Agricultural and Forest Meteorology 224 (2016) 49–63

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

A simple wind–tree interaction model predicting the probability of wind damage at stand level

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ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form 14 April 2016
Accepted 23 April 2016

Keywords:
Forest wind damage
Stochastic wind model
Tree motion
Wind risk

ABSTRACT

Forest wind damage occurs under the passage of strong intermittent wind gusts at tree level. In order to predict the probability of tree damage of a forest, a simple statistical wind speed model was developed and coupled to a tree swaying model. The wind model is based on a stochastic approach and on some universal characters of normalized wind statistics at canopy top. This model aims at generating high frequency (10 Hz) time series of the three wind velocity components at canopy top knowing only the wind intensity from a nearby meteorological station and the height and cumulative plant area index of the forest. Compared to field measurements and large-eddy simulations over different canopy structures and densities, the wind model was able to reproduce accurately the main features of canopy-top wind dynamics, in particular the signature of the mixing-layer type coherent eddy structures developing at canopy top. Coupled with a tree swaying model, the model has allowed to predict the probability of wind damage of forest following the windstorm intensity and duration, and following the main tree characteristics resulting from silvicultural scenarios. By responding to some weaknesses of existing mechanistic wind risk models, this simple wind–tree interaction model may represent the first step toward a new generation of mechanistic wind risk models based on a probabilistic approach.

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1. Introduction

Mechanistic wind risk models have been developed since the last two decades in order to predict and mitigate the risk of wind damage in forests (e.g. Peltola et al., 1999; Gardiner et al., 2000; Byrne and Mitchell, 2013; Seidl et al., 2014; Hale et al., 2015). These models usually consider an entire forest damaged when the wind speed reaches a predicted critical value. Although the approach used by these models has the advantage of being simple and thus easily applicable in an operating mode, it suffers from several weaknesses, in particular regarding the recent findings of Dupont et al. (2015b). In this later study, we unraveled the mechanisms of damage propagation at forest scale from numerical simulations, rising potential source of improvement for wind risk models. First, the predictions of wind risk models are independent of the storm duration while Dupont et al. (2015b) found that storm duration plays a major role for predicting the final level of damage of a forest. Second, mechanistic wind risk models are more deterministic than probabilistic. Dupont et al. (2015b) showed that in similar windstorm conditions the damage level can differ significantly between two similar stands, because of the randomness nature of damaging sweeps. It is, therefore, preferable to develop probabilistic wind risk models rather than deterministic ones. Third, mechanistic wind risk models usually ignore tree damage propagation (Peltola et al., 1999; Gardiner et al., 2000; Hale et al., 2015). Although recent wind risk models (Byrne and Mitchell, 2013; Seidl et al., 2014) introduced dynamical aspects of damage propagation by removing iteratively all susceptible trees from a stand until all remaining trees are stable with the forcing windstorm conditions, this was done without considering storm duration. Dupont et al. (2015b) clarified the process of damage propagation by showing that it involves two stages during windstorms. Damage is first initiated by the impact of strong downward wind gusts (first stage). Then, when the damaged areas reach a critical size, damage increases drastically as the flow accelerates within them (second stage). Fourth, the wind loading is highly simplified in mechanistic wind risk models (Gardiner et al., 2008), especially the gustiness of the flow, which is only accounted for through a gust factor. These weaknesses of mechanistic wind risk models highlight the need for developing a new generation of mechanistic wind risk models.

The model developed in Dupont et al. (2015b) allowed us to predict damage propagation in great details by simulating the three-dimensional intermittency of the turbulent flow within the

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http://dx.doi.org/10.1016/j.agrformet.2016.04.014
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tree canopy and its interaction with tree motion. However, the deterministic approach consisting of resolving the Navier–Stokes equation using a large-eddy simulation (LES) approach, as done in Dupont et al. (2015b), is too time consuming to be used in an operating mode. This approach is also too time consuming to study in details the impact of various forest structures resulting from environmental factors on tree damage. It is, therefore, desirable to have a simpler canopy-top wind speed model that would reproduce high-frequency wind velocity fluctuations, following the canopy structure and the large-scale wind intensity, in order to predict tree vulnerability. Several statistical wind speed models have been developed over the last decade in particular in the context of wind power (e.g. Lei et al., 2009; Morales et al., 2010; Calif, 2012; Zarate-Minano et al., 2013) or for evaluating flux sensor systems (Fotiadi et al., 2005). However, these models work only for surface boundary-layer flow, far from the roughness sublayer flow, usually at low frequency, and they often predict only the main wind velocity component.

This paper presents a simple wind–tree interaction model that may represent a first step toward a new generation of mechanistic wind risk models. It includes a new statistical turbulent wind model at canopy-top to better account for the gustiness of the flow, a simple tree-model to account for tree motion during the process of tree breakage (Pivato et al., 2014), and a coupling between both wind and tree models to predict the probability of tree damage at stand level. The novelty of the wind model is its applicability at canopy top, at high frequency (10 Hz), and to consider the three wind velocity components, by knowing only the wind intensity from a nearby meteorological station and the height and cumulative plant area index of the canopy. The main difficulty of such wind model is to reproduce the footprint of the coherent structures generated at canopy top on the streamwise and vertical wind velocity components following the canopy structure.

The statistical wind speed model and its coupling with the tree swaying model are presented in Section 2. The wind model is first evaluated in Section 3.1 on two different horizontally homogeneous vegetation canopies, a Maritime pine forest and a walnut orchard, against field measurements, as well as against LES of the flow over Maritime pine forests with different densities. Then, the applicability of the coupled model to predict the probability of tree damage following the wind intensity and the tree morphology resulting from different silvicultural scenarios, is investigated in Sections 3.2 and 3.3, respectively. Finally, the model relevance as an initial step toward a new generation of mechanistic wind risk models is discussed in Section 4, before concluding in Section 5.

2. Method

2.1. Outlines

As sketched in Fig. 1, a statistical wind model is first developed to generate high frequency (10 Hz) times series of the three wind velocity components at canopy top under neutral thermal stability, knowing only a reference wind speed (U_{met}) that would be measured at a nearby meteorological station, the canopy height (h), and the cumulative plant area index (PAI) of the canopy (including both stem and leaf area). The use of U_{met} allows to compare the wind speed at the top of different canopies (U_h) under a similar large-scale meteorological condition. U_{met} is first extrapolated to U_h (Section 2.2, step 1 in Fig. 1). Then, turbulent fluctuations around U_h are built to obtain realistic time series that would have similar statistics as measured ones (Section 2.3, step 2 in Fig. 1). Finally, the wind velocity time series are used to load a tree model in order to predict the probability of tree damage at stand level (Section 2.7, step 3 in Fig. 1).

2.2. Mean wind speed at canopy top

The normalized mean wind speed at canopy top (U_h/U_{met}) depends on the canopy structure. Here, U_{met} is the mean wind speed that would be measured at z_{met} = 10 m on an extended homogeneous lawn surface with a roughness length of about z_{0met} = 0.03 m. To extrapolate U_{met} to the canopy-top of the forest site, a 3 steps procedure is used. First, U_{met} is extrapolated to H = 200 m height by assuming a logarithmic velocity profile. Second, the mean wind speed at H is assumed constant between the meteorological and the forest sites. This 200 m height is expected to be high enough for the airflow to be in equilibrium over the landscape. Third, the 200 m height mean wind speed at the forest site is extrapolated down to the canopy top using the unified theory proposed by Harman and Finnigan (2007) that describes the mean wind velocity profile within and above a dense canopy following the canopy type and the atmosphere stability. By dense, Harman and Finnigan (2007) meant that "almost all of the momentum is absorbed as drag on the foliage rather than as stress on the ground". Only near-neutral stability of the atmosphere is considered in this study. With Harman and Finnigan's approach, the mean wind profile above and

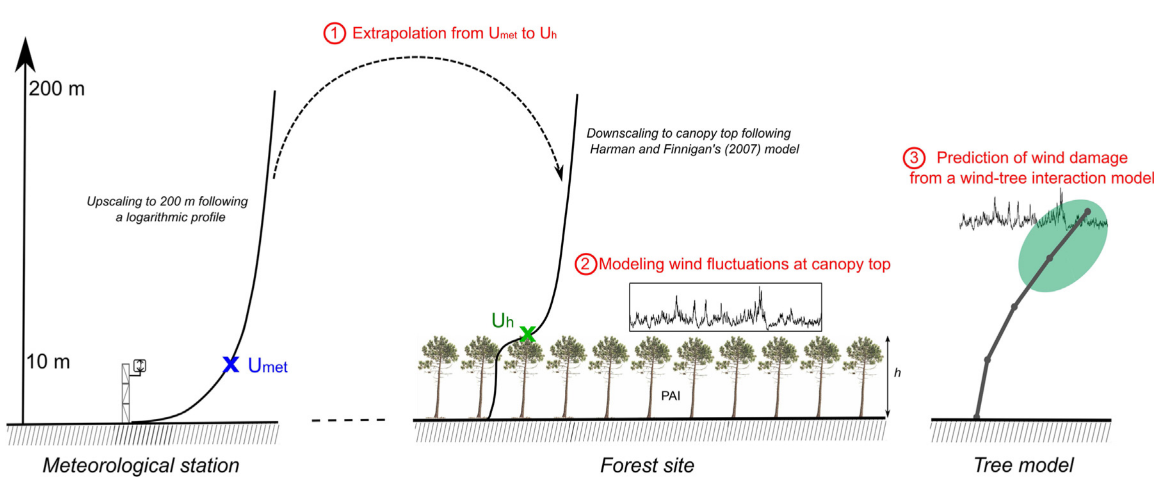

Fig. 1. Schematic representation of the wind–tree interaction model used to predict the probability of tree damage at stand level knowing the mean wind speed U_{met} measured above an open lawn surface of a nearby meteorological station, the canopy height h, and the cumulative plant area index (PAI).

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