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

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ABSTRACT

Wind damage to commercial plantations and natural forests is a serious concern for forest owners and managers all over the world, with notable losses having been reported in the last few decades in Europe, the Americas, and Oceania. Wind-risk models such as ForestGALES allow for a good understanding of the dynamics involved in wind damage, and for calculations of risk to be made, therefore providing vital information on the best practices to minimise such risk. In this paper we parameterise ForestGALES for *Eucalyptus globulus* (Labill.), arguably one the most widespread and commercially important species for pulp and biomass production, with tree-pulling data obtained in Asturias, Spain. Despite the scarce data on tree and stand characteristics available for wind damaged stands of *Eucalyptus* spp., we provide an evaluation of our model's performance under different stocking densities by comparing our simulations with real wind damage data acquired from the literature. We show that ForestGALES is able to accurately model the critical wind speeds responsible for Eucalypts stand damage, hence extending the model's applicability to this important commercial genus. In line with good modelling practice, we present the results of a sensitivity analysis of the model, performed with a Global variance-based method. Our sensitivity analysis confirmed the main role of *Dbh*, stocking density, and tree height in driving the model outputs, and highlighted the importance of accurately knowing the size of any upwind gaps adjacent to a stand to reduce uncertainty in model predictions.

1. Introduction

Species of the genus *Eucalyptus* are some of the most widely adopted in commercial plantations worldwide, primarily for the production of biomass for the pulp and fibre board industries (Diaz-Balteiro and Rodriguez, 2006). Whilst the proportion of biomass extracted from Eucalypt plantations for the global pulp and bioenergy markets is already prominent, it is likely to increase in the future (Gardiner and Moore, 2014). The attractiveness of this genus for commercial purposes is due to its fast growth rates, high productivity, good stem form, good adaptability to different environmental conditions, predisposition to hybridisation and cloning, and natural tendency to sprout vigorously when coppiced (Campinhos, 1999; Giménez et al., 2013; Goncalves et al., 2008). Eucalypt plantations currently provide 50% of the world's wood fibre (FAO, 2007), most of which is produced in South American countries. For instance, in Brazil Eucalypt plantations are planted on an area of 4.7 M ha (ABRAF, 2011), generating ~7.5 M tonnes of pulp per year (Diaz-Balteiro and Rodriguez, 2006), almost equivalent to the country's entire annual wood fibre production (Sedjo, 1999). In Brazil, the mean annual increment (MAI) of *Eucalyptus* spp. under current silvicultural practices is typically around 40 $m^3\ ha^{-1}\ y^{-1}$ (Binkley and Stape, 2004), with recorded maxima of 90 $m^3\ ha^{-1}\ y^{-1}$ in small trial plots (Eldridge et al., 1993). The typical rotation length ranges between 6 and 7 years (Diaz-Balteiro and Rodriguez, 2006). *Eucalyptus globulus* (Labill.) is one of the most successfully adopted plantation species in areas other than the tropics because of its fast growth, high pulp quality, and adaptability to sub-tropical and temperate climates (Campinhos, 1999; Sasse and Sands, 1997; Potts et al., 2004). After being introduced in Europe in the 19th century (Leslie et al., 2011), this species has been increasingly used in commercial plantations in the

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Iberian Peninsula for the production of biomass for pulp and bioenergy (Diaz-Balteiro and Rodriguez, 2006; António et al., 2007). The high density of its wood makes this species particularly sought after for bioenergy purposes (the Forest Products Commission of Western Australia reports a typical value of green wood density of 1040 kg m^{-3}). In Portugal, *E. globulus* is planted on over 26% of the nation's forested area (~812,000 ha), making it the predominant tree species in the country (Águas et al., 2014; Dias and Arroja, 2012). In Spain, *E. globulus* plantations are mostly concentrated in the Northern regions of Asturias and Galicia (Riesco-Muñoz, 2004). In the Iberian Peninsula the typical rotation length is 10–12 years, generating yields between 10 m^3 ha^{-1} y^{-1} and 50 m^3 ha^{-1} y^{-1} (António et al., 2007; Riesco-Muñoz, 2004), with MAI of 10–15 m^3 ha^{-1} y^{-1} (Diaz-Balteiro and Rodriguez, 2006).

The vulnerability of *E. globulus* plantations to environmental hazards such as fire and pests has been extensively studied (e.g. Moreira et al., 2009; Águas et al., 2014; Wingfield et al., 2008), while the occurrence of wind damage is poorly documented. Trabado (2010) reports that 45% of the timber volume damaged by storm Klaus in 2009 in the north-west Spanish region of Galicia (total damage: 1.2–1.8 M m^3) was to *E. globulus* trees. In the same year, in Uruguay, two violent tropical cyclones caused damage to approximately 10% of a private 27,000 ha Eucalypt plantation, corresponding to financial losses of 10 M US$. It is uncertain what Eucalypt species were affected. However, Campinhos (1999) and Vallejos-Barra et al. (2014) report on the extensive use of *E. globulus* in Uruguay. The fact that in the decade preceding such events no wind damage to the plantation had occurred made these massive losses unpredictable from an historical point of view. For these events, data on tree and stand characteristics are not available. Only three papers exist in the literature (Williams and Douglas, 1995; Gerrand et al., 1997; Chen, 2003) where wind damage to Eucalypt stands are reported together with some data on tree and stand characteristics, although the wind speeds responsible for the damage are available only in the latter. These studies are further discussed later in this paper.

Wind is the main cause of abiotic disturbance to forests in temperate and boreal biomes (Schelhaas et al., 2010). European meteorological records of the frequency and severity of extreme winds show a marked increase during the last three decades (e.g. Hanewinkel et al., 2011), as do the records of storm-damaged timber. Part of this increase is due to the larger volume of standing timber in European conifer forests -and hence the amount of timber at risk (Schelhaas et al., 2003). In addition to this, climate model simulations show a tendency for increasing magnitude, and sometimes frequency, of extreme wind events worldwide (Haarsma et al., 2013; Solomon, 2007). The largest European losses resulted from the Vivian/Wiebke storms in 1990 (with more than 100 M m^3 of timber volume losses), the Lothar/Martin storms in 1999 (which is to date the most damaging storm recorded in Europe, with losses of almost 200 M m^3), the Gudrun storm in 2005 (75 M m^3), and the Klaus storm in 2009 (42 M m^3) (Bavard et al., 2013; Blennow et al., 2010; Kilpelainen et al., 2010; Schindler et al., 2012; Schuck and Schelhaas, 2013; Usbeck et al., 2010; Wohlgemuth et al., 2002). Besides Europe, forests in other parts of the world have been severely affected by windstorms, most notably the USA (Uriarte and Papaik, 2007; Beach et al., 2010), Japan (Kamimura and Shiraishi, 2007), New Zealand, Fiji, and Australia (Everham and Brokaw, 1996; Moore and Watt, 2015). However, studies of wind damage in South America are scarce, with a few notable exceptions. Negron-Juarez et al. (2010) and Marra et al. (2014) report the extensive damage caused by a single cross-basin squall event in 2005 to a Central Amazon forest, which resulted in the loss of about 30% of the forested area in the region, estimated to about 23% loss in mean annual biomass accumulation.

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

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

Towards this aim, in this paper we parameterise ForestGALES for *E. globulus* grown under environmental conditions typical of the Northern Spanish region of Asturias, and evaluate the model's behaviour in regards to the presence/absence of a windward gap, and a range of planting densities. We compare model behaviour with the few records of wind damage in eucalyptus forests. In line with good modelling practice, we include a sensitivity analysis, an essential ingredient for validation and corroboration of any