Communication

Exploring the Potential to Improve the Estimation of Boreal Tree Structural Attributes with Simple Height- and Distance-Based Competition Index

Pekka Kaitaniemi [1],* and Anna Lintunen [2,3]

[1] Hyytiälä Forestry Field Station, Faculty of Agriculture and Forestry, University of Helsinki, Hyytiäläntie 124, FI-35500 Korkeakoski, Finland
[2] Institute for Atmospheric and Earth System Research/Physics, Faculty of Science, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland; anna.lintunen@helsinki.fi
[3] Institute for Atmospheric and Earth System Research/Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland
* Correspondence: pekka.j.kaitaniemi@helsinki.fi

Abstract: In many cases, the traditional ground-based estimates of competition between trees are not directly applicable with modern aerial inventories, due to incompatible measurements. Moreover, many former studies of competition consider extreme stand densities, hence the effect of competition under the density range in managed stands remains less explored. Here we explored the utility of a simple tree height- and distance-based competition index that provides compatibility with data produced by modern inventory methods. The index was used for the prediction of structural tree attributes in three boreal tree species growing in low to moderate densities within mixed stands. In silver birch, allometric models predicting tree diameter, crown height, and branch length all showed improvement when the effect of between-tree competition was included. A similar but non-significant trend was also present in a proxy for branch biomass. In Siberian larch, only the prediction of branch length was affected. In Scots pine, there was no improvement. The results suggest that quantification of competitive interactions based on individual tree heights and locations alone has potential to improve the prediction of tree attributes, although the outcomes can be species-specific.

Keywords: allometry; competition; forest inventory; model; tree structure

1. Introduction

Easily measurable forest or tree structural attributes are frequently used as statistical proxies to estimate structural attributes that are more difficult or time consuming to gauge. For example, numerous models use tree height and stem diameter to estimate tree biomass [1]. Due to persisting challenges in the direct measurement of many attributes, there has been a constant need to improve statistical models that are based on proxies [2].

Competitive interactions within individual tree groups are one candidate for model improvement, because they influence the size relationships among the basic structural attributes that are covered by many large-scale forest inventories, such as tree height, stem diameter, and crown size [2–4]. However, traditional information on competitive processes often relies on the use of stem diameter, crown dimensions, or other ground-based measurements [5], which are not automatically compatible with modern remote measurements, such as the capture of canopy height and density using aerial laser scanning (ALS). Moreover, many former studies of competition consider rather extreme stand densities [5,6], hence the importance of such interactions under a more limited density range typical for commercially managed and frequently invented and thinned stands remains poorly known.

To some extent, forest management decisions based on stand density management diagrams account for the outcomes of competition, but they chiefly focus on wood volume

growth within the stand [7]. As the trees and forests are nowadays acknowledged to serve multiple ecosystem functions, there are needs to improve the estimation of multiple aspects of tree structure and function to guide forest management decisions [8]. One step in this process can be improving the precision of predicting structural attributes using forest inventory data. However, although output from remote measurements including ALS can be used to estimate important attributes including stem volume, crown size or tree biomass [9,10], examples of utilising tree-level competition data with ALS remain scarce [11–13]. For example, the use of common competition indices with ALS data may be problematic due to the inability of ALS to detect all individual trees and their spatial locations within a stand [14]. Terrestrial laser scanning (TLS) and unmanned aerial vehicles (UAV) also remain unable to detect full aspects of crown structure, although they can capture more detailed structural information [15,16].

While the capabilities of remote sensing methods keep improving, the potential of remote inventories such as ALS and TLS to employ improved methods for the estimation of structural tree attributes can be already explored. Here we provide an example by investigating the possibilities to improve tree height-based estimates of four structural tree attributes (crown height, breast-height diameter, branch main axis length, and total branch length) of three boreal tree species growing in low to moderate densities within mixed stands. We quantify local tree-level competition with a simple index based on tree heights and distances, which could be readily applicable in forest inventories.

2. Materials and Methods

2.1. Competition Measurements

Structural measurements (Table 1) and estimates of competition for three boreal tree species—Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth.), and Siberian larch (*Larix sibirica* Ledeb.)—were available from the mixed stands of studies by [17,18]. All the target trees ranged from 10 to 40 years in age, and 4 to 22 m in height, and they originated from up to 10 different Myrtillus type forest sites that were distributed along a 400-km southwest-northeast transect in southern Finland. The tree age and height varied between the sites, but was roughly similar within each site. The target tree sample with detailed structural measurements included 55 individuals of Scots pine and 50 individuals of silver birch originating from 10 sites (3 to 10 trees per each site). The 29 Siberian larch individuals (three to nine per each site) originated from five sites that formed part of the transect within a 15 km^2 area in the vicinity of the Hyytiälä Forestry Field Station in southern Finland. The actual number of trees in the individual analyses varied slightly because of missing data.

Table 1. Abbreviations and units.

Variable	Description
h_t	tree height (m)
d_{bh}	tree diameter at breast height (cm)
h_c	relative height of crown base
l_b	branch axis length as a straight line between the branch base and tip (m)
d_b	branch diameter (cm)
L_b	total branch length with all branching orders combined (m)
H	competition index (see text for calculation)

The basal area variation of the target sites (sites 1 to 9 and 12 in [18]) ranged from 11 to 28 m^2/ha. Using silver birch as the guideline—birch has, according to the Finnish management recommendations, intermediate density requirements of the three species [19]—only three stands had reached the density where thinning is recommended [20].

Our previous studies reported the effects of multiple competition indices on growth allocation in these species [17,18,20]. Different variants of competition indices performed best with different growth attributes and species, although the indices typically correlated

with each other. Here, in order to operate consistently with a competition index that would be readily compatible with remote sensing measurements, we relied on a simple form of the widely-applied Hegyi index [21] that requires only tree heights and distances as an input. For each target tree, the value of the index H was calculated based on the tree heights and distances of the crown-bordering neighbouring trees within a 5 m radius from the target tree [17]:

$$H = \sum_{j=1}^{n} \frac{h_j/h_t}{L_{tj}} \tag{1}$$

In the index, t denotes the target tree and j is a neighbouring tree, n is the number of crown-bordering neighbours inside a 5-m radius from the target tree, h_t is the height of the target tree, h_j is the height of the neighbouring tree, and L_{tj} is the distance between the target tree and its neighbour.

The h_j within a 5 m circle was measured using a Haglöf Vertex or a Suunto clinometer, and the heights were used in the calculation of H for each target tree. Diameter at breast height (d_{bh}) was measured for the target trees that were felled gently using a pulley in order to take additional structural measurements without damaging the branches. Target tree height h_t was measured from the felled stems, which were then cut into smaller pieces and placed in an upward position to measure the basal diameter (d_b) and an approximate length (l_b) of each primary branch axis. Only regular branches initiated before the current growth season were included in the analysis. The branch length l_b was measured as the length of a straight line from the branch base to the branch tip.

The total length of an individual branch (L_b) was measured by digitising the 3D structure for a set of sample branches that were distributed throughout the crown [18]. L_b included the combined length of the main branch and all the side branches from all branching orders, and hence can be considered as a proxy for branch biomass. The average number of fully digitised branches per tree was five in Siberian larch, four in Scots pine, and thirteen in silver birch. Relative height of crown base (h_c) was the ratio of crown base height to total tree height, with crown base height measured at the base of the lowest living branch in the continuous crown.

2.2. Allometric Equations

Based on h_t, we first constructed basic statistical allometric models to estimate d_{bh} and h_c, and then investigated how the inclusion of competition as an additional factor influenced the model fit. To further estimate finer details of crown structure, we similarly investigated the effect of competition on allometric models that use d_b to estimate both l_b and L_b.

A simple allometric equation of the form

$$Y = aX^b \tag{2}$$

was applied, and its parameters a and b were estimated using the procedure NLMIXED in statistical SAS software (SAS Institute Inc., version 9.4) for each Y–X pair investigated in each of the three species: d_{bh}–h_t, h_c–h_t, L_b–d_b, and l_b–d_b. For Scots pine, individual d_b for the study branches was not available. Instead, the average length and diameter of the branches within each sampled branch whorl was used.

In the next step, each of the four equations were modified to include competition index H as an additional factor, following the practice described in e.g., [22]:

$$Y = aH^c X^b \tag{3}$$

In the final analyses, the models (1) and (2) were further complemented in NLMIXED by a random subject effect study site (SS)

$$Y = aX^b + SS \tag{4}$$

and

$$Y = aH^c X^b + SS, \qquad (5)$$

as written using the syntax of NLMIXED. Further, the term study tree (ST) was defined as an additional random effect when the structure of data allowed its estimation in NLMIXED. Consequently, for all study species, the equations of l_b in the syntax of NLMIXED became

$$l_b = ad_b{}^b + SS + ST \qquad (6)$$

and

$$l_b = aH^c d_b{}^b + SS + ST \qquad (7)$$

In the analysis of Equations (6) and (7), ST was defined as a subject that was nested within the study site [23].

The procedure NLMIXED estimated the values of the parameters a, b, and c, and also provided Akaike's Information Criterion for small samples (AIC_C) to be used as the measure of model fit. Additional fit statistics, root mean square error (RMSE) and R^2, were obtained from the regressions between predicted vs. observed values. To focus on effects that could be generalised across all sites, we do not report tree- and site-specific information.

3. Results and Discussion

Inclusion of the competition index H in the allometric equations improved the estimates of several attributes for silver birch and Siberian larch (Table 2, Figure 1). In silver birch, the parameter c associated with H was significantly different from zero and provided consistent improvement of model fit in d_{bh}, h_c, and l_b (Table 2). In l_b, the effect was too small to be visible in the rounded value of RMSE (Table 2). In Siberian larch, improvement was detected only in l_b (Table 2). In Scots pine, the inclusion of H did not influence model fit (Table 2).

In silver birch, the signs and values of c suggest that increased competition makes the stems more slender and the crowns and main branches shorter compared to equally tall trees experiencing milder or no competition. This is in line with previous studies, which have reported related responses using much steeper gradients of stand density [6,24]. Although the improvements in the scale of individual trees or branches were modest in the case of silver birch, they may nevertheless be meaningful over large forest areas.

The lack of improvement after the inclusion of H in the allometric equations for Scots pine, and mostly for Siberian larch, does not imply that these species do not respond to competition [25,26]. Rather, in contrast to silver birch, the allometric size relationships between the structural compartments in Scots pine, and also largely in Siberian larch, remained consistent in the presence of mild competition, such that h_t alone predicted their d_{bh} and h_c, and d_b predicted their L_b and l_b in Scots pine. In silver birch, the same allometric relationships were more sensitive to the effects of competition.

Overall, the results imply that aboveground growth allocation in silver birch is more sensitive to mild competition than that in Scots pine or Siberian larch. Laboratory studies with silver birch saplings have shown that silver birch responds to stand density with changes in growth allocation even before actual competition of growth resources takes place, i.e., before the increase in stand density causes reduction in total biomass increment [27]. In the laboratory, the detected changes in growth allocation were increase in stem height:diameter ratio and in shoot:root ratio. The observed growth responses seemed to be caused by changes in light quality sensed by the trees [27]. On the contrary, in Scots pine the lack of responses in the allometric size relationships may be linked to its ability to efficiently avoid competition by shifting its crown towards empty spaces in the canopy [25,28]. In Scots pine, most structural relationships have also shown consistency throughout different developmental stages in similar mesic site types as in our study [29].
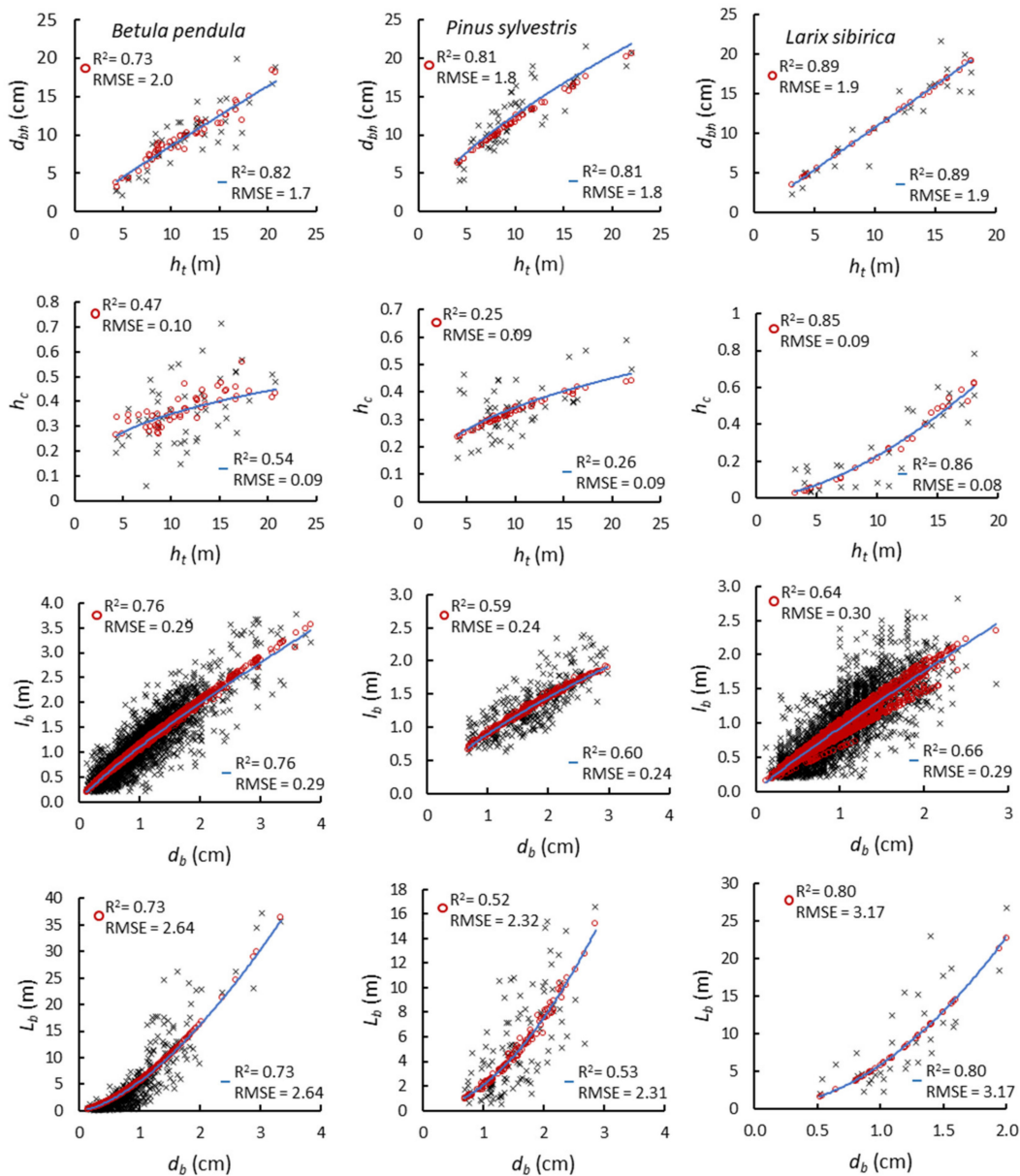
Figure 1. Black crosses show the observed values, red circles and blue lines show the values predicted by models with or without the effect of competition H, respectively.

Table 2. Parameter values, fit statistics and the number of trees for the alternative models. Values of c in bold indicate cases where the 95% confidence limits (CL) do not overlap with zero.

Model	a (±CL)	b (±CL)	c (±CL)	AIC$_C$	R^2	RMSE	N of Trees
Betula pendula							
$d_{bh} = ah_t^b$	1.01 (±0.51)	0.93 (±0.21)		219	0.73	2.0 cm	50
$d_{bh} = aH^c h_t^b$	1.55 (±1.00)	0.84 (±0.22)	**−0.27** (±0.20)	213	0.82	1.7 cm	50
$h_c = ah_t^b$	0.16 (±0.15)	0.34 (±0.41)		−71	0.47	0.10	50
$h_c = aH^c h_t^b$	0.08 (±0.09)	0.52 (±0.39)	**0.35** (±0.30)	−74	0.54	0.09	50
$l_b = ad_b^b$	1.10 (±0.5)	0.85 (±0.03)		653	0.76	0.29 m	45
$l_b = aH^c d_b^b$	1.18 (±0.08)	0.84 (±0.04)	**−0.08** (±0.06)	646	0.76	0.29 m	45
$L_b = ad_b^b$	5.52 (±0.76)	1.56 (±0.14)		2789	0.73	2.64 m	47
$L_b = aH^c d_b^b$	5.65 (±1.13)	1.55 (±0.16)	−0.02 (±0.15)	2791	0.73	2.64 m	47
Pinus sylvestris							
$d_{bh} = ah_t^b$	0.10 (±0.08)	0.70 (±0.16)		242	0.81	1.8 cm	55

Table 2. *Cont.*

Model	a (±CL)	b (±CL)	c (±CL)	AIC$_C$	R^2	RMSE	N of Trees
$d_{bh} = aH^ch_t^b$	0.08 (±0.11)	0.72 (±0.18)	0.03 (±0.13)	244	0.81	1.8 cm	55
$h_c = ah_t^b$	0.14 (±0.07)	0.39 (±0.21)		−106	0.25	0.09	55
$h_c = aH^ch_t^b$	0.13 (±0.08)	0.42 (±0.24)	0.05 (±0.25)	−104	0.26	0.09	55
$l_b = ad_b^b$	0.90 (±0.80)	0.69 (±0.09)		−75.4	0.59	0.24 m	34
$l_b = aH^cd_b^b$	0.92 (±0.10)	0.68 (±0.08)	−0.04 (±0.11)	−74.0	0.60	0.24 m	34
$L_b = ad_b^b$	2.08 (±0.49)	1.86 (±0.29)		1053	0.52	2.32 m	55
$L_b = aH^cd_b^b$	1.77 (±0.57)	1.93 (±0.34)	0.16 (±0.20)	1051	0.53	2.31 m	55
Larix sibirica							
$d_{bh} = ah_t^b$	1.10 (±0.66)	0.99 (±0.23)		127	0.89	1.9 cm	29
$d_{bh} = aH^ch_t^b$	1.05 (±0.85)	1.00 (±0.27)	0.02 (±0.20)	130	0.89	1.9 cm	29
$h_c = ah_t^b$	0.005 (±0.01)	1.66 (±1.10)		−44	0.85	0.09	29
$h_c = aH^ch_t^b$	0.005 (±0.02)	1.70 (±1.12)	−0.16 (±0.39)	−42	0.86	0.08	29
$l_b = ad_b^b$	0.93 (±0.07)	0.90 (±0.07)		676	0.64	0.30 m	25
$l_b = aH^cd_b^b$	1.07 (±0.08)	0.88 (±0.06)	**−0.20** (±0.08)	650	0.66	0.29 m	25
$L_b = ad_b^b$	5.84 (±1.50)	1.97 (±0.49)		289	0.80	3.17 m	29
$L_b = aH^cd_b^b$	5.81 (±2.45)	1.97 (±0.51)	0.01 (±0.39)	292	0.80	3.17 m	29

Since the current stem form and crown length result from complex processes and allocation trade-offs occurring throughout the growth history of a tree, there can be multiple ways to respond to competition. For example, field studies have shown that silver birch increased height:diameter ratio and decreased branching in response to competition, whereas Scots pine did not change its growth allocation [30]. On the other hand, both Scots pine and silver birch can adjust shoot lengths and branch numbers inside the crown in response to competition [17,20]. Besides competition, also site type effects can contribute to structural relationships in Scots pine [31].

Competition itself is an aggregate outcome that may consist of multiple processes, including nutrient, water and light limitation, mechanical abrasion, or indirect effects mediated by additional species. A transient value of a competition index can only capture a small portion of the potential processes, as it can only capture a small portion of the developmental history of a forest stand [32]. Similarly, different aspects of competition may be captured with different explanatory variables, including the choice of competition indices that have been developed and found adequate for different purposes. In spite of the potential problems with interpretation [32], even static estimates of competition can have value as predictive variables for structural traits [33].

In conclusion, this study corroborates for boreal tree species the findings from studies done in more temperate regions [11–13], suggesting that considering competitive interactions using simple height- and distance-based data at the level of individual trees can be beneficial when making calculations based on measurements of tree heights and locations in modern inventories. There is potential for improved structural predictions as observed in silver birch, but the responses can be largely species-specific as suggested by the outcomes of Scots pine and Siberian larch. Here, the approach was simplified and clearly leaves plenty of scope for enhancements when analysing larger datasets. For example, modern machine learning techniques could utilise a time-series of individual tree and stand development data to screen a large set of alternative formulations of competition in order to produce the most precise predictions.

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