



Wind damage risk for Acacia plantations in Thua Thien Hue province of Vietnam

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Supported by:



Federal Ministry
for the Environment, Nature Conservation,
Building and Nuclear Safety

based on a decision of the German Bundestag

Acknowledgment

This work was financed by the German International Climate Initiative (ICI) by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). Technical assistance provided by UNIQUE forestry and land use

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Date: 15.09.2017

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LIST OF ABBREVIATIONS

AH	<i>Acacia</i> hybrid
AM	<i>Acacia mangium</i>
AOI	Area(s) Of Interest
C_{reg}	Coefficient of linear regressions of total overturning moment against stem weight under different soil types and rooting depths
CWS	Critical Wind Speed
DAMS	Detailed Aspect Method of Scoring (measure of windiness of a site used in Britain)
Dbh	Diameter at breast height (1.3m)
DEM	Digital Elevation Model
EG	<i>Eucalyptus globulus</i>
ENSO	El-Niño – Southern Oscillation
FIPI	Vietnamese Forest Inventory and Planning Institute
GCM	Global Climate Model
GIS	Geographic Information System
GoV	Government of Viet Nam
ICI	Finnish Institutional Cooperation Instrument
IMHEN	Vietnam's Institute of Meteorology, Hydrology and Environment
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
MAI	Mean Annual Increment
MARD	Vietnamese Ministry of Agriculture and Rural Development
MOE	Modulus of Elasticity
MONRE	Vietnamese Ministry of Natural Resources and Environment
MOR	Modulus of Rupture

NASA GEOS-5	National Aeronautics and Space Administration Goddard Earth Observing System Model, Version 5
PF	Protection Forests
QGIS	Quantum Geographic Information System
SI _x	Site Index at age x
SO	Southern Oscillation
SF	Special Forests
Sph	Stems per hectare
SRES	Special Report Emissions Scenarios
SST	Sea Surface Temperature
TMC	Turning Moment Coefficient
VFU	Viet Nam Forest University
WAsP	Wind Atlas Analysis and Application Program
WebGL	Web Graphics Library

EXECUTIVE SUMMARY

The Vietnamese commercial forestry sector is heavily reliant on plantations of *Acacia mangium* and hybrid *Acacia*, which currently cover an area within the country of over 1Mha. Currently, these species are mostly used for pulpwood and chipwood, but have potential for saw logs and veneer production. In line with the Forestry Development Strategy 2006 – 2020 and related policies the Government of Viet Nam (GoV) aims at tapping these potentials in order to increase the sector contribution to the economy. Another reason is a growing export-oriented garden furniture industry which currently has to import more than half of the timber from across the globe, as its demand outweighs domestic production by far.

Acacia plantations periodically suffer from wind damage caused by the strong tropical cyclones making landfall in the the country, causing extensive losses and resulting in unpredictable fluctuations within the international pulp and chip wood markets. The GoV seeks to promote sustainable forest management practices aimed at carbon sequestration in a REDD+ framework, while reducing the impact of wood products market fluctuations. One approach to achieving these objectives is to increase the commercial value of the *Acacia* spp. plantations. To this aim, efforts include the exploration and development of alternative species, genotypes, and forest management practices that can maximise yield while reducing the risk of wind damage.

ForestGALES is the industry-standard wind damage risk model, initially developed for commercial conifer plantations in the UK and subsequently expanded and parametrised for a broad variety of tree species. It is an essential component of forest management decision support systems in the UK and has been adopted in a number of countries by the industry and the scientific research community alike. The model's portability to different environmental conditions, together with its ability to be coupled with growth tables and models and with widely adopted airflow models in a spatially explicit setting, make ForestGALES an ideal tool to aid management of Vietnamese *Acacia* plantations to reduce the risk of wind damage.

This study includes a case study focusing on Central Viet Nam Province of Thua Thien Hue, using the best data that could be obtained at this stage. It has confirmed the suitability of ForestGALES to Vietnamese conditions, and highlighted the requirements for further steps to adapt the model to meet the requirements of forest planners and managers in the country. The lack of both *Acacia* growth models and tree-pulling studies required to parametrise ForestGALES will need to be addressed in a follow-up phase of this work. In addition (and particularly if the work is to be scaled up to cover a wider area of Viet Nam), detailed plantation maps and higher quality data from weather stations will be required.

Overall, however, this study's findings bodes well for future work to focus on building a version of ForestGALES tailored to conditions typical of Vietnamese plantations of *Acacia* spp.

1 INTRODUCTION

The forest plantation sector in Viet Nam is predominantly reliant on *Acacia* species and selected hybrids, which currently cover a total area of about 1.1Mha (Nambiar et al., 2015). The forest management practices currently in place favour short *Acacia* rotations (typically between 4 – 7 years) without thinning, aimed at the production of pulp and chip wood. The GoV aims to increase the commercial potential of plantations, promote sustainable forest management including carbon sequestration in a REDD+ framework, and to reduce the risk from fluctuations within the international pulp and chip wood markets.

In order to achieve these objectives, the exploration and development of alternative management practices and different genotypes to promote timber production for saw logs have been promoted (e.g. FIPI, 1995; MARD, 2003; Pistorius et al., 2016). The response of the scientific community (e.g. Hinh, 1999) has focussed on the study and modelling of the growth potential and limitations of *Acacia* spp. in Viet Nam and in the broader Southeast Asia area (e.g. Krisnawati et al., 2011; Huong et al., 2016), partly through international collaborations with European institutions and governmental departments (e.g. Eerikäinen et al., 2012). One such ongoing collaboration is a project supported through the German International Climate Initiative with funds from the German Federal Ministry for the Environment (BMUB): UNIQUE forestry and land use, ClimateFocus, and the Institute of Resources and Environment (IREN) of Hue University have developed restoration business models for short-rotation *Acacia* stands in the North-Central Coast region of Viet Nam.

An initial aim of this collaboration is to improve and differentiate management practices such as different thinning regimes in existing *Acacia* plantations in Thua Thien Hue province to promote optimal tree growth for saw logs production. A major constraint to the successful development and implementation of such practices is the periodic wind damage reported in local *Acacia* plantations due to strong winds associated with extreme weather events, especially tropical storms and typhoons (Pistorius et al., 2016). There are concerns that changes silviculture will lead to increased damage. In fact, it is well known that the risk of wind damage increases greatly immediately after thinning, and typically persists for the thinned stand for quite some time following the intervention. The higher risk is sustained until the trees adapt to the new conditions by growing stronger stems, restoring pre-thinning conditions of canopy closure, and improving the strength of the root-soil anchorage (e.g. Gardiner and Quine, 2000; Kamimura et al., 2008).

While most of Viet Nam typically experiences a tropical monsoonal climate (MONRE, 2016), the spatial and temporal variability of the climate and weather patterns of Viet Nam constitute the main challenges to the forecasting of extremes such as tropical storms and typhoons (Van Tan, 2002). These extreme manifestations of tropical cyclones are driven by a complex system of environmental variables, such as sea surface temperature, and circulation patterns over the Pacific Ocean. The effect of the El Niño – Southern Oscillation coupling (ENSO) on the climate of Viet Nam is large, and has a heavy influence on the pattern of tropical cyclones (Suppiah and Thang, 2014). Climate projections predict a small decrease in the total number of tropical cyclones over the country, but with a larger proportion of high-speed wind events (Nguyen et al., 2014).

Because of the large latitudinal range of the country, current and forecasted climate conditions are quite heterogeneous between the various provinces (IMHEN and UNDP, 2015). The spatial and temporal variability of tropical storms and typhoons, combined with the large topographical complexity of the Vietnamese territory, contribute to the complex effect of local circulation patterns observed in the country on forests and plantations (Tan et al., 2009).

The field of academic research into the impacts of wind on forests and plantations is advanced and active, with a relatively small but focused group of scientists around the world with a strong record of collaboration, and well distributed across the different aspects of the issue and related disciplines (for a recent review see Gardiner et al., 2016). Substantial efforts have been devoted to understanding wind damage in temperate and boreal regions of the world where large-scale conifer plantation forestry is affected by periodic damage, towards the development of models for the prediction of wind damage risk and of improved forest management practices for the mitigation of such risk (e.g. Gardiner et al., 2000; Hanewinkel et al., 2011; Hale et al., 2015).

In the last few decades, the successful development of portable, process-based models that describe the mechanistic relationships between the wind climate and tree and stand characteristics has led to changed practice by forest management communities in a number of countries (e.g. in the UK: Nicoll et al., 2015; in Canada: Mitchell and Ruel, 2015). The most widely adopted mechanistic model for the prediction of wind damage risk in forested stands is ForestGALES (Hale et al., 2015). The model, developed by a team at Forest Research near Edinburgh, UK, was originally parameterised for a range of conifer species growing under conditions typical of British forestry (Nicoll et al., 2006).

The model has in recent years been parameterised for conifer species growing in other parts of the world, and recently for *Eucalyptus globulus* (Labill.) plantations growing in the Iberian peninsula (Locatelli et al., 2016). Kamimura et al. (2008) have shown the flexibility and portability of ForestGALES in their study of typhoon damage to *sugi* trees (*Cryptomeria japonica*) in Japan, successfully coupling ForestGALES with WAsP (Wind Atlas Analysis and Application Program). WAsP is an airflow model for wind resource assessment developed by the Department of Wind Energy at the Technical University of Denmark that allows for wind modelling at the meso- and micro-scales, and therefore is ideal for applications in forest wind risk management.

This report consists of two parts: a desk study and a case study. The review describes the available information on the Vietnamese climate and the growth characteristics of the *Acacia* spp. extensively planted in Viet Nam, with a special focus on the conditions in Thua Thien Hue Province within the North Central Coast (NCC) of Viet Nam, aimed at exploring the potential for the application of the ForestGALES wind-risk model to *Acacia* plantations in the area. This is followed by a brief description of the ForestGALES' model architecture, its applications and data requirements. The information on the current state of *Acacia* plantations in Viet Nam and Southeast Asia is then reviewed, and the availability of growth and yield models necessary for the application of ForestGALES are explored. The current and forecasted climate and weather patterns for Viet Nam as a whole, and NCC including Hue Province, are then summarised. The review part of the report concludes with a brief discussion of the opportunities and challenges for wind risk assessment to *Acacia* plantations in Vietnam.

The second part of the report describes a case study designed to: demonstrate the use of ForestGALES in a spatial setting; demonstrate the adaptability of ForestGALES to conditions typical of Vietnamese plantations; indicate the next steps required to build a working version of

ForestGALES for application in Vietnam; and finally to explore the potential to scale-up to large areas in Vietnam. The report ends by providing some initial recommendations on forest management in the Thua Thien Hue province to reduce the risk of wind damage to local plantations.

2 THE WIND-RISK MODEL FORESTGALES

ForestGALES is a quantitative, semi-mechanistic, probabilistic and predictive model of wind risk damage to forest stands. It is semi-mechanistic in that some components of the model that describe tree characteristics, and the calculations of the uprooting moment, are based on experimental data rather than on engineering principles.

Aside from the most common conifer species commercially grown in Britain, the model has been parameterised for conifer species in Canada, Denmark, France, Japan, and New Zealand (Byrne, 2005; Cucchi et al., 2005; Kamimura et al., 2008; Mikkelsen, 2007; Moore and Somerville, 1998; Ruel et al., 2000). As previously mentioned, Locatelli et al. (2016) have recently parameterised ForestGALES for *E. globulus* grown in Iberian Peninsula, the first instance of the parameterisation of a broadleaf species.

ForestGALES requires a small set of inputs, summarised in Table 1. Variables include tree and stand characteristics and an estimate of the prevailing wind climate.

Table 1 - ForestGALES input variables

Variable	Variable description	Comments
Top height	Height of the tallest tree(s) in a stand	When top height data is not available, mean tree height can be used.
Dbh	Mean diameter at breast height (1.3m)	One of the most important variables driving the distinction between modes of failure: breakage vs overturning.
Sph	Stocking density	Alternatively: mean tree spacing.
Soil type	Predominant soil type in the stand	Soil grouping in ForestGALES based on typical conditions in temperate and boreal forests.
Rooting depth	Predominant depth of rooting system in the stand	Rooting depth affects the anchorage of the trees. The current version of ForestGALES differentiates between “shallow” (<80cm) and “deep” rooting (>80cm).
Gap size	Size of largest upwind gap adjacent to the stand	Complex effect on airflow over canopy – affects the calculation of mean wind loading (Poëtte et al. 2017).
DAMS/Wind speed distribution parameters	An estimate of the prevailing winds	DAMS scores Available for Britain only. Alternative is to use Weibull A and k parameters of distribution of prevailing winds.

For British sites, the prevailing wind climate is normally described with DAMS scores (Detailed Aspects Method of Scoring). These describe the windiness of a site based on topographic characteristics and wind zone, and are only available for Britain (Quine and White, 1994). Alternatively, shape and scale parameters of a Weibull distribution fitted to time series of local wind speed data can be used when DAMS scores are not available (Quine, 2000). Since most calculations in the model are based on species-specific values and allometric calculations, tree

species serves as a trigger and must be specified together with the other inputs. The original and most common version of ForestGALES is sometimes referred to as the “roughness” method (Hale et al., 2015). In this approach, the wind momentum stress (Raupach, 1994), acting on the rough canopy surface of a stand, is partitioned between trees to calculate the stress on individual trees. These calculations are then corrected for the effect of gust winds. Recently, Hale et al. (2012) have proposed an alternative method, referred to as the “turning moment coefficient” (TMC), calculated from stem volume and influenced by competition with neighbouring trees, which removes the need to account for gust winds by focussing on single trees characteristics.

This new method has been validated by Hale et al. (2015) and current efforts are focussed on expanding the applicability of the methods to different species. The main advantage of the TMC version of the model is that it can be used in irregular and mixed stands, and can deal with more complex and realistic silvicultural management practices than the original method. Regardless of the version of the model, ForestGALES is composed of two main modules: GALES, where the critical wind speeds for stem breakage and uprooting are calculated, and a “Wind Climate” module (WCM), where the probabilities of damage and the return periods of critical wind speeds (from ForestGALES) are calculated from information on the local wind climate.

The rationale of the model can be summarised as:

1. the model estimates the moments required for breaking or uprooting the average tree in the stand (roughness method) or individual trees (TMC method) – GALES module;
2. the Critical Wind Speeds (CWS) to generate such moments are calculated – GALES module;
3. the probabilities of exceeding these CWS under the local wind climate are estimated – Wind Climate module).

The diagram in Figure 1 shows a simplified structure of the model from the viewpoint of the user input variables. The main differences between the ‘roughness’ and the TMC method are shown.

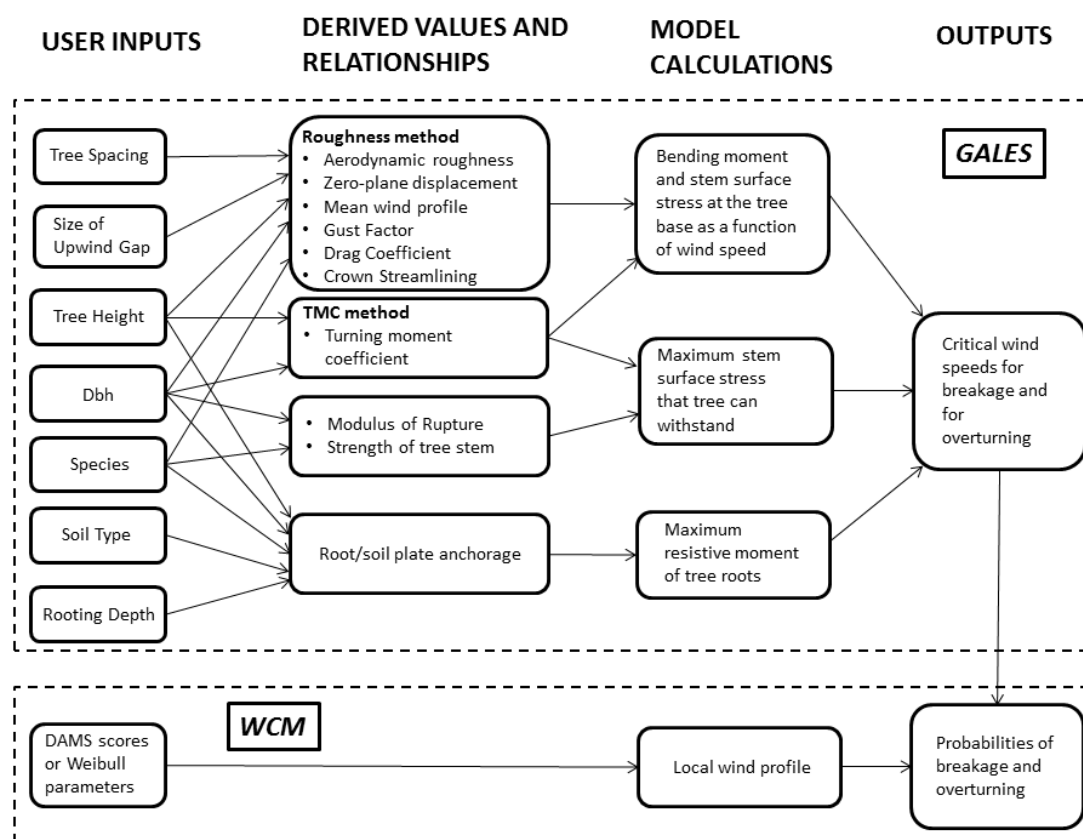


Figure 1 - Basic schematic of the structure and rationale of ForestGALES (adapted from Gardiner et al., 2000). The dashed boxes delimit the two main modules that compose ForestGALES. The GALES module calculates the critical wind speeds for breakage and overturning. WCM: Wind Climate Module, where the probabilities of breakage and overturning are calculated.

Soil type and rooting depth data are incorporated into the model to calculate the critical uprooting moment, while the Modulus of Rupture (*MOR*) of green wood is used in the calculation of the critical breaking moment (Gardiner et al., 2000). The term ‘critical’ here refers to the moment of the force required for overturning or breaking the stem of the tree, respectively. The critical overturning and breaking moments are then used in the GALES module for the calculations of the corresponding critical wind speeds that would cause damage, by translating these into the forces on the trees that would match or exceed the critical damage moments. *MOR* is derived from the literature or from destructive bending tests. Resistance to breakage is also influenced by the presence of wood knots that can decrease wood strength (Lavers, 1969). The effect of these is accounted for in ForestGALES with a dimensionless species-specific multiplier (Ruel et al., 2010).

In ForestGALES, soil types are broadly grouped on the basis of their draining potential and mineral content (Avery, 1990; Kennedy, 2002), as shown in Table 2. Two rooting depths (shallow: < 80 cm; and deep: > 80 cm) complement the soil type data. The four soil groups and two rooting depths represent the columns and rows of a table populated with empirically derived values of the overturning moment multipliers. These multipliers (C_{reg}) are species-specific coefficients of

linear regressions of total overturning moment, as measured empirically in the field, against stem weight under different soil types and rooting depths (Nicoll et al., 2006). For the first versions of ForestGALES, a large tree-pulling database (~2,000 trees) assembled in the UK by Forest Research was used to calculate C_{reg} values for the most common conifer species planted in Britain (Nicoll et al, 2006).

Table 2 - Soil classification used in ForestGALES. Soil classification based on Avery (1990) and Kennedy (2002).

A	B	C	D
Freely-draining mineral soils	Gleyed mineral soils	Peaty mineral soils	Deep peats
Brown earth (freely-draining)	Ironpan (gleyed)	Ironpan (peaty)	Juncus (or basin) bogs
Ironpan (freely-draining)	Podzol (gleyed)	Podzol (peaty)	Molinia (or flushed blanket) bogs
Podzol (freely-draining)	Brown earth (gleyed)	Peaty gley	Sphagnum (or flat or raised) bogs
Calcareous soil	Surface-water gley		Unflushed blanket bog
Rankers and skeletal soils	Ground-water gley		Eroded bog
Littoral soils			
Man-made soils			

In practice, C_{reg} values are not available for all combinations of species*soil types*rooting depths, due to the environmental conditions of the areas where the tree-pulling tests required for parameterisation of a new species were conducted. Additional fieldwork is normally required to obtain C_{reg} values for missing combinations, as for *E. globulus* (Locatelli et al., 2016). However, values of C_{reg} of similar species are often used for the missing combinations of soil types and rooting depth, these similarities being in wood properties, canopy dimensions and foliar density, and root system architecture, as in the case of maritime pine (*Pinus pinaster* (Ait.)) and Scots pine (*Pinus sylvestris* (L.)) (Gardiner et al., 2000).

Occasionally, when C_{reg} values for a species are only available for certain soil type*rooting depth combinations, the missing values of interest for such species have been calculated by multiplying one of its known C_{reg} values by a ratio calculated between C_{reg} values of a species with a complete set of combinations, such as Sitka Spruce. This approach stems from the assumption that the proportionality of the resistance to overturning across combinations of soil type*rooting depth is the same for different species.

Rooting depth is treated as a discrete parameter in ForestGALES, and varies with species and soil properties, such as induration (e.g. Cucchi et al., 2005). It is well known that the presence of an upwind gap typically increases the risk of wind damage to downwind forested stands (e.g. Somerville, 1989). This is particularly true for newly created gaps, such as when a stand is harvested, exposing the trees at the edge of neighbouring stands to completely different wind loadings which they sometimes have little time to acclimate to (Quine et al., 1995). However, trees acclimate to an altered wind regime over time, and trees that are acclimated to pre-

existing edges are considered to be at no greater risk than trees well inside the forest (Morgan and Cannell, 1994).

Recently, Poëtte et al. (2017) in their study of the effect of landscape fragmentation on airflow around forest canopies have shown the complex effect of gap creation on horizontal wind velocity and turbulence. They concluded that small gaps within a forest (gap-to-forest ratio $\leq \frac{1}{2}$) do not dramatically change the airflow around the forest canopy, but do decrease the mean wind loading on a tree. It is not immediately clear however what the effect would be of creating frequent, multiple gaps within a plantation, such as in the business models proposed in Pistorius et al. (2016). From the point of view of airflow within the canopy, very small (equal to about 1 tree height) and frequent gaps do not have large effects. Poëtte et al. (2017) verified that forests with large gaps (gap-to-forest ratio ≥ 3.5) behave like isolated forests, while intermediate values of gap-to-forest ratio experience some influence from the previous forest patch. In their numerical simulation study with Monte Carlo methods, Zeng et al. (2009) concluded that forest fragmentation has the potential to increase the risk of wind damage in boreal forests at both patch and landscape levels.

Lastly, the probability of winds exceeding the CWS requires knowledge of the average windiness of the site. For sites in Britain, this is done by converting DAMS scores for the site of interest to the scale and shape parameters of a Weibull distribution. The scale parameter has wind speed units and is indicative of the average wind speed of the distribution, while the shape parameter (≥ 1) defines the skewness of the distribution, with typical values between ~ 2 and ~ 3 for wind speed data (Badger et al., 2015). When DAMS data are not available, high resolution local wind data are fitted to a Weibull distribution and the distribution parameters are extracted directly. Weibull distributions have been used for several decades to describe distributions of wind speed and directions (Justus et al., 1978), and this was confirmed in a recent review as remaining the most reliable method for such purposes (Seguro and Lambert, 2000). In addition to this, Weibull distributions allow for values obtained at an anemometer's altitude to be effectively extrapolated to other altitudes (Justus et al., 1978).

Because of the large sensitivity of the Weibull distribution, small changes in CWS result in large differences in the probability of extreme events (Gardiner et al., 2008). Once the probability of wind damage for a site has been determined from the Weibull distribution parameters, return periods of extreme events can be calculated in ForestGALES simply as the inverse of the probability. Therefore the model can help with decisions on when forest management procedures such as thinning should be performed, e.g. for forest stability or to maximise financial gain (Gardiner and Quine, 2000).

The Weibull parameters values can be used in an airflow model such as WASP to account for local topography and changes in roughness surface values (e.g. from water, to grassland, to forest canopies) to produce estimates for the forest (Kamimura et al., 2015). The WASP software can operate from either wind data recorded at meteorological stations within the same region of interest (typically less than 50 km from the forest), or from wind climate "libraries" generated from mesoscale modelling (Badger et al., 2015). The approach to airflow modelling used in WASP is first to perform a regional climate normalisation, whereby the effects of coarse-detailed local topography and roughness are removed, thereby producing 'normalised' wind conditions. The fitting of the wind data to a Weibull distribution is typically done for 12 wind direction sectors

for 5 standard heights above ground level (10m, 25m, 50m, 100m, and 200m) and 5 standard roughness lengths (0.0002m – for water, 0.03m, 0.1m, 0.4m, 1.5m). Secondly, the detailed topography (e.g. from Digital Elevation Models) and changes in roughness length (e.g. from aerial orthophotography, updated digital maps, or field surveys) are applied to calculate the local, micro-scale wind climate.

2.1 Limitations of ForestGALES

Besides being based on a set of assumptions, every model has its limitations, and ForestGALES is no exception. In this section the model's limitations are listed and briefly discussed.

- The model outputs are binary. That is, ForestGALES is not able to calculate probabilities of different levels of damage, but rather provides the user with either no damage to the stand ('roughness' method) or tree (TMC method), or complete damage. This is due to a number of reasons, some related to data availability issues and others to model structure.
- The model is quasi-static, in that it is not able to model the propagating wind loading on downwind trees that is experienced after upwind trees fail under the wind action. Byrne and Mitchell (2013) have attempted to solve this issue by coupling a modified version of the model, called ForestGALES_BC (Byrne, 2005) with the ArcView extension WINDFIRM. By running the coupled model iteratively it is possible to mimic the changes in the overall canopy structure of a stand exposed to a storm as the trees progressively fail under the changing wind loading (Gardiner et al., 2008).
- As previously mentioned, values of regression coefficients of uprooting moment against stem weight (C_{reg}) are not available for all combinations of rooting depth and soil type. Obviously, neither the values directly borrowed from similar species, nor those calculated with the known C_{reg} ratios of other species, have been experimentally tested.
- For the 'roughness' method, the calculations of gap, edge, and gust factors, experimentally derived, are based on very small datasets. Hence, the uncertainty associated with these is potentially large.
- The taper functions used in the calculations of tree stem mass and branch width are based on a generic tapered column shape rather than on species-specific taper equations. As a consequence, stem weight (used in the calculation of the overturning moments), stem mass (used in the calculation of the wind speeds responsible for stem breakage and overturning), and canopy weight (used in the calculation of the additional turning moment provided by the canopy), might be over- or under-estimated.
- With regards to the calculated outputs of the model, the confidence range of the application of ForestGALES is restricted to the range of tree dimensions (i.e., height and Dbh) of the experimental trees tested during tree-pulling. Very short trees (height < 5m) are typically excluded from tree-pulling experiments, due to the flexibility of their stem. In fact, very small trees are normally pulled vertically to measure their resistance to uprooting (e.g. Mokotedi et al., 2010).
- Complete validation of wind risk models such as ForestGALES has been difficult because of the relative infrequency of severe, damaging windstorms in tropical and boreal forests. Moreover, model validation requires knowledge of the variables required for the simulations, such as stand and tree characteristics of the affected areas, and accurate values of the wind

speeds experienced during the event. However, a partial validation was provided by Hale et al. (2015) based on storm damage to conifer plantations in central Scotland, and by Kamimura (2007) for Japan.

3 ACACIA SPP. IN SOUTHEAST ASIA

This section explores the available information on growth properties of *Acacia* spp. in Viet Nam and other areas in Southeast Asia where these species are grown extensively in plantations. Special attention is given to reviewing the available growth and yield models, which are a core requirement for modelling tree characteristics necessary for the application of ForestGALES to these species.

In the first part of this section we review the literature on growth properties and patterns of *Acacia* spp. for different areas in Southeast Asia including Viet Nam, and in the second part we describe the available growth and yield models for these species in these areas.

3.1 Growth and yield properties

Acacia spp. are planted from latitudes of 10°N and 22°N, and have quickly become prominent tree plantation crops in Viet Nam, grown predominantly for the production of pulpwood, and occasionally but increasingly for saw logs. Nambiar et al. (2015) reported that in 1992 *Acacia* plantations contributed only about 7% (~65,000 ha) of the total plantation area in Viet Nam (~915,000 ha), while by 2005 at least 500,000 ha of new *Acacia* plantations had been established. This is consistent with the figures provided by Kha (2001) who reports that at the beginning of the 2000s *Acacia* spp. covered about 400,000 ha. The growing stock of these species had expanded to cover an area of about 1.1 Mha in 2013, corresponding to ~51% of the total plantation area in Viet Nam, and yielded about 10 Mm³ of harvested wood (Nambiar et al., 2015). The biggest market for *Acacia* products is pulpwood, especially woodchip, which contributes to a large part of the international exports from the Vietnamese forestry sector. Under suitable conditions, *Acacia* spp. can provide good wood for furniture (Harwood et al., 2012), which is becoming a priority for forest growers because of the heavy reliance of the Vietnamese furniture-making and export sector on international imports: in 2013 ~80% of logs for were imported, and in 2012 the logs imports were valued at ~ US\$930M (Nambiar et al., 2015).

Acacia plantations in Viet Nam consist largely of one pure species (*Acacia mangium* (Willd.)) and one hybrid (*A. mangium* x *Acacia auriculiformis* (A.Cunn. ex Benth.)). The native habitats of *A. mangium* are in northern Australia and Papua New Guinea (Sein and Mitlöhner 2011a), and this species was introduced to southern Viet Nam in the 1960s before spreading to the northern territories in the early 1980s (Nambiar et al., 2015). The naturally occurring hybrid (*A. mangium* x *Acacia auriculiformis*) was first discovered in Malaysia in 1972 (Kim et al., 2009) and because of its superior traits was quickly adopted in other countries within Southeast Asia.

Development of *Acacia* hybrid clones began in Viet Nam in 1992 from occasional hybridisation found in *A. mangium* plantations, and to date most hybrid genotypes come from open pollination by *A. auriculiformis* growing near *A. mangium* plantations (Harwood et al., 2012). For a period in the mid-2000s, the *Acacia* hybrid had become the most extensively planted *Acacia* in Viet Nam (~220,000ha out of ~400,000ha of total *Acacia* plantations) (Sein and Mitlöhner 2011b), while the most recent figures place the hybrid slightly behind the parent *A. mangium* in terms of plantation area (~400,000ha and ~500,000ha, respectively) (Nambiar et al., 2015). This might be due to improved genetic selection and breeding programmes of *A. mangium* seeds,

which result in very similar yields to those of the hybrid (Harwood et al., 2012). However, under typical conditions *Acacia* hybrid shows marked heterosis, as it produces larger pulp yields with superior paper quality, grows straighter stems, and exhibits growth rates twice as high as those of its parental species, especially when *A. auriculiformis* is the female parent (Kim et al., 2009). Because of the large longitudinal extension of Viet Nam, different climatic conditions affect tree growth differently in different regions, with conditions generally becoming more favourable from the North to the South, irrespectively of species, or seed origin (Kim et al., 2011), resulting in highly variable growth rates. The growth of *Acacia* spp. is stunted by low rainfall and cool temperature (Turnbull et al., 1998), and mortality in plantations is known to be high after severe droughts or prolonged low (5 – 6°C) temperatures (Zhigang and Minquan, 1987).

However, while *Acacia* spp. are predominantly grown in lowlands (<600m asl), the influence of topography on the local climate and consequently on the growth of *Acacia* spp. is not to be underestimated, as shown by Hung et al. (2016). The authors report that volume mean annual increment (MAI) for *Acacia* hybrid plantations typically range between 10 and 25 m³ha⁻¹yr⁻¹, being lower in the North than in the south (17.6 vs 23.0 m³ha⁻¹yr⁻¹, respectively), and lowest in central Viet Nam (11.0 m³ha⁻¹yr⁻¹), which might be ascribable to the complex topographic features of the region. However, much higher levels (20.0 – 28.7 m³ha⁻¹yr⁻¹) have been reported for *Acacia* hybrid plantations in Hue province (Dong et al., 2014).

The variability of the topography is correlated with latitude, and shows complex interactions with different land uses, soil types, and ownership, with very different effects in terms of *Acacia* productivity. *Acacia* spp. grow well on very different soil types, from the shallow ferrasols in the mountainous areas of the North Central areas, to the deeper old alluvial sediments in the South, which as expected support higher volume MAI (Harwood et al., 2012). The steep hilly slopes of the North and Central regions are used for *Acacia* plantations, because the flatter land is reserved for agricultural use.

Growth rates and productivity vary largely with position up the slope, with the lowest increments (16.5 m³ha⁻¹yr⁻¹) found at the top, and the highest increments (25 m³ha⁻¹yr⁻¹) obtained at the bottom (Harwood et al., 2014). This phenomenon is likely to be at least partially due to soil run-off typical of short rotation forestry on steep slopes (Hung et al., 2016), likely resulting in deeper, more fertile soils at the bottom of the slopes (Sam, 2001). The small parcels found on these hills reflect the larger proportion of small growers – who own about ~50% of the nationwide *Acacia* resources – in these areas than in the South, where larger plantations owned by public and private agencies are grown on moderately steep to relatively flat land (Nambiar et al., 2015).

3.1.2 Silviculture of *Acacia* spp. in Vietnam

Acacia plantations are mostly grown for pulpwood, and marginally for production of saw logs, and are managed very differently according to the objective. Differences pertain to the length of the rotation and to the initial spacing between planted trees. For *A. mangium* in Viet Nam, the Ministry of Agriculture and Rural Development (MARD) recommends a 3m x 3m (*between rows x between plants*) spacing (i.e. ~1,111sph), or 3m x 2m (~1,666) for pulpwood, while narrower spacings of about 2m x 2m or 2.5m x 2.5m are not uncommon to discourage the growth of epicormic branches, since this species displays poor self-pruning tendencies; however, for saw

logs production planting at 3.5m x 3.5m spacing is adopted to promote stem diameter growth (CARD, 2005).

A possible consequence of applying wide initial planting for saw logs or veneer production is that singling (the practice of removing non-dominant leaders) might become necessary, because *Acacia* do not self-single and have a tendency to develop multiple leaders (Krisnawati et al., 2011). Singling, like pruning, increases the risk of infections to the stem (e.g. heart rot, caused by wound basidiomycete parasites, commonly known as white fungi), which while normally localised in young trees, can become extensive in mature trees (Orwa et al., 2009). Beadle et al. (2013) report that tropical *Acacia* spp. require to be planted at densities over 1,000sph to encourage adequate tree form and apical dominance. For this reason, forest management for saw logs require that the initial establishment of the stand is done at reasonably high densities.

For pulpwood production, thinning and pruning are not necessary, while they are encouraged for the production of saw or veneer logs. For timber, three thinnings are normally recommended, at 3, 5, and 7 years (from ~900sph to 200-300sph). For pulpwood, one thinning at 18 months is recommended to reduce stockings from 1250sph to 600-700sph (Sein and Mitlöhner, 2011a), although this practice is seldom implemented. *A. mangium* trees grown in commercial plantations exhibit distinct growth tendencies for Dbh and tree height. In a good site, in the first 3 years, a rapid increase in Dbh ($>4 \text{ cm yr}^{-1}$) until ~15cm, and a similar increase in height ($>4 \text{ m yr}^{-1}$) up to 10 – 15 m are expected. The rate of Dbh increment gradually slows ($1.5 - 2 \text{ cm yr}^{-1}$) until the 5th year of the rotation before levelling off at around 8 years of age, while height increments show an increase relatively faster than that of Dbh up to ~25m at approximately age 5 ($2 - 2.5 \text{ m yr}^{-1}$), before levelling off (Krisnawati et al., 2011).

The *Acacia* hybrid has received increased attention from private companies and the public sector, with 19 clones approved for plantations by MARD in 2008. These clones feature different genotypes that are suitable for a number of desirable traits, following a process of selection from phenotypical traits, coppicing, clonal propagation via rooted stem cuttings, and field trials before being approved by MARD. Selection traits can be assessed at a tree age between 3 and 5 years, e.g. by Dbh mensuration, extraction and analysis of stem disks or cores, or by pilodyn penetration at breast height, a method for estimation of whole-tree basic wood density at harvest age (Harwood et al., 2012).

Typically, the most important traits include ease of rooting, growth rate, branch size (for knots), stem form, and susceptibility to pest and disease (Nambiar et al., 2015). Of the 19 MARD-approved clones, only six are widely adopted by growers. One reason for this low uptake ratio is due to the skewed Vietnamese commercial system that favours plantations for pulpwood. In fact, while all growers choose clones that guarantee high wood density and large yields, production for pulpwood shows a preference for genotypes with high pulping quality.

Contrarily, producers of sawn timber typically select against knot-related defects, while seeking clones that can provide high wood stiffness and hardness, and proportion of heartwood. In Viet Nam, the selection of the appropriate *Acacia* hybrid clone types in relation to the local environment is of great importance, due to the heterogeneity of topography, soils, and local climate (Harwood et al., 2012). The effects of these environmental traits on the variability of rainfall and the severity and duration of droughts – which can sometimes last for five consecutive months– combined with a wide range of temperatures and soil fertility in different parts of the country, provide serious challenges to achieving and maintaining high productivity

in plantations of *Acacia* hybrid. However, for these same peculiarities of the Vietnamese territory, in locations in central Viet Nam trees typically exhibit symptoms of only mild water stress even at the end of the dry season (Hung et al., 2016). This might suggest superiority of *Acacia* hybrid to at least one of its parental species, *A. auriculiformis*, which typically shows reduced growth rates during the dry season in South Viet Nam (Huong and Binh, 2008). Thinning practices can positively affect the soil moisture available to the retained trees, as tree water stress decreases with reduced stand-level transpiration and canopy rainfall interception (Huong et al., 2016).

Harwood et al. (2012) describe the average *Acacia* hybrid rotations in Viet Nam as being 5 years in length for pulpwood production on productive sites and 12 years on poorer sites, while for saw logs extraction rotations of 12 years are carried out on productive sites. Kha (2000) reports that *Acacia* hybrid can reach annual volume increments twice as large as those of its parental species. On a productive site in South Viet Nam, productivity in a 5 years rotation at 3m x 2m spacing exceeded $30 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$. The authors report differences between average *A. mangium* and *Acacia* hybrid plantations, related to latitudinal location of the sites, with the former reaching 26% shorter mean height at 4 years of age than the latter in the North. Differences in productivity show a similar trend: on a difficult site in the Northern areas (shallow and infertile soil, cool and dry winter season), *Acacia* hybrid stands reach volume MAI increments of $15 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$, while *A. mangium* is limited to $9 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$. In southern locations, *A. mangium* stands typically reach mean heights about 9% shorter than *Acacia* hybrid.

Huong et al. (2016) performed a thorough field experiment on the effects of different intensities and timings of thinning on tree growth and canopy development in stands of *Acacia* hybrid in Phu Binh, South Vietnam. In their 18 experimental stands (in a randomised block design comprised of 1 control and 5 treatment stands), they performed combinations of light and heavy, single and double thinnings at age 2, 3, or both. The experiment was carried on until the trees were 5 years old, thus for the typical rotation length for the production of pulpwood. The authors report temporal variability in *Dbh* development across all the treatments, with *Dbh* increments being faster in the thinned stands at age 2 and 4 years than at 3 and 5 years.

All the thinned stands showed larger rates of *Dbh* growth than the unthinned stands and the heavier the thinning intensity, the faster were the *Dbh* increments. More specifically, heavy thinnings resulted in *Dbh* increments up to year 3; early light thinning (age 2) promoted faster *Dbh* increments for 1 year after the treatment; late light thinning (age 3) did not show an increased significant increment, but combining early and late thinning resulted in *Dbh* increment sustained at least until 2 years after the late thinning. Even if the early light thinning alone only increased the rate of *Dbh* increment for 1 year after thinning, at age 5 the absolute mean *Dbh* in these stands was still larger than in the unthinned stands. At age 5, the values of absolute mean *Dbh* and mean tree height in all the thinned stands were higher than in the unthinned ones, resulting in a large increase in the proportion of saw logs. Interestingly, at the end of the experiment the mortality across all stands was lower than 2% and did not show any significant relationship with the thinning regimes.

The results of the thinning practices in this experiment are in accordance with those of Beadle et al. (2013) for central Vietnam. The authors report that a single thinning at 2.5 years into the rotation, reducing the initial stocking from 871sph to either 600sph, 450sph, or 300sph, led to significant diameter increments amongst the retained trees. With regards to the canopy at stand

level, in the experiment of Huong et al. (2016) reductions in Leaf Area Index (LAI, green leaf area per unit ground surface area) were evident after thinning, as expected. The reduction however only lasted about 1 year after thinning, as the canopies of the retained trees quickly grew to occupy the available space. This seems to be a common property of tropical *Acacia*, as the canopy of *A. mangium* is reportedly very responsive to the additional growing space provided by thinning (Orwa et al., 2009).

3.1.3 *Acacia* tree properties of relevance for modelling wind damage risk

In this section, the growth properties of *Acacia* spp. discussed in the previous paragraphs are put into context with regards to wind damage modelling. Table 3 lists several important traits that characterise the form and development of *A. mangium* and *Acacia* hybrid. These traits are discussed in the last column of Table 3 with regards to their implications for wind damage risk and the associated modelling of tree and stand behaviour under wind loading.

Table 3 - Properties of *Acacia* trees relevant for the modelling of the risk of wind damage

Growth properties and traits	Sources	Relevance to wind damage modelling
Large, coriaceous, and sturdy phyllodes (~25cm in length and 3.5 – 10cm in breadth). Dense foliage, evergreen.	Orwa et al., 2009; Sein and Mitlöhner, 2011b	Large surface area exposed to wind likely to result in large canopy drag. Streamlining of crown likely to be different from conifer species, but similar to <i>Eucalyptus</i> spp. (e.g. Locatelli et al., 2016)
Strong tendency to form reaction wood and wood knots	Harwood et al., 2012; Sein and Mitlöhner, 2011a	Traits known to affect the mechanical properties of the stem (Ruel et al., 2010). Resistance to stem breakage in the calculations of critical breaking moment requires careful consideration.
Low green wood density	Sein and Mitlöhner (2011a) report values between 560 and 1,000 kg m ⁻³ at 15% moisture content (MC) for AM. Kha (2000) reports values at 12% MC of 414 kg m ⁻³ and 455 kg m ⁻³ for 4 year-old AM and AH trees, respectively, grown in North Vietnam. Harwood et al. (2012) report values of 474 kg m ⁻³ and 539 kg m ⁻³ for AH at age 5 and 8, respectively.	The values of density of green wood are lower than those for other commercially important tropical species, such as <i>E. globulus</i> (~1,250 kg m ⁻³ , Locatelli et al., 2016; McKinley et al., 2002). <i>Ceteris paribus</i> , the weight of <i>Acacia</i> trees will be lower than that of <i>Eucalypti</i> of similar size, resulting in lower risk of overturning.

Relatively low value of Modulus of Rupture (MOR)	Sein and Mitlöhner (2011a) report an average value of MOR for AM of 106 MPa.	The MOR values for AM are considerably higher than those for commercially important conifer species grown in temperate and boreal climates (e.g. 34 MPa and 36 MPa for <i>Picea sitchensis</i> (Bong.) Carr. and <i>P. pinaster</i> , respectively; see Lavers (2002)). However, the MOR values for <i>Eucalyptus</i> spp. of similar commercial importance are considerably higher, typically registering at around or above 120 MPa (Locatelli et al., 2016; McKinley et al., 2002; Yang and Evans, 2003). This might suggest that <i>Acacia</i> trees might be at higher risk of stem breakage under wind loading.
Vigorous rooting	AM rooting vigour is not affected by periodic waterlogging associated with heavy monsoonal rains (Awang and Taylor, 1993), although root rot can become an issue in infected and untreated soils (Krisnawati et al., 2011). AH are known for growing deeper and more vigorous roots than their parent species (IUFRO, 2000).	The good rooting properties of <i>Acacia</i> trees suggest that uprooting is unlikely to be the most common mode of failure under wind loading. AH is typically favoured over AM in conditions considered suboptimal for tree establishment, such as steep slopes (Sein and Mitlöhner 2011b), and are reportedly less prone to uprooting than their parent species (IUFRO, 2000).

AM: *Acacia mangium*; AH: *Acacia* hybrid

Table 3 highlights some of the favourable characteristics of *Acacia* spp. with regards to resistance to wind damage, especially overturning, while highlighting the opportunities, challenges, and some of the knowledge gaps that would need to be addressed for the development of wind damage risk models tailored for *Acacia* spp. in Vietnam.

As shown by Locatelli et al. (2017) ForestGALES is particularly sensitive to changes in tree height and Dbh. Because the growth and form of tree characteristics such as these are typically addressed in growth and yield models, the next section is dedicated to a review of the available models for *Acacia* spp., particularly those grown in Vietnamese conditions.

3.2 Growth and yield models for *Acacia* spp.

3.2.1 The requirement of ForestGALES for growth models

In order to simulate the risk of wind damage to a stand throughout its rotation, ForestGALES requires information on the development of the stand and of some features of the surrounding environment. Trees grow in height, diameter, canopy size, root depth, and the silviculture of the stand of interest and of neighbouring ones will have an effect on the wind loading on the trees, and hence on the risk of wind damage, that will evolve during the duration of the rotation. Most of the seven model input variables shown in Table 1 are expected to change during a rotation. While soil type and the overall wind climate are going to remain constant during the duration of

one or – likely – more rotations, other variables will show continuous or discrete changes throughout the rotation. The local wind climate aside, tree height and Dbh are the two single most important determinants of wind damage risk, followed by stocking density and the creation of upwind gaps (Locatelli et al., 2017).

It is straightforward and relatively cost-effective to measure Dbh at regular intervals and to store the information in forest inventories. Tree height mensuration is feasible when trees are young, but becomes increasingly difficult with age, especially at high stocking densities. When trees outgrow a certain height threshold, their height must be determined with tools such as the clinometer, a procedure which inevitably adds measurement errors that become larger with increasing tree height. A more modern – and costly – technological alternative is to employ LiDAR systems to estimate tree characteristics such as height and Dbh. Rosette et al. (2011) tested the application of satellite LiDAR data obtained from the Geosciences Laser Altimeter System (GLAS) for use with ForestGALES. The authors report acceptable linear relationships between data on tree height ($R^2=0.73$) measured on the field and those estimated with LiDAR.

The fit of the linear relationship for Dbh varied between conifer ($R^2=0.72$) and broadleaves ($R^2=0.41$) species. However, the average differences between observed and modelled values, expressed in root-mean squared error values (RMSE) were too large for confident application of ForestGALES (tree height: RMSE=4.5m; conifer Dbh: RMSE=7cm; broadleaves Dbh: RMSE=11cm), given the sensitivity of the model to these two parameters. Airborne LiDAR systems employed for small forest patches can provide better quality data on tree characteristics (e.g. Asner et al., 2012), but typically require employing contractors for this highly specialised job. As shown by Mcinerney et al. (2010) airborne LiDAR data can be combined with field and satellite data to effectively model the tree dimensions within plots of ~20mx20m, typically sufficient to account for local variation in topography and soil profiles. Suarez et al. (2008) have used airborne LiDAR data to model canopy dimensions for predicting the probability of wind damage in mixed and pure stands of conifers and broadleaves with ForestGALES. The authors report good results for conifer trees, although these procedures become more complicated and have larger errors when the canopy of broadleaved species are modelled.

A typical alternative to surveys in the field or from aerial or satellite systems is to obtain tree and stand data from growth models or yield tables, as shown by Locatelli et al. (2016) for the calculations of wind damage risk to *E. globulus* plantations in Northern Iberia. In the next sections the available growth/yield models for *Acacia* spp. in Southeast Asia, and Viet Nam in particular, are reviewed.

3.2.2 Modelling growth of *A. mangium* plantations in Southeast Asia

Some of the first attempts at modelling the exceptional growth of tropical *Acacia* were carried out by Forss et al. (1996) and Forss et al. (1998) in South Kalimantan plots in Indonesia. The two studies used tree and stand data measurements spanning a period of 4 years from thinned (at age ~4) and unthinned stands, planted with seeds from South Sumatra and Papua New Guinea, on rotations of about 10 years. Data from plots with a broad range of spacing were used, although the two most common stocking densities were 1,111sph (3mx3m) and 1,250sph (2mx4m). No information on the application of stem singling practices is reported in either study.

Forss et al. (1996) developed equations for dominant height (i.e. the mean height of the 100 trees within 1 ha with the largest Dbh) based on stand age and Site Index at 5 years (SI_5 , i.e. the maximum tree height at age 5); the authors created functions of stocking density (tree survival) based on age of the stand and SI_5 , and for the calculation of basal area based on age, dominant height, and stocking density. Their parametric functions are fairly simple and showed very low prediction errors. However, their attempts at creating a function to allocate the number of stems per Dbh classes were less successful.

Forss et al. (1998) provide methods for calculating the Dbh distribution in a uniform stand, from Dbh inventory data, and a function for modelling tree height. Their method is to fit a Weibull distribution to Dbh inventory data to model Dbh based on its mean value within a stand and the age of the stand; tree height is modelled with mean Dbh and dominant height, and stocking density. Krisnawati et al. (2010) review a number of similar functions for predicting tree height in unthinned *A. mangium* plantations in South Sumatra. They divided a large dataset with broad ranges of stocking density, tree height and Dbh, in a subset for model calibration and one for model validation. While the general form of the tested models is of the exponential or logistic type, they concluded that the best fit with the validation data ($R^2 \sim 0.85$, low RMSE, good predicting ability) was provided by a fairly simple, 3-parameters exponential model. It is to be expected that, for all these examples, the homogeneous structure of *Acacia* plantations contributed to the good fit of their models.

Forss et al. (1998) noticed that their functions did not model well stand and tree characteristics immediately after thinning, as the height – diameter relationship is affected. However, they noticed that data collected 2 – 3 years after thinning well represented the stand development in terms of height and Dbh, probably because thinning from below does not usually affect the dominant height of a stand. The authors suggest that their approach of calculating stand and tree characteristics from easily measurable forest inventory variables can successfully complement the growth models in Forss et al. (1996). The latter could be used to predict the development of whole-stand characteristics until a certain age; these modelled data could then be used in their models to predict single tree characteristics. Alternatively, inventory data could be fed to the models of Forss et al. (1998) to simulate stand growth over time.

3.2.3 Growth models specific to Vietnam

Recently, the quantification and modelling of tree and stand characteristics and productivity for the management of different tree species and plantation types has received increasing interest in Vietnam. A number of growth and yield models and tables have been developed from the mid-1990s, with more sophisticated models becoming available in recent years (e.g. Hung et al., 2016). The development in the study of forest and plantations growth has attracted interest from the international community, and collaborations and partnerships between Vietnamese and foreign institutions have flourished.

The result of one such collaboration is that between the Finnish Forest Research Institute (Metla), the Vietnamese Forest Inventory and Planning Institute (FIPI) and Viet Nam Forest University (VFU), coordinated by the Finnish Institutional Cooperation Instrument (ICI). These organisations, together with their Nepalese equivalents, have collaborated to review (as of 2012) the applicability of existing models for the prediction of tree and forest characteristics in forest inventories in Viet Nam (and Nepal). The resulting document (Eerikäinen et al., 2012)

laments the lack of models for predicting the rate of increment of tree and stand characteristics, while reporting on the extensive use of two types of models: one of relationships between variables (e.g. height and Dbh), and another based on static relation models for the prediction of volume, biomass, and amount of carbon stored in a tree/stand.

The species-specific logarithmic model of tree height developed by FIPI is an example of the former type (FIPI, 1995). Static relation models can be further divided in two families: one for projections at stand level, and the other for modelling tree-level characteristics. A prime example of stand-level models is that of growth and yield tables, such as the “Inventory and trading tables for 14 main plantation species” published by MARD (2003), while the volume model based on Dbh and height data developed by Khan (2001) is a typical case of tree-level static relation model.

These models are currently expected to be updated with new data, as a data survey aimed at the formulation of tree-level models for volume and biomass in the Kon Tum province in Central – South Viet Nam has been launched by FIPI and VCU with support from ICI (Eerikäinen et al., 2012). The report document includes separate appendices for Viet Nam and Nepal with brief information on the type and aims of the models, modelled species, geographical areas and factors and variables used in the models. Acquiring and analysing the original documents in depth is complicated because they are written in the local languages. Table 4 summarises this information for the Vietnamese models aimed at *Acacia* spp.

Table 4 - Available growth and yield models/tables for *Acacia* spp. in Vietnam

Aim	Species of Interest	Geographical areas	Environmental factors considered	Model type	Model variables	Reference
Managing and guiding planting activities, and evaluating plantation productivity	<i>A. mangium</i> ; <i>A. auriculiformis</i>	Numerous provinces in Viet Nam, including Thua Thien Hue	Soil; Site; Climate. No information on thinning.	Growth and productivity tables	Dbh, tree height, Age, stocking density	MARD (2003)
Establishing new growth tables and verifying the existing yield tables of plantation species to apply the results across the whole Vietnam	<i>A. mangium</i>	All of Vietnam	Soil; Site; Climate (5 ecological regions; stand age: 2 – 12 years). No information on thinning.	Growth and productivity tables	Dbh, tree height, stand basal area, dominant height, stocking density	Khanh (2001)
Growth and yield modelling of <i>A. auriculiformis</i> to increase productivity and support trade	<i>A. auriculiformis</i>	All of Viet Nam (some data collected in Thua Thien Hue province)	Climate (air temperature, rainfall). No information on thinning.	Relationship between mean and dominant tree height, complemented with formulas for stand volume	Dbh, tree height, stocking density, thinning intensity (only for volume calculations). Temperature (unsure whether mean, max, or min).	Hinh (1999)
Supporting forestry inventory and planning throughout Vietnam	General applicability to <i>Acacias</i> spp.	All of Vietnam	Soil; Site; Climate. No information on thinning.	Linear relationship between logarithms of Dbh and tree height, calculated and used to populate stem volume tables	Dbh, tree height	FIPI (1995)
Promote trade of biomass and carbon credits alongside sustainable forest management	<i>A. mangium</i> ; <i>Acacia</i> hybrid	Applicable to whole Vietnam. Survey data from numerous provinces including Thua Thien Hue	Soil; Topography; Climate; Forest Type. No information on thinning.	Models for predicting carbon stocks and biomass in different above- and below-ground tree components. Power functions based on Dbh	Dbh	Phuong (2009)

Despite the fact that not all the outputs of the growth and yield models/tables summarised in Table 4 might be directly useful for modelling the tree and stand characteristics required by ForestGALES (e.g. Phuong, 2009), their relative straightforward forms make them attractive for preliminary wind damage risk scoping exercises for *Acacia* spp. in Viet Nam. Provided that time and resources are available, acquisition of the raw data used for the formulation of these models and tables would allow for the integration and validation of suitable components of different models within those reviewed in these sections, so as to be able to build more detailed models of the temporal development of tree characteristics, and possibly of the influence of silvicultural practices.

Ideally, mechanistically-robust models should be adopted to be able to model tree characteristics with high accuracy across large plantation areas that are grown under very different environmental conditions and to identify the constraints to their optimal growth. These models however typically require complex and detailed information on the climate of the area, forest management practices, and the physiological traits that drive forest growth; moreover, these models are typically designed for volume and biomass estimation (e.g. the 3-PG model, parameterised by Hung et al. (2016) for *Acacia* hybrid) and often do not need to formulate specific equations for determining characteristics such as tree height and Dbh.

Having reviewed the available growth/yield models and tables for *Acacia* spp. in Viet Nam and Southeast Asia, and having discussed their relevance with regards to the requirements for modelling the risk of wind damage to forested stands with ForestGALES, the focus of the subsequent sections of this report now shifts towards reviewing the climatic conditions of Viet Nam as a whole, and in particular of the NCC region that comprises Thua Thien Hue province. Given that the intention of this report is to scope the Vietnamese silvicultural and climatic conditions with relation to wind damage, special attention is dedicated to the phenomena of tropical cyclones in the North-West Pacific, which heavily influence weather patterns at the national, regional, and local scales.

4 CLIMATE AND WEATHER PATTERNS OF VIETNAM

The most common climate over Viet Nam as a whole is tropical, governed by the South-West and the North-East monsoons, i.e. the periodic reversal in the predominant wind direction due to the varying contrast between land and ocean heating, in response to seasonal levels of solar radiation (Suppiah and Thang, 2014). Monsoons are typically characterised by strong winds and increased rainfall (Van Tan, 2002). The annual cycle can be divided into four distinct seasons based on patterns of temperature, rainfall, and wind speeds.

Two main monsoon seasons are identified in Vietnam: in the summer, winds predominantly come from southwest, originating south of India and typically lasting from the end of May until September. However, the onset date of the summer monsoon season is highly variable, the earliest recorded being at the end of April, and the latest around mid-June. Low-pressure systems predominate, especially in the North. The winter monsoon season typically lasts from December to March and is characterised by colder winds coming predominantly from the northeast and influenced by temperatures in Siberia and Mongolia. During this phase, the pressure systems are distinct between North and North-Central regions (high pressure) and South and South-Central parts of the country (medium pressure).

During the two monsoons seasons, the pressure gradients over Viet Nam are particularly strong and localised, while they are generally much milder over the rest of the Southeast Asian region. While this typically means that winds are locally mild, small perturbations in the pressure system can enhance the effect of the large-scale strong pressure gradients, resulting in high wind speeds and heavy precipitations being periodically experienced over Vietnam. April and May are called the first inter-monsoon season, while October and November are called the second inter-monsoon season. Temperatures in these short transitional seasons are intermediate between those of the two monsoons, and show similar mid-level pressure patterns, generally with weak winds (Suppiah and Thang, 2014).

In the tropics, non-frontal low pressure systems at synoptic scales, associated with a structured convection and a well-defined wind circulation are referred to with the generic term ‘tropical cyclones’. They form in the presence of low-pressure systems, high winds, and high sea temperatures that drive the formation of convective clouds near the warmer centre of the cyclone (Van Tan, 2002). Tropical cyclones are typically characterised by wind speeds attained during the event. They are called ‘tropical depressions’ when their wind speed is lower than 18 m s^{-1} ; above this threshold, they are typically given a name and categorised as ‘tropical storms’ when their maximum wind speed is below 33 m s^{-1} , and ‘typhoons’ when they exceed that.

Aside from the strong winds, heavy rainfall is associated with tropical cyclones, especially after they have made landfall. The North Western Pacific Ocean is one of the major tropical genesis areas in the world, and tropical cyclones that form over the Western Pacific Ocean are responsible for some of the most severe natural disasters affecting Viet Nam, particularly in the Northern and Central regions (Nguyen et al., 2014). Damage caused by storms and typhoons typically comes in the form of direct wind damage, storm surges in the coastal regions, and floods caused by the heavy rains.

The trajectories of tropical cyclones show strong temporal variability at the seasonal, interannual and interdecadal scales (Camargo et al., 2007). The largest portion of this variability in the tropical region of the Pacific Ocean is attributable to the El Niño – Southern Oscillation

(ENSO) events, which are known to affect monsoonal variability and the activity of tropical cyclones. ENSO reflects pluriennial fluctuations in the ocean-atmospheric system via large changes in the Walker and Hadley atmospheric cells throughout the tropical portion of the Pacific Ocean, predominantly triggered by anomalies in sea-surface temperatures (SST) in the Eastern and Central equatorial Pacific Ocean (Van Tan, 2002).

Large-scale interannual variations in oceanic characteristics described by ENSO events are not limited to SST, but also include changes in sea level and currents, and consequently in the extent and depth of the thermocline. Positive SST anomalies are referred to as El Niño events, while the opposite condition of negative SST is called La Niña. These two phases alternate with periods of neutral conditions, defined as when the variance of recorded SST is within 0.5°C. While the terms ‘El Niño’ and ‘La Niña’ indicate anomalies in SST, the Southern Oscillation (SO) is the atmospheric component of this ocean-atmospheric coupled system. SO refers to the periodic fluctuations in sea-level air pressure between Tahiti and Darwin, Australia.

In El Niño years, high and low pressures are recorded at Darwin and Tahiti, respectively, while the opposite is found in La Niña years. Consequences of SO over the tropical Pacific Ocean are seen in the variations of the patterns of rainfall and winds (Suppiah and Thang, 2014). During El Niño years, weaker trade winds and increased rainfall are recorded over the Central and Eastern Pacific. The opposite situation is observed during La Niña years, when trade winds are stronger and precipitation increases over the Western Pacific. In terms of the timing of the genesis of tropical cyclones, the onset tends to be delayed in El Niño years and anticipated in La Niña years, although a trend of earlier formation has been observed in most years since 1993 (Suppiah and Thang, 2014), effectively lengthening the typhoon season (MONRE, 2016).

In general terms – and without considering complex patterns of local variability – for Viet Nam these variations result in higher precipitation in La Niña years (especially in the North-Central, South-Central, South, and Central Highlands regions), and in less rainfall in El Niño years. While the total number of tropical cyclones in the North-Western Pacific basin have not felt the influence of the fluctuations between warm and cold phases, the annual frequency of tropical cyclones forming in the Bien Dong Sea and making landfall in Viet Nam has shown an ENSO effect, with more tropical cyclones than in neutral conditions being recorded during La Niña and less in El Niño years (see Fig. 2; Ngu, 2000).

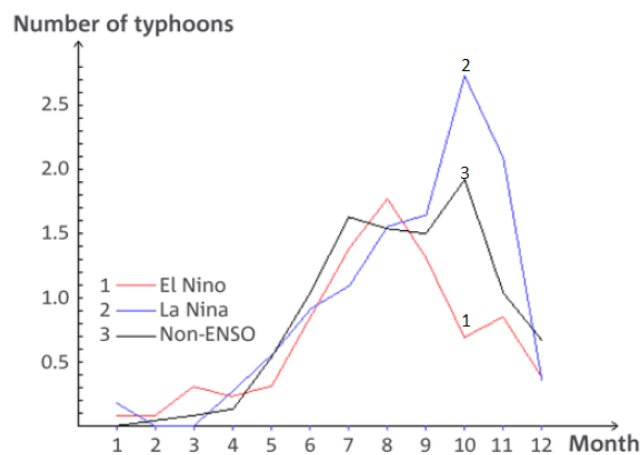


Figure 2 - Monthly frequencies of typhoons (wind speed > 33m s⁻¹) making landfall in Viet Nam in El Niño, La Niña, and neutral years (adapted from Ngu, 2000).

The strong seasonality of extreme wind events (i.e. typhoons) affecting inland Viet Nam is also evident from the above graph. Tropical cyclones follow a similar pattern, being most active during the summer monsoon and the second inter-monsoon season, while sharply declining at the onset of the winter monsoon (IMHEN and UNDP, 2015). Data from the second half of the 20th century show strong latitudinal patterns as well as temporal. The tropical cyclones season typically starts just before the onset of the summer monsoon, with most storms making landfall in South and South-Central Viet Nam (MONRE, 2016). The storm season then quickly shifts to the North, reaching the Northern regions around May, persisting there until September and showing an increase in storm frequency: in May there are typically 1 to 5 tropical storms, while in September the count is between 16 and 20. In October, the storm tracks begin moving southwards, with a peak in landfall numbers around 16 – 20 storms in November, mostly in Central to Southern Vietnam. Figure 3 summarises the historical annual frequency of storms and typhoons (i.e. all tropical cyclones with wind speed $\geq 18 \text{ m s}^{-1}$) that made landfall in Viet Nam between 1945 and 1998 (Nguyen et al., 2014).

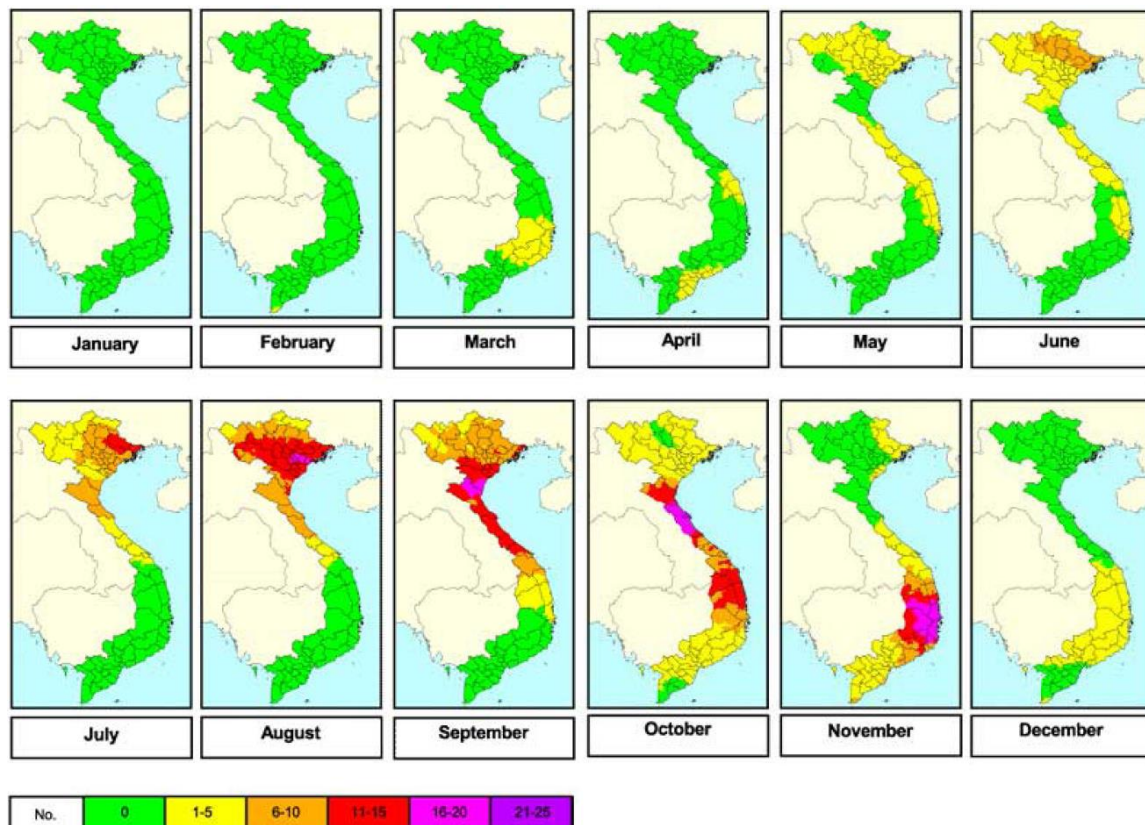


Figure 3 - Geographical distributions of annual tropical storms and typhoons (wind speed > 18m s⁻¹) making landfall in Viet Nam between 1945 and 1998 (from Nguyen et al., 2014).

As expected, a marked temporal variability is also found with rainfall patterns over Vietnam. While the summer monsoon is the main rainfall season, being strongest during the initial 3 months and beginning to retreat during September, a significant portion of annual rainfall is provided by tropical cyclones that make landfall in Viet Nam, including the Southern and Central regions, during the second inter-monsoon season (Suppiah and Thang, 2014). Less precipitation in the North, and more in the South, has been observed in the last 50 – 60 years (MONRE, 2016).

The large longitudinal span of the Annamese Mountains, which separate Viet Nam from Laos and Cambodia, results in the deflection of the surface winds carried by the tropical cyclones, generating increased rainfall to the windward side of the range and often causing extensive damage. The overall high vulnerability of Viet Nam to extreme weather and climatic events such as storms, floods, and drought, is due to the country's tropical location and complex terrain, and to the influence of the climate of the Western Pacific Ocean (Suppiah and Thang, 2014).

The widespread and extensive damage caused in Viet Nam by tropical cyclones means that their influence on the national economy is large. In fact, the average annual number of major storms and typhoons hitting the country (5 to 8 per annum) is responsible for human and property losses estimated at about 1% of Vietnam's annual GDP (Nguyen et al., 2014). The most violent and damaging typhoons having affected Viet Nam in recent years include the Linda Typhoon, that hit the Southern part of the country in 1997 causing the death of ~3,000 people, the collapse of ~100,000 houses, and damage to >300,000ha of crops. In 2006, the Xangsane Typhoon in Central Viet Nam caused 37 deaths for the direct impact of the strong winds, and further 39 due to the subsequent floods, and injured 532 people; heavy damage to infrastructure in a number of provinces amounted to ~450M US\$, largely incurred in Thua Thien Hue province. Typhoon Ketsana in 2009 affected the Central and Central Highlands regions, bringing particularly heavy rains and causing extensive floods. The death toll reached the count of 179 people, and almost 10,000 houses collapsed because of the strong winds and floods, contributing to the total estimated monetary damage of over 600M US\$ (IMHEN and UNDP, 2015).

4.1 North-Central Coast of Viet Nam

The degree of variation in temperature and rainfall over Viet Nam is particularly large due to the varying topography, whose effect is considerably amplified during the monsoon seasons. In fact, the complex interplay between large-scale monsoonal weather patterns and micro-scale effects provided by the numerous hills, mountains, and steep terrain that characterise most of the country, results in the various regions having very different climate regimes.

The province of Thua Thien Hue is one of the most affected by tropical storms and typhoons. It is located at the southernmost part of NCC, a narrow region extending from Thanh Hoa to the North to Hai Van Pass in the South. From the eastern boundary with the East Viet Nam Sea, the terrain becomes increasingly complex and more elevated, quickly reaching heights of ~100-200m in the coastal hills, before steeply increasing to the 1,000-1,500m high peaks in the rugged terrain of the Truong Son Mountains. From these, a number of smaller mountain ranges periodically extend eastwards towards the coastal plains, adding to the complexity of the local topography.

The annual climatic cycle in the North-Central region is peculiarly different from the rest of the country. Winters are cool and hoarfrost is not uncommon while the weather is predominantly hot and dry in the summer (Katzfey et al., 2014a). Although the region does experience a rainy season during May and June, significant droughts can affect the region during the summer, brought about by hot and dry westerlies. The annual rainfall peaks are seen during the second inter-monsoon season and the winter monsoon from August until December, with maximum rainfall in September. This is remarkably different from the climate in the North and South regions, where summer is the primary rainfall season, with precipitation sharply decreasing

through September (Suppiah and Thang, 2014). The weather during the second inter-monsoon and the winter monsoon seasons in NCC is mostly driven by an increase in the frequency of tropical cyclones and disturbances, meaning that the highest temperatures are not associated with the period of most intense precipitation. The northerlies that descend from Siberia and Mongolia in December bring with them conditions of localised high pressure over the North-Central region, with a sharp decrease in rainfall.

In the last 30 years, the NCC region has seen a higher frequency of tropical cyclones than the rest of the country (Nguyen et al., 2014). This is likely due to the combination of ENSO, whose strongest effect is on the central and southern regions, with the complex topography of the North-Central region (IMHEN and UNDP, 2015). The maximum wind speeds are typically experienced during November in the coastal areas and in April in the mountains. The wind speed distribution is very skewed: while mean annual wind speeds in different parts of the North-Central region are in the order of $1.5 - 3 \text{ m s}^{-1}$, maximum wind speeds can be sustained for up to 20 – 25 hours in extreme cases (IMHEN and UNDP, 2015) and often reach $30 - 40 \text{ m s}^{-1}$ during typhoons (Katzfey et al., 2014a) and $15 - 20 \text{ m s}^{-1}$ during the winter monsoon (Hoang, 2017; *Pers. Comm.*).

The complex topography of NCC can influence the geographical reach of strong winds: in fact, little attenuation of wind speeds is seen in open areas until 100 – 150km inland, while wind penetration is reduced to 20 – 50km when the path of the storm crosses hilly and mountainous areas. During the Becky storm that made landfall in NCC Viet Nam on 29th August 1980 maximum wind speeds on the coast were recorded at 54 m s^{-1} at Ky Anh, while at Huong Khe, at the same latitude but further inland, wind speeds reached a maximum of 40 m s^{-1} (IMHEN and UNDP, 2015).

The recorded temperatures and precipitation in NCC have shown mostly significant trends in the last 50 years. Annual increases in temperatures have ranged between $0.11 - 0.24^\circ\text{C}$ per decade in most of the country, with a small, non-statistically significant decrease seen in Hue city (-0.08°C per decade). Maximum daily temperatures have increased in the whole region, but less in Thua Thien Hue province. The minimum daily temperatures have increased faster than the maximum. The number of days with maximum daily temperature exceeding 35°C has increased to up to 7 days per decade, and 3 to 4 more days per decade with maximum temperatures exceeding the 90th percentile temperature in the last 50 years have been recorded.

The number of days with minimum daily temperature below 15°C has decreased by up to 2 days per decade. With regards to precipitation, in the northern part of the region a small, non-significant decrease in rainfall (-2.7% per decade) has been observed, while in Thua Thien Hue province an opposite trend is evident, with an increase in precipitation of up to 11% per decade. In this province, this increase has been accompanied with an even stronger increase (up to 20% per decade) in extreme precipitation, expressed as the number of days per annum when rainfall exceeds the 95th percentile of the last 50 years (Katzfey et al., 2014a). The trends of extreme rainfall follow those of total rainfall over most of the country, with increases in the Central regions (near Hue city) and decreases in the North and South (MONRE, 2016).

4.2 Climate projections

The complex climate of Southeast Asia presents a number of challenges for the application of global climate models (GCM). While the latest generation of GCM can simulate the large-scale atmospheric patterns of tropical cyclones, they operate at temporal and spatial resolutions too coarse to reproduce small-scale features such as very high surface wind speeds (Nguyen et al., 2014). Similarly, the interannual variability of ocean temperatures that drive the ENSO phenomenon is still poorly captured by GCM (Katzfey et al., 2014b).

Due to global increases in temperature the areas of tropical cyclone genesis are expected to increase at the global level as well as in the North-West Pacific (IMHEN and UNDP, 2015; MONRE, 2016). There is however a moderate level of confidence within the scientific community that the frequency of tropical cyclones is likely to decrease by the end of the century by a percentage comprised between 6% and 35%, depending on the GCM adopted in the studies. Despite the projected decrease in the number of tropical cyclones, the frequency of tropical storms and typhoons is expected to increase – globally as well as over Viet Nam (MONRE, 2016) – with mean maximum wind speeds between 2% - 11% (Nguyen et al., 2014).

The confidence of regional projection for the East Viet Nam Sea is typically low, since different modelling approaches predict either a decrease of the numbers of tropical cyclones between 5% and 20%, or more favourable general conditions for cyclone formation. Interestingly, however, models combining both approaches still predict a decrease in the number of total tropical cyclones over Viet Nam (Nguyen et al., 2014). In terms of tropical storms and typhoons, while in the last 50 years the annual maximum wind speeds in almost all the weather stations in the Vietnamese territory have shown a small decreasing trend, according to the IPCC SRES classification (Nakicenovic et al., 2000) emissions scenarios A1B ('medium emissions') and A2 ('medium-high emissions'), mean maximum wind speeds are projected to increase over the whole country by about 2 m s^{-1} . Typhoon tracks are expected to shift to the South and to a certain extent to later dates (MONRE, 2016).

Rainfall within a radius of 100km from the moving centre of tropical cyclones is likely to increase by ~20% (Knutson et al., 2010). The forecasted patterns of rainfall in Southeast Asia are complicated by projected changes in monsoon seasonality, as the onset of the summer monsoon is expected to be anticipated and its retreat delayed, with increased precipitation (MONRE, 2016). In the North-Central region of Viet Nam, GCM predict increases in temperatures all year round, especially during the summer monsoon season, but more damaging cold days in the mountainous areas in the North and North-Central regions (MONRE, 2016). Temporal rainfall patterns are more complicated. Large increases in precipitation are expected during the winter monsoon and the second inter-monsoon season, while a strong decrease is projected for the summer monsoon, which in combination with the likely increase in summer temperature is expected to result in severe drought.

5 BRIEF DISCUSSION ABOUT ACACIA SPP. SILVICULTURE AND VIETNAMESE CLIMATE

The objectives of the first part of the report was to review the information on growth characteristics of *A. mangium* and *Acacia* hybrid, together with the climate and weather of Viet Nam, with a special focus on the Thua Thien Hue province in the North-Central region.

The review of the *Acacia* spp. growth characteristics and the available growth and yield models has highlighted a general scarcity of readily-usable resources for the input requirements of ForestGALES. However, the variety reported in the document by Eerikäinen et al. (2012) shows great promise, especially as the authors report that at the time of publication new forest inventory data were expected to become shortly available.

Useful qualitative information on the behaviour of *Acacia* spp. and their response to some silvicultural practices was found in this initial review. *Acacia* spp. respond very quickly and effectively to thinning, a practice which reduces intraspecific competition and redistributes resources such as light, water, and nutrients to the retained trees. These species show increased growth rates especially of Dbh, canopy, and root system (Huong et al., 2016). The strong rooting of the *Acacia* hybrid promotes the use of this tree in Viet Nam to stabilise steep hill slopes (Sein and Mitlöhner 2011b).

The risk of promoting faster growth through forest management is that the wood density of the stem might be reduced (Kim et al., 2011), possibly affecting the strength of the stem. This might be an issue as – for instance – *Acacia* hybrid is known to be prone to stem breakage under high wind loading (Sein and Mitlöhner 2011b), although the predominance of this mode of failure might also be affected by particularly strong rooting. While thinning stimulates growth and provides an opportunity for shortening the optimal rotation, some related aspects need to be considered. Especially when applied to fast-growing tropical species like *A. mangium* and *Acacia* hybrid, the timing of thinning is likely to be as important as the intensity, as shown by Huong et al. (2016) in order to take maximum advantage from the increase in growth rate stimulated by thinning. This is of particular relevance as the reduced yields need to be compensated with a product of higher value such as sawn logs and veneer logs, which require particular care as these species are prone to knot formation (Harwood et al., 2012). With regards to canopy growth, temporary reductions of leaf area in the first 12 months after thinning might result in changes in wind penetration in the stand, and on the overall stand canopy roughness.

These wind risk-related characteristics of *Acacia* spp. are particularly relevant because of the location of Viet Nam within one of the most active areas of tropical cyclone genesis in the world. Nguyen et al. (2014) report that Viet Nam ranks in the top-ten countries in the world in terms of damage from natural disasters such as floods and storms. The Vietnamese Ministry of Natural Resources and Environment (MONRE) emphasised the need for mapping risk, exposure, and vulnerability to improve forecasting for more efficient early warning systems (IMHEN and UNDP, 2015). In an optic of promoting short term benefits while reducing long-term vulnerability, MONRE promotes a more modern and better-managed forestry sector to integrate climate change adaptation and risk-reduction measures. For instance, a dynamic system of forest management might track the ENSO to forecast for a number of months in advance the activity

of tropical cyclones over the Western Pacific, and tailor silvicultural practices according to the ENSO regime.

The Southern Oscillation Index measures the interannual variability of the SO and is routinely used for large temporal scale forecasting in the tropics (Suppiah and Thang, 2014). By combining GCM with Regional Climate Models it is possible to model inter-annual variation of the number of tropical cyclones, especially in El Niño and La Niña years with accuracy within the uncertainties of the available tropical cyclones datasets (Nguyen et al., 2014). However, it should be considered that predicting the return periods of particularly strong typhoons making landfall within a province or an entire region is likely to be more complicated, given the exceptional nature of these extreme events. For instance, while Typhoon Linda that struck the Southern region was tagged with a return period of 100 years (Nguyen et al., 2014), the Becky storm that hit Ky Anh in the North-Central coast in 1990 with wind speeds of 40 m s^{-1} was followed in 1992 by another typhoon with recorded wind speeds of 46 m s^{-1} over the same area (IMHEN and UNDP, 2015).

Localised wind risk in inland areas of high topographical complexity is typically less than on the coast, due to the progressive dissipation of wind speeds as the storm makes landfall. However, the micro-scale effects of hills, valleys, and mountains can affect the local wind speed in multiple ways. Kamimura et al. (2008) concluded that while WAsP can be used to estimate variation of wind speeds during typhoons, mesoscale airflow models specific for areas affected by tropical cyclones needed to be developed to improve the micro-scale prediction of wind speed distributions required for forestry applications with WAsP. Badger et al. (2015) provide a first attempt at mesoscale wind modelling for Viet Nam, which bodes well for the application of WAsP to the complex terrain of the westernmost regions of the country.

6 CASE STUDY

The second part of the report makes use of a case study to: demonstrate the use of ForestGALES in a spatial setting; to demonstrate the adaptability of ForestGALES to conditions typical of Vietnamese plantations and to indicate the next steps required to build a working version of ForestGALES for application in Vietnam; to explore potential scale-ups covering large areas in Vietnam; and finally to provide some initial recommendations on forest management in the Thua Thien Hue province to reduce the risk of wind damage to local plantations.

6.1 Overview

This section demonstrates the potential for wind risk assessment in the Thua Thien Hue province using ForestGALES in combination with the WASP airflow model and QGIS. To this aim, a case study is presented in which the risk of wind damage in three areas within the province is calculated and displayed on 2D and 3D maps. A GIS map of the distribution of forest types in the province was used to identify 16 potential plantation sites which differ in terms of altitude, characteristics of the surrounding topography, and distance from the coast.

As reported in the first part of this report, growth models for Vietnamese *Acacia* spp. that are able to satisfy the input data requirements for ForestGALES wind damage risk simulations are presently unavailable. This, together with the current lack of parametrisation of ForestGALES for *Acacia* spp., means that simulating the risk of wind damage for the most common plantation species in Viet Nam is currently not possible. For this reason, the case study focusses on a different model species: *Eucalyptus globulus*. This species was chosen for the case study for the following reasons:

- It is used in Vietnamese plantations, albeit not as extensively as *Acacia* spp.;
- it has high commercial importance worldwide, especially in the pulp industry, which has prompted the development of numerous growth models, at least one of which is compatible with ForestGALES' input requirements and has previously been coupled with ForestGALES;
- its wind damage risk can be confidently calculated in ForestGALES, as the model has been parametrised for this species grown in the Asturias region in the Northern Iberian peninsula ((Locatelli et al., 2016).

While the information on tree and stand characteristics generated by the *E. globulus* growth model can be used in ForestGALES to calculate the mean critical (damaging) wind speeds for breakage and overturning for the different sites, estimating the probabilities of damage and the associated return periods of wind speeds that match or exceed the critical wind speeds at the plantation sites requires information on the wind climate of the area.

The wind climate of an area can be obtained in various ways which primarily differ with regards to the temporal and spatial resolutions of the data. While the best source for the most comprehensive wind speed and direction data is a weather station local to the area of interest, it is often also the most complicated and costly to obtain. Conveniently, as briefly discussed in Section 2, modern airflow models such as WASP can downscale freely and publicly available large- and meso-scale wind climate data to provide a localised wind climate of a satisfactory quality for the demonstration purposes of this case study.

The data and the methods used in this case study are described in section 6.2. The results of the wind climate simulations and the wind damage risk simulations are shown in section 6.3, together with 2D mapping of the results. The 3D maps of the localised wind climate and of the risk of wind damage to the 16 plantation plots are provided in the supplementary material and require a web browser to be displayed. The results of the case study are discussed in section 6.4. Section 6.5 summarises the lessons learned from this exercise with regards to data requirements and the potential for upscaling a similar study to cover a larger area, and to provide some preliminary recommendations to reduce the risk of wind damage in the Thua Thien Hue province.

6.2 Methods and Data

6.2.1 Areas of Interest

Figures 4 and 5 show Thua Thien Hue province in Viet Nam, and the locations of the three areas of interest (AOI) for which the localised wind climate and the risk of wind damage to *E. globulus* plantations were calculated. The three AOI are provided with a Digital Elevation Model (DEM) background layer showing the different and sometime complex topographies typical of the area. As reported in Section 4, Thua Thien Hue province is located in the narrow central part of Viet Nam, separated from Laos by the Annamese mountains.

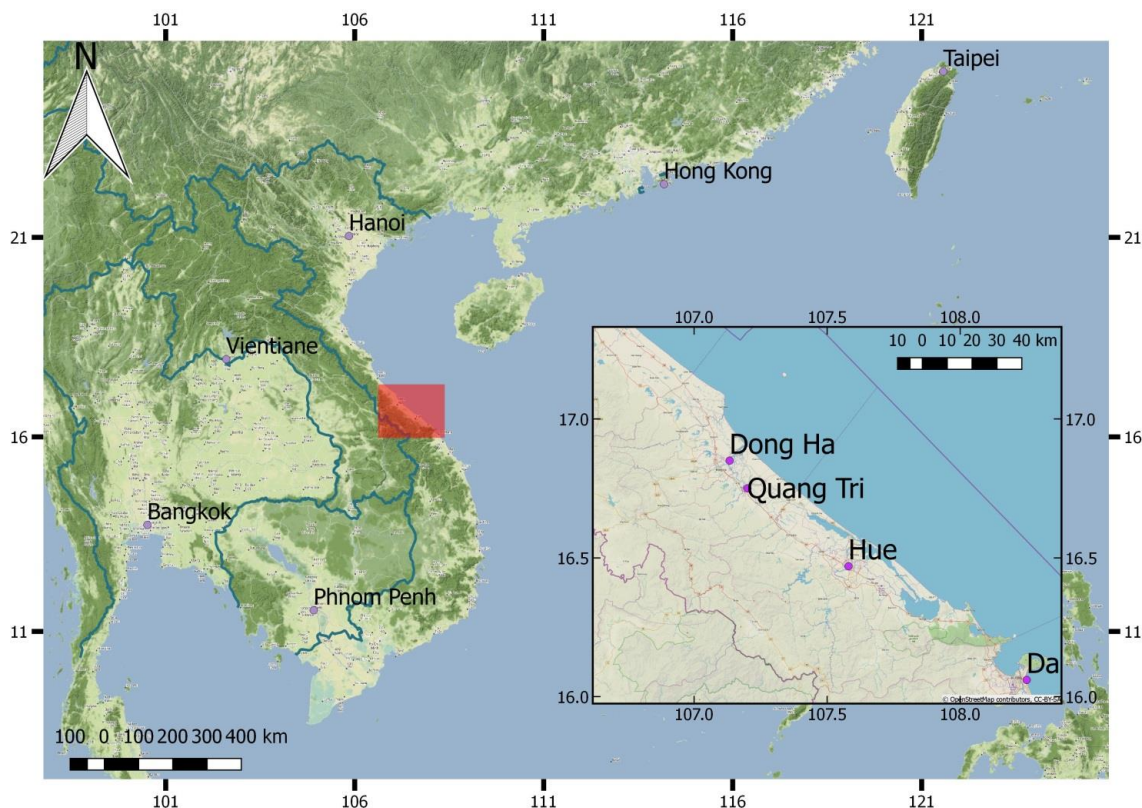


Figure 4: Position of Thua Thien Hue province within Vietnam. The border with Laos is marked in purple in the inset (credits: © OpenStreetMap contributors, CC-BY-SA).

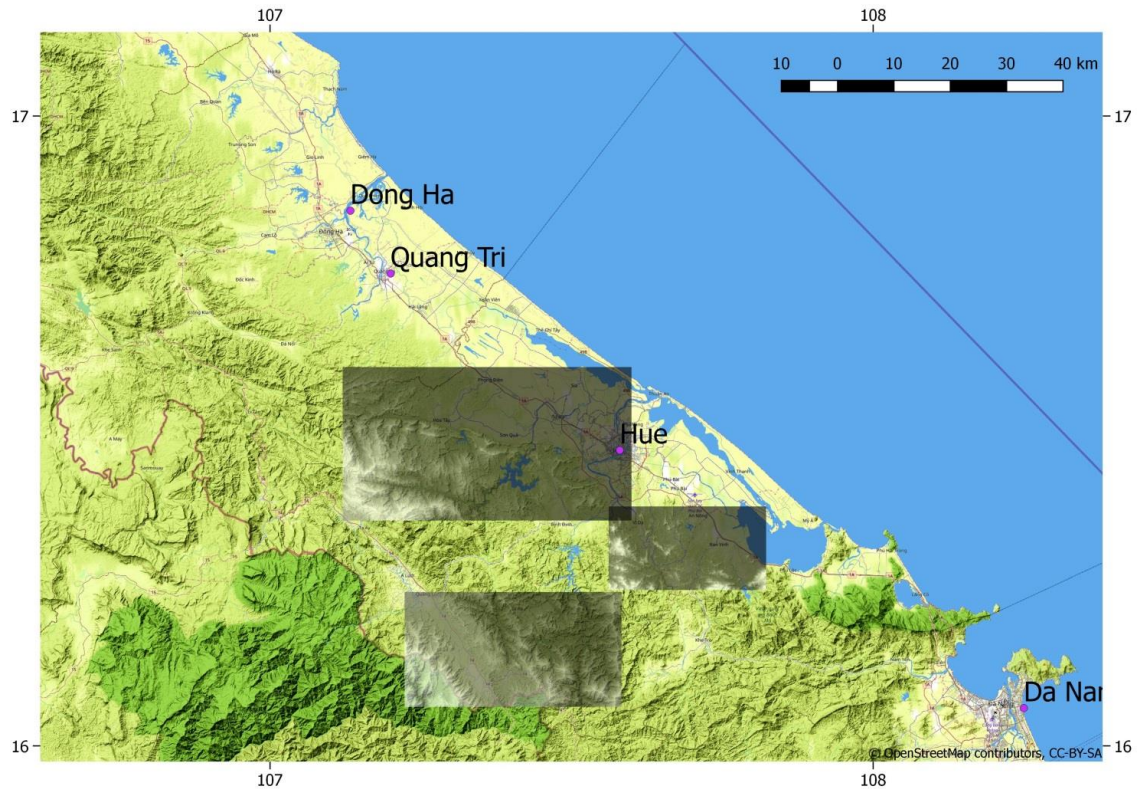


Figure 5: Locations of the three areas of interest (AOI) within Thua Thien Hue province. The Digital Elevation Model shows the different topographies of the three AOI. The border with Laos is marked in purple (credits: © OpenStreetMap contributors, CC-BY-SA; ASTER GDEM is a product of METI and NASA).

The output of a GIS map of forest cover in the province, provided by partners of UNIQUE, was added to the above map to identify areas of protected forest (PF), special forest (SF), and areas used for plantations. PF and SF areas were delimited and nominal values of mean tree height were assigned to them on the basis of the most common topography within the areas (see Table 5). Within the areas where plantations are grown, 16 plots were identified where the growth of *E. globulus* plantations was simulated.

6.2.2 Plantation forests scenarios

As seen in Figure 5, the locations of the AOI reflect the complex and varied topography of Thua Thien Hue province which extends westwards to the Annamese Mountains. This mountainous range acts as a barrier to the surface winds coming from the coast, promoting increased rainfall to the windward side of the range (Suppiah and Thang, 2014) and effectively contributing to a topographical gradient of precipitation and humidity. A qualitative estimation of this gradient was combined with data on the local climate (see references in Section 4, e.g. Katzfey et al., 2014a; Suppiah and Thang, 2014) to assess local differences in mean climate (e.g. temperature and precipitation). Data from a meteorological station in Nam Dinh province was used to gauge a reasonable range of mean, maximum, and minimum temperature, as well as of total number of days per annum with precipitation. These datasets were used for two purposes: 1) to generate a number of scenarios based on identifying and locating suitably representative areas within

Thua Thien Hue province to provide contrasting sites for wind-risk simulations; and 2) to produce climate estimates for the variables required by GLOBULUS, the *E. globulus*' growth model used in this case study.

The GLOBULUS model (Soares et al., 2006) has been created for Portuguese conditions and is able to calculate a number of tree and stand variables for 1st rotations and coppice rotations of *E. globulus*. Only 1st rotations settings were used in our simulations as ForestGALES was parametrised for *E. globulus* for 1st rotations alone (e.g. Locatelli et al., 2016). For the purpose of wind risk simulations with ForestGALES, it is convenient that GLOBULUS can simulate the development of tree height and Dbh, and can account for mortality at stand-level as the number of stems per ha (sph) decrease, thus providing a way of simulating commercial thinnings. In our simulations, however, only mortality was allowed, rather than accounting for scheduled thinnings.

GLOBULUS uses the mean altitude of the area to calculate the dominant Dbh via calculation of basal area. For this case study, we have obtained the value of the mean elevation for each plot from the DEM used in QGIS. GLOBULUS simulates the development of the dominant tree height within a stand from data on the number of days per annum with precipitation and Site Index₁₀ (SI₁₀), a measure of stand productivity that equates to the height of the mean tree in the stand at age 10.

In defining the characteristics of the *E. globulus* plots in our scenarios we have used the aforementioned topographical gradient to estimate the different number of days with precipitation between coastal and mountainous sites, with: dry areas nearer the coast; wet areas at the foot of the east mountainous range; wet areas between the east and west mountainous range; and dry areas behind the west mountainous range. Similarly, we have assigned values of SI₁₀ that are a reflection of both the location (coast vs mountains) and the rainfall regime of the sites.

In decreasing order of productivity, the plots' SI₁₀ are: high-precipitation and coastal (SI₁₀ 18); low-precipitation and coastal (SI₁₀ 15); high-precipitation and mountainous (SI₁₀ 12); and low-precipitation and mountainous (SI₁₀ 10). For each combination we have assigned two contrasting forest objectives: timber and pulp, to determine the rotation length and the value of stems per ha at planting (timber: 15 years rotation and 1,000 sph; pulp: 12 years rotation and 1,666 sph). For each final combination of these characteristics, we have created two nearby plots, to investigate the differences in the micro-climate generated with WAsP, and the consequences on the risk of wind damage. Finally, for our simulations with ForestGALES we have assigned a value of shallow rooting to the plots grown on the steep slopes of the mountainous sites, and of deep rooting for coastal sites. The details of the scenarios and the characteristics and nomenclature of the plots are summarised in Table 5. The location of the plots is shown in Figure 6.

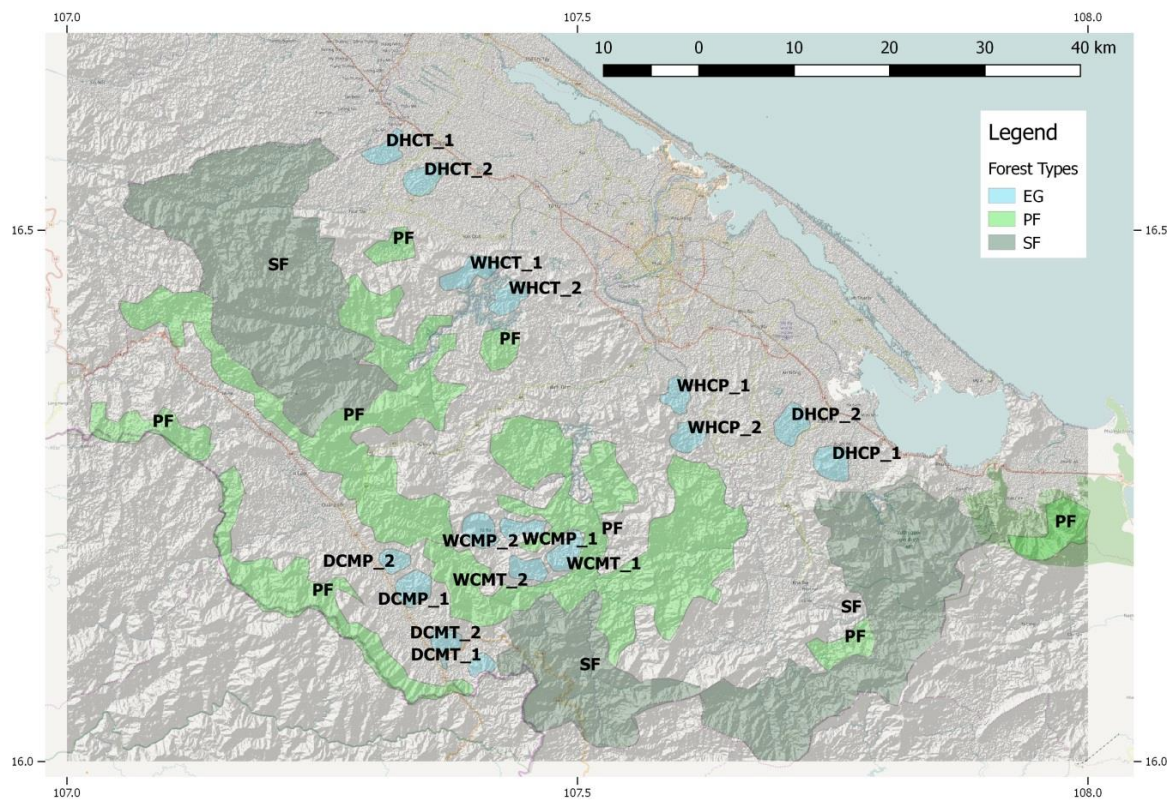


Figure 6: Locations of the *E. globulus* plantations plots (EG) and of the areas of protection (PF) and special forest (SF) within Thua Thien Hue province. The Digital Elevation Model shows the complex topography of the area. The nomenclature of the plots is explained in Table 5 (credits: © OpenStreetMap contributors, CC-BY-SA; ASTER GDEM is a product of METI and NASA).

Table 5: Properties of the simulated forest plots within Thua Thien Hue province.

Forest type	Plot ID	N° of days with rain	Mean elevation (m)	Location type	SI ₁₀ (m)	Sph at planting	Objective	Age at mid-rotation (years)	Mean height at mid-rotation (m)	Mean Dbh at mid-rotation (cm)	Sph at mid-rotation	Age at end-rotation (years)	Mean height at end-rotation (m)	Mean Dbh at end-rotation (cm)	Sph at end-rotation	Rooting
SF	-	-	-	-	-	-	-	-	-				15	-	-	
PF	-	-	-	-	-	-	-	-	-				12	-	-	-
EG	DHCT_1	134	25	Coastal	15	1000	Timber	7	11.3	10.1	915	15	19.7	15.7	827	Deep
EG	DHCT_2	134	33	Coastal	15	1000	Timber	7	11.3	10.1	915	15	19.7	15.7	827	Deep
EG	DHCP_1	134	54	Coastal	15	1666	Pulp	6	9.8	8.1	1530	12	17.1	12.2	1404	Deep
EG	DHCP_2	134	19	Coastal	15	1666	Pulp	6	9.8	8.1	1530	12	17.1	12.2	1404	Deep
EG	WHCT_1	171	134	Coastal	18	1000	Timber	7	13.6	12.0	915	15	23.4	17.9	827	Deep
EG	WHCT_2	171	104	Coastal	18	1000	Timber	7	13.6	12.0	915	15	23.4	17.9	827	Deep
EG	WHCP_1	171	28	Coastal	18	1666	Pulp	6	11.9	9.6	1530	12	20.4	14.0	1404	Deep
EG	WHCP_2	171	83	Coastal	18	1666	Pulp	6	11.9	9.5	1530	12	20.4	13.9	1404	Deep
EG	WCMT_1	171	279	Mountains	12	1000	Timber	7	8.4	8.9	915	15	16.8	14.4	827	Shallow
EG	WCMT_2	171	353	Mountains	12	1000	Timber	7	8.4	8.8	915	15	16.8	14.3	827	Shallow
EG	WCMP_1	171	215	Mountains	12	1666	Pulp	6	7.0	7.2	1530	12	14.1	11.3	1404	Shallow
EG	WCMP_2	171	331	Mountains	12	1666	Pulp	6	7.0	7.1	1530	12	14.1	11.2	1404	Shallow
EG	DCMT_1	134	678	Mountains	10	1000	Timber	7	6.9	7.2	915	15	14.1	12.1	827	Shallow
EG	DCMT_2	134	630	Mountains	10	1000	Timber	7	6.9	7.3	915	15	14.1	12.2	827	Shallow
EG	DCMP_1	134	680	Mountains	10	1666	Pulp	6	5.8	5.9	1530	12	11.8	9.6	1404	Shallow
EG	DCMP_2	134	651	Mountains	10	1666	Pulp	6	5.8	6.0	1530	12	11.8	9.7	1404	Shallow

SF: Special Forest; PF: Protection Forest. EG: *Eucalyptus globulus*; SI₁₀: Site Index at age 10, i.e. mean stand height at 10 years; Sph: stems per hectare; Dbh: diameter at breast height (1.3m). Deep rooting indicates that the C_{reg} value obtained in tree-pulling experiments in the Asturias region in northern Spain (162.32) was used in ForestGALES simulations. Shallow rooting indicates that the lower C_{reg} value obtained in tree-pulling experiments in the Spanish Basque Country was used (153.04).

6.2.3 Localised wind climate

For each AOI, the outputs of tree height at the end of the rotation simulated with GLOBULUS were used to calculate values of surface roughness for the relevant scenarios plots to incorporate roughness elements in the maps used for the calculations of the localised wind climate in WAsP. From recent work on ForestGALES, the roughness length of forests as calculated in the model has been found to correspond to ~ 0.12 times tree height, irrespective of tree type (conifers or broadleaves). Therefore, values of roughness length for our EG plots, as well as for the other forest types, were calculated by multiplying the simulated values (or assigned, for SF and PF plots) of tree height by this coefficient.

As per the industry standards in wind resource assessments, fixed values of roughness length were assigned to the East Viet Nam Sea water bodies such as those near the coast (value: 0.00). Similarly, the standard value of grassland (0.03) was assigned to unspecified areas surrounding the forest and plantation areas. Using WAsP Map Editor, these roughness elements were added to elevation (contour) layers of the AOI extracted from the DEM.

Freely available wind data were obtained online for the area shown in Figure 5 from the Global Wind Atlas (<http://globalwindatlas.com>), a dataset of global wind data provided by a consortium led by DTU Wind Energy that provides mesoscale level wind data at varying resolutions between 250m and 1km grids. The meteorological reanalysis data from the NASA GEOS-5 data-assimilation system grid-point model were used in this case study. These data come at a $1/2^\circ - 2/3^\circ$ resolution (large scale) and are then translated to mesoscale – level data in the downscaling process of the Global Wind Atlas. These mesoscale-level data were combined in WAsP with the roughness – elevation maps for the three AOI to calculate the microscale-level (100m) wind climates of the AOI, from which the A and k (akin to the mean and variance of the distribution) parameters of the Weibull distributions of the mean and maximum wind speeds for 12 cardinal directions were extracted in raster map format.

6.2.4 Simulating the risk of wind damage

The tree and stand level data reported in Table 5 were used as input data in ForestGALES to calculate the critical wind speeds (CWS) for each year in the rotation for all the scenarios plots. The Weibull A and k maps generated with WAsP for the three AOI were then loaded in QGIS to assign the mean and maximum values to the attribute tables of each of the plantation plots in Figure 6. This information was used in ForestGALES together with the calculated CWS to estimate the return periods of wind speeds equal or above the CWS for each year in the rotation, for mean and maximum wind climates calculated with WAsP, and for all the scenario plots. The maximum return periods (i.e. those indicating stands at low risk of wind damage) were capped at 200 years. The minimum height of the trees was capped at 5m to account for the current operational limits of ForestGALES. Depending on the planting density and the chosen values of SI_{10} , the trees reach this height between 4 and 6 years into the rotation.

6.3 Results

In this section, both spatially-explicit (i.e. observable on a GIS map) and non-spatial results are presented. The latter pertain solely to the results of the wind damage simulations with ForestGALES, while the former show the localised wind climate in the three areas as calculated with WAsP, as well as the return periods calculated in ForestGALES from the combination of CWS and Weibull parameters.

6.3.1 ForestGALES simulations

Critical Wind Speeds

Results from the wind damage simulations performed with ForestGALES are presented, which have been calculated from the tree and stand – level data in Table 5 and the mean and maximum Weibull A and k parameters derived in WAsP. CWS for breakage were more often lower than those for overturning (i.e. trees were more prone to breakage than uprooting – in 11 plots out of 16), while the mode of damage for the remaining 5 plots was either breakage or overturning (i.e. the CWS for the two modes of damage were very close).

The results in this section are for the CWS of damage, i.e. the lower of the two, as no preference over the type of damage is assumed. The development of CWS throughout the rotation for all the plots is shown in Figure 7. The nomenclature used in the plot's legend reflects the data shown in Table 5. In the order used in this case study, the letters in the legend correspond to: 1st) number of days with rainfall (d: dry; w: wet); 2nd) mean temperature (c: cold; h: hot); 3rd) mean elevation (m: mountains; c: coastal); and 4th) objective – planting density (p: pulp – 1,666 sph; t: timber – 1,000 sph). The second part of the label indicates the SI_{10} , i.e. the growth rate of the trees in the plot, from 10 (low) to 18 (high). Using the topmost plot in the legend of Figure 7 (*dhcmp_SI10*) as an example: this plot has a low number of rainy days (*d*), and low mean annual temperature (*dc*). It has a high mean elevation (*dcm*) and is grown for pulp (i.e. the initial planting density was 1,666 spp; *dcmp*). Given its local climate and mean altitude, the estimated SI_{10} for the plot is 10 (*dhcmp_SI10*).

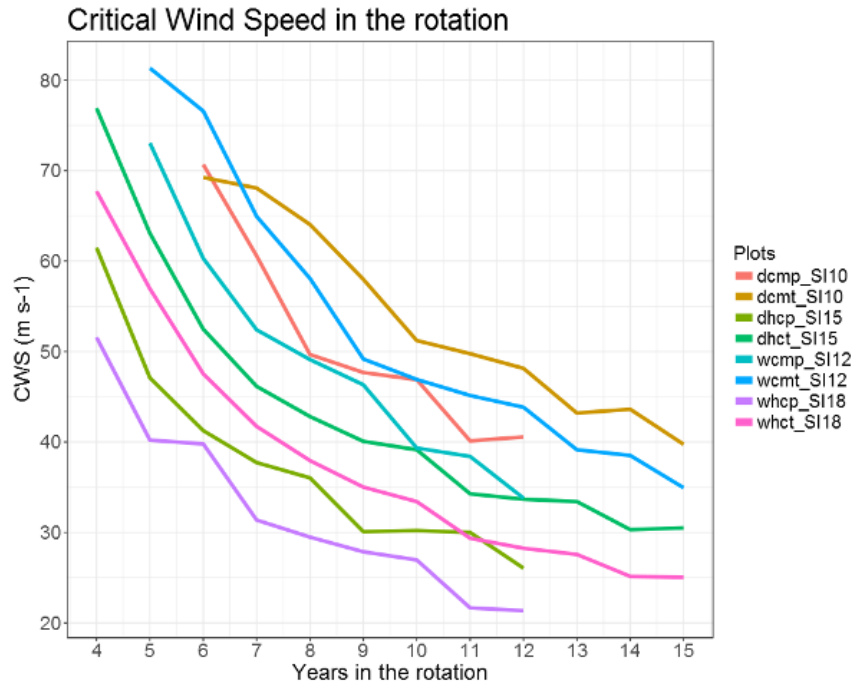


Figure 7: Critical wind speeds of damage calculated with ForestGALES for all the plots in the areas of interest. The nomenclature in the legend reflects the model inputs described in Table 5 and is explained in the main text.

The line plot in Figure 7 shows consistent trends between the plots, with very little overlapping and interception between the plots. The simulations show that the most vulnerable plot throughout the rotation, i.e. that with the lowest CWS, is *whcp_SI18*. This plot has a fast growth rate ($SI_{10} = 18$) and was initially planted at high density ($sph = 1,666$). It is interesting to notice that the 2nd and 3rd worst plots are *dhcp_SI15* and *whct_SI18*, because the former has similar mean temperature and elevation, but a value of SI_{10} immediately lower than *whcp_SI18* in our range of growth rates, while the latter has the same value of SI_{10} as that of the worst plot, but a much lower planting density ($sph = 1,000$). With regards to the plots at the opposite end of vulnerability, the four plots with the highest CWS, in decreasing order, are: *dcmt_SI10*, *wcmt_SI12*, *dcmp_SI10*, and *wcmp_SI12*. By referring to the plot nomenclature described in the previous paragraph, and focussing on growth rate and planting density, these plots rank as: 1) $SI_{10} = 10$ and 1,000 sph; 2) $SI_{10} = 12$ and 1,000 sph; 3) $SI_{10} = 10$ and 1,666 sph; 4) $SI_{10} = 12$ and 1,666 sph.

The effects of SI_{10} and initial planting density on the CWS throughout the rotations in all the plots are further explored in Figure 8.

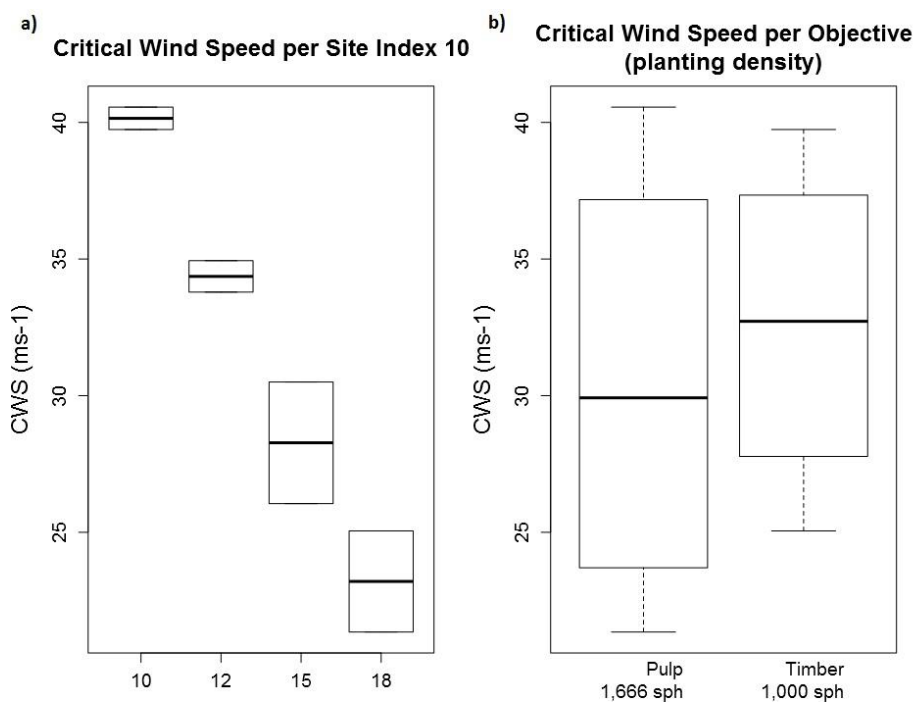


Figure 8: Boxplots of critical wind speeds of damage calculated with ForestGALES for all the plots in the areas of interest, differentiated between growth rate (Site Index10) and objective/initial planting density.

The boxplots in Figures 8a and 8b show the effects of SI_{10} and planting density, respectively, on the CWS calculated by ForestGALES for all the plots throughout their rotations. Large differences can be observed between different values of SI_{10} , and a clear gradient of decreasing CWS (and hence increasing vulnerability) with increasing SI_{10} values is evident from Figure 8a. The effect of initial spacing on the calculated CWS is less marked than that of SI_{10} , but it is nonetheless clear that trees in plots planted at higher initial densities (e.g. for pulp in this case study) are associated with lower CWS (and hence more vulnerable).

Return Periods

Using the mean values of the Weibull parameters of the WAsP – calculated wind climate to calculate the return periods of the CWS yielded very large values of the return periods (which in ForestGALES are capped at 200 years), which correspond to minimal probabilities of damage. For this reason, the results shown in this section focus on the return periods calculated from the maximum values of the Weibull parameters within the area of each plot.

Figure 9 shows the return periods of the CWS at the end of the rotations, i.e. when the plots are most vulnerable, as previously shown in Figure 7.

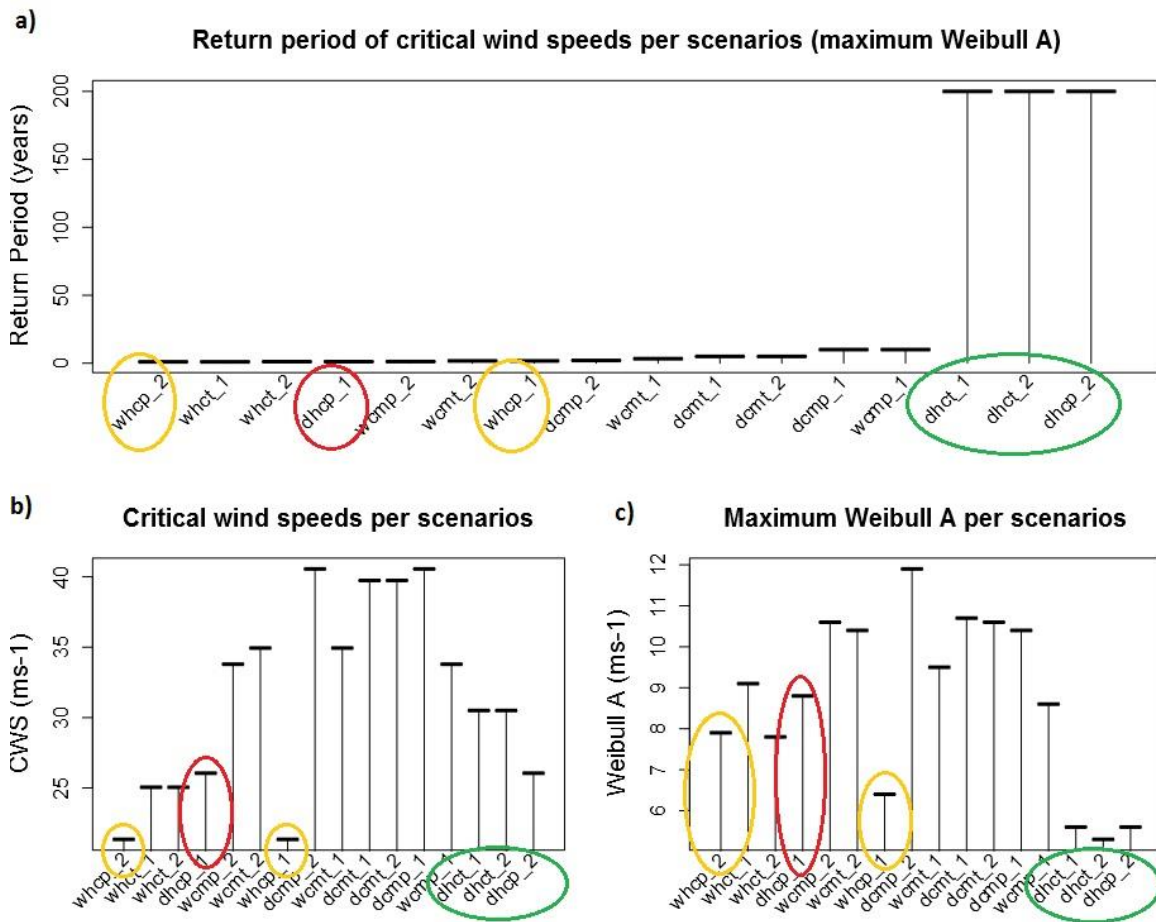


Figure 9: Values of return periods (plot a), associated critical wind speeds (CWS, plot b), and maximum Weibull A parameter of the wind speed distribution in each plot (akin to the mean wind speed, plot c). Values are for the end of the rotation, i.e. when the plots are most vulnerable. Return periods and CWS calculated with ForestGALES, and Weibull A calculated with WAsP. The nomenclature of the plots is similar that of Table 5, with the suffix (1 or 2) indicating plot replicates. Marked plots show differences between plots of similar growth properties and are explained in the main text.

The plots in Figure 9 are ranked in increasing return period. As shown in Figure 9a, all the plots apart from the two dhct and one of the dhcp plots (i.e. three of the four plots with low rainfall, high mean temperature, and low elevation – marked in green) have very low calculated return periods (i.e. their probability of damage under the selected wind climate is almost certain). This indicates that, for maximum wind climate in the plots, only these three plots are typically expected to be able to complete a full rotation, with plots dcmp_1 and wcmp_1 showing borderline risk. To explore the reasons behind the large differences in return periods between the plots (including those between replicates plots) it is useful to investigate the different vulnerability (i.e. the CWS) and maximum wind climate (i.e. maximum Weibull A) in the plots. These are shown in Figures 9b and 9c. From these plots it can be observed that while the three plots with the highest return periods, and the “missing” replicate dhcp_1 (marked in red) all have quite low CWS (high vulnerability, Figure 9b), their maximum wind climates differ substantially (Figure 9c). Another interesting example of the importance of the local wind

climate is given by the whcp plots (marked in yellow). Despite the low values of maximum Weibull A for whcp_1 (Figure 9c), its return periods is very low because of its exceptionally low CWS (Figure 9b). Its CWS is naturally the same as that of its replicate whcp_2 (leftmost plot in Figure 9b), which is however associated with a much higher Weibull A and hence has the lowest calculated return period.

6.3.2 Three-dimensional maps of wind climate and return periods of damaging wind speeds

The spatially-explicit plots presented in this section are derived from 3D objects created for each AOI with QGIS' *Qgis2threejs* plug-in. The 3D objects are created as HTML files and their associated Java Scripts files. Provided that this document is located on a computer equipped with a browser that supports WebGL (as most browsers do), and that the relative position of the folder of the *Qgis2threejs* 3D objects is unchanged, it is possible to launch the original 3D maps in a web browser by clicking on the each hyperlinked-Figure in this section.

Weibull A maps

The wind climate of the three AOI shown in Figure 5, calculated with WASP and expressed as the Weibull A parameter of the wind speed distribution for all cardinal directions, are shown in Figures 10 to 12. The layers shown in the map include the location of the *E. globulus* plots, and the local topography obtained from NASA's DEM (credit for all Figures: ASTER GDEM is a product of METI and NASA). Please note the Figures have different scales (visible in the *Qgis2threejs* 3D objects). The nomenclature of the plots is the same as in Table 5.

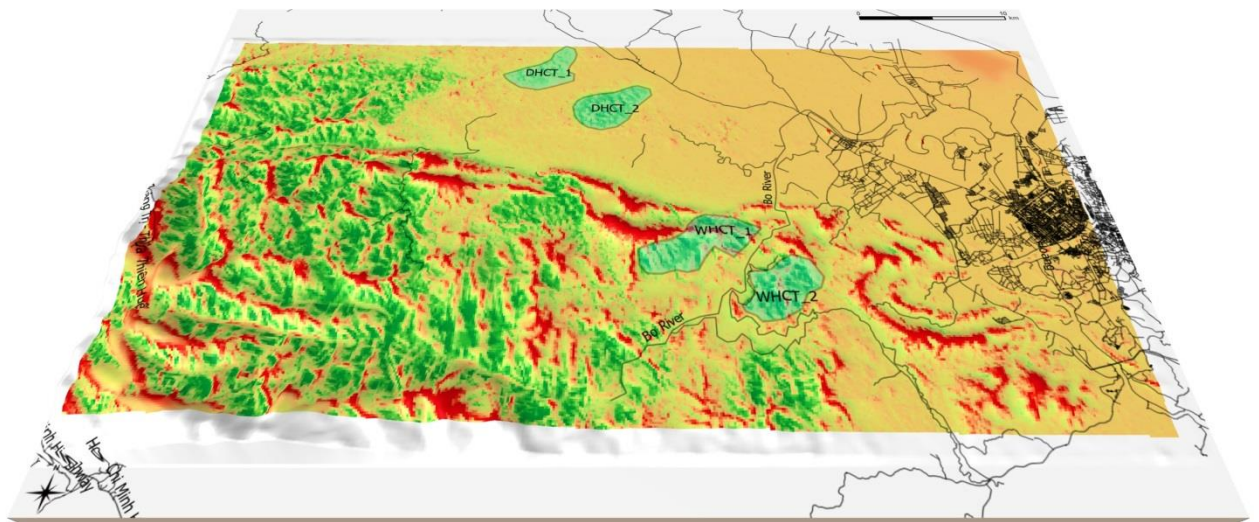


Figure 10: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the northern AOI generated from WASP – calculated values of the Weibull A parameter of wind speed for all cardinal directions. Areas in transparent light blue colour are the locations of the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

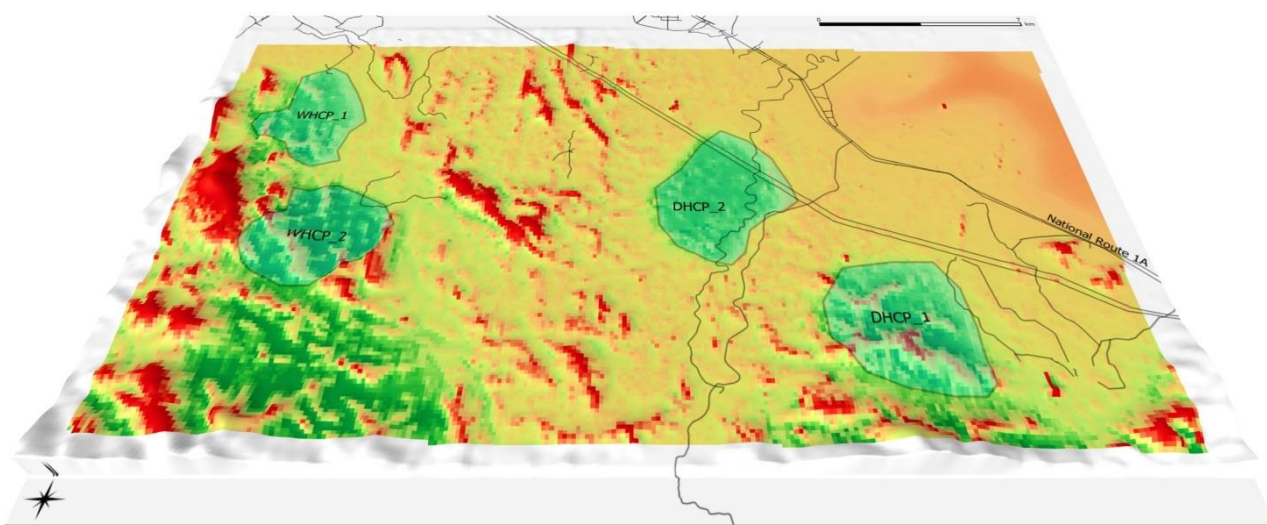


Figure 11: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the eastern AOI generated from WAsP – calculated values of the Weibull A parameter of wind speed for all cardinal directions. Areas in transparent light blue colour are the locations of the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

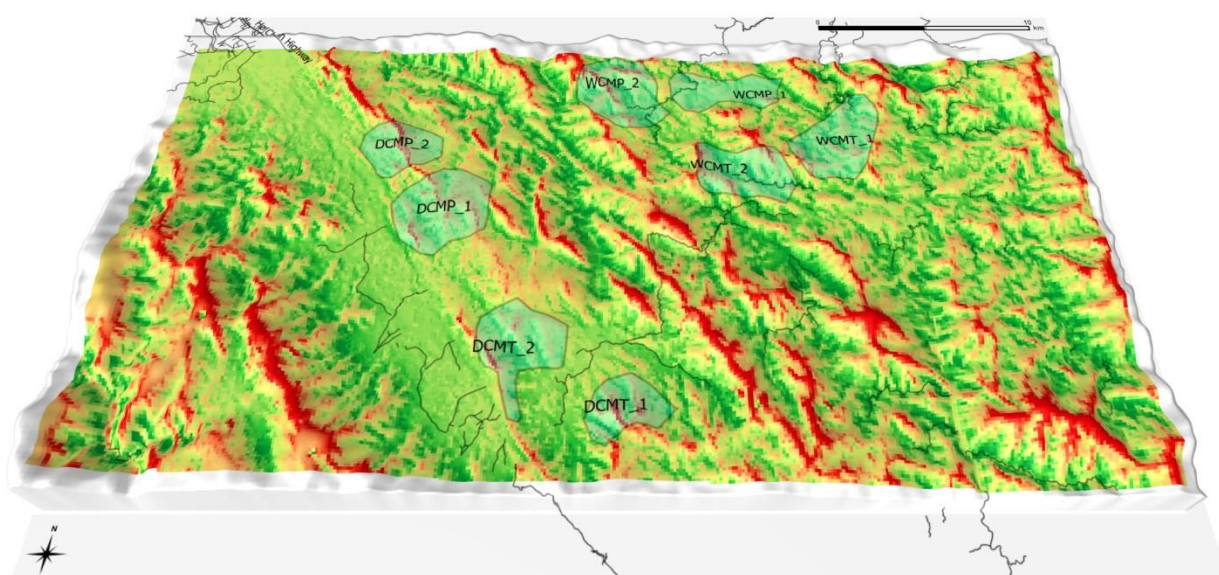


Figure 12: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the south-western AOI generated from WAsP-calculated values of the Weibull A parameter of wind speed for all cardinal directions. Areas in transparent light blue colour are the locations of the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

The colour gradient in Figures 10 to 12 describes areas of low mean wind speed (in green) up to areas of high mean wind speed (in red). As expected, ridges and large downwind areas experience higher wind speeds than sheltered areas in valleys of the complex terrain of the hills and mountains in Thua Thien Hue province. It should be noted that some of the plots experience very complex wind climates within their areas. It should also be remembered from section 6.2.3 that the resolution used in this case study in the WASP calculations is 100m.

Return periods

For all the plots in the AOI, the return periods for the maximum values of Weibull A reported in the previous section were superimposed on the above Weibull A – DEM maps in the form of 3D objects whose height is proportional to the values of the return periods. These were graded in green (~200 years), orange (almost the length of a full rotation) and red (less than 3 years), to show the importance of forest management practices, and their timing, in managing for wind damage risk. These are shown in Figures 13 to 15. As for the previous Figures, the scales are different and can be visualised more clearly in the *Qgis2threejs* 3D objects. The nomenclature of the plots is the same as in Table 5, with the addition of the value of the calculated return period.

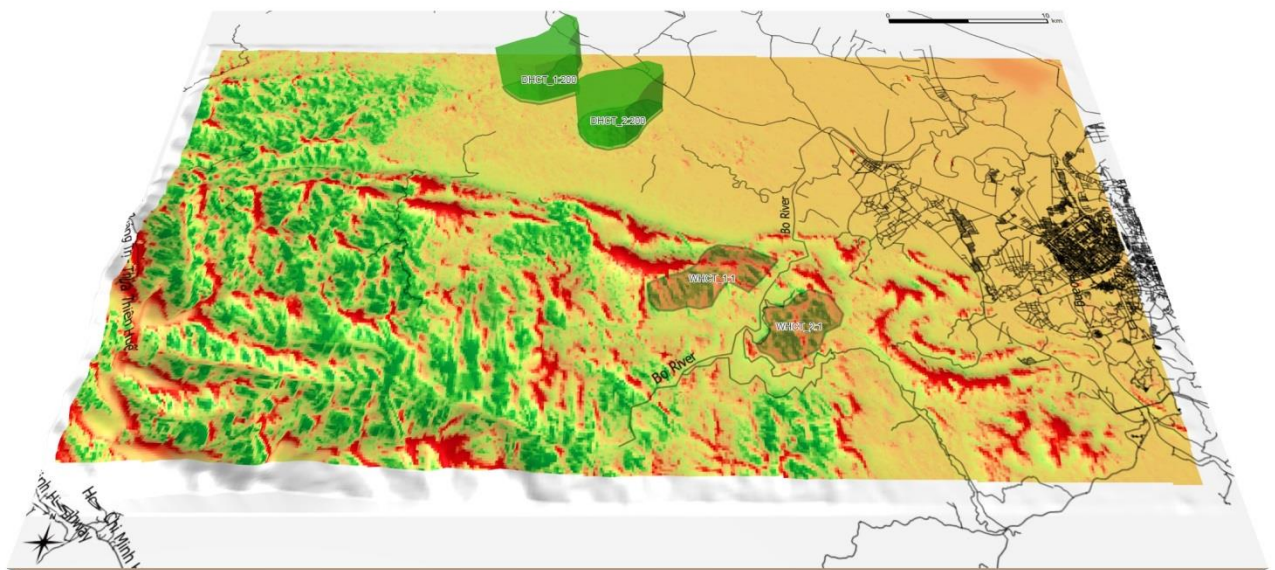


Figure 13: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the northern AOI generated from WASP-calculated values of the Weibull A parameter of wind speed for all cardinal directions. The heights of the 3D polygons are proportional to the return periods calculated with ForestGALES. The colour gradient (green, yellow, and red) reflects the level of risk in the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5, with the additional value of the return periods. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

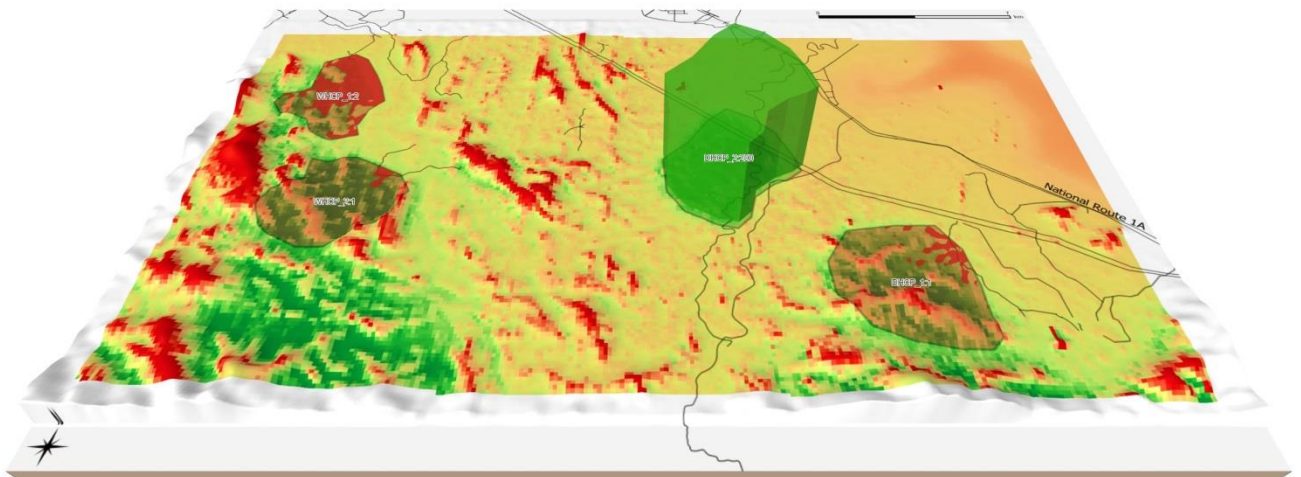


Figure 14: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the eastern AOI generated from WASP-calculated values of the Weibull A parameter of wind speed for all cardinal directions. The heights of the 3D polygons are proportional to the return periods calculated with ForestGALES. The colour gradient (green, yellow, and red) reflects the level of risk in the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5, with the additional value of the return periods. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

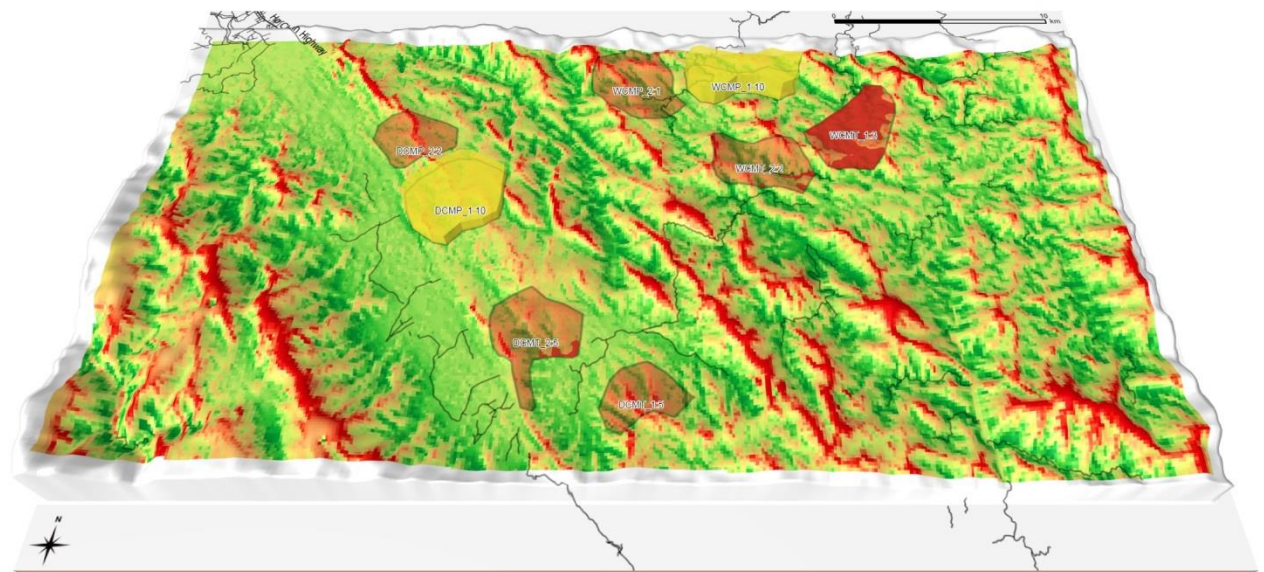


Figure 15: Snapshot of the *Qgis2threejs* 3D object showing the wind climate of the south-western AOI generated from WASP-calculated values of the Weibull A parameter of wind speed for all cardinal directions. The heights of the 3D polygons are proportional to the return periods calculated with ForestGALES. The colour gradient (green, yellow, and red) reflects the level of risk in the *E. globulus* plots. The nomenclature used in the plots is the same as in Table 5, with the additional value of the return periods. If hyperlinks are activated, click on the image to launch the corresponding *Qgis2threejs* 3D object in a browser (WebGL required).

The return periods 3D polygons shown in Figures 13 - 15 show the locations of the *E. globulus* plots and their risk of wind damage. The three plots with large return periods are located in the northern and eastern AOI, on flat terrain where the maximum values of Weibull A are considerably lower than those in other locations, as previously shown in Figure 9c. It is interesting to note that the return periods of the other plots in the northern and eastern AOI have very low return periods, a consequence of the large differences in terrain between the flat areas near the coast and the hilly areas to the west. Conversely, the highly complex and rugged terrain of the south-western AOI, while resulting in generally low return periods, show a large spatially heterogeneous distribution of return period values.

6.4 Discussion

Three areas of interest in Thua Thien Hue province in Central Viet Nam were compared in this study. Because of the current unavailability of growth models for *Acacia* spp., *E. globulus* was chosen as the demonstration species and the GLOBULUS growth model was used to simulate the growth of trees in 16 plots within the three AOI under different climatic conditions and two initial planting densities for different objectives. The location of the plots with regards to the eastern coast and to the hills and mountains within the province was used in estimating growth rate of the trees in the different plots (SI_{10} , Site Index at age 10), and the mean rooting depth for wind stability simulations with ForestGALES.

While the number of days with precipitation has some effect on the simulated values of tree height and Dbh in GLOBULUS, the model is highly sensitive to changes in SI_{10} with regards to the rate of development of tree height, and to the initial planting density on the development of Dbh. As a consequence, fast growth rates (e.g. in this study SI_{10} 18 and 15) and high initial planting densities (e.g. in this study 1,666 for pulp production) result in trees that are particularly tall and slender. Conversely, slow growth rates (SI_{10} 12 and 10 in this study) and low initial planting densities (e.g. 1,000 sph as for timber in this study) simulate the growth of trees that – other parameters remaining equal – are shorter and with larger Dbh. These tree and stand characteristics play very important roles in the calculations of the critical wind speeds of damage in ForestGALES. It should be noted that the rotation length set in this case study for the production of pulpwood from *E. globulus* (12 years) is much larger than the current practice with Vietnamese *Acacia* trees (~6 years). In this report the rotation length for this objective was set at 12 years (see Table 5) because the GLOBULUS model is parametrised for Portuguese conditions. As specified in an earlier section, the main purpose of this case study is to demonstrate the capability of the model couplings between ForestGALES, the airflow model WAsP, and a tree/stand growth model.

Trees are known to acclimate to the prevailing wind climate and typically respond to these stimuli by allocating resources during their growth to the most appropriate components (e.g. the rooting system, stem height and diameter, canopy size and shape). As a consequence, trees at the upwind edge of an unthinned stand are often the most wind-firm, while thinnings open up a stand's canopy with the effect of exposing the retained trees to wind loads they did not grow accustomed to until that point, therefore increasing their vulnerability. Similarly, uncoordinated harvesting of stands within a mosaic of plots of relatively small sizes typically exposes the neighbouring stands to larger wind loads, and can be a serious issue in areas where stands ownership is highly fragmented (e.g. Kamimura et al., 2015), as is often the case for

Vietnamese plantations. The high complexity of the processes involved in tree acclimation to wind means that it is very complicated to model these, and the current release version of ForestGALES is unable to account for acclimation. In most cases however, the form of the tree stems described by tree height and Dbh, and the number of trees in a stand are the main drivers of the risk of wind damage in forested stands (e.g. Albrecht et al., 2012; Hanewinkel et al., 2008). As shown by Locatelli et al. (2017), ForestGALES performs well in capturing these influences in its calculations of CWS. This explains the trends observed in Figures 7, 8, and 9b, where the CWS decreases as trees grow in height through the rotation – slender trees being more vulnerable, and SI_{10} and planting densities show a very large effect on the mean CWS.

By comparing the calculated CWS with the wind climate of a forested area, it is possible to calculate the probability of damage, and from this the return period of wind speeds equal or greater than the CWS. In this study, the wind climate of the three AOI was calculated in the airflow model WAsP by processing freely available mesoscale meteorological reanalysis data, in combination with topographical data obtained from a NASA's DEM, and a description of the roughness lengths of the roughness elements in the AOI (i.e. water bodies, grassland, forests – the latter based on tree height). As reported in Section 2, wind speed distributions are typically described with the A and k parameters of a Weibull distribution (Seguro and Lambert, 2000). Because the Weibull A parameter is akin to the mean wind speed, it is typically used to visually display the wind climate of an area. The Weibull A maps shown in Figures 10 to 12 show the effect of topography on the wind climate of the AOI: it is evident that the complex and heterogeneous terrain in the south-western AOI contrasts markedly with the large flat areas encountered to the east of the northern and eastern AOI.

The maximum value of the Weibull A parameter in the areas of the *E. globulus* plots, rather than the mean, is used in the calculations of the return periods shown in Figure 9, and in Figures 13 to 15. This approach has a number of benefits. First of all, the low resolution (100m) of the microscale WAsP – calculated wind climates means that the mean Weibull A was likely underestimated, as suggested on the Global Wind Atlas website (e.g. see Figure 2 on <http://globalwindatlas.com/methods.html>). Thus, a more accurate mean value of Weibull A, as one that would be calculated at a finer resolution, would be closer to the maximum Weibull A value calculated for the present study. For this work, the maximum Weibull A value of the *E. globulus* plots could be also interpreted as the worst wind climate that can be expected in each of the plots. Therefore, estimates are provided of the return periods for both the most exposed sites within the plots, and for the worst wind climate expected in the area. Given the predicted increases in extreme events in Viet Nam, and in the Central region in particular (Katzfey et al., 2014a; Suppiah and Thang, 2014), the wind climate and the return periods for what are currently the worst expected conditions in a given area may be the most relevant in understanding future wind risk. In addition, the CWS and return periods for the plots in Figure 9 are shown for the end of the rotation (i.e. at age 12 for timber and 15 for pulp) as they are most vulnerable and valuable immediately prior to harvesting.

Because of the unavailability of *Acacia* spp. growth models, and because tree-pulling studies required to parametrise ForestGALES has never been performed for *Acacia* spp., it is not possible to directly extrapolate the results of this case study to plantations of either *A. mangium* or *Acacia* hybrid. This limitation is particularly relevant to the calculations of the risk of uprooting, which in ForestGALES relies on fieldwork-derived experimental values of resistance to

overturning (the soil type and species-specific C_{reg} parameters discussed in Section 2). Given that the resistance to stem breakage depends largely on the modulus of rupture of green wood, it is however possible to speculate on how *Acacia* spp. would fare in comparison to *E. globulus* by comparing the MOR values of the two species. As reported in Table 3 in Section 3, while there seems to be large variation in the MOR values of *Acacia* spp., these are typically lower (by between 20% and over 50%, ranging from 414 kg m⁻³ and 1,000 kg m⁻³; Kha, 2000; Sein and Mitlöhner, 2011a; Harwood et al., 2012) than those of *E. globulus* (~1,250 kg m⁻³, Locatelli et al., 2016; McKinley et al., 2002). These values would suggest that the CWS for the areas of the plots simulated in this case study would have been considerably lower for *Acacia* spp. However, given this large variability in reported MOR values, testing of the mechanical properties of the selected *Acacia* varieties used in Viet Nam will be required, alongside tree-pulling experiments, to parameterise ForestGALES to provide robust wind risk assessments.

In addition to the above considerations, forest planning that incorporates wind risk management will require a wind climate map with higher resolution. In fact, the ability to identify the most suitable (i.e. less exposed) areas for the chosen plantation species and forest objective is likely to considerably reduce the losses due to catastrophic wind damage. While producing better quality maps of wind climate is a feasible task, some considerations should be made with regards to data requirements and other resources. Access to high quality data from one or more weather stations local to the area of interest of a wind risk assessment study would be ideal. Such data would dramatically increase the confidence of the fine-scale resolution of the wind resource mapping. On a related note, as noted in Section 4, Badger et al. (2015) report ongoing work on the production of a Vietnamese Wind Atlas, which is expected to have better resolution than the Global Wind Atlas and to provide adjustments for the complex terrain encountered in certain areas of Vietnam. While the release date of this wind atlas is at present uncertain, once produced it would allow highly accurate calculations of microscale wind climate, when paired with local weather station data, as well as providing a higher degree of confidence about the localised wind climate in situations where obtaining local weather station data would be difficult.

Finally, constraints to the level of the microscale calculation of the wind climate are related to the fairly large computational requirements of calculations with WAsP. As a practical example, calculating the wind climate of the ~70,000 ha of the northern AOI at a 100m resolution on a modern desktop computer equipped with 4GB of RAM and an Intel i5 microprocessor clocked at 2.30 GHz took about 2 hours of computing time. Increasing the resolution to 10m caused WAsP to crash because of lack of memory. This applied to all the AOI, including the much smaller eastern area. Of course, an alternative is to produce maps of wind speed that cover much smaller areas, and assemble these in the fashion of a mosaic to obtain a larger area. WAsP can also be set up to run on a number of computers in parallel, thereby reducing the total computation time. However, the person-hours required to manually prepare a “mosaic-map”, including digitising the roughness elements, increase linearly with the number of smaller maps required.

6.5 Conclusions

A number of interesting conclusions can be drawn from this case study. Firstly, despite the relatively low resolution of the microscale wind mapping, the maps of wind climate for the three AOI show that while plots located in sheltered valleys within the mountainous ridges to the West seem at low risk of wind damage, plots on exposed mountain ridges in the West, and plots on eastward slopes facing the prevailing winds, are exposed to the most severe wind speeds in Thua Thien Hue province.

While trees are known to be able to acclimate to the local winds by allocating resources to the rooting system and by developing more stable stem and canopy forms, it is unknown whether *Acacia* trees grown under plantations conditions are able to do so. The high planting densities often adopted in plantations for pulp production, and ultimately the short rotation lengths adopted in such silvicultural systems are probably unfavourable to the trees' adaptation to high winds. Given that ownership and management of plantations plots can be highly fragmented in Viet Nam, it would be beneficial from the point of view of wind risk management if activities such as thinning and harvesting were coordinated between adjacent plots, as these practices can create gaps and significantly alter the wind climate of downwind plots.

In general, as is often the case in windy areas, the geographical distributions of wind speeds should set the priorities and objectives for plantation forestry. This might mean that only short rotations are grown on more exposed sites, so as to minimise the value of the assets exposed to high risk at any given time, while more sheltered locations might be used for growing high-value products such as timber and veneer that require longer rotation lengths.

Secondly, coupling ForestGALES with the GLOBULUS growth model and the WASP airflow model in a spatially explicit setting within QGIS has shown robustness and flexibility. The dynamic interplay between inputs and outputs of the various components of this approach ensures that the results of the simulations at each step of the process take into account the highly complex and dynamic interactions between topography, wind climate, and the characteristics of the forested stands. From the point of view of this "system of models", this case study shows that – provided that time and computational requirements are met – it is possible to further simulate forest management practices, e.g. to model the effect of harvesting on the surrounding wind climate, therefore further increasing the predictive abilities of the system.

Thirdly, this case study has confirmed the suitability of ForestGALES to Vietnamese conditions, and highlighted the requirements for further steps to adapt the model to meet the requirements of forest planners and managers in the country. The large diversity of species and environmental conditions across which ForestGALES has now been parametrised, and is used, demonstrates the portability of the model. This bodes well for future work to focus on building a version of ForestGALES tailored to conditions typical of Vietnamese plantations of *Acacia* spp.

Lastly, the possibility of scaling-up the work presented in this case study to cover a much larger area in Viet Nam, e.g. focussing on the neighbouring provinces to Thua Thien Hue, is primarily dependent on: the availability of detailed maps showing the locations of plantation and forested areas; detailed information on the mean height of non-plantation forests, and on forest inventories and growth models for *Acacia* spp. plantations; on the availability of climate data (including wind speed and direction) from local weather stations – this failing, the availability of the upcoming Vietnamese Wind Atlas; and lastly, sufficient computing time to calculate the wind

climate for a mosaic of small patches. Availability of these data and resources would allow assessments to be carried out of wind damage risk to forest plantations across Viet Nam if required, and an adapted version of the ForestGALES decision support tool to be developed to explore forest risk implications of local and regional management decisions.

6.5.1 Road-map for Phase II

A number of tasks are required to produce a reliable version of ForestGALES for *Acacia* spp. grown in Vietnam. These tasks can be categorised as those that are required to parametrise the model for these species, and those that are required for implementation of the new parametrisation. In addition to these, some preliminary activities are required.

Preliminary activities

Selection and characterisation of suitable sites and plantations for the parametrisation field work.

Task 1 – Site selection

As shown in the case study, the complexity of the Vietnamese topography has a profound effect on the localised wind climate. Furthermore, plantations sited on the slopes of hill and mountains, as discussed in Section 3, are typically grown on shallower soils than those located on flat coastal areas. This has an effect on tree stability – and on tree growth, discussed in Task 5 below. To account for the heterogeneous Vietnamese landscape, two contrasting sites – one in the central highlands and one in the lowlands coastal areas – should be selected for the parametrisation activities. Site selection should also take into account features such as: accessibility, e.g. proximity to major roads; safe conditions for transportation of instrumentation to the sites; proximity to an automated weather station (see Task 6); and soil maps as described below.

Task 2 – Characterisation of soil types

The type of soil on which trees are grown has a marked effect on their anchorage. Before and during the site selection process, the soils in the area should be characterised with regards to their texture, organic content, and presence/depth of a hardpan that often can restrict rooting depth. Soil characterisation and mapping is important to select the most representative sites, and/or the best/worst case scenarios, for the tree pulling experiments described in Task 3.

Parametrisation of ForestGALES for *Acacia* spp.

Once the sites have been selected, field work can commence. The parametrisation tasks pertain to the work necessary to obtain information on the resistance of a species to stem breakage and overturning. A complete description of field work practices and techniques can be found in Nicoll et al. (2006) and in Locatelli et al. (2016). In this section, two main tasks are discussed.

Task 3 – Tree pulling

Tree pulling is done to calculate the trees' resistance to overturning. Typically, a minimum of 15 – 18 trees, equally divided in 3 size classes, are identified on each site to ensure that sufficient statistical power is preserved for data analysis. Normally, four to five days' work is required for

each site, depending on manpower and available expertise. To describe the tree-pulling activities in a nutshell, a mechanical winch is attached to the stem of a tree, at about $\frac{1}{3}$ to $\frac{1}{2}$ tree height. A force is applied to pull the tree and recorded on a data-logger. The increasing bending of the stem under the pulling force is measured and recorded at the same time using 2 or 3 inclinometers attached to the stem. After the pulling, stem diameter is measured at 1m intervals; a section of the stem is weighted for green wood density calculations; the tree crown is removed and weighted to estimate the additional canopy load; when roots are exposed, rooting depth is measured and the health of the rooting system is estimated. It should be noted that fieldwork campaigns require a concerted effort with local institutions to share staff and equipment and to arrange for compensation if necessary to the site owner for lost timber/pulp.

Task 4 – Measurement of mechanical properties

As described in Section 2, resistance to breakage in ForestGALES is modelled by incorporating the Modulus of Rupture (MOR) in the calculations of stem strength. The Modulus of Elasticity (MOE) is required to model the bending of the tree when subject to wind loading. While these values can often be obtained from the literature, it is common practice to transport the sections used for green wood density calculations described in Task 3 to a facility where small clears of wood (~40 cm X 2 cm X 2 cm) can be extracted, conditioned to a nominal moisture content (typically 12%), and then used to destructively measure MOR and MOE with a bench-top three-point bending machine or a similar tool.

Implementation of the new parametrisation

While the portability of ForestGALES demonstrated in the case study will ensure that once the model has been parametrised for *Acacia* spp. it will be operational, the lack of an equally portable growth model for *Acacia* spp. that can provide the input variables required by ForestGALES will impede further applications of the parametrisation in Vietnam. The optimal solution to this issue would of course be either the expansion of an existing growth model, or the *ex-novo* development of an appropriate growth model. The latter option would ensure that variables of interest for the portability of a growth model for future scale-up projects covering the whole of Viet Nam (e.g. local climate and weather, soil properties, topography) are measured and – when appropriate – used to model tree and stand growth. While these activities are strongly advised, it is expected that they would result in a considerable cost. For the purpose of estimating wind damage to *Acacia* spp. plantations in Thua Thien Hue province, a possible workaround solution is suggested in Task 5. The importance of higher resolution wind climate maps, introduced in Section 6.4, is the focus of Task 6.

Task 5 – Tariff plots surveys

Measurements of tree and stand characteristics (tree height, Dbh, crown depth and width, stand density) for intervals (e.g. each year) through the rotation of a number of typical stands in the highlands and the lowlands would provide sufficient data for the creation of growth tables and perhaps a simple, static growth model for the surveyed *Acacia* spp. in the two contrasting areas. Replication of the survey for upland and coastal sites is important because the likely deeper soils in the lowlands are expected to be also more productive. Under the assumption that the

selected tariff plots are representative of *Acacia* silviculture in the province, this growth tables/simple growth model would ensure that wind risk assessments with ForestGALES could be performed for the entire Thua Thien Hue province.

Task 6 – Mosaic of high-resolution wind climate maps

The spatial resolution of the wind climate maps used in the case study in Section 6 was set at 100m. While this is an acceptable setting for the scope of the case study, for operational use the resolution should not exceed 50m. This is especially relevant for areas such as Thua Thien Hue province where the plantations landscape is highly fragmented. As discussed in Section 6.4, increasing the resolution of the wind climate maps generated with WASP considerably increases the computing load. For a cost-effective solution, it is suggested that a number of 50m (or higher) resolution wind climate maps are created for a mosaic of smaller areas within the AOI in the province, and then assembled to calculate the risk of wind damage to the local *Acacia* plantations. For maximum confidence of the calculated wind climate maps, it is suggested (but not essential) that the AOI are located in the proximity (i.e. typically less than 50km) of an automated weather station, to further refine the calculations of the localised wind climate.

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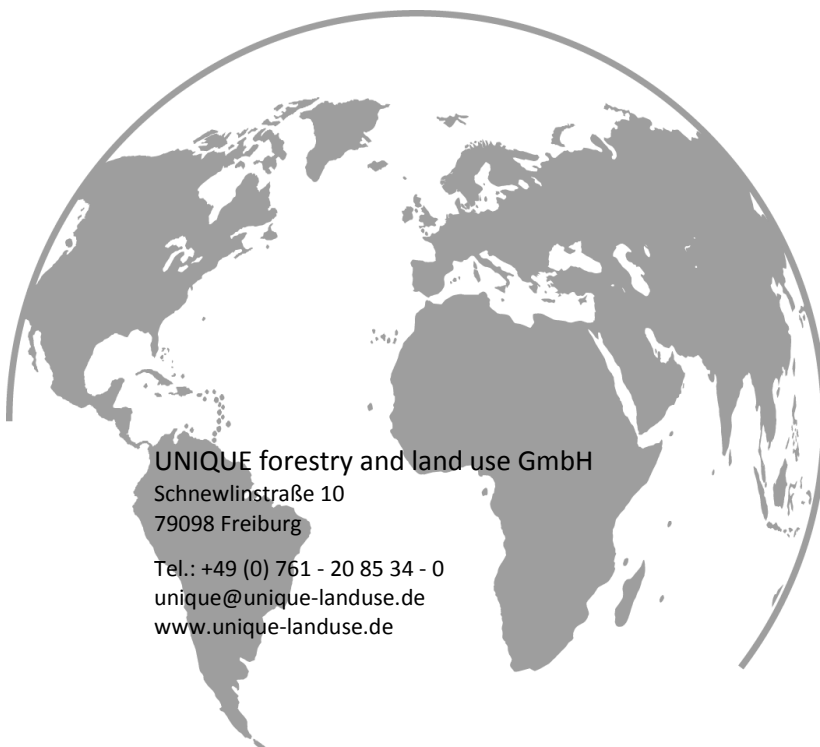
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