EDITORIAL

Wind effects on trees

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The interactions between airflow and trees and forest stands are diverse. They include the reduction in near-surface wind speed and production of turbulence by trees. Near-surface wind conditions affect physiological processes in trees, tree growth, and survival (Ennos 1997; Eugster 2008). Turbulent components of the flow field dominate the tree response behaviour (Mayer 1987; Gardiner 1995; Schindler et al. 2010) and drive the scalar exchange at the forest–atmosphere interface (Finnigan 2000).

Wind–tree interactions take place at a wide range of temporal and spatial scales (de Langre 2008). Aerodynamic drag at all surfaces of the aerial parts of trees—from individual leaves (Vogel 1989) to whole tree crowns (Kane et al. 2008)—perturbs the airflow inside forest canopies (Shaw et al. 1974; Baldocchi and Meyers 1988; Turnipseed et al. 2003). Therefore, detailed information on forest structure is an essential precondition for understanding wind–tree interactions and the successful application of flow models to tall canopies. In flow models, forest structure is often represented by the mean vertical profile of the plant area density. Queck et al. (2011, this issue) present a method that can be used to record detailed 3D stand structure from terrestrial laser scanning. They investigated the relationship between wind speed, aerodynamic drag,

and plant area density and show how 3D laser scanner data can be used to derive turbulence parameters for flow models.

The structure of windward forest edges (Mitscherlich 1973; Dupont and Brunet 2008a, b) as well as the stand structure (Gardiner et al. 1997; Marcolla et al. 2003; Dupont and Brunet 2008b, c; Queck and Bernhofer 2010) affects the flow field within and above forests. In the near-edge region, pronounced gradients of flow quantities provoke high wind load on trees (Stacey et al. 1994; Peltola 1996; Gardiner et al. 1997), which may trigger damage in strong wind conditions. Although Gardiner and Stacey (1996) as well as Dupont and Brunet (2008a) report that tapered forest edges reduce wind loading and related bending moments of trees near the edge, it is still not completely clear, how changes in edge and stand structure affect the flow field at the canopy near forest edges, and whether these changes can contribute to the mitigation of damage in high wind conditions. In a detailed wind tunnel study, Ruck et al. (2011, this issue) investigated the effect of changes in taper angle of windward forest edges on the flow field for different stand densities. Their results demonstrate the impact of edge shape and stand density on quantities of the flow field near the canopy top, the region most relevant for tree failure in strong wind conditions.

The aerial parts of trees start to vibrate in response to wind excitation (Sellier and Fourcaud 2005; Rodriguez et al. 2008). In forests, dynamic tree responses are not only observed at the single tree level (Mayer 1987; Gardiner 1995; Peltola 1996; Flesch and Wilson 1999; Rudnicki et al. 2008; Schindler et al. 2010) but also at the tree group level (Rudnicki et al. 2001, 2003; Schindler et al. 2011, this issue). At both levels, the resulting tree response patterns are complex and complicated. So far, even in horizontally homogeneous terrain, not all physical and biological

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processes that govern wind-induced motion of forest trees are completely understood. Analyses of coherent responses of groups of trees to wind excitation (Schindler et al. 2011, this issue) contribute to a better understanding of spatial response pattern formation and dissipation of wind energy transferred into tree motion.

In strong wind conditions, wind excitation of trees may lead to damage. Branches, crowns, and stems can break, or trees can be thrown, when stem and root plate overturn (Quine and Gardiner 2007). Damage resulting from high-impact winds of large intensive depressions or from thunderstorm downburst may be catastrophic (Gardiner et al. 2008) and inflict substantial ecological, social, and economic impacts (Gardiner et al. 2010). Over the period 1950–2000, windstorms were responsible for 53% of the total damage caused by natural disturbances in European forests (Schelhaas et al. 2003). However, while forest ecosystem disturbance through storms usually causes undesired impacts in forests managed for timber production, windstorms are also important and positive stimuli for changes in forest structure and composition as well as landscape patterns.

The factors influencing the probability of storm damage in forests may be divided into four groups, which are: (1) meteorological conditions, (2) site conditions, (3) topographic conditions, as well as (4) tree and stand characteristics (Mayer and Schindler 2002; Quine and Gardiner 2007). With respect to storm damage, site and topographic conditions can be characterised as quasi-static. Meteorological conditions as well as tree and stand characteristics show dynamic behaviour.

After the passage of high-impact windstorms, the resulting damage patterns are commonly analysed to reassess and, if required, to adapt current silvicultural concepts to mitigate future storm damage. Post-event analyses are often based on model-based investigations of wind–tree and root–soil interactions. Among the model-based approaches, a large variety of statistical models can be distinguished from semi-mechanistic models like GALES (Gardiner et al. 2000), HWIND (Peltola et al. 1999), and FOREOLE (Ancelin et al. 2004). Although semi-mechanistic models require extensive sets of input parameters, they are well suited to identify and explore physical processes contributing to storm damage in forests. For this purpose, semi-mechanistic models calculate the critical wind speed, which is the wind speed above the forest canopy required to damage trees within a forest. Based on local wind climatology, the probability of a critical wind speed event can be determined (Gardiner et al. 2008). In their current versions, the semi-mechanistic models use the "mean" tree within uniform stands for predicting the probability of wind damage. The next generation of forest wind risk models will be able to calculate the wind risk to individual trees. Hale et al. (2011, this issue) demonstrate how the effects of tree size and thinning could be applied to future versions of semi-mechanistic models to assess storm damage risk to individual trees in forests with heterogeneous structures.

Semi-mechanistic models are also used to explore and simulate effects of root–soil interactions during strong wind events (Peltola et al. 1999; Gardiner et al. 2000, 2008; Nicoll et al. 2008). However, a better understanding of the interactions between rooting and soils is required to improve modelling of resistive forces of root systems. Besides the soil type, soil moisture is an important factor that controls resistive forces of the roots (Fraser 1962; Hütte 1967; Mayer 1987; Ray and Nicoll 1998; Gardiner et al. 2008; Peltola et al. 2010). Heavy rainfall associated with storm systems can raise soil moisture rapidly and hence also the predisposition of trees to windthrow (Usbeck et al. 2010). However, these effects have rarely been quantified. Here, the investigations of Kamimura et al. (2011, this issue) into the effects of rapid soil wetting on root anchorage will help to improve the description and parameterisation of root–soil interactions in semi-mechanistic models.

To assess the probability of storm damage in forests, statistical models are commonly used, although they provide only general insights into the physical mechanisms of storm damage and assume that future damage will occur under circumstances similar to those found for the analysed events. Among the published models are logistic regression models (Jalkanen and Mattila 2000; Mitchell et al. 2001; Hanewinkel 2005; Scott and Mitchell 2005; Schindler et al. 2009), neural networks (Hanewinkel et al. 2004; Hanewinkel 2005), classification and regression trees (Dobbertin 2002; Lindemann and Baker 2002), and generalised regression models (Schmidt et al. 2010; Albrecht et al. 2011, this issue). The special feature of the model developed by Albrecht et al. (2011) is that it is based on a very large data set of individual trees from long-term growth and yield experiments, thus covering several storm events. The stepwise modelling approach used in this paper facilitated identification of the main risk factors for stand-level occurrence of storm damage, of total or partial stand damage, and for damage of individual trees within partially damaged stands. The analysis of data from forests in southwestern Germany showed that, in addition to tree species and stand height, previous silvicultural interventions were the most important predictors for storm damage.

In areas where recent silvicultural operations have decreased stand stability against wind loading, partial storm damage has many important, and not necessarily negative, implications for forests. In forested river ecosystems, one implication is that wind-thrown trees, which are deposited in a stream, contribute to island formation,

physical complexity, as well as biocomplexity of a stream (Gurnell et al. 2005). For small streams bordered by forest, fallen trees can be the main source of large woody debris input from a riparian buffer (Lienkaemper and Swanson 1987). Since riparian buffers are particularly susceptible to partial storm damage after harvesting operations (Steinblums et al. 1984), the impact of partial wind damage in riparian buffers was analysed by Bahuguna et al. (2011, this issue). Their results show that wind-thrown trees are a potential source of sediment and that large woody debris adds to the structural complexity of small streams, where the former effect of windthrow is an undesirable and the latter a desirable outcome from a management perspective.

Although their location, frequency, or strength may change, severe windstorms will continue to occur all around the world. For example, Rauthe et al. (2010) reported that the current high level of storm activity will not drop considerably in future decades over southern and central Germany. Over northern Germany, the level of storm activity may even rise. As a consequence, more studies on the physical processes of storm damage and consistent further development of existing wind risk models should be valuable to adapt forest management systems on a site- and tree species-specific basis. But not only airflow characteristics of high-impact storms are important for the occurrence of future damage in forests. Gardiner et al. (2010) proposed that a higher air temperature in Europe during winter (Kjellström 2004) will result in longer periods of unfrozen soils, in which the root anchorage is reduced. This might promote wind damage particularly in northern European forests. Furthermore, winter precipitation intensity associated with storms might increase in decades to come (Palmer and Räisänen 2002). Heavier rainfall events involve more saturated soils and lead to an increase in storm damage probability (Usbeck et al. 2010). In combination with the ongoing build-up of growing stock in European forests, increased damage levels can be expected in the future (Schelhaas 2008; Hanewinkel et al. 2010).

Summarising the existing knowledge on wind–tree interactions at different scales, in particular wind-induced damage to forests and its reduction in the future, research should aim to improve our understanding of

- spatial (area of high-impact winds) and temporal (storm duration) scales of severe storms,
- interactions between high-impact winds and trees at the local and landscape level,
- interactions between high-impact winds and complex forest structures,
- small-scale variability of the soil–water balance and tree–soil interactions under rapidly changing meteorological conditions associated with high-impact storm events,

- impacts of climate change on regional risk of wind damage.

To address the knowledge gaps outlined above in the field of wind–tree interactions, the 2nd International Conference "Wind Effects on Trees" was held at the Albert-Ludwigs-University of Freiburg (Germany), 13–16 October 2009. The conference brought together experts in theory, applications, and method development to present and discuss advances in this highly interdisciplinary field. Among the topics covered at the conference were (1) wind climatology, (2) airflow at forest edges, (3) air flow around trees, (4) aerodynamic interactions between wind and trees, (5) storm impacts and risk modelling, (6) mechanics of trees under wind loading, (7) failure criteria of trees, (8) ecological dynamics and strong wind conditions, (9) ecological dynamics following windthrow, (10) silviculture, tree level management, and harvest design to reduce wind damage, and (11) post-storm damage responses. Hence, the focus of the conference was on the behaviour of trees in high winds as well as the occurrence of storm damage and their impacts on forests (Mayer and Schindler 2009).

The papers that were selected to be presented in this special issue "Wind Effects on Trees" in the European Journal of Forest Research provide a good overview of the different issues discussed at the conference.

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