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Individual tree crown width models for Norway spruce and European beech in Czech Republic

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ABSTRACT

Both spatially explicit and spatially non-explicit individual tree crown width models were developed for Norway spruce (*Picea abies* (L.) Karst.) and European beech (*Fagus sylvatica* L.) using a large dataset from fully stem-mapped permanent research plots (PRPs) located in various parts of the Czech Republic. A number of tree and stand characteristics were evaluated for their potential contributions to the description of the crown width variations. In addition to diameter at breast height (DBH), other significant predictor variables identified for crown width models are dominant height (HDOM), height-diameter ratio (tree slenderness coefficient), height to crown base, DBH sum of all tree species per PRP and proportion of DBH sum for a species of the interest (spatially non-explicit competition measures), and Hegyi's index (spatially explicit competition measure). Among various base functions evaluated, a simple power function was chosen to expand through the integration of tree and stand variables. The PRP-level random effects were also included using mixed effect modeling approach. Both spatially explicit and spatially non-explicit models and their mixed effect versions described large parts of the crown width variations [R^2_{adj} = 0.76–0.78 (Norway spruce), 0.70–0.73 (European beech)] without significant residual trends. For both species, spatially explicit mixed effect model described larger part of the crown width variations than its spatially non-explicit mixed effect counterpart. The models showed that after DBH, height-diameter ratio for Norway spruce and HDOM for European beech showed the largest contribution to the models. The crown width increased with increasing dominant height, but decreased with increasing height-diameter ratio, height to crown base, and competition among the trees within a stand. For both species, spatially explicit competition exhibited significantly larger effect on crown width than spatially non-explicit ones. This suggests that spatially explicit models can be more appropriate for description of the individual tree growth dynamics than spatially non-explicit ones. However, because of a little difference between the fit statistics of spatially explicit and spatially non-explicit models, the later models can be applied for precise predictions of crown width as they do not require spatially explicit competition measures, which are computationally complex and difficult.

1. Introduction

The crown is an aboveground part needed for a tree to survive, grow, and reproduce, and it is largely influenced by genetics and physical environment (Kozlowski et al., 1991). The crown displays the leaves to allow capture of radiant energy for photosynthesis, a key physiological process in tree growth. Measurement of the crown dimensions is often done for understanding and quantification of the tree growth (Korhonen et al., 2006). Since crown size is strongly correlated with a tree height and diameter growth, crown measurements are frequently used to develop growth and yield models, which serve as decision-making tools in forest management (Canavan and Ramm, 2000; Leites et al., 2009; Pretzsch, 2009). The crown dimensions are also used as predictor variables in the individual tree growth models (Vacek and Lepš, 1987; Biging and Dobbertin, 1995; Hasenauer and Monserud, 1997; Hynynen et al., 2002; Pretzsch et al., 2002), mortality models (Monserud and Sterba, 1999), and aboveground biomass models (Kuuluvainen, 1991; Carvalho and Parresol, 2003; Tahvanainen and Forss, 2008). Measures of the crown dimensions are used to assess tree vigor and health (Assman, 1970; Short III and Burkhart, 1992; Hasenauer and Monserud, 1996; Zarnoch et al., 2004), wood quality (Kershaw Jr et al., 1990; Kuprevicius et al., 2014), wind firmness (Navratil, 1997), and stand density (Clutter et al., 1983). Measures of the crown dimensions are also useful

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for assessing recreation and wildlife habitats (McGaughey, 1997; Tews et al., 2004), modeling forest fires (Keane et al., 1999), and modeling light interceptions in the canopy (Oker-Blom et al., 1989; Pukkala et al., 1991).

Changing tree and stand variables over the course of a growth projection necessitates models to update the estimates of the crown dimensions. The updating can be possible either with direct measurement of the crown dimensions for all trees on each sample plot or indirect estimation made using previously established crown models. However, as compared to other tree dimensions, measuring crown dimensions including crown width (CW) of all trees on each sample plot is costly and time consuming, and also difficult to measure in dense stands for tall trees, where the base of live crown is obscured. When CW measurements for adequate number of trees and other tree and stand variables are available, the CW model can be established using CW as a function of these variables (Bragg, 2001; Condes and Sterba, 2005; Temesgen et al., 2005; Sönmez, 2009; Fu et al., 2013).

The application of the CW models may involve estimation of crown surface area and crown volume, which are also used for quantification of crown production efficiency (Larocque and Marshall, 1994), tree-crown profiles and canopy architecture (Hann, 1999; Marshall et al., 2003), forest canopy cover (Gill et al., 2000), and the arrangement of trees in forest visualization programs (Hanus and Hann, 1997). The crown projection area and crown volume can be used as proxy measures of leaf area and leaf biomass (Binkley et al., 2013; Forrester, 2013). The CW models can be used to estimate potential growing space required by a given species (Gill et al., 2000; Foli et al., 2003; Pretzsch and Schutze, 2005; Sharma, 2006; Pretzsch et al., 2015). The stand canopy density, which is important to assess wildlife habitat suitability, fire risk, and understory light conditions for regeneration, can also be estimated using CW models (Crookston and Stage, 1999). The CW models are simple allometric models and commonly developed using diameter at breast height as a single predictor variable (Foli et al., 2003; Rautiainen and Stenberg, 2005; Sönmez, 2009; Pretzsch et al., 2015). However, these models may be biased as CW-diameter allometry is largely influenced by tree characteristics (height, tree slenderness, crown length, height to crown base) and stand characteristics (site quality, stand densities or competition). Thus, the potential biases can be substantially reduced through the integration of these variables into the CW models (Gill et al., 2000; Bragg, 2001; Fu et al., 2013; Hao et al., 2015).

The influence of stand density or competition on the crown dimensions is significantly high, and therefore its inclusion into the crown models is necessary (Davies and Pommerening, 2008; Thorpe et al., 2010; Hao et al., 2015). The competition measures can be computed using either spatial arrangements of the trees (spatially explicit competition measures) or without spatial arrangements (spatially non-explicit competition measures). The forest stand can be understood as a collection of individual trees interacting in a spatial manner over the restricted distances (Canham and Uriarte, 2006; Purves et al., 2007; Thorpe et al., 2010). The qualification of the influences of competitive interactions among individual trees can be useful for decision-making in forest ecosystem management. To the authors' knowledge, only a few crown models have been developed so far using spatially explicit competition measures (Rouvinen and Kuuluvainen, 1997; Rüdiger, 2003; Purves et al., 2007; Davies and Pommerening, 2008; Thorpe et al., 2010), but they all have used only diameter and competition measures as predictor variables. Also, sample plot-level variations have not been included as random effects in those spatially explicit crown width models.

The random effect parameters, which account for heterogeneity and randomness in the data caused by various factors, can be included using mixed effect modeling approach (Vonesh and Chinchilli, 1997; Pinheiro and Bates, 2000). In recent years, this approach has been increasingly used to develop various forest models including CW models (Calama and Montero, 2005; Adame et al., 2008; Meng et al., 2009; Crecente-Campo et al., 2010; Fu et al., 2013, 2015; Hao et al., 2015; Sharma and Breidenbach, 2015). The mixed effect modeling approach is more useful than ordinary least square fitting (Fox et al., 2001), and increases the prediction accuracy of the CW models. This study thus aims to develop mixed effect CW models by including sample plot-level random effects, spatially explicit and non-explicit competition measures along with other tree and stand characteristics that have substantial influences on the CW of two major tree species (Norway spruce and European beech) in the Czech republic. This study uses a large dataset from fully stem-mapped permanent research plots located in various parts of the country. These sample plots cover both pure and mixed species stands of Norway spruce and European beech.

2. Materials and methods

2.1. Study area

This study was conducted in the forest stands where permanent research plots (PRPs) with Norway spruce and European beech covering 18 Natural Forest Areas (NFA) in the Hercynian geomorphological system (out of total 33 NFAs in the Czech Republic) (Fig. 1). Based on the canopy structures, natural regenerations and stocks of dead woods, squared-shaped PRP (50 m $\times$ 50 m) were established following the Field-Map technology of the IFER-Monitoring and Mapping Solutions Ltd (Šmelko and Merganič, 2008). The low and middle lands are the Kokořínsko, Český kras, Křivoklátsko and Třebechovice. The higher and mountain regions in the Sudeten mountain system are Broumovsko, Krkonoše, Orlické hory, Šumava, and Jeseníky mountains. The altitude ranges from hornbeam-oak coppice forest with admixture of beech (240 m above sea level) through the spruce-pine stands, mixed beech-fir-spruce high forest to mountain pure spruce stands in ecotone of upper limit of the forest (1370 m). All forests fall within the Protected Area System (National Park, Protected Landscape Area, Nature Reserve, Natural Monument). The mean annual temperature ranges from 4 to 9.5 °C, the mean annual precipitation ranges from 500 to 1550 mm. Length of the growing season ranges from 35 to 180 days. Detailed descriptions of the study area can be found in the literature (Vacek and Lepš, 1996; Vacek et al., 2009, 2014, 2015). Our field studies were in accordance with the notification provisions of the protection of nature and not detrimental to wildlife and soil. Research was conducted with permissions for access to the territory of PRPs. In total, 100 PRPs (42 for Norway spruce and 58 for European beech), which were fully embedded within a stand, were identified for the purpose.

2.2. Data

The positions of all trees on each PRP including regenerations were recorded. Total height and over-bark diameter at 1.3 m above ground (DBH) were measured for all trees (individuals with DBH $\geqslant$4 cm). Diameters were measured by caliper with a precision of 1 mm and heights using laser Vertex with a precision of 0.1 m. Height to live crown base (HCB) and crown radii were also measured. Height to live crown base was measured at the point where branches formed a continuous whorl of a crown. The crown radii were measured at right angle to each other through the centroid of the crown. The CW was then computed as the arithmetic mean of crown widths obtained from measurements of crown radii