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Deriving individual tree competition indices from airborne laser scanning

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ABSTRACT

This article deals with quantification of competition on the single-tree level. Three new classes (non-spatially explicit, spatially explicit and hybrid) of tree competition indices based on airborne laser scanning were derived. By comparison to a selection of existing competition indices both spatially and non-spatially explicit, it was concluded by the performance of a growth model fitted using the competition indices as independent variables, that the ability to predict the diameter growth at breast height of individual trees of Norway spruce (*Picea abies* (L.) Karst.) was better for many of the derived competition indices, than for the existing competition indices. In addition, the Spearman rank correlation for the best derived index calculated on plot level revealed a highly significant correlation ($p < 0.001$) between diameter growth at breast height and competition ranging from −0.81 to −0.18 on plot basis. For data pooled from 20 plots used in the study the best of the derived indices increased the adjusted R^2 of the growth model by 18%, when compared to the adjusted R^2 of a growth model excluding competition as an independent variable. The best of the existing indices increased it by 10%. Some of the derived indices only require the spatial location and properties (diameter at breast height, crown width, height to base of crown and total height) of the subject tree, and not of the competing trees. Logic shows that such indices eliminate plot edge bias, which was supported empirically. When airborne laser scanning data is available, these competition indices should be preferred.

1. Introduction

The growth of a tree is affected by its surroundings and by biotic as well as abiotic factors. The level of available resources vary according to the habitats in which the tree grows, and if the needs of the tree with respect to such factors as nutrient supply, water or light, are only partially met, then these factors become the limiting resources.

When the availability of some resources are scarce, and organisms must share these, competition among individuals arise (Kimmins, 2004), which may be quantified using a competition index (CI). A number of studies have incorporated CIs into models of individual tree growth (Bella, 1971; Biging and Dobbertin, 1995; Pretzsch and Biber, 2010). Some report a limited improvement of such growth models over models not including competition (Lorimer, 1983; Wimberly and Bare, 1996; Wichmann, 2002; Nord-Larsen, 2006), which shows that competition is not always important for growth prediction. As mentioned by Dimov et al. (2008) this may relate to the fact that studies are often conducted in monospecific even-aged forests, with small size differentiation. A stronger correlation between growth and competition is expected in mixed species forests, and stands of natural growth. The use of a CI is appealing in case of a shift in the management regime towards target diameter harvesting, where predictions of individual tree growth is an important tool for simulation of future outcomes, i.e. economic optimization (Lexerød and Eid, 2006a; Meilby and Nord-Larsen, 2012), just as models of regeneration (Bollandsås et al., 2008) and mortality (Eid and Tuhus, 2001; Eid and Øyen, 2003; Peltoniemi and Mäkipää, 2011) are related to competition. One often-encountered problem for spatially explicit growth models is the plot edge bias. This problem occurs when trees standing at the plot or stand edge are affected by neighboring trees for which no spatially and mensuration information is available. Some methods have been made to account for this problem during model calibration, like the reflection and shift of the experimental plot (valid for noncircular plots) (Pretzsch, 2009), or plot edge bias correction by the linear expansion method for circular and noncircular plots described by Martin et al. (1977). These methods rely on assumptions of the stand outside the data range, which are sometimes questionable. The role of plot edge bias and its impact on the validity of the computed competition level has been discussed (Martin et al., 1977; Radtke and Burkhart, 1998). It is recognized that ignoring plot edge bias may lead to severe bias, caused by underestimation of the competitive level for the subject tree near the edge of the plot. Pommerening and Stoyan (2006) investigate numerous structural indices (which in nature are closely related to a CI). They concluded by means of both empirical data and simulation using different assumptions of forest structure, such as the homogeneous poison process and the Matérn hard-core

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process, that the effectiveness of the plot edge bias correction varies considerably between methods, and that some are performing even worse than simply ignoring the problem. Further, the performance of the plot edge bias correction seems to vary with the structural index tested, and the stand density, thus complicating the choice of method even further. Radtke and Burkhart (1998) showed how plot edge bias evaluated by crown closure estimates decreased with age in an even-aged stand. In addition, it was shown how plot size and shape of the unit that constitutes the research area is of importance, since the circumference of the plots varies with the geometric shape of these units. For instance, the circular plots utilized in many surveys including the current study have a smaller border zone than rectangular plots. Size of trees and their location outside the plot area is obviously difficult to mimic, and in the authors opinions empirical data should always be preferred over methods using assumptions. It is possible to reduce the problem of plot edge bias by creating a buffer zone (often referred to as the border or guard method) (Ripley, 1981; Pommerening and Stoyan, 2006). This means that only trees inside the plot further away from the plot edge than some limit are considered. An alternative method was introduced by Hanisch (1984) which only accepts the subject tree for analysis if the distance from the subject tree to the edge is longer or equal to the distance to any of the neighboring trees. The number of neighbors is subjectively chosen. For both these methods the number of trees remaining for data analysis decreases and, especially for small plots, the variance of the parameters of the individual tree growth model increases. Furthermore, the maximum distance for which competitors are included shrink dramatically and, as shown by Lorimer (1983), the estimate of the competitive level becomes uncertain. For example in Norway, the National Forest Inventory (NFI) plots, which are often used in studies of individual tree growth, have a radius of 8.92 m (Anon, 2007), and methods of classic plot edge bias correction must be used to ensure that a sufficient number of trees is available for growth predictions, especially in old and heavily thinned stands, with a small number of trees per area unit. Stoyan and Stoyan (1994) recommend supplementary measurements of trees close to the plot border for small plots as an unbiased alternative to the border and Hanisch methods, and refer to this as plus sampling. However, for large datasets it is not easy to revisit all the plots, and for time series it can be impossible to obtain historic records of the trees outside the plot.

Recently airborne laser scanning (ALS) information has become available for some of the NFI plots and the number are expected to increase in the future. In addition to extracting the spatial information from ALS on the plot, ALS data can also be extracted for a buffer around this. Thus, spatial information is available in the area where plot edge bias is potentially a problem. On the NFI plots (and experimental plots) the locations of the trees inside the plots and the dimensions of each subject tree are often known. Only competitors outside the plot area are unknown. It was the basic assumption of this study, that the individual locations and sizes in the form of coordinates, tree height, crown width, diameter at breast height (dbh), etc. of the competitors need not be known, which is different from spatially explicit (regarding size and distance) and non-spatially explicit (size) CIs. The input needed in order to fulfill these assumptions is present in the Norwegian NFI data (except crown width) as well as other data sources commonly used for growth modeling. Therefore, the methods are applicable to calibrate a growth model from data sources, such as NFI, from a later stage. It was assumed that the laser returns themselves might be used to derive information about the competitive level. When using ALS, spatial information about the location of biomass is found in the form of returns from laser pulses, emitted by a laser instrument. Thus, in the same manner that a classic CI utilizes information about the proportions and distances of the competing trees (assuming a spatially explicit CI), the locations of returns in the three-dimensional space around the subject tree are an indication of biomass and hence possible competition from neighboring trees. Therefore it should be possible to create a CI, which needs only information about the proportions of the subject tree (dbh, height, crown width (CW) and height to base of crown (CH)) and spatial information about neighboring competitors obtained from the laser returns to calculate the competitive level. Such indices require no additional work in tree positioning.

Our objectives were:

- To derive a number of CIs, which utilize ALS information to calculate the competitive level of the individual tree.
- To select a number of existing CIs, in order to weight the performance of ALS-CIs against tested references.
- To investigate if it is possible to give acceptable predictions of individual tree growth using ALS.
- To test the ability of the derived CIs to cope plot edge bias against the linear expansion method presented by Martin et al. (1977).

2. Materials

2.1. Field data

The data utilized consist of 20 circular plots with size 0.1 ha located in the Østmarka Boreal Reserve in southeastern Norway (59°50′N, 11°02′E, 190–370 m.a.s.l.). The plots were established during the spring of 2003. Procedures related to determination of plot centers and tree measurements in May 2003 are described by Bollandsås and Næsset (2007), and for more detailed technical information the reader is referred to this reference. Descriptive statistics for the field data are given in Table 1. The plots are established in uneven-aged forest, with multiple layers, which have not been exposed to logging since the 1940s (Økland, 1994). The plots are with respect to stem number dominated by Norway spruce (*Picea abies* (L.) Karst.) (90% on average), with a mixture of Scots pine (*Pinus sylvestris* L.) (less than 1% on average) and deciduous species (around 10% on average) (mainly birch – (*Betulaceae*), aspen (*Populus tremula* L.) and rowan (*Sorbus aucuparia* L.).

The plots were re-measured in June 2011. All trees registered in 2003 were re-calippered, using the original procedure, to ensure consistency. This means that dbh at 1.3 m was recorded for trees > 3 cm. Sample trees for measurements of height, crown width (CW) and the height to base of crown (CH) were selected by a relascope (factor 2). Height was measured by a Vertex III hypsometer. The CW was defined as the shortest distance of the projected crown perimeter to the tree stem. CW was measured in the four points of the compass by a measuring tape. The CH was defined as the distance from the ground to the green branch closest to the ground with less than two dead whorls between this and the second closest green branch.

Trees alive in 2003 but recorded dead in 2011 were used in the calculations of competition in the hybrid and classic CIs (explained later), whereas snags standing in 2003 were not considered. The former accounted for approximately 8.9% of the conifers and 24.1% of the broadleaves recorded alive in 2003. In 2011, 1.3% and 5.6% ingrowth beyond the threshold of 3 cm (in percent of all trees in each species class) were registered for broadleaves and conifers respectively. These were disgarded because of the negligible effect of such small trees on competition. Further, an inclusion would have required dubious assumptions about the time of inclusion within the 2003–2011 time range, and the weight to give the trees in the successive calculations. The effect of