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Modelling wind risk to *Eucalyptus globulus* (Labill.) stands

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1 1. Introduction

2 Species of the genus *Eucalyptus* are some of the most widely adopted in commercial plantations
3 worldwide, primarily for the production of biomass for the pulp and fibre board industries (Diaz-
4 Balteiro and Rodriguez, 2006). Whilst the proportion of biomass extracted from Eucalypt plantations
5 for the global pulp and bioenergy markets is already prominent, it is likely to increase in the future
6 (Gardiner and Moore, 2014). The attractiveness of this genus for commercial purposes is due to its
7 fast growth rates, high productivity, good stem form, good adaptability to different environmental
8 conditions, predisposition to hybridisation and cloning, and natural tendency to sprout vigorously
9 when coppiced (Campinhos, 1999; Giménez et al., 2013; Goncalves et al., 2008). Eucalypt plantations
10 currently provide 50% of the world's wood fibre (FAO, 2007), most of which is produced in South
11 American countries. For instance, in Brazil Eucalypt plantations are planted on an area of 4.7 M ha
12 (ABRAF, 2011), generating ~7.5 M tonnes of pulp per year (Diaz-Balteiro and Rodriguez, 2006),
13 almost equivalent to the country's entire annual wood fibre production (Sedjo, 1999). In Brazil, the
14 mean annual increment (MAI) of *Eucalyptus* spp. under current silvicultural practices is typically
15 around $40 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ (Binkley and Stape, 2004), with recorded maxima of $90 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ in small trial
16 plots (Eldridge et al., 1994). The typical rotation length ranges between 6 – 7 years (Diaz-Balteiro and
17 Rodriguez, 2006). *Eucalyptus globulus* (Labill.) is one of the most successfully adopted plantation
18 species in areas other than the tropics because of its fast growth, high pulp quality, and adaptability
19 to sub-tropical and temperate climates (Campinhos, 1994; Sasse and Sands, 1997; Potts et al., 2004).
20 After being introduced in Europe in the 19th century (Leslie et al., 2011), this species has been
21 increasingly used in commercial plantations in the Iberian Peninsula for the production of biomass
22 for pulp and bioenergy (Diaz-Balteiro and Rodriguez, 2006; António et al., 2007). The high density of
23 its wood makes this species particularly sought after for bioenergy purposes (the Forest Products
24 Commission of Western Australia reports a typical value of green wood density of 1040 kg m^{-3}). In
25 Portugal, *E.globulus* is planted on over 26% of the nation's forested area (~812,000 ha), making it the
26 predominant tree species in the country (Águas et al., 2014; Dias and Arroja, 2012). In Spain,
27 *E.globulus* plantations are mostly concentrated in the Northern regions of Asturias and Galicia
28 (Riesco-Muñoz, 2004). In the Iberian Peninsula the typical rotation length is 10 – 12 years,
29 generating yields between $10 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ and $50 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ (António et al., 2007; Riesco-Muñoz,
30 2004), with MAI of 10 – 15 $\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ (Diaz-Balteiro and Rodriguez, 2006).

31 The vulnerability of *E.globulus* plantations to environmental hazards such as fire and pests has been
32 extensively studied (e.g. Moreira et al., 2009; Águas et al., 2014; Wingfield et al., 2008), while the
33 occurrence of wind damage is poorly documented. Trabado (2009) reports that 45% of the timber
34 volume damaged by storm Klaus in 2009 in the north-west Spanish region of Galicia (total damage:
35 $1.2 - 1.8 \text{ M m}^3$) was to *E.globulus* trees. In the same year, in Uruguay, two violent tropical cyclones
36 caused damage to approximately 10% of a private 27,000 ha Eucalypt plantation, corresponding to
37 financial losses of 10 M US\$. It is uncertain what Eucalypt species were affected. However,
38 Campinhos (1999) and Vallejos-Barra et al. (2014) report on the extensive use of *E.globulus* in
39 Uruguay. The fact that in the decade preceding such events no wind damage to the plantation had
40 occurred made these massive losses unpredictable from an historical point of view. For these events,
41 data on tree and stand characteristics are not available. Only three papers exist in the literature
42 (Williams and Douglas, 1995; Gerrand et al., 1997; Chen, 2003) where wind damage to Eucalypt
43 stands are reported together with some data on tree and stand characteristics, although the wind

44 speeds responsible for the damage are available only in the latter. These studies are further
45 discussed later in this paper.

46 Wind is the main cause of abiotic disturbance to forests in temperate and boreal biomes (Schelhaas
47 et al., 2010). European meteorological records of the frequency and severity of extreme winds show
48 a marked increase during the last three decades (e.g. Hanewinkel et al., 2011), as do the records of
49 storm-damaged timber. Part of this increase is due to the larger volume of standing timber in
50 European conifer forests -and hence the amount of timber at risk (Schelhaas et al., 2003). In addition
51 to this, climate model simulations show a tendency for increasing magnitude, and sometimes
52 frequency, of extreme wind events worldwide (Haarsma, 2013; Solomon, 2007). The largest
53 European losses resulted from the Vivian/Wiebke storms in 1990 (with more than 100 M m³ of
54 timber volume losses), the Lothar/Martin storms in 1999 (which is to date the most damaging storm
55 recorded in Europe, with losses of almost 200 M m³), the Gudrun storm in 2005 (75 M m³), and the
56 Klaus storm in 2009 (42 M m³) (Bavard et al., 2013; Blennow et al., 2010; Kilpelainen, 2010; Schindler
57 et al., 2012; Schuck and Schelhaas, 2013; Usbeck et al., 2010; Wohlgemuth et al., 2002). Besides
58 Europe, forests in other parts of the world have been severely affected by windstorms, most notably
59 the USA (Uriarte and Papaik, 2007, Beach et al., 2010), Japan (Kamimura and Shiraishi, 2007), New
60 Zealand, Fiji, and Australia (Everham and Brokaw, 1996; Moore and Watt, 2015). However, studies of
61 wind damage in South America are scarce, with a few notable exceptions. Negron-Juarez et al.
62 (2010) and Marra et al. (2014) report the extensive damage caused by a single cross-basin squall
63 event in 2005 to a Central Amazon forest, which resulted in the loss of about 30% of the forested
64 area in the region, estimated to about 23% loss in mean annual biomass accumulation.

65 The large wind-induced losses experienced in European conifer forests have stimulated scientific
66 research on wind damage to forests. Statistical methods have been widely used in the literature,
67 correlating stand properties and tree position within a stand with frequency and severity of wind
68 damage (Albrecht et al., 2012). As recently reviewed by Hanewinkel et al. (2011), the main shortfall
69 of statistical approaches is the inability to generalise the findings of one specific study to other cases,
70 due to the large variations in the geography, topology, and species from one case to another. In fact,
71 these methods do not provide any information on the processes involved, but do indicate the key
72 variables controlling wind damage risk (Kamimura et al., 2015). Since the end of the 20th century
73 this approach has been complemented by process-based, semi-mechanistic models such as
74 ForestGALES and HWIND (Gardiner et al., 2008). Process-based models allow us to use tree and
75 stand characteristics to calculate the critical wind speeds that would result in tree breakage or
76 uprooting (Gardiner et al., 2000). Therefore, these models are transferable to different forest stands,
77 rather than being restricted to a specific case, provided that the models are suitably parameterised.
78 For instance, ForestGALES was developed to predict wind damage to British coniferous trees
79 (Gardiner et al., 2000), and has subsequently been successfully adapted to a broad range of
80 coniferous species in other parts of the world: France (Cucchi et al., 2005), Japan (Kamimura, 2007),
81 and Canada (Byrne et al., 2005). A practical advantage of process-based models is that they can aid
82 forest managers to minimise the risk of wind damage, by informing on species suitability and best
83 silvicultural practices (Peltola, 2006).

84 Besides the forestry sector, the issue of wind damage to plantations is relevant for forest insurance.
85 As the demand for wood fibre and the moratoriums on harvesting mixed tropical hardwoods have
86 forced forest companies to establish plantations, the number of forestry and plantations projects

87 seeking insurance from damage due to natural hazards has increased steadily in the last 10 years. In
88 terms of wind damage, the perceived unpredictability of catastrophic wind events, and the lack of
89 methods to estimate risk in the absence of historical data, have restricted insurers from providing
90 clients with coverage against wind-induced losses. The lack of wind loss data has been an important
91 issue as wind damage is infrequent but often catastrophic, unlike fire losses that have a high
92 frequency and usually low impact (Phil Cottle, pers. comm.). The importance of quantifying
93 environmental risks to commercial plantations is particularly evident when the current pressure on
94 natural forests to provide ecosystem services (e.g. biodiversity, soil and water conservation) is
95 considered. In fact, by maximising the productivity of planted forests, the requirement for extracting
96 timber and other wood products from natural forests can be greatly reduced (Sedjo, 1999). The
97 development of process-based models of wind damage has largely focussed on conifer species,
98 which are extensively managed in boreal and temperate regions. At present, a number of spruce, fir,
99 and pine species are featured in these models, with birch the only broadleaf (in the HWIND model,
100 Peltola et al., 2000). Because of the general scarcity of historical data on wind damage to Eucalypt
101 plantations, and in light of their commercial importance and wide geographical distribution, species
102 of this genus are ideal candidates for the application of process-based models for predicting their
103 level of risk to wind damage.

104 Towards this aim, in this paper we parameterise ForestGALES for *E.globulus* grown under
105 environmental conditions typical of the Northern Spanish region of Asturias, and evaluate the
106 model's behaviour in regards to the presence/absence of a windward gap, and a range of planting
107 densities. We compare model behaviour with the few records of wind damage in eucalyptus forests.
108 In line with good modelling practice, we include a sensitivity analysis, an essential ingredient for
109 validation and corroboration of any model-based assessment. In the Methods section we describe
110 the fieldwork requirements for the parameterisation, and the adopted methods for the evaluation of
111 model behaviour and sensitivity analysis. In the Results section we present the results of the
112 parameterisation and model performance, and of the sensitivity analysis. we close the paper with a
113 discussion of the value of the model for evaluating wind damage risk to eucalyptus.

114

115 **2. Materials and Methods**

116 **2.1 The ForestGALES model**

117 ForestGALES is a quantitative, semi-mechanistic, probabilistic and predictive model of wind risk
118 damage to forests. It is semi-mechanistic in that some components of the model that describe tree
119 characteristics, and the calculations of the uprooting moment, are based on experimental data
120 rather than on engineering principles. The model estimates the probability of exceeding the
121 calculated wind speeds for uprooting and breakage for the average tree in a stand.

122 The user-input requirements for the execution of ForestGALES are simple. These include tree and
123 stand characteristics, and quantification of the prevailing wind climate. Tree and stand
124 characteristics used as inputs are: height of the tallest tree(s) in a stand, tree diameter at breast
125 height (*Dbh*), planting density (*Sph*), soil type, and rooting depth. The size of any windward gap
126 adjacent to the stand is also required to calculate the effect of wind gusts on trees at increasing
127 distance from the stand edge. Wind flow at the interface between an open area and a forest stand is

128 such that the wind loading is greater in the presence of an upwind gap (Stacey et al., 1994; Gardiner
 129 et al., 1997). Moreover, trees newly exposed to an upwind gap have not grown acclimated to the
 130 increased wind speeds and are therefore at higher risk of damage (Somerville, 1989). In Britain,
 131 where ForestGALES was developed, the prevailing wind climate is normally described with DAMS
 132 (Detailed Aspects Method of Scoring) scores, which describe the windiness of a site based on
 133 topographic characteristics (Quine and White, 1994). Alternatively, shape and scale parameters of a
 134 Weibull distribution fitted to the time series of local wind speed data can be used when DAMS
 135 scores are not available (Quine, 2000). Most calculations in the model are based on species-specific
 136 values and allometric calculations.

137 While the maximum wind speeds affecting a stand occur in short-lived gusts of just a few seconds,
 138 wind data standardly available for the model calculations are in the form of maximum hourly wind
 139 speeds (Hale et al., 2015). This data-availability issue prompted the development of a Gust Factor,
 140 using empirical relationships between mean and maximum bending moments. The Gust Factor is
 141 defined as the ratio between maximum turning moment and mean turning moment (Gardiner et al.,
 142 2000). In the model, individual trees are treated as rigid cantilevers, and the force of the wind is
 143 assumed to act on a tree at the zero-plane displacement height (Thom, 1971). The force of the wind
 144 is calculated from the drag of the canopy on the airflow, which is a function of the aerodynamic
 145 roughness of the canopy (Raupach, 1994). Gardiner et al. (2000, 2008) and Quine and Gardiner
 146 (2007) discuss the modelling approach, and the equations that form the basis of ForestGALES are
 147 available in Hale et al. (2015). The rationale of the model can be summarised in 3 main points:

- 148 1. the model estimates the average bending moments able to break or uproot a tree;
- 149 2. the hourly Critical Wind Speeds (CWS) to generate such moments are calculated; and
- 150 3. the probability of exceeding the CWS under the region's wind climate is estimated.

151 However, for the parameterisation and evaluation of the model's behaviour presented in our study,
 152 only points (1) and (2) are relevant, as the calculation of the probabilities of exceeding CWS does not
 153 directly depend on tree species, but rather on the local wind climate.

154 The resistive overturning moment is calculated by multiplying the weight of the stem by an
 155 empirically obtained coefficient (C_{reg}). C_{reg} values are calculated from linear regressions of stem
 156 weight against the overturning moment measured in the field from tree-pulling experiments (Nicoll
 157 et al., 2006), as described in Section 2.2. The resistive breaking moment is calculated from the
 158 Modulus of Rupture of green wood (MOR), Dbh cubed, and a factor to account for the presence of
 159 wood knots. The critical wind speeds for breakage and uprooting are obtained by equating the
 160 formulas of the resistive breaking and overturning moments, respectively, with the equation to
 161 calculate the maximum turning moment exerted by the wind on the tree canopy. The critical wind
 162 speeds (for overturning: uh_{crit_over} ; for breakage: uh_{crit_break}) are calculated with Eqs. (1) and (2):

$$163 \quad uh_{crit_over} = \frac{1}{kD} \left[\frac{C_{reg} * SW}{\rho G d} \right]^{\frac{1}{2}} \left[\frac{1}{f_{CW}} \right]^{\frac{1}{2}} \ln \left(\frac{h-d}{z_0} \right) \quad (1)$$

$$164 \quad uh_{crit_break} = \frac{1}{kD} \left[\frac{\pi * MOR * Dbh^3}{32 \rho G (d-1.3)} \right]^{\frac{1}{2}} \left[\frac{f_{knot}}{f_{CW}} \right]^{\frac{1}{2}} \ln \left(\frac{h-d}{z_0} \right) \quad (2)$$

165 where k is Von Karman's constant (value = 0.4, dimensionless), D is the average spacing between
166 trees (in m), SW is the stem weight of the average tree (in kg), calculated from stem volume and
167 green wood density, ρ is the air density (kg m^{-3}), G is the Gust Factor (dimensionless), d is the zero-
168 plane displacement (in m), f_{CW} is the tree mass factor (dimensionless), h is the average tree height
169 (in m), z_0 is the canopy surface roughness (in m), and Dbh is the stem diameter at 1.3m (in m). The
170 remaining parameters are species-specific: C_{reg} (N m kg^{-1}) is the coefficient of the linear regression of
171 total overturning moment vs stem weight, and is a function of soil type and rooting depth; MOR is
172 the Modulus of Rupture (Pa) of green wood, and f_{knot} is a dimensionless multiplier to account for the
173 presence of knots, whose values usually range between 0.8 and 1 (Ruel et al., 2010). Calculation of
174 the mass factor (f_{CW}) that accounts for the additional moment from the overhanging weight of the
175 stem and canopy uses the bending equations defined by Neild and Wood (1999). This requires
176 knowledge of the mass distribution along the length of the tree. The values of z_0 and d are calculated
177 using the method of Raupach (1994) and make use of a "drag coefficient" term (function of wind
178 speed) to describe the reduction in effective canopy area with wind speed (calculation is described
179 below).

180

181 **2.2 Data collection for parameterisation**

182 *2.2.1 Eucalyptus globulus tree pulling in Asturias*

183 Tree-pulling was carried out in November 2014 on 24 trees of *E.globulus* in the Asturias region in
184 northern Spain to obtain the necessary data for the parameterisation of ForestGALES. The
185 experimental site is located at 6°11'43.00"W, 43°28'29.20"N, and has an elevation of 282 meters asl.
186 The terrain of the experimental area is flat, with a predominant soil classified as Agro-ecological
187 Class VI, Edaphic, Aquic Dystrudept and Typical Dystrudept (acidic, well-drained soils). The area is
188 characterised by mild temperatures, without important limitations for vegetation (Papadakis' Agro-
189 climatic index II (Papadakis, 1966)). The annual precipitation is 996mm, with an average of 161 days
190 per annum with rainfall >0.1 mm. Frost days happen rarely more than twice per year. Monthly
191 average temperatures range between 7 and 23 °C, with a mean annual temperature of ~14 °C. The
192 prevailing winds are westerly and south-westerly. The forest used to be populated with a range of
193 conifer species before *E.globulus* was introduced some 50 years ago to provide pulpwood for the
194 local paper industry (Ernesto Alvarez, personal communication). The stocking density at the site was
195 741 trees ha^{-1} at age 24.

196 24 trees equally divided in three dominance classes, from within diameter ranges based on quartile
197 data were randomly selected from the site. We followed the pulling method described in Nicoll et al.
198 (2006) except for the following slight differences:

- 199 1. Three inclinometers were used: one at tree base, one at the pulling cable attachment height,
200 and one halfway between the two;
- 201 2. The attachment height of the pulling cable was lower than half tree height and varied from
202 tree to tree. The objective of the study was to uproot the trees rather than breaking them,
203 to obtain C_{reg} values for ForestGALES.

- 204 3. Crown dimensions were measured prior to pulling, by visually projecting the maximum
 205 lateral extent of the canopies in the four cardinal directions to the ground, and measuring
 206 the horizontal distance from the base of the tree;
- 207 4. Pulleys were used to increase the force for large trees, or when another tree was used as a
 208 pivot because of site restrictions.
- 209 5. For uprooted trees, three measurements of root depth were taken, at each of the 2 lateral
 210 extremities of the exposed root plate, and close to the tree base. Maximum rooting depth
 211 was difficult to establish, but was measured as the distance between the tree base and the
 212 furthest coarse root (diameter > 0.5 cm) that had become exposed. Root rot was recorded if
 213 present.

214 Details of all the equipment used are given in the online supplement. The method of Nicoll et al.
 215 (2006) was used to obtain the stem green density, and the masses of the canopy and the stem. The
 216 volume of the stem was calculated as a series of tapered columns of 1 m length.

217

218 2.2.2 Measurements of wood mechanical properties

219 For each pulled tree the 1 m long logs used for the calculation of green wood density were
 220 transported to a laboratory to be conditioned to 12% moisture content (*MC*). A flitch was cut from
 221 north to south and as many wood samples (40cm X 2cm X 2cm) as possible were extracted. On
 222 average, 5 samples were obtained from each log. The samples were then destructively tested to
 223 obtain Modulus of Elasticity (*MOE*) and *MOR*, and kept in a thermal test chamber at constant
 224 temperature and relative humidity (21°C and 65%, respectively) to maintain *MC*~12%. The tests
 225 were performed with a bench-top three-point bending machine. Post-test weights were also
 226 recorded. The samples were then brought to a constant weight at a temperature of 103°C. Their
 227 weight was again recorded and used to calculate their *MC* at the time of the bending tests with Eq.
 228 (3).

$$229 \quad MC\%_{test} = \frac{Weight_{after\ test} - Weight_{dried}}{Weight_{dried}} * 100 \quad (3)$$

230 This value was used to calculate the *MOE* and *MOR* of green wood of the tested trees, which are
 231 used in ForestGALES. *MOE* was calculated with the method of Unterwieser and Schickhofer (2011).

$$232 \quad MOE_{green\ wood} = \frac{MOE_{MC\%_{test}}}{1 - 0.00825 * (MC\%_{test} - FSP)} \quad (4)$$

233 *FSP* stands for Fibre Saturation Point and corresponds to *MC*~28%, a moisture content value above
 234 which *MOE* and *MOR* remain relatively constant (Unterwieser and Schickhofer, 2011). *MOR* for
 235 green wood was calculated with Eq. (5).

$$236 \quad MOR_{green\ wood} = MOR_{MC\%_{test}} - (MOR_{MC\%_{test}} * \frac{FSP - MC\%_{test}}{100}) \quad (5)$$

237

238

239

240 2.3 Data Processing for model parameterisation

241 2.3.1 Crown streamlining parameters

242 Modelling of crown streamlining is fundamental to the calculation of critical wind speeds, as the
243 wind drag acting on the canopy is a function, amongst other things, of the crown area exposed to
244 the wind. Because of the lack of wind tunnel measurements for the streamlining of the canopy of
245 *E.globulus*, parameters to model crown behaviour under wind loading were extrapolated from black
246 cottonwood (*Populus trichocarpa* Torr. & A. Gray) data in Vollsinger et al. (2005). This species was
247 chosen because of the similarities of its canopy with *E.globulus* in terms of morphology and leaf area
248 density. ForestGALES uses two parameters, C and N , to model the drag coefficient of the tree's
249 crown (Eq. 6).

$$250 \text{ Drag Coefficient} = C * u^{-N} \quad (6)$$

251 where C is the value of the drag coefficient at rest, N is the exponent that describes the power fit to
252 the data, and u is the wind speed of interest (m s^{-1}). The drag coefficient is used to adjust the tree
253 frontal area in the calculation of z_0 and d .

254

255 2.3.2 Canopy dimensions parameters

256 The parameterisation process requires measurements of canopy width and breadth for the
257 calculation of the canopy's frontal area and canopy volume. The latter is used in combination with
258 canopy weight for the calculation of canopy density. Canopy depth was calculated by subtracting the
259 height of the lowest live whorl from the total height of the tree. Calculation of canopy breadth
260 required approximation of the irregular elliptic shape of the canopies to regular ellipses, using the
261 crown vertical projections as described in Section 2.2. To parameterise ForestGALES, canopy depth
262 and canopy breadth were regressed against mean tree height and Dbh (see Table 4).

263 To obtain crown volume for canopy density calculations, the sectional area of the canopy was
264 calculated under the assumption that *E.globulus* canopies are ellipsoid-shaped. Because the canopy
265 of most trees was not centred on the stem's vertical axis, the crown sectional area of the canopy
266 was assumed to be shaped as the sum of 2 half-ellipses (e.g. the "Northern" and the "Southern" half-
267 ellipses), and calculated with Eq. (7).

$$268 \text{ Sectional area} = \frac{\pi}{4} * (N + S) * (E + W) \quad (7)$$

269 where the capital letters indicate the distance between the tree base and the projection of the
270 crown to the ground in each corresponding cardinal direction.

271

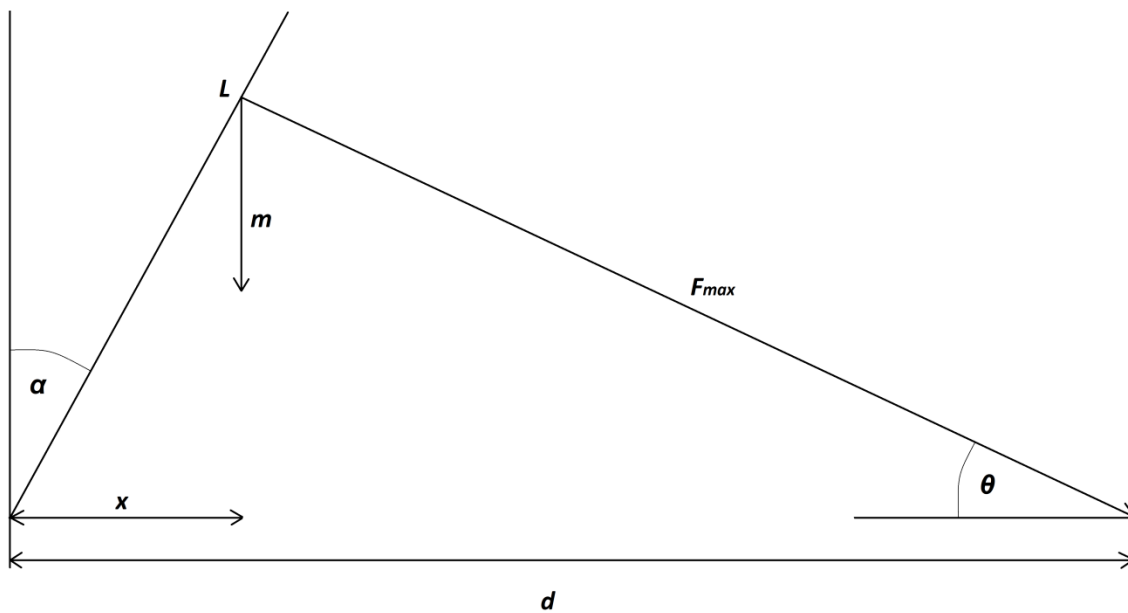
272 2.3.3 Critical overturning moment

273 The pull exerted by the winch (F_{max} , in kg force) was the major force acting on the tree. In addition to
274 this, stem mass and canopy mass (m) contributed to the vertical force as the tree was pulled over. At
275 tree failure, corresponding to the maximum applied force, the angle (α) of the test tree towards the
276 anchor tree was calculated as the difference between the top-clinometer readings at tree failure

277 minus the reading before the force was applied. The pulling angle (θ) was derived trigonometrically
 278 from the distance between the test and anchor tree (d) minus the horizontal displacement of the
 279 tree (x), and the winch cable attachment height. Fig. 1 shows the schematic of the forces acting on a
 280 tree during tree-pulling experiments.

281 Fig. 1: Schematic representation of forces acting on a tree during tree-pulling experiments, and angles involved in the
 282 calculations of total critical bending moment (adapted from Nicoll et al., 2006). F_{max} : maximum force applied with the
 283 winch; m : masses of the stem and the canopy; α : inclination of test tree at maximum force; θ : angle between pulling cable
 284 and horizon at maximum force; d : distance between test tree and anchor tree; x : horizontal displacement of test tree at
 285 maximum force.

286



287

288 Because in our pulling tests the height of the attachment point corresponds to the height of the top
 289 clinometer, we did not need to discriminate between lean of the tree above and below the
 290 attachment point. In fact, we assumed that the stem behaved like a rigid cantilever within the
 291 distance between the base and the top clinometers. Nicoll et al. (2006) have shown this to be a good
 292 approximation. The critical turning moment applied at stem base was calculated with Eq. (8) to
 293 obtain values in Newtons.

$$294 \quad TM_{crit,applied} = F_{max} * 9.81 * \cos \theta * L * \cos \alpha \quad (8)$$

295 The centre of gravity of the stem was assumed to be located at $\frac{1}{3}$ tree height (based on stem taper),
 296 while the centre of gravity of the canopy was assumed to be in the middle of the canopy. The
 297 additional loading provided by the masses of the stem and the canopy was then calculated in
 298 Newtons with the Eq. (9).

$$299 \quad TM_{crit,tree\ components} = 9.81 * \sin \alpha * \left[Canopy_W * \left(tree\ height - \frac{Canopy_D}{2} \right) + SW * \frac{Tree_H}{3} \right] \quad (9)$$

300 where $Canopy_W$ is the weight of the canopy; $Canopy_D$ is the depth of the crown, and SW is the weight
 301 of the stem. The two turning moments were then added together to give the Total Critical Bending

302 Moment ($Total_{TM}$). These values were then used in linear regression models of $Total_{TM}$ vs SW , for
303 trees with and without an obvious tap root, as well as for trees with apparent root rot, to calculate
304 C_{reg} values for our experiment. The linear models were forced through the origin because, as the
305 weight of a tree approaches zero, so should $Total_{TM}$ (Gardiner et al., 2000).

306

307 **2.4 Evaluation of model behaviour**

308 Throughout this section and the rest of the paper, to differentiate between when we discuss tree
309 height, dbh, sph, and gap as model variables, and when we refer to them as tree or stand
310 characteristics, we will denote the former with a capital letter and italics (i.e. “*Tree Height*”, “*Dbh*”,
311 “*Sph*”, and “*Gap*”). The scarcity of wind damage data to *Eucalyptus* spp. in the literature makes
312 validation of this version of ForestGALES difficult. Ideally, data from forest inventories of damaged
313 *E.globulus* stands, and the damaging wind speeds should be known for a number of windthrow
314 events to perform a proper validation. Therefore, we have decided to investigate the behaviour of
315 the model in regards to *Tree Height* and presence/absence of a windward *Gap* for a range of
316 planting densities. We discuss our findings by comparing them to the only three papers that report
317 wind damage to Eucalypts: Williams and Douglas (1995), Gerrand et al. (1997), and Chen (2003).

318

319 *2.4.1 Investigating the behaviour of our parameterisation of ForestGALES*

320 The investigation of the behaviour of this parameterisation of ForestGALES was performed for
321 simulated *E.globulus* trees growing under climatic and environmental conditions typical of our
322 experimental site. To obtain tree-input parameters for ForestGALES, we used the environmental and
323 climate data reported in section 2.2.1 with a modified version of the GLOBULUS model (Soares et al.,
324 2006). The GLOBULUS model calculates dominant height and mean diameter of *E.globulus* trees.
325 Typically, ForestGALES converts automatically top height to mean height with species-specific
326 equations using regression parameters from multiple stands data. However, this was not possible for
327 our study because of our small sample size. Similarly, we could not determine the dominant dbh
328 from our data. Therefore, to obtain mean tree height for our ForestGALES simulations, we used the
329 only formula amongst those presented by Soares and Tomé (2002) to calculate mean height in a
330 *E.globulus* stand that does not require knowledge of the dominant dbh. This formula calculates
331 mean tree height as a function of dominant tree height and mean dbh. In fact, because the latter is
332 calculated in GLOBULUS from the total basal area of the stand, calculation of mean height is also a
333 function of sph. While the authors advocate the use of this formula only for young trees (<4 years),
334 and suggest a different equation for older trees, they also show that for trees of height > 5m the
335 relationship between the two is basically linear, and that the disagreement is minor. GLOBULUS
336 requires knowledge of the Site Index₁₀ (SI_{10}), i.e. the average dominant height at 10 years, to
337 describe the productivity class of a site. Although data on the geographical distribution of the SI_{10} of
338 *E.globulus* in Asturias are scarce, based on the work of Merino et al. (2003) SI_{10} values in the region
339 are believed to range between 10 and 30. The mean height of our sampled trees was ~23m (see
340 Table 3 in the Results section), and dendrometric measurements suggested an average tree age of
341 24 years. Calculations of mean tree height with the formula of Soares and Tomé (2002) suggested
342 that 15 was an appropriate SI_{10} value for our site. We present our results for trees older than 3 years.

343 Using GLOBULUS and the formula of Soares and Tomé (2002), this corresponds to a tree height of
344 ~3.7m. To model the canopy of young *E.globulus* trees, we set a condition in ForestGALES that for
345 trees shorter than 5m, canopy depth is calculated as half of tree height. For trees taller than 5m,
346 canopy depth is modelled with the regression equation shown in Table 4 in the Results section.
347 Based on data from our experimental site, we set the upper limit of tree height at 25m for the
348 simulations. Mortality was removed from GLOBULUS in order to test the model for fixed stocking
349 densities.

350 Soil type and rooting depth could not be changed because we only have one regression between *SW*
351 and resistance to uprooting (based on the tree pulling at our experimental site). We simulated our
352 stands for presence/absence of an upwind gap because this is known to make a forest stand more
353 prone to wind damage (e.g. Somerville, 1989). Wind climate data was not used as an input because
354 we adopted an intermediate output of ForestGALES, the CWS that is able to cause tree failure. This
355 allows investigation of the impact of stand and site characteristics without the complication of wind
356 climate. We did not discriminate between modes of failure: our final model output was the lower of
357 the two CWSs. These factors mean that the sensitivity of the model's output to soil type, rooting
358 depth, and wind climate were not investigated.

359

360 *2.4.2 Data for model evaluation*

361 We evaluated the model by comparison to three published studies on wind damage to *Eucalyptus*
362 spp. We extracted data about tree, stand, and -where available- wind speeds that resulted in wind
363 damage, from the papers of Williams and Douglas (1995), Gerrand et al. (1997), and Chen (2003).
364 The relevant data from these studies are summarised in Table 1.

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378 Table 1: Data on tree and stand characteristics and wind speeds from the three evaluation papers. *Sph*: stems per hectare;
 379 *MAI*: Mean Annual Increment ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$).

Reference	Tree height	Stocking density	Upwind gap	Max Wind Speed	Comments
Williams and Douglas (1995)	Damage threshold suggested at 9m.	N/A	N/A	N/A	Study area included 3 <i>Eucalyptus</i> spp. (not including <i>E.globulus</i>). Taller trees more exposed to damage.
Gerrand et al. (1997)	Dominant stand height between 28m – 30m at age 11.	Initial stocking >1,300 sph, thinned to 900 sph and 300 sph.	Present, associated with damage.	N/A	<i>E. globulus</i> . Highly productive site ($MAI = 30\text{m}^3/\text{ha}/\text{yr}$). Damage occurred (7% of stand) after late thinning. Slender trees due to high initial stockings and late thinning suggested as more prone to wind damage.
Chen (2003)	Between 6m and 8m, equally distributed between plots.	3 plots: 3,333 sph; 1,666 sph; 1,111 sph.	Not specified but likely present (coastal plots).	32.6 m/s	<i>Eucalyptus</i> spp. <i>urophylla</i> and <i>urophylla X grandis</i> hybrid. The study refers to typhoon damage in the Leizhou Peninsula in China. Very young trees (1 to 2 years). The higher the stocking density, the more resistant the stands.

380

381 Based on the stocking densities reported in the evaluation papers (Table 1), we decided to run
 382 ForestGALES for the following scenarios, which include the planting density of our experimental site
 383 (see section 2.2.1): 300 sph; 741 sph; 900 sph; 1110 sph; 1300 sph; 1650 sph; 3300 sph. *Gap* size was
 384 fixed to 0 or 250m to simulate absence and presence of a gap, respectively. The maximum value of
 385 *Gap* (250) was chosen because in ForestGALES there is no impact for gaps larger than 10 times mean
 386 tree height and a gap size of 250m covered the entire range of *Tree Height* in our study.

387

388 2.5 Global sensitivity analysis

389 It is critical to estimate the sensitivity of any model output to the variation of its inputs. Sensitivity
 390 analysis is a necessary ingredient for model-based assessments, model validation and corroboration
 391 (Oreskes et al., 1994). A number of methods for performing a sensitivity analysis exist, which can be
 392 broadly grouped in two main categories: local sensitivity analyses (LSAs) and global sensitivity
 393 analyses (GSAs). The main advantage of GSA methods is that they consider the entire range of values
 394 of each variable, and the effect of each variable on the model outputs by taking into account the
 395 variability of all the other variables (Saltelli et al., 2004). Variance-based GSA methods use variance
 396 as an indicator of the inputs' contribution to the model's outputs. This approach allows for the
 397 identification of the input variables that drive most of the variation in the output, and hence are

398 most important, by relating the inputs' variance with the outputs' (Saltelli et al., 2000). For the
 399 purpose of this paper, we perform a variance-based GSA of the version of ForestGALES used in this
 400 study for *E.globulus*, as described in the previous section. We focus our GSA on the input variables of
 401 ForestGALES. We used the method of Kucherenko et al. (2012) for the calculation of first-order and
 402 total sensitivity indices in the case of correlated variables, because of the high correlation between
 403 *Tree Height* and *Dbh* (Pearson correlation coefficient $\simeq 0.91$). This approach is analogous to the
 404 extended method of Sobol' described by Saltelli (2002). This technique is based on Monte Carlo
 405 methods, and in the case of correlated variables it has a computational cost of $(2p + 2) * n$ model
 406 evaluations. Here, p is the number of input variables, and n is the length of the input vectors chosen
 407 by the analyst (typically, the higher n , the more accurate the indices). First-order sensitivity indices
 408 (S_i) describe the contribution of an input variable to the output's variance without accounting for
 409 interactions between variables, while total indices (S_i^T) represent the entire contribution of a
 410 variable by taking into account all the interactions with the other variables (Sobol', 2001). Large
 411 differences between a variable's S_i^T and S_i highlight the importance of its involvement in interactions
 412 with other variables, and might suggest model nonlinearity (Saltelli et al., 2000).

413 To calculate the sensitivity indices, a large number of model runs is required (Saltelli et al., 2000). For
 414 the methods analogous to that of Sobol', the input data is generated "quasi-randomly" (Sobol',
 415 1998) from the probability distribution functions (PDFs) of the input variables. We fitted PDFs to our
 416 experimental dataset to calculate distribution parameters for *Tree Height* and *Dbh*. However, the
 417 small size of our dataset meant that choosing the appropriate distribution was problematic, as
 418 different types of distributions described the data equally well, based on Akaike Information
 419 Criterion values. Of the PDFs that fitted the data, we chose to describe *Tree Height* and *Dbh* with
 420 normal distributions, because the calculations of the sensitivity indices with the method of
 421 Kucherenko et al. (2012) are more straightforward for normal distributions. For *Sph*, we decided to
 422 adopt a uniform distribution ranging from 300 sph to 3300 sph, as per section 2.4.2. We chose to
 423 describe *Gap* with two different distributions. We chose a binomial distribution with values 0 and
 424 250 (i.e. no gap vs large gap, defined for our range of *Tree Height* in section 2.4.2), as well as a
 425 uniform distribution within the same range. While the choice of allowing *Gap* to vary uniformly
 426 within its range allows for a more complete exploration of the input space, for forest managers it is
 427 very often convenient to differentiate between whether a large gap is present or not. Table 2 shows
 428 the range of values of the four inputs used in the sensitivity analysis. We calculated the sensitivity
 429 indices with 21,350 model executions, sufficient for the indices to converge to their true value using
 430 the quasi-random method of Sobol'.

431 Table 2: Range of values used for the generation of random samples from the probability distribution functions of the
 432 inputs. *sd*: standard deviation; *Dbh*: diameter at breast height, *Sph*: stems per hectare; *Gap*: size of the upwind gap.

Input Variables	Distribution	Parameters		Units
<i>Tree Height</i>	Normal	Mean: 23.17	sd: 4.59	Meters
<i>Dbh</i>	Normal	Mean: 21.78	sd: 7.52	Centimetres
<i>Sph</i>	Uniform	Min: 300	Max: 3300	N ^o of stems
<i>Gap</i>	Binomial OR Uniform	Min: 0	Max: 250	Meters

433

434 **3. Results**

435 **3.1 Model parameterisation**

436 The values of the physical and biomechanical characteristics of the pulled trees, empirically
 437 measured for the parameterisation of ForestGALES during our tests on *E.globulus* in Asturias, are
 438 reported in Table 3.

439 Table 3: Empirical values of tree variables for *Eucalyptus globulus* required for the parameterisation of ForestGALES. Field:
 440 measured directly during the experiments; Derived: calculated from field measurements; Laboratory: measured in a
 441 laboratory after completion of the pulling experiments; MC: moisture content. *sd*: standard deviation.

Variable, Acronym and Units	<i>n</i>	Min	Max	Mean	sd	Source	Comments:
Height (m)	24	15.6	32.2	23.18	4.69	Field	
Dbh (cm)	24	12.42	38.21	21.78	7.68	Field	
Stem volume (m ³)	24	0.097	1.458	0.45	0.39	Derived	
Stem weight (kg)	24	114.49	1580.36	513.61	415.88	Derived	
Green wood density (kg*m ⁻³)	24	982.32	2805.40	1229.81	394.43	Derived	
Crown weight (kg)	24	11	289	92.71	81.58	Field	
Crown density (kg*m ⁻³)	24	0.234	1.616	0.45	0.29	Derived	
Canopy depth (m)	24	3.5	15.3	8.22	3.21	Field	
Canopy breadth (m)	24	2.80	6.75	4.68	1.20	Field	
Tree lean at failure (degrees)	24	0.3	19.2	3.38	4.16	Field	Max: Tree 30 - Dominant; Min: Tree 46 – Sub-Dominant.
Modulus of Rupture – MOR (MPa)	111	99.45	156.40	122.49	12.05	Laboratory	MC~12%. On average, between 4 and 5 flitches from each tree.
Modulus of Elasticity – MOE (MPa)	111	11088.25	16472.00	13859.63	1514.27	Laboratory	MC~12%. On average, between 4 and 5 flitches from each tree.
Canopy loading (Nm)	24	215.99	8068.87	1698.32	2118.51	Derived	
Stem loading (Nm)	24	499.10	12857.02	2840.06	3322.52	Derived	
Total Turning Moment (TM) (Nm)	24	10047.12	257106.6	82224.75	71531.67	Derived	
Tree components TM (Nm)	24	716.13	19821.76	4538.38	5370.24	Derived	

442

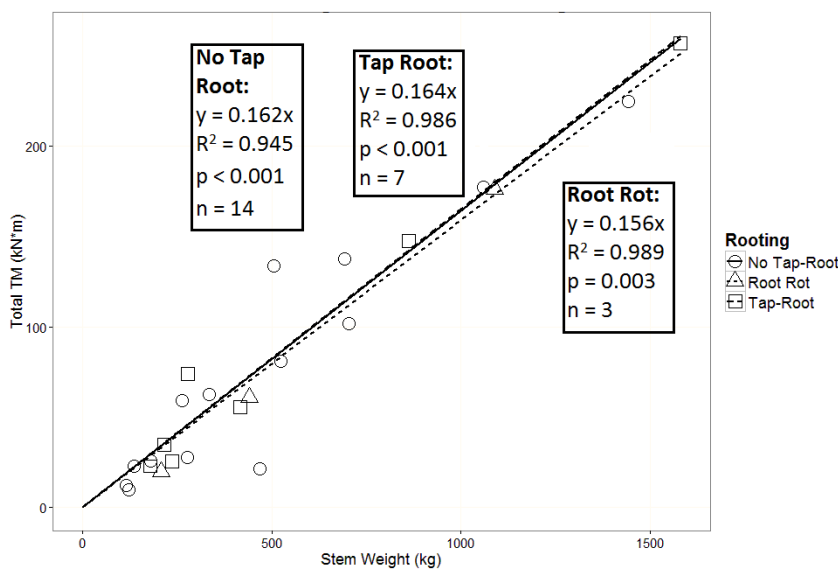
443 From the values recorded in our experiments, as shown in Table 3, ForestGALES model parameters
 444 and formulas were calculated with the formulas described in sections 2.2 and 2.3. Table 4 shows the
 445 parameter values and equations used in ForestGALES.

446 Table 4: *E.globulus* ForestGALES model parameters.

Parameter	Formula / Value	R ²	p – value	Comments
Mean Height (m)	1.0 * Top Height	n/a	n/a	
Canopy Breadth (m)	0.138 * <i>Dbh</i> *100 + 1.764	0.73	< 0.001	Value of <i>Dbh</i> in meters
Canopy Depth A (m)	0.405 * Mean Height -1.163	0.35	0.002	Original form of ForestGALES regression
Canopy Depth B (m)	-0.53 * Mean Height + 0.6257 * <i>Dbh</i> + 6.872	0.72	< 0.001	Improved regression
Canopy Depth C (m)	0.5 * Mean Height	n/a	n/a	When Mean Height < 5m
Stem Density (kg m ⁻³)	1229.81	n/a	n/a	
Canopy Density (branches + leaves: kg m ⁻³)	0.45	n/a	n/a	
Modulus of Rupture (MPa)	105.65	n/a	n/a	Calculated. MOE of green wood
Modulus of Elasticity (MPa)	12447.63	n/a	n/a	Calculated. MOR of green wood
Knot Factor	1	n/a	n/a	
C	3.03	n/a	n/a	Graphically extrapolated from Vollsinger et al., (2005)
N	1	n/a	n/a	Graphically extrapolated from Vollsinger et al., (2005)
Root Bending Term	0	n/a	n/a	
<i>C_{reg}</i> with Tap Root (<i>N m kg⁻¹</i>)	164.1	0.98	< 0.001	n=7
<i>C_{reg}</i> without Tap Root (<i>N m kg⁻¹</i>)	162.32	0.94	< 0.001	n=14
<i>C_{reg}</i> with Rot in Root System (<i>N m kg⁻¹</i>)	156.52	0.99	0.003	n=3

447 The values in Table 4 are used in the *E.globulus* species-specific parameter file of ForestGALES for
 448 our simulated stands, as shown in the next section. The R^2 of the regression formula normally used
 449 in ForestGALES to calculate canopy depth from mean height (formula A) is quite low (0.35, p -
 450 value=0.002). However, this R^2 is within the range of the conifer species already included in
 451 ForestGALES (e.g. Ruel et al., 2000). However, including *Dbh* in the regression formula (B) increased
 452 the fit to the data ($R^2=0.72$, p -value<0.001). It should be noted that, while the R^2 of the regressions
 453 for the Overturning Moment Multipliers (C_{reg}) between stem weight and critical turning moment are
 454 very high, they were however calculated from very small samples. The values of C_{reg} for the different
 455 rooting systems (evident presence of tap root vs absence of tap root vs presence of rot) are
 456 displayed in Fig. 2. We could not assess the rooting system in the 2 trees that snapped. However,
 457 because their values for *MOE* and *MOR* did not differ from those of the trees that failed by
 458 overturning, we assumed that their rooting was highly resistant, and we grouped them with the
 459 trees with a tap root.

460 Fig. 2: Effect of changes in rooting on resistance to overturning of *E.globulus*.



461 The scatterplot in Fig. 2 shows the relative unimportance of the architecture and integrity of the
 462 rooting system for our *E.globulus* trees, for which the presence of a tap-root does not seem to
 463 influence tree resistance to overturning. In fact, the two regression lines for tap-root and no tap-root
 464 almost overlap. Similarly, the trees for which rot in the root system was recorded do not differ from
 465 those without evident rot. Despite the very small number ($n=3$) of pulled trees which exhibited root
 466 rot, the validity of this finding is corroborated by the fact that their stem weights are well distributed
 467 across the ranges of Stem Weight and Total Turning Moment. A final confirmation of the low
 468 importance of the quality of the rooting system in our experiment is provided by an Analysis of
 469 Covariance (ANCOVA) where the total turning moment is the response variable, stem weight the
 470 continuous explanatory variable, and the type of rooting is a factor with the three levels described
 471 above. Indeed, the differences between the types of rooting are confirmed to be non-significant (p -
 472 value = 0.806). For this reason, in our simulations we only adopted one value of C_{reg} ($162.32 \text{ N m kg}^{-1}$,
 473 for trees without a tap-root, selected because it was calculated from a larger dataset (see Table 4)).

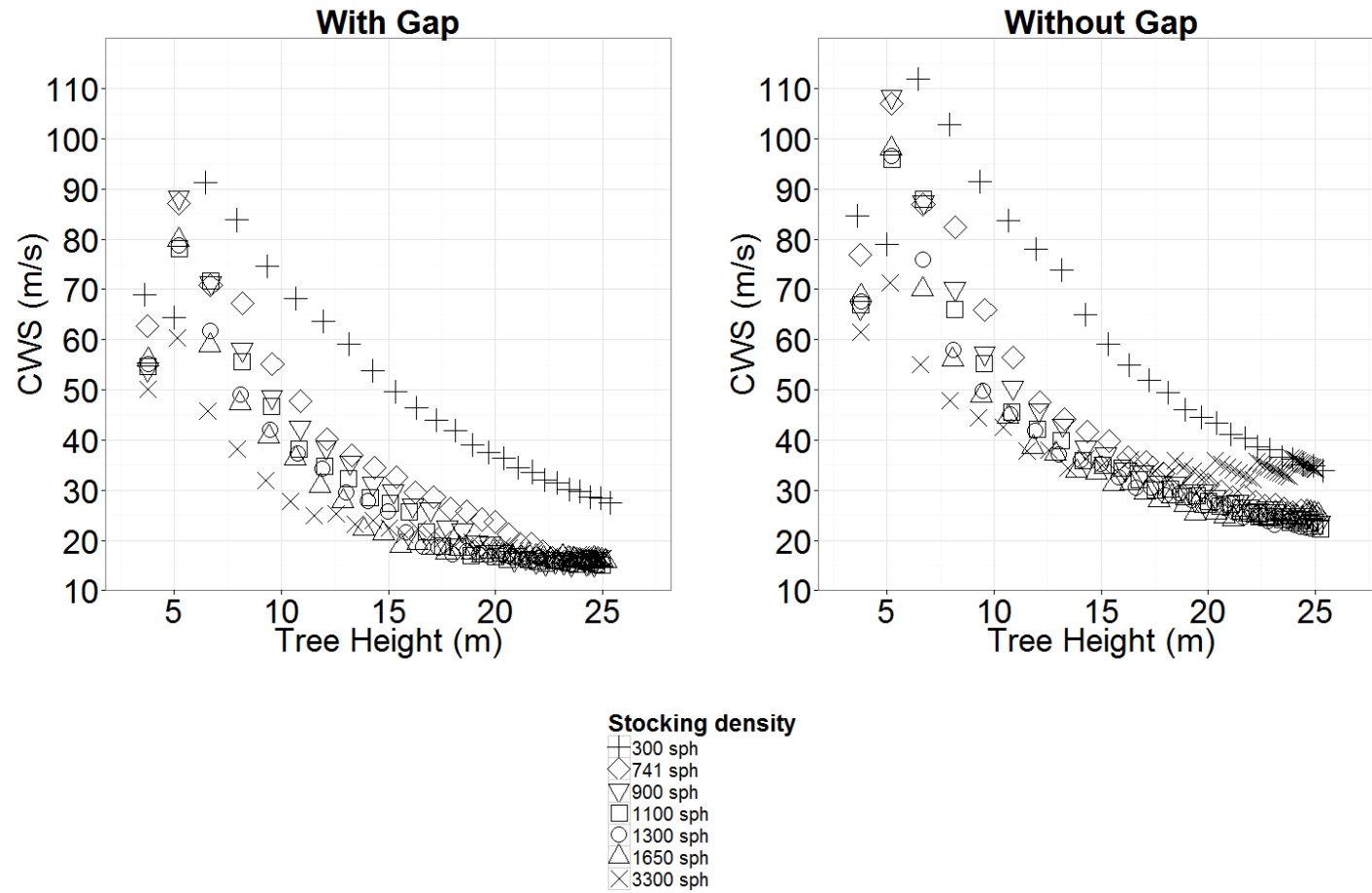
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476 **3.2 Model evaluation**

477 *3.2.1 Investigation of model behaviour*

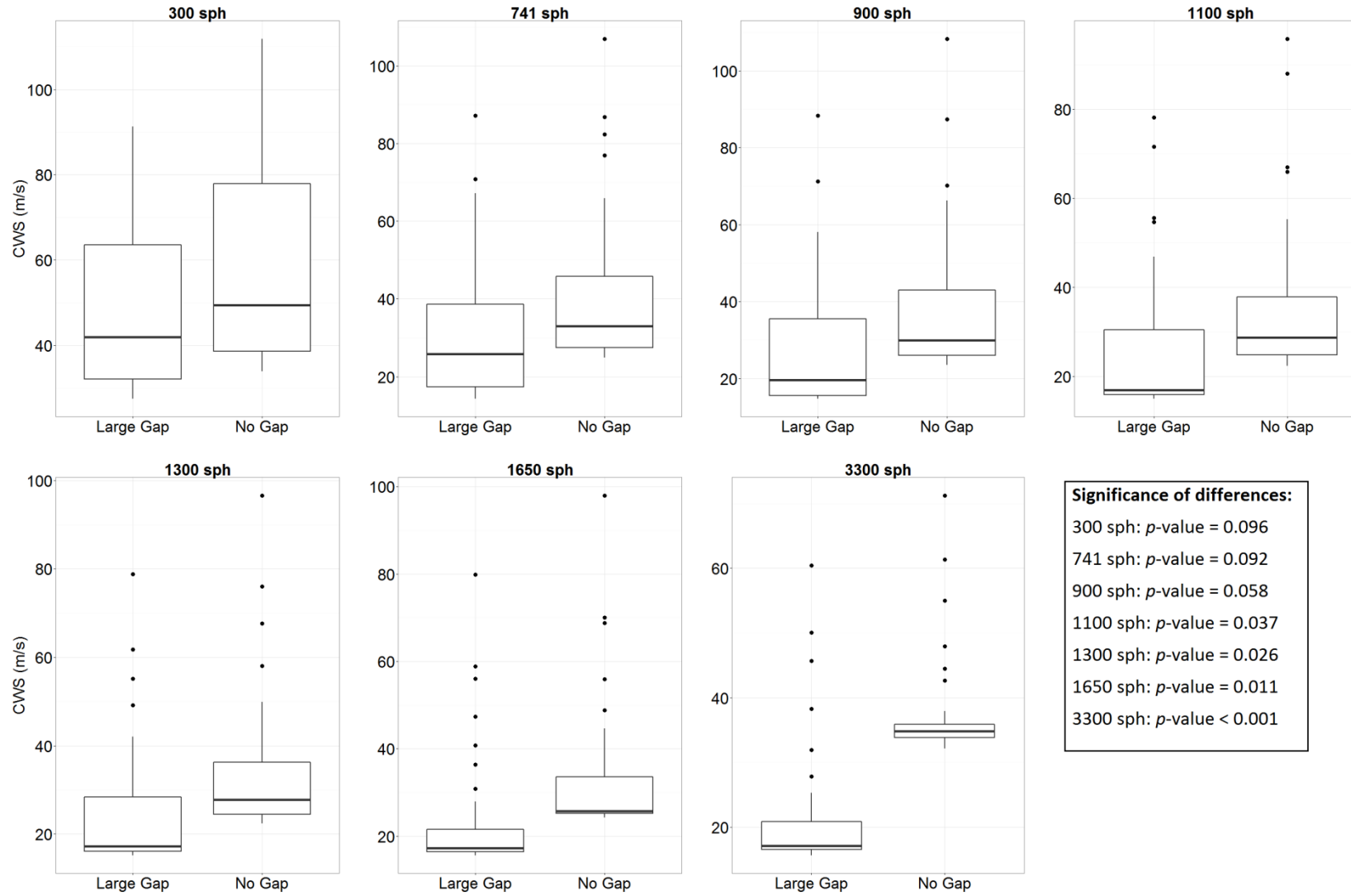
478 The results of our ForestGALES simulations for *E.globulus* stands at increasing stocking densities, in
479 the presence/absence of a windward *Gap*, are shown in Fig. 3.

Fig. 3: Scatterplots of critical wind speeds as a function of tree height and stocking density, in the presence and in the absence of a large windward gap, as calculated with ForestGALES.



As shown in Fig. 3, in the presence of an upwind *Gap*, for trees taller than 5m and for all the stocking densities, the critical wind speeds calculated for our virtual stands monotonically decrease (i.e. the stands are more prone to wind damage) as *Tree Height* increases. This finding is in agreement with the well-known tenet that, regardless of their species, trees become more prone to wind damage as they grow taller (e.g. Gardiner et al., 2000). For small trees (height < 5m) our CWS are lower than for trees immediately past this height, as seen in the peaks on the left of the scatterplots. This behaviour is independent of the stocking density used, although it becomes less marked as the density increases, probably due to the form (i.e. the taper) of our simulated trees under different stocking densities. As shown in Fig. 3, CWS decrease more rapidly from a *Tree Height* of about 6 – 15m. The effect of spacing is also evident, with decreasing CWS as stocking density increases. The scatterplots show that for stocking densities over 900 sph the CWS vs *Tree Height* curves level off asymptotically past a certain *Tree Height*. This threshold becomes lower as stocking densities increase (for stocking densities above 900 sph). We ascribe this behaviour to the increasing *Tree Height/Dbh* ratios for increasing stocking densities, as calculated with GLOBULUS and the method of Soares and Tomé (2002). This behaviour is also reflected in the boxplots in Fig. 4, where the quartiles of the CWS distributions become narrower as the stocking density increases. The trends observed for the presence of an upwind *Gap* are also evident for stands not exposed to a large upwind *Gap* (scatterplot on the right of Fig. 3). In the absence of a *Gap*, the calculated CWS are higher than for the scenario with a *Gap*, as can be noticed by comparing the two scatterplots in Fig. 3: without a *Gap*, the curves shift upwards, corresponding to lower vulnerability to wind damage. As shown in Fig. 4, this difference becomes larger as stocking density increases, as does its significance, as confirmed with two-tailed t-tests (p -values shown in Figure). For high stocking densities, the values of our calculated CWS fluctuate a little for taller trees (Fig. 3). This model behaviour is particularly evident for stocking density = 3300 sph in the scenario without an upwind *Gap*.

Fig. 4: Distributions of critical wind speeds by stocking densities and presence/absence of a windward gap. p -values denote the significance of the differences between presence/absence of a gap.



3.2.2 Model evaluation against literature data

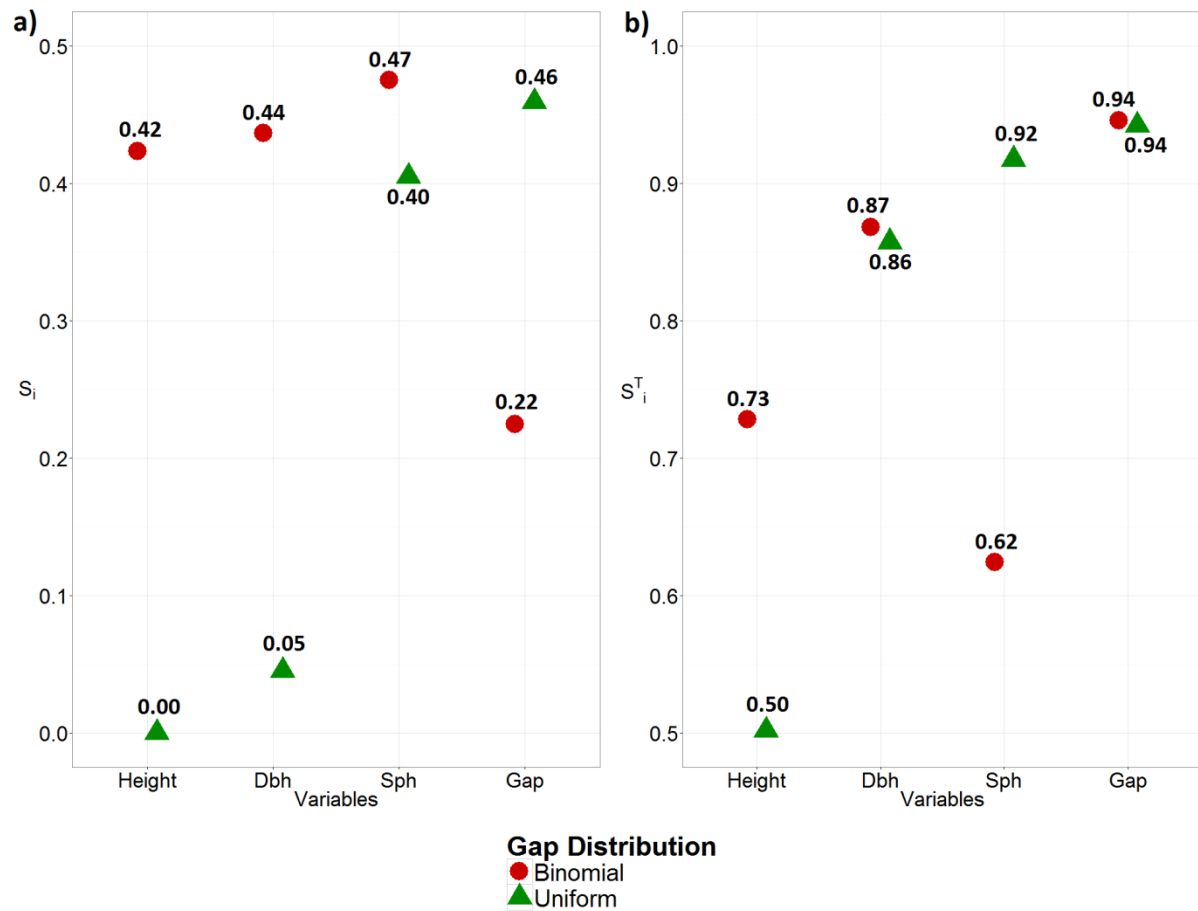
The stocking densities 300 sph, 900 sph, and 1300 sph in Fig. 3 (presence of *Gap*) are representative of Gerrand et al. (1997), while stocking densities 1100 sph, 1650 sph, and 3300 sph are similar to the plots in Chen (2003). Due to the lack of stocking and gap data in Williams and Douglas (1995) we could not relate any specific stocking density to the damage reported by the authors. Our simulations generally agree with the threshold tree height of ~9m suggested by Williams and Douglas (1995), above which trees become more vulnerable to wind damage. However, in our simulations this is more evident for low to medium stocking densities (up to 1650 sph), where the risk of wind damage increases markedly (i.e. CWS decreases rapidly), as seen in Fig. 3.

Gerrand et al. (1997) report that, for tall trees (height $\geq 25\text{m}$) of taper within the range of 0.90 to 1.13, thinning from 1,300 sph to 900, and subsequently 300, increased the risk of wind damage in stands exposed to a gap. The values of taper are consistent with those of our simulated trees. The trend reported by Gerrand et al. (1997) is not evident in our simulations with an upwind *Gap*, as Fig. 3 shows that tall trees are associated with lower CWS for high stocking densities than for very low stocking densities. This disagreement is likely to be due to the fact that - in the study of Gerrand et al. (1997) - thinning operations exposed trees that had not previously become acclimated to the wind, while in our simulations we did not focus on the effect of thinning on the vulnerability of a stand to wind damage. Our model simulations do not fit well with the young Eucalyptus trees data in Chen (2003). The author reports that a max wind speed of 32.6 m s^{-1} caused 10 – 50% cumulative damage to their stands, the level of damage being inversely proportional to the stocking densities. Both graphs in Fig. 3 show that our simulations calculated CWS in excess of $\sim 45 \text{ m s}^{-1}$ for *Tree Height* between 5 and 10m for medium stocking densities (1100 sph), while CWS for tree height within this range decrease markedly as *Sph* increases.

3.3 Sensitivity analysis

The results of the Global Sensitivity Analysis for uniformly and binomially distributed values of *Gap*, using the method of Kucherenko et al. (2012) for correlated variables, are displayed in Fig. 5a and 5b for first order and total sensitivity indices, respectively.

Fig. 5: Sobol' First Order (a) and Total (b) sensitivity indices for uniformly and binomially distributed values of *Gap*. Note difference in scales on the ordinate.



The complex interactions between the four input variables used in our sensitivity analysis of ForestGALES are evident from Fig. 5, as seen from the large differences between the values of the first-order (S_i) and the total (S_i^T) sensitivity indices. This result indicates that the number and the size of the interactions between the inputs are large, and that the behaviour of the model with regards to our inputs is nonlinear. Knowledge of the exact size of an upwind *Gap* has also a large effect on the contribution of the input variables to the variance of the output. When we allowed *Gap* to vary uniformly between 0m and 250m, the direct importance of *Sph* and of *Gap* itself outweighed that of *Tree Height* and *Dbh*, as measured by their S_i values (Fig. 5a, *Gap* Distribution: Uniform). However, the large differences between the S_i^T and the S_i of *Tree Height* and *Dbh* when *Gap* was uniformly distributed suggest very significant interactions particularly between the two variables, and all the four variables overall (Fig. 5a and 5b, *Gap* Distribution: Uniform). In contrast to this, the results of the analysis where the only values of *Gap* were the extremes of its distribution show that *Tree Height*, *Dbh*, and *Sph* were the main drivers of the variation of critical wind speed, in almost equal measure (Fig. 5a, *Gap* Distribution: Binomial). This corresponds to the practical case when the exact size of an upwind gap is not known, and gap is defined as either present or absent. Under the scenario of a binomially-distributed *Gap*, the interactions between the inputs are less marked than in the case of a uniformly-distributed *Gap*. This is especially evident for *Dbh*, whose interactions with the other variables were the most enhanced of all the inputs when *Gap* was described by a uniform distribution. In the simulations when *Gap* was distributed binomially, the interactions involving *Sph*

were the least significant, while the extreme values of *Gap* amplified its importance in driving the variation of the output (Fig. 5b, *Gap* Distribution: Binomial).

4. Discussion

In this study, we have performed a parameterisation of the wind-risk model ForestGALES for *E.globulus* from field data acquired in a monospecific forest in Asturias, Spain. This is the first time that this model has been parameterised for a broadleaved species. We focussed on *E.globulus* because of its prominence in the pulp and biomass industry sectors worldwide, including the Iberian Peninsula, where *E.globulus* stands were accessible and available for our experimental work. To model *Tree Height* for different stocking densities we used the growth model GLOBULUS (Soares et al., 2006), together with a formula proposed by Soares and Tomé (2002) which calculates mean tree height as a function of dominant tree height and mean dbh. The scarcity of detailed wind-damage data to *Eucalyptus* spp. means that attempting to validate our parameterisation would not have been a rigorous process. Instead, we have investigated the behaviour of our parameterisation of ForestGALES for different stocking densities with scatterplots of the critical wind speeds calculated by the model against *Tree Height*. We also attempted to evaluate whether our model predictions fit logically with the observed damage to *Eucalyptus* spp. as reported from three studies found in the literature (Williams and Douglas, 1995; Gerrand et al., 1997; and Chen, 2003). For our investigation and evaluation of model behaviour we have simplified the model's structure by fixing those input variables for which we had no variation in our experimental plot (Rooting Depth, Soil Type). In accordance with sound modelling practices, we have provided a sensitivity analysis of the model, using the method of Kucherenko et al. (2012) for correlated variables, an extension of the variance-based method of Sobol' (Saltelli, 2002). Below we carefully scrutinize the major steps in our analysis.

4.1 Model parameterisation

To perform the parameterisation for *E.globulus* we followed the methods used for coniferous species already included in ForestGALES (e.g. Ruel et al. (2000), Elie and Ruel (2005), Nicoll et al. (2006)). We found that, by including *Dbh* in the modelling of canopy depth, we were able to considerably improve the fit of our regression. This simple adjustment is of relevance to the practical applications of ForestGALES, for which limiting the input variables to those normally recorded in forest inventories is paramount. This is the first instance that ForestGALES has been parameterised for a broadleaved species, and challenges in the modelling of tree characteristics are expected. Because of the differences in crown morphology between conifers and broadleaves, modelling of canopy dimensions and streamlining is likely to be one of the major challenges for other broadleaves to be included in the model. Our approach of modelling the crown of *E.globulus* trees as an ellipsoid, from data obtained by visually projecting the breadth of the canopy to the forest floor, provides a first attempt. Time constraints during tree-pulling fieldwork need to be accounted for, as this method is more time-consuming than the traditional approach of measuring the crown after a tree has been pulled over. In our parameterisation we used the streamlining parameters calculated by Vollsinger et al. (2005) for black cottonwood, a species of similar crown shape as *E.globulus*. Ideally however, more experiments like that of Vollsinger et al. (2005) would be required to investigate the

streamlining and drag of broadleaves crowns, especially given the differences in leaf size in broadleaves and the resulting effect on drag.

Our experiment was designed to have a range of tree sizes. Hence, the large variations in some of the recorded variables reflect the differences between tree dimensions across the three dominance classes. It is interesting to note how *MOR* and *MOE* are not affected by the same degree of variation, suggesting that tree size and dominance class do not have a sizeable impact on *MOR* and *MOE*. Our mean value of *MOE* is lower than those reported by Yang and Evans (2003) ($MOE \approx 18$ GPa) and Wentzel-Vietheer et al. (2013) (≈ 18.6 GPa), but very close to that reported by McKinley et al. (2002) (≈ 13.7 GPa) for *E.globulus*. The mean value of the *MOE* of our trees (13.9 GPa) is very similar to that of *Eucalyptus diversicolor* (F.Muell.) reported in the FPL Wood Handbook (Bergman et al., 2010) and of *Eucalyptus pilularis* (Sm.) in Lavers (2002). Our *MOR* value is in agreement with Yang and Evans (2003) ($MOR \approx 119$ MPa) and with McKinley et al. (2002) (122 MPa). The values of the density of green wood of the *E.globulus* trees in McKinley et al. (2002) is in very good agreement with our data (1229.81 kg m⁻³).

There are a number of limitations in our study. Since we gathered field data on only one site, this does not allow variation of soil types for our data analysis. Similarly, we did not measure soil moisture. However, there is currently no agreement in the literature on the role of soil moisture in tree anchorage (e.g. Dunham and Cameron, 2000; Cucchi et al., 2004; Kamimura et al., 2012). Both soil type and water availability are associated with *E.globulus* root development (e.g. Fabião et al., 1995). However, the soil of our experimental site was not waterlogged at the time of the survey, which suggests that our experimental trees had optimal anchorage. The importance of the root-soil system is more evident in poorly drained soils or soils with a hardpan, which are not favourable for the development of sinker roots or taproots, resulting in a shallow rooting depth (Peltola, 2006). Under such circumstances, an emphasis on roots developing radially and laterally would increase the anchorage of the tree (Nicoll and Ray, 1996). In our experiment we attached the winch cable below the standard half-tree height traditionally used in tree-pulling experiments (Nicoll et al., 2006) because we expected the *E.globulus* trees on our site to break along their stem rather than overturn under static pulling at half tree height. In order to calibrate ForestGALES for this new species we needed to ensure a number of overturned trees in each dominance class to perform the linear regressions to calculate the overturning moment multipliers (C_{reg}). Nicoll et al. (2006) found that deep rooting increased anchorage in conifer trees by 10 – 15%. Therefore, we expected that the presence of a tap root, which is known to be able to reach large sizes in *E.globulus* (Stone and Kalisz, 1991), would influence greatly the trees' resistance to overturning, but this did not appear to be the case in our study (Fig. 2). It would be of great interest to investigate the resistance of *E.globulus* trees to uprooting in different soil types.

4.2 Investigation of the behaviour of our parameterisation

We investigated the behaviour of our parameterisation for different stocking densities and for climatic and environmental conditions typical of our experimental plots. As seen in the scatterplots of critical wind speed (CWS) vs *Tree Height* (Fig. 3), trees of height lower than 5m are associated with lower CWS than those immediately above this threshold. However, critical wind speeds are known to be negatively correlated with tree height (e.g. Somerville, 1989), and previous applications of

ForestGALES to conifer species have accurately reproduced this tenet (e.g. Gardiner et al., 2000). The aberrant behaviour of our parameterisation of ForestGALES for small *E.globulus* trees is then probably due to our decision to model the depth of the crown of short trees as half of tree height (see Table 4). There are small fluctuations in the CWS calculated for high stocking densities, as shown in Fig. 3. In our interpretation, this behaviour is due to the calculation of mean tree height with the formula of Soares and Tomé (2002): for high stocking densities and tall trees, the calculation of tree-taper results in some small fluctuations, which propagate through ForestGALES to produce the fluctuations in our calculated CWS. As expected, the contribution of an upwind gap in the calculations of CWS is maintained in our parameterisation. In fact, in the absence of acclimation to wind, trees exposed to a newly formed gap are known to be more susceptible to wind damage (Somerville, 1989). As shown in the boxplots in Fig. 4, our virtual stands exposed to a gap are associated with lower CWS than those without a gap. The role of *Gap* in the calculations of CWS becomes larger as *Sph* increases, as shown in Fig. 4. This is confirmed by the *p*-values in Fig. 4, which become increasingly significant as stocking density becomes larger. This behaviour of ForestGALES is due to the fact that both stocking density and the size of *Gap* are involved in the calculations of the maximum and mean bending moments acting on the average tree.

4.3 Model evaluation against literature data

Our simulations did not reproduce well the wind damage described by Chen (2003). This might suggest that ForestGALES is currently unable to effectively simulate the susceptibility of young/short *E.globulus* trees to wind damage. Besides the issues with the modelling of crown dimensions discussed in the previous section, there are two likely explanations for this. Firstly, there are very few young trees in the UK Forestry Commission's tree-pulling database that was used to derive empirical values for resistance to overturning in ForestGALES, because the model was built to aid in the management of mature stands against wind risk. Young trees have larger ratios of sapwood/heartwood, which reduce the density of the wood and its mechanical properties (i.e. *MOE* and *MOR*), and hence probably behave differently than mature trees under wind loading. Secondly, very short trees result in values outside the confidence range for model calculations of some key parameters of ForestGALES that control the wind loading on a mean tree in a stand (e.g. spacing/height). However, the percentages of damaged young trees in the study by Chen (2003) are lower than 5% in all the plots (i.e. not significantly different from the annual mean in undisturbed plots in the area) but one, where 12.5% of the stand was damaged. ForestGALES assumes all trees in a stand to be equal to the mean tree, and can only predict catastrophic damage (~40%) or no damage at all (Hale et al., 2015). In addition to this, the *MOE* and *MOR* of the *Eucalyptus* spp. in the paper by Chen (*E.urophylla* and hybrid *E.urophylla* X *E.grandis*) are considerably lower than for *E.globulus* (Gonçalves et al., 2013). Because the calculations of the critical bending moments in ForestGALES include *MOE* and *MOR*, lower values of these parameters would result in trees more susceptible to wind damage (i.e. lower CWS). Gerrand et al. (1997) suggest that mature, tall trees (> 25m) become more susceptible to wind damage when stocking density decreases if thinning is not done early to promote larger dbh/height ratios. While our simulated trees of similar taper seem in agreement with this, especially for stands without a gap (Fig. 3), we did not explore the behaviour of our parameterisation for very tall trees. Moreover, we did not investigate the effect of thinnings in our virtual stands. Thinning practices favour the penetration of wind inside a stand, exposing trees

that relied on mutual support from neighbouring trees (and hence did not grow acclimated to such wind action) to higher wind forces. While ForestGALES can simulate thinnings, it is not able to deal explicitly with mutual support. However, our simulations show that lower stocking densities are associated with higher CWS (i.e. stands with wider spacing are at lower risk of damage), which is consistent with the findings of Achim et al. (2005) in their study of balsam fir's (*Abies balsamea* (L.) Mill.) resistance to windthrow. Our results also agree with the existence of a threshold tree height above which CWS decrease steeply and monotonically, as proposed by Williams and Douglas (1995). From the forest manager viewpoint, our simulations suggest that a safe approach would be to plant *E.globulus* seedlings at high densities and carry out an early thinning of mid-intensity before the stands reach a height of ~ 10 – 15m, to provide an initial return on planting costs, and to make the stands more stable. Stands should then be harvested before they reach a height of ~22 - 25m to reduce the risk of a large wind-caused loss. This is particularly relevant in areas that are susceptible to high wind speeds, and for stands recently exposed to an upwind gap. Ruel et al. (2000), in their parameterisation of ForestGALES for balsam fir suggest a similar approach for exposed stands. As shown in Fig. 3 and 5, trees at the edge of a stand exposed to a gap have a lower CWS than those within a stand or not exposed to a gap, regardless of stocking density.

Given the large variety of *Eucalyptus* spp. commercially planted worldwide, and their associated characteristics and climatic optima, it is of great interest that ForestGALES is parameterised for other species in the *Eucalyptus* genus. This is all the more important as the minimisation of wind-risk to commercial plantations can allow for more secure and higher productivity, and hence alleviate the requirement of exploiting natural forests and their resources for the timber and pulp industries (Gardiner and Moore, 2014), ensuring the provision of ecosystem services such as soil and water protection. Furthermore, *E.globulus*' resistance to wind damage needs to be compared with that of other species currently used in commercial plantations. One such species is *P.pinaster*, widely grown on the Iberian Peninsula and in south-western France. An associated article has been submitted, in which we compare the susceptibility of these two species to wind damage using ForestGALES for soil and wind climate conditions typical of the Aquitaine region of France.

4.4 Sensitivity analysis

By performing our sensitivity analysis with the variance-based method of Kucherenko et al. (2012), we were able to determine the sensitivity of the output of ForestGALES to our four input variables. Using the method of Kucherenko et al. (2012) for correlated variables is especially important since *Tree Height* and *Dbh* are naturally highly correlated, and using the original method of Sobol' (Saltelli, 2002) would have miscalculated the proportion of the output's variance explained by the input variables. Our analysis has shown that – in our parameterisation of ForestGALES for *E.globulus* – the calculations of critical wind speeds are characterised by a high degree of non-linearity, and that the interactions between our four input variables are numerous and complex, as shown by the large differences between total and first-order sensitivity indices (Fig. 5a and 5b). These interactions are particularly evident for *Tree Height* and *Dbh* when the exact size of a windward gap is known (i.e. when we described *Gap* with a uniform distribution). Given the well-known strong correlation between tree height and wind damage (e.g. Gardiner and Quine, 2000; Peltola 2006), we expected our analysis to identify *Tree Height* as the main driver of variation of the model's output. However,

when *Gap* was distributed uniformly, the direct contribution of *Tree Height* and of *Dbh* were outweighed by those of *Gap* and *Sph*, as opposed to when *Gap* was binomially distributed, when *Tree Height* and *Dbh* were responsible for significantly larger portions of the output's variance (Fig. 5a). However, the large values of S_i^T , calculated for all the four inputs indicate that these variables are all approximately equally important, regardless of whether the exact size of a gap is known. From a wind-risk modelling standpoint, this suggests that all the variables should be retained in future versions of the model, given that the structure of the model itself remains significantly similar to the current version. From the point of view of practical applications of the model, our findings suggest that accurately knowing the size of an upwind gap, and the stocking density and the mean dbh of the stand, would provide more robust estimates of the calculated critical wind speeds. This is convenient, since with traditional fieldwork techniques it is easier to measure with similar accuracy these variables than tree height. However, this is true for homogeneous stands with respect to tree height, since ForestGALES assumes that all trees within a stand are equal to an ideal tree with the mean characteristics calculated with the formulas in Table 4.

In the real world, the size of a windward gap can have any values between 0 and “very large”, rather than the extreme scenarios of *Gap* being either present or absent. These two cases correspond to the uniform and binomial distributions of *Gap* adopted in our paper, respectively. A number of studies (e.g. Somerville, 1989; Quine et al., 1995) report that the contribution of a windward gap in increasing the susceptibility of a stand to wind damage is most commonly experienced when a new edge is formed (e.g. following clear-felling of an adjacent stand), rather than when a gap was already present, which would give time to the trees to acclimate to the stronger winds at the forest edge. Similarly, the effectiveness of a dense edge in reducing the rate of wind loading, as well as the positive correlation between upwind gap size and wind loading on forest edges, are well known (Stacey et al., 1994; Gardiner et al., 1997). Because ForestGALES is not capable of directly simulating tree acclimation to wind exposure in correspondence to a gap that was formed before the establishment, or at the early growth stage of a forest, for practical applications of the model it is useful to know the importance of a gap in driving the calculations of the critical wind speeds. When using variance-based methods of sensitivity analysis such as that of Sobol', the uncertainty associated with a binomially-distributed variable with values “*a*” and “*b*” is larger than that of a uniform distribution of the same variable defined between the same values “*a*” and “*b*”. Therefore, it is expected that a binomially-distributed variable will have a larger contribution to the output's variance. However, in our case *Gap*'s S_i was larger for the uniform case than for the binomial (0.46 and 0.22, respectively). With regards to interactions between the input variables, the extreme values of *Gap*'s binomial distribution amplify the interactions between *Gap* and *Tree Height* and *Dbh*, while *Sph* was negatively affected (Fig. 5b). The sum of the first order effect indices is positively affected by these artificially-induced interactions. Indeed, when we allowed *Gap* to vary uniformly within its range, $\sum S_i$ decreased from 1.56 to 0.91. These seemingly unexpected behaviours are ascribable to the presence of a “trap” in the code of ForestGALES by which when a *Gap* is larger than 10 times *Tree Height*, *Gap* is replaced by a constant. In our simulations under the binomial case, this substitution was more likely to happen than in the uniform case, which likely reduced the *Gap*'s S_i .

Finally, our decision of hardcoding rooting depth and soil type to a fixed value, dictated by the uniformity of our experimental plots in Asturias, might have concealed the model's sensitivity to these variables. However, sensitivity analysis cannot help with this, as it cannot confirm whether the

assumption of fixing certain variables to their nominal values is realistic or not, nor can it alert the modeller to an incorrect characterisation of a variable.

5. Conclusions

In this study we have presented a parameterisation of ForestGALES, a semi-mechanistic model of the risk of wind damage to forests, for *Eucalyptus globulus* (Labill.). Our results show that the resistance to overturning at our experimental site in Northern Spain was not influenced by the presence or absence of a tap-root. This finding suggests that in soils that are not waterlogged, the anchorage of *E.globulus* trees is likely not to be affected by the presence or absence of a tap-root. The evaluation of the behaviour of our parameterisation shows that modelling the shape of the canopy of *E.globulus* trees with an ellipsoid provides a good approximation to account for the drag of the wind on the trees canopies. Despite the additional fieldwork required for this, future parameterisations of ForestGALES for other broadleaved species might benefit from our approach. Our results show that tree height and stocking density are negatively correlated with critical wind speeds (i.e. they are positively correlated with risk of wind damage), and stands recently exposed to a large upwind gap are at higher risk of wind damage, especially when stocking densities are high. Based on these findings, in order to reduce the risk of wind damage we suggest that owners and managers of *E.globulus* forests and plantations should favour stands with low-to-medium stocking densities, carry out an early thinning at around a height of 10 – 12m, and harvest the stands soon after they have reached ~20m in height. This is especially true in areas with an unfavourable local wind climate. Similarly, management of adjacent stands should be carried out in such a way that the creation of upwind gaps following harvests is minimised.

Our global sensitivity analysis of the version of ForestGALES used in this study shows the complex interactions in the model's code between tree height, dbh, stocking density, and size of an upwind gap. Tree height unexpectedly was not the main driver of output variation but was still largely involved in the calculation of critical wind speeds. Therefore, in order to reduce the variability of the model outputs, efforts should be focussed on accurate measurements of dbh, which are more easily obtainable than tree height. Similarly, knowledge of the stocking density of a stand, and the size of any upwind gaps, would effectively improve the reliability of the model predictions. When differentiating between a large upwind gap and no gap, tree height significantly contributed to the calculation of critical wind speed. The findings should be of particular interest to forest managers and wind-risk modellers concerned with wind damage risk to *Eucalyptus* spp.

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