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ANCHORAGE AND STABILITY OF THREE MAJOR PLANTATION FOREST SPECIES IN VIETNAM

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Pulling experiments were conducted to determine the mechanical resistance of trees to overturning. We selected two different sites in Vietnam with three major plantation forest species (*Acacia* hybrid, *Eucalyptus urophylla* and *Pinus caribaea*) to determine the correlation between tree stability or stembase inclination index (stiffness index, SI) and tree characteristics (e.g. tree size, tree species, DBH and height), and site conditions. Statistical analyses based on Cox regression model and generalised linear mixed models (GLMMs) showed that tree stability was strongly affected by tree characteristics and site. There was a positive relationship between the risk of tree failure and tree size, in which tree size was the best indicator for all models (Akaike information criterion of 180, $p < 0.05$), and the tree resistance probability to uprooting increased as tree size increased. In addition, the hazard ratio varied significantly among sites, and between *A.* hybrid and *E. urophylla*. It was also found that the SI increased with increased tree size and was highly affected by species. The study confirmed that site conditions affected tree species vulnerability, induced by wind damage, and provided information for further development of mechanistic wind damage risk assessment models for each specific tree species, especially in the tropical forest.

Keywords: Tree stability, tropical forest, tree characteristics, wind damage

INTRODUCTION

Strong tropical storms that occur in Asia cause serious natural disturbances to forest ecosystems, because wind-induced damage can substantially change forest ecosystem functions, owing to changes in forest structure (e.g. opening of gaps) (Quine & Gardiner 2007). The negative effects of wind disturbances can cause considerable economic losses (Gardiner et al. 2008). In addition, the windthrow risk due to typhoons is predicted to increase because climate change is expected to strengthen typhoon wind speeds (Oouchi et al. 2006). Therefore, risk evaluation of wind damage on forests is an urgent topic for maintaining ecosystem services and developing methodologies to assess and predict the risk of wind damage for sustainable forest management. Vietnam's climate is tropical monsoon, which is typically characterised by strong winds. Vietnam receives many typhoons (4–6 per annum), causing multiple socio-economic and environmental impacts (Wang et al. 2017). The damage caused by typhoons in Vietnam was estimated to be nearly 1.2 billion USD (World Bank 2010), in which the northern and central parts of Vietnam were subjected to more serious damage than other parts, due to complex topography. In Vietnam, the most common species are *Acacia* hybrid, *Eucalyptus urophylla* and *Pinus caribaea*, in which *A.* hybrid accounts for over 500,000 ha with the forest plantation area around 4.3 million ha (Bon et al. 2019, VNFOREST 2019). Since silvicultural scenarios that reduce wind damage have not been developed, detailed research on tree stability, to estimate damage risk related to wind hazard, has become critical for forest management. In addition, because of the limited data from tree failure models under high wind speed events in Asian tropical regions, an accurate damage risk model of tree failure is required to assess wind hazards and develop effective management strategies.

Several models have been developed over the last 30 years to assess forest risk in terms of windthrow occurrence, including empirical, statistical and mechanistic approaches. Although empirical and statistical models are widely portable, their use is limited in terms of data availability and generality, because they are usually constrained by unique local conditions. In contrast, mechanistic models are more general, and thus are suitable for various situations. These models predict the probability of damage based on the relationship between critical wind speed which causes trees to uproot or stems to break, and tree stability under strong wind conditions. Mechanistic models have been developed and used efficiently including HWIND, GALES and WindFIRM/ForestGALES (Peltola et al. 1999, Gardiner et al. 2008, Byrne & Mitchell 2013). To build these models, one of the most important initial steps is to obtain information about tree species resistance to stem breakage or overturning, by establishing tree-pulling experiments required to parameterise mechanistic models. To date, estimating tree resistance to wind load has been conducted in temperate region and boreal zone, but remain limited in tropical forest (Cucchi et al. 2003). A mechanistic model of wind damage risk, developed for the major exotic tree in timber plantation of the tropical zone (northern and central Vietnam), will provide useful information to estimate the turning moment (TM) of trees, needed to predict the threshold wind speeds for tree uprooting or stem breakage.

The TM value depends on soil conditions and is strongly related to above-ground tree parameters such as tree weight (TW), stem mass, tree volume, tree age, diameter at breast height (DBH) and tree height (H) (Cucchi et al. 2005, Lundström et al. 2007a, 2007b, Peterson & Claassen 2013). For example, TM generally increases with tree size and does not differ significantly across species for similar sized trees (Cannon et al. 2015). A large variety of model approaches have been used in previous research, such as logistic regression models, Cox hazard proportion regression model and neural networks (Kamimura et al. 2013, Hanewinkel 2015, Krejci et al. 2018). In general, all models determine the factors impacting TM and establish suitable equations for predicting TM at the moment of tree failure (uprooting or stem breakage). This is also the first core step for assessing risks of forest management, related to wind hazards. Moreover, to predict the critical wind speeds for tree uproot, knowledge about the relationship between TM and inclination (stem deflection) is required, especially for modeling tree swaying. Kamimura et al. (2012) used stiffness index (SI) to present this relationship, which is explained by using tree characteristics such as multiplication of DBH and H, and pointed out that SI was affected by soil conditions (e.g. water content). However, the impacts of other factors (e.g. tree species and TW) on the TM–inclination relationship have been less studied (Kamimura et al. 2012, Sagi et al. 2019).

In an effort to increase understanding of processes behind the occurrence of wind-induced damage in the tropical region, this study was adopted to examine the stability of some major forest trees by establishing a static tree-pulling experiment in Vietnam. In this research, tree stability was studied by applying the Cox regression model, based on relationships between TM and site characteristics, tree species, TW and tree size for *A.* hybrid, *E. urophylla* and *P. caribaea*. The impact of these factors on TM–inclination relationship, with a generalized linear mixing model, was also investigated. The study aimed to assess the influence of various factors (e.g. TW, DBH, H, tree size, species and site) on the model of tree failure, for three main plantation forest species. Moreover, the study aimed to determine the relative contributions of site factors and tree characteristics to obtain SI in the study site. The results will contribute towards knowledge relating to mechanistic models of tree failure, and the further development of mechanistic wind damage risk models.

MATERIALS AND METHODS

Site and data description

As shown in Figure 1, two research sites were selected for the tree-pulling experiments in Vietnam, located in the north of Vietnam (Dai Lai) and central Vietnam (Thanh Hoa). The target sites were mainly in a forest plantation area. In Dai Lai, the annual average temperature is around 23 °C, and the average annual rainfall ranges from 1400 to 1600 mm. The slope of sample plots is from 15 to 25° in low mountain. Soil characteristics are related to topography, in which the main soil is Ferralic Acrisols, poor in mineral and nutrients (NIAPP 2003). In Thanh Hoa, the average slope is from 20 to 30° with the major soil type being Ferralsols on the mountain. The annual temperature in Thanh Hoa is about 22 °C, and the average annual rainfall is more than 2200 mm (NIAPP 2004).

The pulling tests were established in 2012 and 2014 with a total of 41 trees winched during experiments. Tree size, used for the pulling test, had a range of DBH from 8.6 to 29.9 cm and H from 6.6 to 26.2 m (Table 1). The TW of sample trees were 97.6–526, 82.7–774 and 33–398 kg for *A.* hybrid, *P. caribaea* and *E. urophylla*, respectively. The tree age of the selected three species was around 12-year-old in both sites. In Dai Lai sample plots, the selected three species had similar site conditions (e.g. soil type and soil texture).

Tree-pulling experiments

The pulling experiment, using a wire rope and a winch, was conducted according to Kamirura et al. 2012. The target tree was pulled down mechanically using a wire cable of 10 mm in diameter, by setting a winch attached to an anchor tree. Three inclinometers (D5R-L02-60) were set on the stem of pulled trees, ranging from 0.2 to 5 m. A load-cell (maximum load 1.3 ton) was positioned on a steel cable between the anchor tree and target tree. The inclinometers and load-cell were connected to a data logger (GL200A) used for simultaneously recording the data. The blocks were set at heights of 0.2–0.3 m on the anchor tree and 1–5 m on the pull tree to decrease pulling force. The wire was directly pulled using a hand winch. The angles of tree stem (measured from the slope

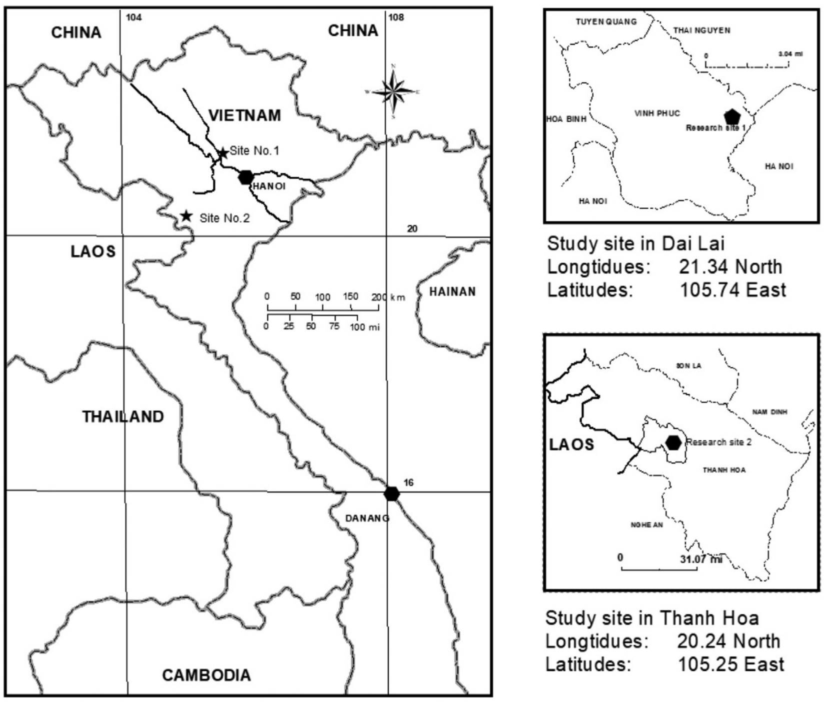

Figure 1 Location of research sites in Dai Lai and in Thanh Hoa, Vietnam

Table 1 Description of sample trees in the tree pulling experiments

Site	Species	TW (Std) (kg)	DBH (Std) (cm)	H (Std) (m)	Experiment time
Dai Lai	*Acacia* hybrid	97.6–526 (145)	11.2–23.1(3.96)	19.9–26.2 (2.09)	2012.12
	Pinus caribaea	82.7–774 (188)	8.6–22.7 (4.44)	6.6–19.7 (4.76)	2012.12
	Eucalyptus urophylla	33–398 (120)	9.8–25.9 (4.09)	14.6–27.3 (4.93)	2012.12
Thanh Hoa	*Acacia* hybrid	75.6–938 (362)	13.2–29.9 (8.56)	11.8–23.5 (5.13)	2014.07

TW = tree weight, DBH = diameter at breast height, H = tree height, Std = standard deviation sensors) and the force (measured from load cell) were recorded by the data logger every 10 ms (millisecond) until the tree was uprooted or broken. To calculate the TM applied on the pull tree, the following data were collected: (i) the horizontal distance between the anchor tree and the pull tree, (ii) the angle of the cable from the attachment point of the winch to the attachment point of the pull tree, (iii) the height of the winch-cable attachment point and (iv) the height of inclinometers attachment. The tree characteristics (H, DBH and tree species) were also recorded. The stem weight, calculated at 2 m interval from the base of the pull tree, after each tree fell under maximum load capacity, was combined with the leaf weight to determine the total TW (above biomass weight).

Data calculation

The maximum turning moment (TM_{max}) at the base of each pulled tree was calculated according to Kamirura et al. 2012. The TM_{max} (kNm) is divided into horizontal (applied) force ($TM_{applied}$, kNm) by pulling, and vertical force ($TM_{gravity}$, kNm) caused by the self-weight of a tree. The $TM_{applied}$ and $TM_{gravity}$ were calculated as follows:

$$TM_{applied} = F \times H_{cable} (\cos\alpha\sin\beta + \sin\alpha\cos\beta) \quad (1)$$

where F (kgf) is the maximum load, α (degree) is the angle between the wire and the horizontal line from the anchor tree's stem base, β (degree) is mean stem angle from the original position of the stem at maximum force, and H_{cable} (m) is the attached wire height.

$$TM_{gravity} = TW \times G \quad (2)$$

where TW (kg) is the tree weight and G (m) is the horizontal displacement of the center of gravity of a tree.

The SI was used to indicate the TM–inclination relationship, which was calculated as the ratio between the maximum turning moment and the inclination of the stem under maximum force. In this case, the inclination of the stem was considered as β (radian) and defined as an average of three inclined sensors value. The function to calculate SI was indicated as follows:

$$SI = TM_{max} / \beta \quad (3)$$

where SI = stiffness index, TM_{max} = maximum turning moment and β = radian

Data processing

To investigate factors influencing the tree stability, such as TW, tree size (H × DBH^2), H, DBH, tree species, the ratio of tree height to stem diameter (H-D ratio) and site, the Cox hazard model (Cox DR 1972) was used, defined as the probability of occurrence per unit time. In the analysis process, first, the moment of tree failure was considered as the time of event occurrence and indicated as the horizontal axis. Second, the best model regression for risk of failure probability was selected using Akaike information criterion (AIC) value, to determine which tree characteristics were most significantly associated with survival probability. The models were fitted using the 'survival' package in R software (R Core Team 2018).

To explore the site impacts on the risk of tree failure, the factor 'site' was considered as the random factor and the "coxme" package in R was applied (Terry & Patricia 2000). After checking for variance among different sites, the effect of species was tested along with the main effects (tree size or TW) in the model.

To check the influence of candidate factors on SI, the study used generalised linear mixed models (GLMMs) in the 'glmm' and 'lme4' packages in R (Mcculloch & Searle 2001). In this case, the effects of species group, tree size and TW were considered as independent variables, and SI was the dependent variable. All models are described in Table 2.

RESULTS

The influence of tree characteristics and site on tree stability

Based on Model 1.1, used to detect the impacts of explanatory factors, significant correlations were found between the risk of tree failure and factors such as tree size, TW, H and DBH with a highly statistically significant coefficient ($p < 0.05$) except for the H-D ratio ($p > 0.05$) (Table 3). These factors can reduce the risk of failure; the coefficient parameters of factors were −4.964, −0.012, −0.187 and −0.372 for tree size, TW, H and DBH respectively. Therefore, an increase in tree size, TW, DBH and H led to an increase in

Table 2 Model fomulation used for predicting the hazard ratio of tree failure and stiffness index (SI)

Model code	Model formulation	Regression model types
(1.1)	$h(t,x) \sim h_0(t)\exp(a\times X_i)$	The Cox regression
(1.2)	$h(t,x) \sim h_0(t)\exp(a\times X_i + c_{site})$	The Cox regression
(1.3)	$h(t,x) \sim h_0(t)\exp(a\times X_i + b\times species)$	The Cox regression
(1.4)	$h(t,x) \sim h_0(t)\exp(X_i$ ※ $species)$	The Cox regression
(1.5)	$SI \sim a\times X_i + b$	GLMMs
(1.6)	$SI \sim a\times X_i + c_{site}$	GLMMs
(1.7)	$SI \sim a\times X_i + b*species$	GLMMs

X_i is an explanation factor (tree size, TW, DBH and H), a and b are parameter coefficients, c_{site} is the random effect for each site, ※ represents the interaction between explanatory variables and species, h(t,x) is the the hazard function, $h_0(t)$ is the baseline hazard function related to t, t is considered as the moment of tree failure

Table 3 Estimated parameters for all participated variables by Cox regression.

Model code	Factors	Coef	P-value	AIC
1.11	Tree size	-4.964	0.000***	180.0
1.12	Tree weight	-0.012	0.000***	185.5
1.13	H-D ratio	0.002	0.786	230.0
1.14	Tree height	-0.187	0.000***	203.4
1.15	DBH	-0.372	0.000***	190.0

***Pearson correlation is significant at the 0.001 level (2-tailed); Coef = coefficient parameter in the Cox regression, AIC = Akaike information criterion

tree resistance to uprooting and stem breakage (a reduced risk of tree failure). The best model (Model 1.11), selected to indicate the risk of tree failure, contained tree size variable with the lowest AIC value (180), and was highly statistically significant ($p < 0.05$).

The impact of site on tree resistance to uprooting and stem breaking was evaluated based on a comparison between Dai Lai and Thanh Hoa for *A.* hybrid with similar range of DBH and H (Table 4). In this case, the site was considered as a random factor in the Cox regression model. Results on the tested model showed that the difference between sites was significant, in which, the hazard ratio was higher in Thanh Hoa than in Dai Lai. The tree size influenced the risk of tree failure with a decreasing trend of hazard rate (negative coefficients, Table 4). The signal for site impact was indicated by the different in frailty value (2.01 and −2.01 for Thanh Hoa and Dai Lai respectively), and the large variance for random effect (Table 4). This difference in hazard risk demonstrated that the survival probability of *A.* hybrid in Thanh Hoa was lower than that in Dai Lai, or that the resistance of *A.* hybrid was lower in Thanh Hoa than in Dai Lai.

Species effects on the hazard model were investigated among species groups in Dai Lai for the three species. Two models (1.3 and 1.4) were used, of which the former was used for investigating the hazard ratio among species group, and the latter was used for testing the interaction between tree size and species. In Model 1.4, there was no significant interaction between tree size and species (all estimated parameters had $p > 0.05$). Hence, tree size and species were independent in the regression model. In Model 1.3, the difference of the risk of tree failure among the species groups in Dai Lai was highly significant (Table 5). A difference was clearly seen between *E. urophylla* and *A.* hybrid, with hazard ratio being higher in *E. urophylla* ($p < 0.05$). The survival probability dramatically reduced around 30 kNm for all species in the selected model (Figure 2).

Table 4 Site impacts on hazard ratio for *Acacia* hybrid in Thanh Hoa and Dai Lai

Fixed effects (Tree size)		Random effects (Site as a random factor)	Frailty
Coef	P-value	Variance	
-4.999	0.000***	8.70	Dai Lai: - 2.01 Thanh Hoa: 2.01

Frailty denotes the common risk acting as a factor on the hazard function; ***Pearson correlation is significant at the 0.001 level (2-tailed); Coef = coefficient parameter in the Cox regression, AIC = Akaike information criterion

Table 5 Impacts of tree species on the model of hazard proportion in model 1.3 based on the Cox regression model

Explanation variables	Coef	P-value	AIC
Tree size	-8.03	0.000***	127.7
Eucalyptus urophylia	1.10	0.033*	
Pinus caribaea	0.53	0.282	

***Pearson correlation is significant at the 0.001 level (2-tailed), *pearson correlation is significant at 0.05 level (2-tailed); *Acacia* hybrid was used as the basis for comparison between species; Coef = coefficient parameter in the Cox regression, AIC = Akaike information criterion

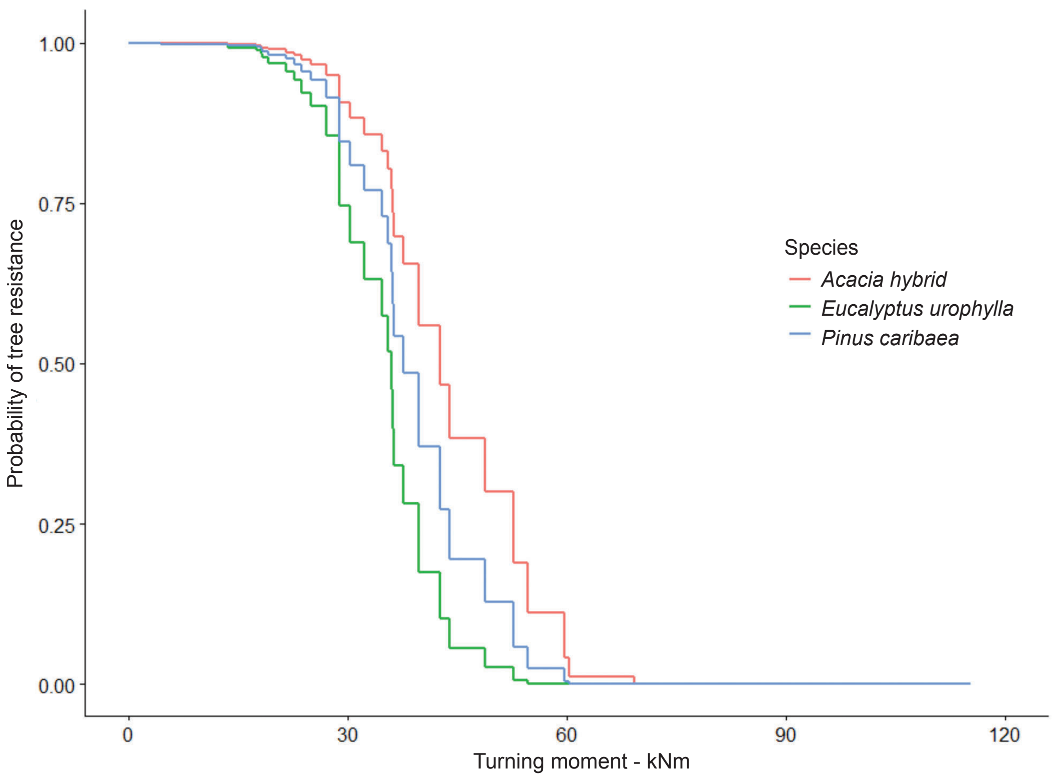

Figure 2 Probability of tree resistance to uprooting and stem breakage among the species group with tree size as the explanatory factor

The influence of tree characteristics and site on stiffness index (SI)

The results on GLMMs determined that tree size, TW and DBH were strongly associated with SI for all species in the research sites. The lowest AIC value was found in the model between SI and tree size (AIC of 21.17), and the value of SI increased with the increase of tree size (the slope of estimated parameters was positive, Table 6). Using Model 1.6, it was found that there was no significant difference between the two sites (the variance for random effects = 0). Therefore, there was no clear impact of site on the change of SI value in this study.

It is important to note that the relationship between SI and tree size was also influenced by species (e.g. *P. caribaea* and *A.* hybrid with $p < 0.05$, Table 7). The SI value was lower for *P. caribaea* than for *A.* hybrid (the coefficient was negative in the model), meaning that the angle (β) was considerably higher than that of *A.* hybrid for the same tree size. However, the difference between *A.* hybrid and *E. urophylla* was not significant at a confidence level of 95%. The difference between *P. caribaea* and *A.* hybrid was clear with the increase of tree size (Figure 3).

DISCUSSION

The study applied Cox regression model to identify the indicators and their effects on the model of survival probability under a tree pulling experiment. The correlation between tree size and survival ratio fitted well across all sites, despite substantial differences in tree size, tree species and other factors.

Factors affecting the risk of tree failure

The tree resistance to uprooting has been typically estimated by pulling trees over with a winch system and determining regressions between the maximum applied bending moment, and various tree physical characteristics such as stem weight or combinations of variables such as H and DBH, considering the results separately for each combination of species and soil type (Gardiner et al. 2008). Based on this idea, the Cox regression model reflexibility was applied

Table 6 Parameters estimation for the model representing the relationship between SI and tree size, TW and DBH

Parameter	Model expression: $SI = a \times X_i + b$		
	Coef	P-value	AIC
(Intercept)	-0.123	0.207	21.17
Tree size	0.841	0.000***	
(Intercept)	-0.048	0.589	22.31
Tree weight	0.002	0.000***	
(Intercept)	-0.571	0.009*	29.85
DBH	2.625	0.000***	

Xi is an explanation factor (tree size, TW, and DBH), a and b are parameter coefficients, Coef = coefficient parameter in the Cox regression, AIC = Akaike information criterion

Table 7 Impacts of tree species on the model regression of stiffness index using GLMMs

Model type	Parameters	Estimate	Std	P-value	AIC
1.7	Intercept	0.062	0.121	0.609	13.91
	Tree size	0.739	0.136	0.000***	
	Eucalyptus urophylia	-0.150	0.113	0.191	
	Pinus caribaea	-0.272	0.113	0.022*	

Acacia hybrid was used as the basis for comparison; Std = standard deviation, AIC = Akaike information criterion

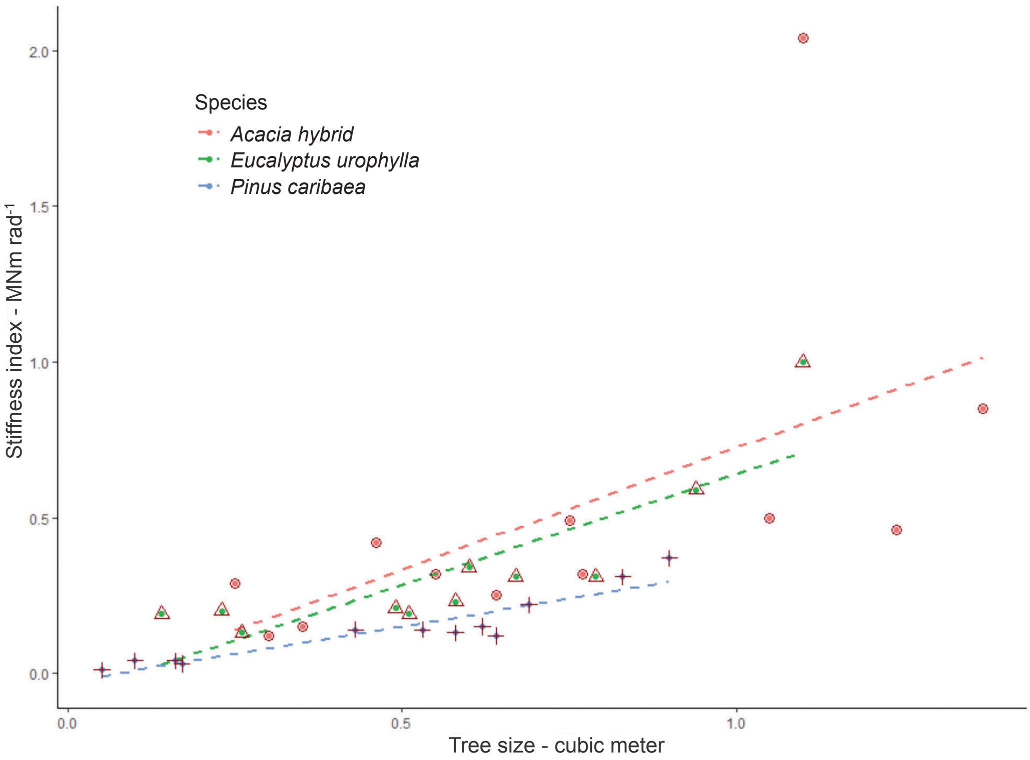

Figure 3 Stiffness index (SI) trend in different species at the research site

to evaluate the magnitude of element impacts on the survival proportion. Based on the AIC value of each model, the best model was selected in which tree size was the most suitable indicator for estimating the risk of tree failure (Table 3). In the Cox model, tree size had a negative coefficient for the risk, thus increasing tree size led to increased survival probability (the tree being more resistant to uprooting or stem breakage). The pulling test confirmed the effect of tree size on TM, as suggested by previous studies carried out in different forest types (e.g. structure and species composition), where tree stability increased substantially with increase in tree size (Cannon et al. 2015, Peltola et al. 1999, Ribeiro et al. 2016). The increase in tree size will require more force to cause the tree to fall. Other factors such as H and TW were not chosen because these factors produced higher AIC value. In the study, tree age was not considered because the planting year was almost the same in each region. In summary, the tree size is one of the most important factors contributing towards the model of tree resistance. There was clear evidence that site influenced tree resistance to uprooting or stem breakage when comparing the hazard ratio of *A.* hybrid among the site groups (Table 4). Site is the primary factor that distributed tree growth and development, and caused the difference between the growth of DBH and H. Moreover, site was considered the controlling factor for unobserved heterogeneity in which there were various factors contributing to TM. For example, water contents inside and below the root plate significantly correlated with TM (Kamimura et al. 2013). Douglas fir grown on mineral soil was better anchored than radiata pine (*Pinus radiata*) in a study conducted in New Zealand (Moore & Gardiner 2001). Gardiner et al. (2000) produced a model for estimating the TM required to break or overturn a tree and found that TM was influenced by site and soil type. Based on the results provided by the National Institute of Agricultural Planning and Projection in Vietnam (2003, 2004), the study sites showed a significant difference in soil type and condition. The main soil type in Dai Lai was Ferralic Acrisols with a thickness of around 70 cm, whereas in Thanh Hoa the main soil type was Ferralsols derived from basalt with thickness from 30 to 50 cm. Therefore, the differences related to soil type and thickness strongly affect the estimated TM. Compared with previous research, the results of the pulling experiment clearly supported the impacts of site on tree resistance to uprooting. Therefore, there is a need to consider the influence of site to build a model for TM or survival probability caused by high wind speed. It is highly recommended that a mixed-effects model of Cox regression is used to identify the variance between the site groups, in which site is treated as a random factor.

The study confirms that tree resistance to uprooting and stem breakage differs among the groups of tree species depending on tree size, and some species were more resistant than others. For instance, for a given tree size, *E. urophylla* was less resistant than *A.* hybrid. In contrast, no significant difference was found when comparing hazard rate between *A.* hybrid and *P. caribaea* in Dai Lai. The decreasing trend of tree resistance to uprooting or stem breakage was clearly seen from 30 to 70 kNm for the three species, and hazard rate of *E. urophylla* was higher compared to *A.* hybrid (Figure 2). A TM over 120 kNm forces trees to fall, and thus this is a limitation of wind resistance for all three species in this study. Differences are influenced by tree characteristics, for example, the variety of wood strength or root components (lateral or tap roots) (Fourcaud et al. 2008). The result did not corroborate with previous studies in which no differences in TM were found between species (Cannon et al. 2015, Peterson & Claassen 2013). However, the finding were in accordance with Ribeiro (2016) in which TM varied among species groups in the Amazon forest based on tree size (e.g. DBH, above-ground biomass,and slenderness). The wind damage of *E. urophylla* was assumed to be larger than that of *A.* hybrid based on tree resistance. However, other factors such as crown form or leaf distribution should be considered when discussing the total wind damage risks at stand level. Another interesting finding was that *E. urophylla* tap-root was easily broken, and this finding was similar to *E. globulus* (Locatelli et al. 2016). In conclusion, it was found that species have a significant impact on the risk of failure, and the combination of species and soil is an important factor contributing to tree resistance to uprooting.

Factors affecting stiffness index (SI)

The other objective of this study was to clarify the impacts of factors such as tree size, TW, site and tree species on SI. It was found that SI was also positively correlated with tree characteristics (tree size, TW and DBH, Table 6). The change of these factors led to the change in SI, in which SI increased with an increase in tree size and showed clear differences among species groups (Table 7). One practical advantage of this finding is that it can be used in modeling to indicate the SI, and to explain the effects of tree characteristics on SI. Kamimura (2012) found that the relationship between SI and H × DBH^2, for uprooted trees by tree-pulling experiments in 2008 and 2009, followed a linear regression. The current results agree with the above research finding. However, together with site effects, the current study proposed scientific evidence for the impact of species. The SI was also strongly dependent on species groups, for example, *A.* hybrid had a high SI value compared with *P. caribaea*. This may be related to the wood properties of the species. The wood of *P. caribaea* is more flexible than that of *A.* hybrid (Figure 5). The average modulus of elasticity

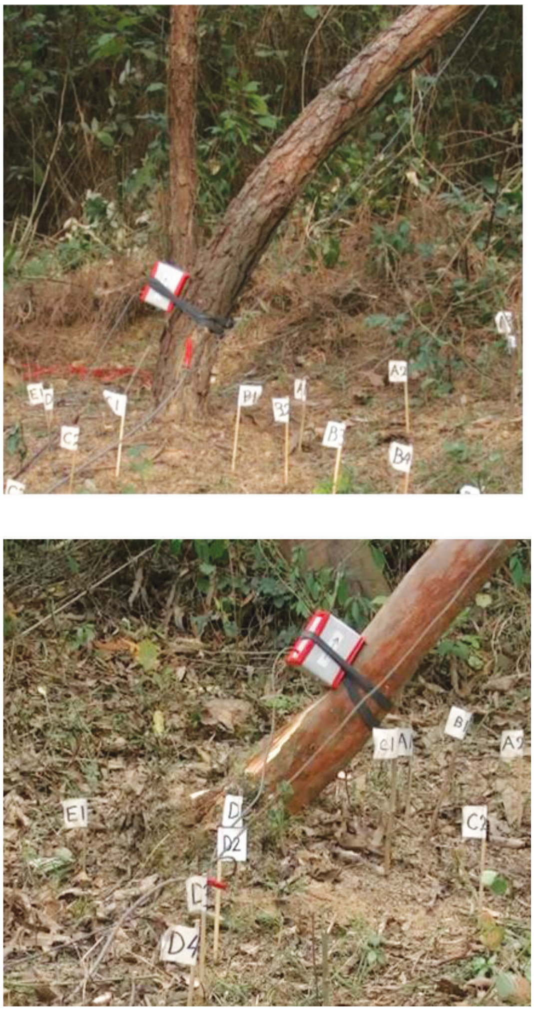

Figure 4 The flexible stem of *Pinus caribaea* (upper image) and tap-root broken of *Eucalyptus urophylla* (lower image) in the pulling experiment

of *P. caribaea* was 9045 MPa, while *A.* hybrid was 9600 MPa (Jusoh et al. 2013, Zangiácomo 2016). Therefore, with a smaller elastic modulus, *P. caribaea* will deflect more than *A.* hybrid under the same load (β has a bigger value). This leads to *P. caribaea* having a smaller SI value under the same TM and tree size. This signal was clearly seen in recorded videos while pulling these tree species. The stem of *P. caribaea* still continued to curve, while that of *A.* hybrid was uprooted or broken. Figure 4 presents images of *P. caribaea* stem and tap-root of *E. urophylla* under maximum load in the pulling test.

CONCLUSION

This study describes the relationship between tree characteristics or site, and survival probability and SI of three major forest plantations in Vietnam based on a tree pulling experiment. The results provided the Cox hazard proportion that can be used to predict the risk of tree failure. The first objective showed comparison of anchorage between exotic species (*A.* hybrid, *E. urophylla* and *P. caribaea*) in a tropical monsoon climate forest plantation. The data analysis revealed that the hazard ratio in the model of tree failure and SI were governed by tree size attributes, and varied among tree species and site properties. The results clearly indicated that increase of tree size promoted tree stability, and led to increased SI value by applying fixed and random effects on modeling. In addition, the study also evaluated the impact of species on SI value, depending on multiple regression model between SI and tree size. The study, therefore, contributes knowledge about the role of tree characteristics related to resistance to uprooting (SI value). Based on the findings, it is strongly recommended that tree pulling experiments are established for each combination of species and soil grouping, and the different characteristics of tropical species that contribute towards tree resistance to uprooting or stem breaking should also be considered.

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