rangle / h_{ref}$
 398 showed an increase with decreasing water depth (Fig. 5d, h). The bed drag per water volume
 399 $\langle F_{bed} \rangle / h_{ref}$ was significantly small compared to the vegetation drag $\langle F_{veg,obs} \rangle / h_{ref}$, more
 400 than 15 times smaller during most of the measurement time.



401
 402 Figure 5. Time-series measurements on September 10 and 11, 2018, respectively, of (a, e)
 403 water depth near the reference tree (h_{ref}); (b, f) flow velocity (ADV-measured velocity, average

404 of EM-measured velocities, and channel mean velocity U_{ref} near the reference tree provided by
 405 the velocity profiling); (c, g) water level difference between the ends of transect A–B ($\Delta\eta$); and
 406 (d, h) bed $\langle F_{bed} \rangle$ and vegetation $\langle F_{veg,obs} \rangle$ drag divided by h_{ref} . The angle bracket denotes
 407 spatial average between A–B. The values for $\langle F_{bed} \rangle$ were given by Eq. (4).

408 Figure 6 shows the composite of velocity profile normalized by spatially averaged
 409 velocity at $z = 0.1$ m ($u_{0.1}$) for the two-days measurement. The local velocity profiles (u_p)
 410 normalized by $u_{0.1}$ showed some variations depending on the measurement locations (P1–4)
 411 (Fig. 6a). Overall, the flow velocities measured at the sides of the reference tree (P2, P4) were
 412 higher than the front (P3) or back (P1) of the tree at $z > 0.25$ m. The velocities were greatly
 413 attenuated below 0.25-m height and showed smaller variations among the locations. The profile
 414 of the spatially averaged velocity (u) also showed significant decrease below 0.25 m (Fig. 6b),
 415 corresponding to a significant increase in a (Fig. 4). The profile of u showed agreement with a
 416 theoretical predictor of spatially averaged velocity profile (red line in Fig. 6b) derived by
 417 Lightbody and Nepf (2006).

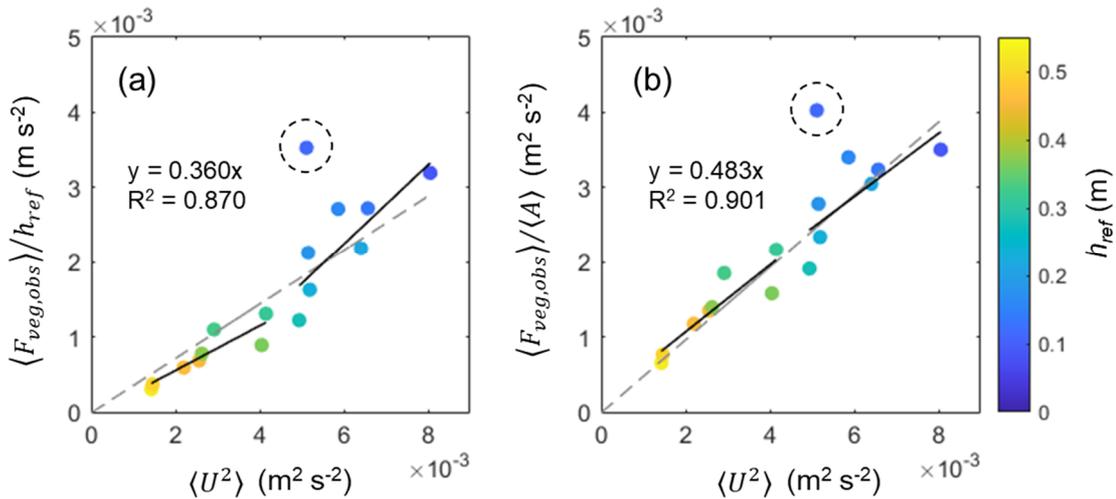


418 Figure 6. Vertical profile of streamwise horizontal velocity: (a) local velocity measured at P1–
 419 P4 (u_p) normalized by the spatial average (P1–P4) of velocity at 0.1 m above the bed ($u_{0.1}$); and
 420

421 (b) spatial average of velocity (u) normalized by $u_{0.1}$ (markers) with a predictor of $u(z)/u_{0.1}$ (red
 422 line), where $a_{0.1}$ is the spatially averaged vegetation projected area density at 0.1 m above the
 423 bed. The normalized velocities shown are the mean values of the different velocity
 424 measurements during the two-days measurement and the horizontal bars in panel “(b)” indicate
 425 the standard deviation.

426 3.3 Drag coefficient and application of the drag model

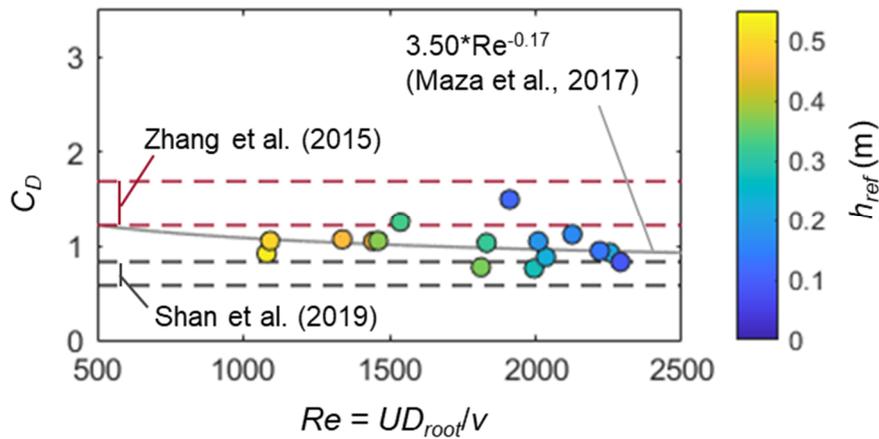
427 The $\langle U^2 \rangle$ and vegetation drag averaged for unit water volume $\langle F_{veg,obs} \rangle / h_{ref}$ showed
 428 significant correlation ($R^2 = 0.870$), but separate line fitting for $h_{ref} > 0.3$ m and $h_{ref} < 0.3$ m
 429 exhibited different line slopes (Fig. 7a). Note that the data taken on September 11, 14:00, was
 430 excluded from the line fitting as the data of U_{ref} may not be accurate (see Fig. 5b). Instead, the
 431 $\langle U^2 \rangle$ and drag averaged for unit vegetation projected area $\langle F_{veg,obs} \rangle / \langle A \rangle$ showed higher
 432 correlation ($R^2 = 0.901$), and separate line fittings did not show significant difference in the
 433 line slopes (Fig. 7b).



434
 435 Figure 7. Comparison of the velocity squared with (a) vegetation drag averaged for unit water
 436 volume and (b) for unit vegetation projected area. The parameter A is total vegetation projected
 437 area per ground area ($\text{m}^2 \text{m}^{-2}$) and the bracket denotes spatial average between the ends of
 438 transect A–B. The gray dashed line indicates linear fit with intercept fixed at zero while the

439 black lines indicate linear fit for $h_{ref} > 0.3$ m and $h_{ref} < 0.3$ m, respectively; the data enclosed
 440 by the dashed circle (data for September 11, 14:40) was excluded from the line fitting.

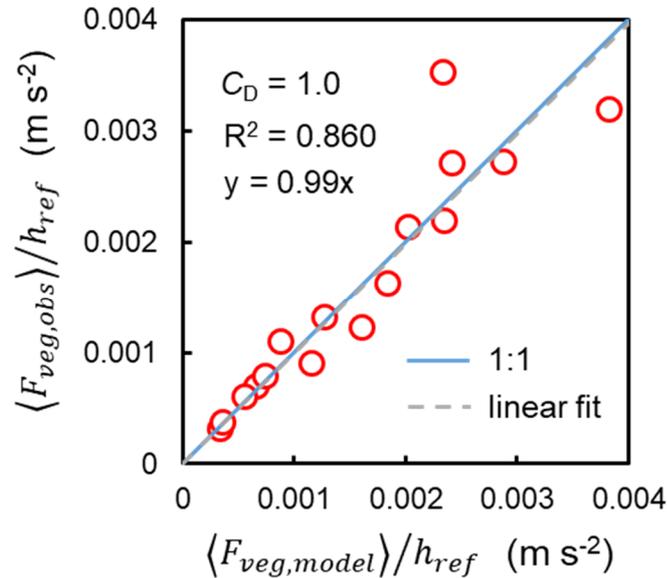
441 The value of C_D derived for each measurement using Eqs. (6) and (7) is shown in Fig.
 442 8; a mean value and standard deviation of 1.01 ± 0.18 were obtained. The derived C_D showed
 443 close values to the results obtained in laboratory-based studies of Zhang et al. (2015), Maza et
 444 al. (2017), and Shan et al. (2019). The Reynolds number, Re , defined using D_{root} as length scale,
 445 suggests the fully turbulent structures of root-generated wakes ($> 1,000$) and the derived C_D
 446 showed no dependence on Re . The C_D also did not show dependence on water depth.



447
 448 Figure 8. Drag coefficient (C_D) estimated for each hydrodynamic measurement and plotted
 449 against the Reynolds number (Re). The Re is defined by root diameter (D_{root}) as length scale
 450 and ν for kinematic viscosity. The empirical curve obtained by a flume experiment by Maza et
 451 al. (2017) and ranges obtained by flume experiments of Zhang et al. (2015) and Shan et al.
 452 (2019) are also shown.

453 Given the independent trend of C_D from Re and water depth and the small variations of
 454 the obtained values, it was inferred that C_D can take a constant value in the studied mangrove
 455 forest regardless of the timing of tidal cycles. The vegetation drag was then computed as model
 456 estimates using Eq. (7), a rearrangement of the drag model Eq. (1), with the mean C_D value

457 (1.0) and the measured a profile shown in Fig. 4. The result showed a high coefficient of
 458 determination ($R^2 = 0.86$) for the vegetation drag averaged for unit water volume (Fig. 9).



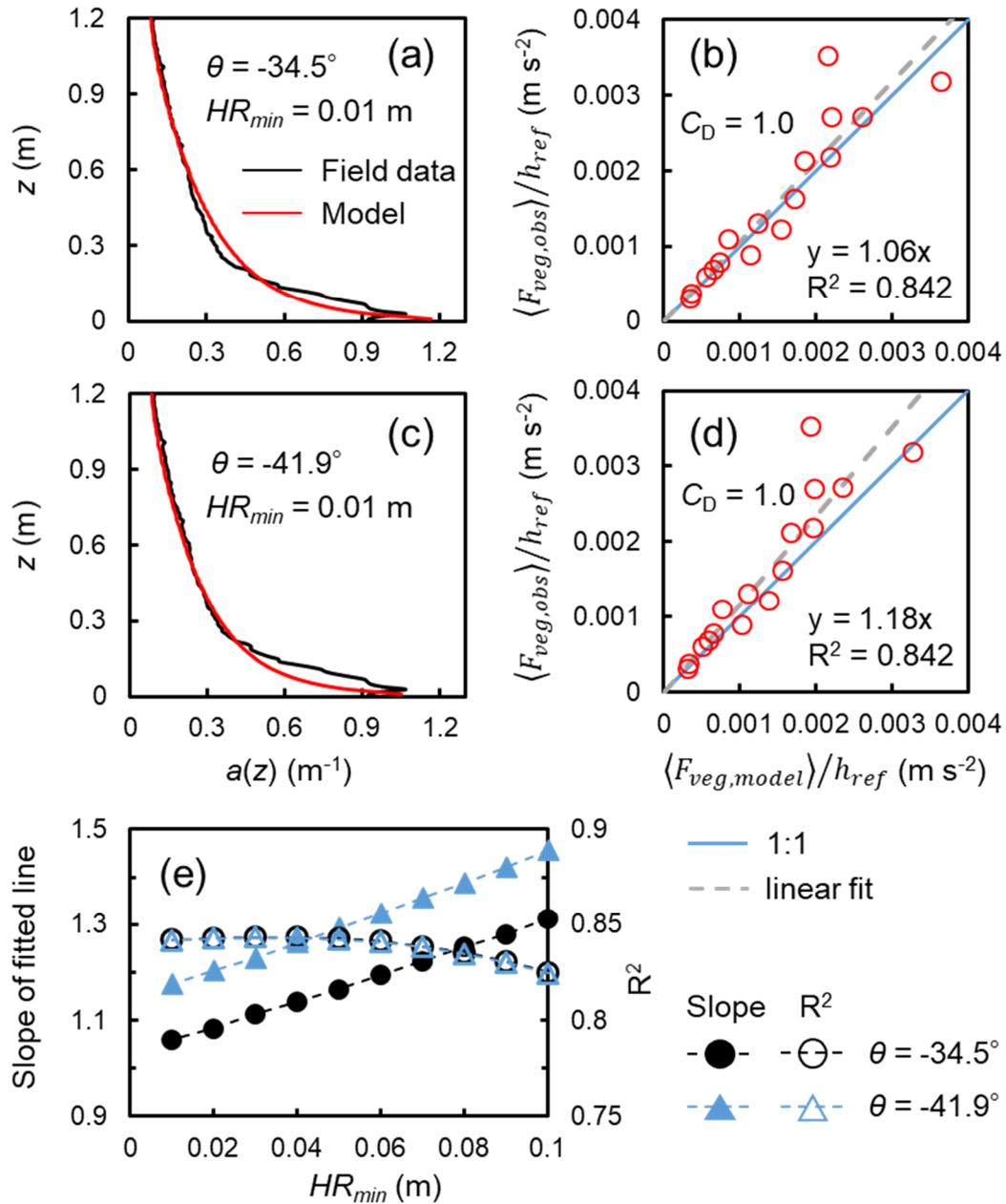
459
 460 Figure 9. Comparison of measured and modeled vegetation drag. The modeled values were
 461 given by Eq. (7), a rearrangement of Eq. (1) with $C_D = 1.0$, and the measured profile for a
 462 shown in Fig. 4.

463 3.4 Prediction of drag using the *Rhizophora* root model

464 The *Rhizophora* root model well-predicted the overall vertical profile of a composed
 465 of multiple order roots, using a parameter setting of $\theta = -34.5^\circ$, a value determined for the
 466 Bakhawan Ecopark study site (Fig. S3a), and $HR_{min} = 0.01$ m (Fig. 10a). The modeled
 467 vegetation drag computed with the modeled a and $C_D = 1.0$ showed good agreement with the
 468 measured drag, with a slope of 1.06 and $R^2 = 0.84$ of the linear fitted line (Fig. 10b). The use
 469 of θ value obtained in another mangrove forest (-41.9° ; Fig. S3b) resulted in the
 470 underestimation of a due to the steeper angle of the approximated root shape (Eq. (11))
 471 specifically at the lower part ($z < 0.3$ m) (Fig. 10c). Due to the underestimation of a , the

472 predicted vegetation drag also showed underestimation trend, with the fitted line slope of 1.18,
473 while the R^2 value did not vary significantly compared to when $\theta = -34.5^\circ$ (Fig. 10d).

474 The increase in the value of HR_{min} from 0.01 m to 0.1 m resulted in underestimation of
475 the vegetation drag as seen in the increased slope of fitted line (Fig. 10e). When $\theta = -34.5^\circ$, the
476 increase in slope was almost linear with the increase in HR_{min} ; the slope reached 1.17 at HR_{min}
477 = 0.05 m and 1.31 at $HR_{min} = 0.10$ m. Alternatively, the R^2 value of the line fitting did not
478 change significantly with the changes in HR_{min} . When $\theta = -41.9^\circ$, the slope increased by around
479 0.12 compared to when $\theta = -34.5^\circ$, and reached 1.46 at $HR_{min} = 0.10$ m. The R^2 value of the
480 line fitting showed almost same value as the result obtained for $\theta = -34.5^\circ$.



481

482 Figure 10. Comparisons of field-measured and modeled (a, c) a and (b, d) vegetation drag using
 483 the parameter settings $\theta = -34.5^\circ$ and $\theta = -41.9^\circ$, respectively; and (e) changes in the slope and
 484 R^2 of the linear fitted line of the relationship between $\langle F_{veg,model} \rangle / h_{ref}$ and $\langle F_{veg,obs} \rangle / h_{ref}$
 485 plotted with the changes in HR_{min} for the two different values of θ . The parameter setting $\theta = -$
 486 34.5° is the value derived for the study site (see Fig. S3a) while $\theta = -41.9^\circ$ is the value obtained
 487 from another mangrove forest (Fukido mangrove forest; Fig. S3b).

488 4. Discussion

489 **4.1 Flow and drag in the studied field mangrove forest**

490 The spatially uniform distribution of the *Rhizophora* trees with the same age at the site
491 investigated in this study (Bakhawan Ecopark in Aklan, Philippines; Fig. 1d; Fig. 2a) represents
492 a setting that previous laboratory-based studies have examined using model mangroves (Zhang
493 et al., 2015; Maza et al., 2017; in-line distribution configuration in Shan et al., 2019). A notable
494 difference between the field and model mangrove forest is the complexity of the root system.
495 For instance, Maza et al. (2017) used a *Rhizophora* tree model with 24 roots assuming a DBH
496 of 0.2 m, while the reference tree in the study site with DBH of 0.076 m had 96 roots; the latter
497 is way more complicated, and this complexity is not exceptional at all compared with other
498 *Rhizophora* mangrove forests (Yoshikai et al., 2021a, b). Specifically, it was observed that the
499 number of roots higher than 1st order drastically increased below $z = 0.3$ m, shaping the
500 significant vertical variations in the parameter a . Physical models of such complicated root
501 systems for more realistic representations of the *Rhizophora* root systems in flume experiments
502 could be challenging to make. This emphasizes the importance of the field-based studies for
503 the quantification of drag in a mangrove forest.

504 The values of a measured in the study site showed comparable values to the results
505 obtained in other mangroves with *Rhizophora* species (Horstman et al., 2015: $a = 0.19$ – 1.22
506 m^{-1} at $z = 0.1$ m) and mangroves dominated by pneumatophores of *Sonneratia* species (Norris
507 et al., 2017: $a = 0.04$ – 1.17 m^{-1}). The value of U measured during the spring tide were 0.08 m
508 s^{-1} at the maximum (Fig. 5b, f), which is also comparable to the velocity measured in other
509 mangrove forests (e.g., Chen et al., 2016; Horstman et al., 2021). The mangrove forest
510 investigated in this study is thus considered to have a typical vegetation projected area density
511 and tidal flow regime that can be observed in other mangrove forests. This implies that the
512 insights obtained in this study are applicable to other mangrove forests.

513 The normalized local velocity ($u_p/u_{0.1}$) showed larger spatial variations at higher
514 elevation ($z > 0.25$ m) compared to lower elevation (Fig. 6a). Generally, roots are more
515 clumped around the stem at the higher part of the root system, making locally low root blockage
516 areas especially at the sides of a tree (P2, P4; Fig. 1d). The relatively higher velocity at P2 and
517 P4 may be due to flow redistribution to the low blockage area (Maza et al., 2017), and the
518 lower velocity at P1 or P3 may be due to the influence of wakes generated by roots and stems
519 or velocity deceleration upstream of the clumped roots (Chen et al., 2012). Roots are spread
520 widely at the lower part of the root system (Méndez-Alonzo et al., 2015; Fig. 1d) making a
521 relatively uniform root distribution, which may explain the smaller spatial variations of
522 velocity at lower elevations.

523 The profile of normalized velocity averaged for P1–P4 (u) showed a good agreement
524 with the theoretical model of Lightbody and Nepf (2006), which predicts the profile of spatially
525 averaged velocity in vegetations with vertically-varying frontal area (Fig. 6b). This model is
526 based on the quadratic drag law of vegetation and assumes a constant C_D throughout the water
527 depth and the examined flow conditions. The model is applicable to a fully developed flow
528 where the viscous and turbulent stresses are significantly smaller than vegetation drag. It has
529 successfully predicted the velocity profile of flow through various types of vegetation
530 (Lightbody and Nepf, 2006; Nepf 2012; Xu and Nepf, 2020). The agreement of u with the
531 model that only uses the profile of a as explanatory variable emphasizes the significant
532 influence of vegetation morphology on flow structures in the studied mangrove forest. This
533 agreement also implies the validity of the assumption that the velocity averaged for P1–P4
534 represents the spatially averaged velocity.

535 One key feature observed in the field mangrove forest is the depth dependence of drag
536 per water volume as seen in Fig. 7a. The different slopes of the relationship between $\langle U^2 \rangle$ and
537 $\langle F_{veg,obs} \rangle / h_{ref}$ depending on the water depth indicates the enhancement of drag per water

538 volume relative to flow velocity when the water depth decreased. This may be considered the
539 result of the vertical variation of the parameter a , leading to increased depth-averaged
540 vegetation projected area to exert drag per unit water volume as the water depth decreases (Fig.
541 4). This highlighted the difference of drag characteristics in *Rhizophora* mangrove forests from
542 an array of vertical emergent cylinders and the difficulty in parameterizing mangrove drag
543 effects in roughness parameters such as Manning's roughness coefficient and Chezy coefficient
544 (Li et al., 2012, 2014; Zhang et al., 2012). Interestingly, the depth dependence observed in the
545 relationship between $\langle U^2 \rangle$ and $\langle F_{veg,obs} \rangle / h_{ref}$ was not evident when the $\langle U^2 \rangle$ was compared
546 with $\langle F_{veg,obs} \rangle / \langle A \rangle$ (Fig. 7b), suggesting that the drag exerted per unit vegetation area solely
547 depends on the square of flow velocity. This signifies that the quadratic drag law is applicable
548 to the studied field mangrove forest.

549 **4.2 Applicability of the drag model in the field mangrove forest**

550 Previous laboratory-based studies for flows in *Rhizophora* mangrove forest showed C_D
551 values around 1 at Re high enough to ensure turbulent wakes (Zhang et al., 2015; Maza et al.,
552 2017; Shan et al., 2019). Our field data showed that Re estimated using the mean root diameter
553 indicates turbulent wake structures ($> 1,000$) throughout a tidal phase, and the derived C_D is
554 independent of Re (Fig. 8). Interestingly, the C_D derived for the studied field mangrove forest
555 also showed values around 1.0, close to the ones obtained for the model mangroves despite the
556 complicated root systems that field mangroves have. This value also agrees with the value (1.0)
557 which is typically used for the drag coefficient of other type of vegetation (e.g., seagrass) at
558 high Re (Nepf, 2012; Kalra et al., 2017; Moki et al., 2020; Cao et al., 2021). The independence
559 of C_D on water depth is consistent with the results of Maza et al. (2017), and Xu and Nepf
560 (2020) who investigated drag exerted by a salt marsh plant *Typha* with vertically varying
561 frontal area.

562 This study used spatially averaged equations (Eqs. (1), (4)–(7)) for deriving C_D .
563 Therefore, the estimates of C_D could be significantly biased by the error in measuring the
564 channel mean flow velocity, U . While it is challenging to obtain the true value of channel mean
565 velocity and assess the measurement error, we refer to the results of the PTV survey conducted
566 around the reference tree (Text S1, Fig. S1). The results suggest that the velocity averaged for
567 the four locations (P1–P4) deviates 10% to 20% from the PTV-estimated spatially averaged
568 velocity. This deviation leads to C_D error estimates of 20% to 35%, which are close to the
569 variations of the derived C_D values (Fig. 8). We thus consider that the derived C_D in the field
570 mangrove forest may have errors of approximately 20–35% and the variations of the obtained
571 C_D are attributed to the errors in measuring the channel mean flow velocity.

572 Our observation of the quadratic dependence of drag on velocity (Fig. 7b) and the
573 obtained value of $C_D \approx 1$ (Fig. 8) suggests the applicability of the drag model, Eq. (1), to field
574 mangrove forest settings. The good agreement with the modeled and observed drag shown in
575 Fig. 9 verifies that Eq. (1) is a good model for predicting drag in field mangrove forests. The
576 flow and drag in mangrove forests have been investigated mainly through flume experiments
577 (Zhang et al., 2015; Maza et al., 2017; Shan et al., 2019). Our results imply that the insights
578 obtained by these flume experiments are applicable to field mangrove forests with complicated
579 root structures. Overall, this is the first study that collected sophisticated data set on
580 hydrodynamics and vegetation needed for properly quantifying drag and deriving the drag
581 coefficient and showed the applicability of the drag model proposed by laboratory-based
582 studies to field mangrove forest.

583 Although our results are consistent with previous laboratory-based studies, the derived
584 drag coefficient showed different trends from Mazda et al. (1997), which obtained large
585 variations in C_D from 0.4 to more than 10. Given the improvement in the experimental design
586 made in this study, we argue that our results more likely represent the actual drag in mangrove

587 forests. On the other hand, it should be noted that compared with our site, the site studied in
588 Mazda et al. (1997) had different vegetation morphological complexities. Specifically, Mazda
589 et al. (1997) reported significantly high vegetation solid volume fraction, $\varphi = 0.15\text{--}0.3$, at lower
590 elevation, compared to our study site that showed $\varphi = 0.025$ near the bed (Fig. S4); this is the
591 level where the inertial drag effects or sheltering effects could significantly contribute to or
592 reduce the spatially averaged drag force (Tanino and Nepf, 2008; Liu et al., 2020; Gijón
593 Mancheño et al., 2021), which may not be the case for our study site. Further study is needed
594 to examine the drag model applicability in field mangrove forests with high solid volume
595 fraction. Similarly, there are also some factors that were not investigated in this study. For
596 instance, Shan et al. (2019) demonstrated different drag coefficients between in-line and
597 random tree distributions while the trees are distributed in-line in our study site, suggesting the
598 need for additional investigations in natural mangrove forests. The flow investigated in this
599 study is characteristically fully developed while those in Maza et al. (2017) and Shan et al.
600 (2019) showed different flow and drag characteristics at the leading edge of a mangrove forest.
601 Further field-based studies are needed to consider these aspects.

602 **4.3 Implications for representing mangrove drag effects in hydrodynamic models**

603 Representing mangrove drag effects using Eq. (1) in hydrodynamic models have been
604 challenging because of the need for information on vegetation morphology for the parameter
605 a , which is labor-intensive to obtain in the field. This study presented a measure to predict a in
606 addition to the field estimates of C_D , which none of the previous field-based studies on
607 mangrove drag were able to consider (e.g., Mazda et al., 1997; Horstman et al., 2021). We used
608 the *Rhizophora* root model of Yoshikai et al. (2021a) to predict a , which is based on the
609 allometric scaling of root structures. This model is valid for complicated root systems
610 composed of multiple order roots, and accurately predicted the vertical profile of a in our study

611 site (Fig. 10a). The good agreement of the modeled drag using the field-derived $C_D \approx 1$ and the
612 predicted a with the measured drag (Fig. 10b) suggests that the drag in *Rhizophora* mangrove
613 forests in the field can now be predicted once the input parameters of the *Rhizophora* root
614 model are given. Note that because the roots higher than the 1st order could dominate in a
615 specifically at lower elevations as shown in Fig. 4, the use of Ohira et al. (2013) model, which
616 is valid only for root systems with 1st order roots, may result in large underestimation of a and
617 inaccurate prediction of drag.

618 The input parameters of the *Rhizophora* root model are basically DBH of individual
619 trees (in Eq. (9)–(10)) and tree density, n_{tree} (in Eq. (3)), in the area to predict drag. These are
620 basic information collected for forest inventories and are easy to measure in the field; these can
621 be even estimated from remotely sensed data such as airborne LiDAR and UAV optical
622 imagery (Fatoyinbo et al., 2018; Zhu et al., 2019). Therefore, we expect that simulating the
623 flows in mangrove forests using hydrodynamic models using implementation of the drag model
624 Eq. (1) is now feasible.

625 Some considerations should be noted when using the *Rhizophora* root model, especially
626 on its parameter settings. First, the scaling parameters of root systems (Table 1) are site- or
627 species-specific (Yoshikai et al., 2021a, b), thus applying the model to a forest without
628 available information on the scaling relationship requires field survey (see Yoshikai et al.,
629 2021a for the methods in obtaining the scaling relationship in the field). Next, the value of
630 HR_{min} should be properly defined for the site as demonstrated in Fig. 10e. The setting $HR_{min} =$
631 0.01 m gave the best estimates of a and drag in our study site; however, this value may not be
632 always applicable to other mangrove forests. For instance, the setting $HR_{min} = 0.15$ m gave the
633 best prediction of the root morphology of *Rhizophora stylosa* in Fukido mangrove forest
634 (results not shown). Therefore, we suggest the measurement of the minimum root heights in
635 the field to find a representative value of HR_{min} at the site in addition to the parameters for

636 obtaining the scaling relationships. Lastly, the root angle of the approximated linear root shape
637 in Eq. (11) seems to vary depending on the site or species (Fig. S3). The use of root angle
638 determined for Fukido mangrove forest, which is 7.5° steeper than our study site, affected the
639 prediction of the a and the drag to some extent as shown in Fig. 10c–e. The root angle was
640 determined from the relationship between $n_{root,i}(z)$ and $a_{root0,i}(z)$, and both parameters are labor-
641 intensive to obtain in the field. Hence, determining the representative root angle for the site of
642 model application may be challenging. Nevertheless, the responses of the predicted a and drag
643 with the different parameter settings provided in Fig. 10 can be used as benchmark for model
644 uncertainty when applying the settings to other mangrove forests. Notably, the drag can still be
645 predicted with reasonable accuracy using estimates of root angle from the other mangrove
646 forests (Fig. 10c–e), thus highlighting the significance of this work in contributing to a better
647 prediction of drag in mangrove forests.

648 **5. Conclusions**

649 This study presents the drag force and drag coefficient estimated from a 17-year-old
650 planted *Rhizophora* mangrove forest based on comprehensive hydrodynamics and vegetation
651 morphology data collected from the field. The vegetation projected area density, a , showed
652 nearly exponential increase towards the bed mainly due to root branching, highlighting the
653 complex root systems of mangroves. Consequently, the drag averaged for unit water volume
654 showed depth dependence relative to velocity, suggesting the difficulty in parameterizing the
655 drag effects of *Rhizophora* mangroves using bed roughness parameters. Instead, the drag
656 averaged for vegetation projected area depended solely on square of velocity regardless of
657 water depth, thus confirming the adherence of drag in the mangrove forest to the quadratic drag
658 law. The derived drag coefficient, C_D , was comparable with the values derived for model-
659 mangroves in previous laboratory-based studies. Using the mean C_D value, the drag model

660 accurately predicted the measured drag, thus verifying the applicability of the drag model
661 proposed by laboratory-based studies to mangrove forest in the field. We also showed that the
662 *Rhizophora* root model by Yoshikai et al. (2021a) can predict well the value of a – another
663 unknown parameter in the drag model aside from C_D – suggesting the model’s usefulness in
664 accurate drag prediction. The input parameters of the *Rhizophora* root model are DBH of
665 individual trees and tree density, which can be easily measured in the field. These results
666 provide a way to use the drag model in hydrodynamic models for representing mangrove drag
667 effects, thus contributing to a better understanding and evaluation of the coastal protection
668 function of mangroves.

669 **Data Availability Statement**

670 Data for this study are available at Zenodo at the following link
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