A Novel Approach to Evaluate the Effect of Neighboring Trees and the Orientation of Tree Social Area on Stem Radial Increment of Norway Spruce Trees

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Abstract: Tree growth depends on many factors such as microsite conditions, vitality, and variations in climate and genetics. It is generally accepted that higher growth indicates both an economic benefit and better vitality of any tree. Here we use a modified approach of evaluating tree social area to study mutual tree competition based on the orientation and shape of trees social area. The investigation was performed in nine Norway spruce stands in the Czech Republic. The objective of this study performed from 2008 to 2012 was to quantify relative tree radial increments with respect to the lowest and highest competition found in specific sectors of tree social area (AS). Specific groups of trees (tree classes) were evaluated according to their classes (dominant, co-dominant and sub-dominant) and their composition status in ninety-degree sectors of AS using established classifying rules. The results showed that a spatially-available area (AA) is an inappropriate parameter for predicting tree growth, whereas AS provided robust explanatory power to predict relative radial growth. Tree size was observed as an important indicator of relative radial increments. A significantly positive correlation was found for a radial increment of sub-dominant trees with the lowest competition from western directions; whereas a negative correlation was observed when the lowest competition was observed from eastern directions. For dominant trees, there was an evident growth reaction only when more than 50% of the AS was oriented towards one of the cardinal points. Individual differences in the orientation of tree AS may be important parameters with regard to competition and its spatial variability within an area surrounding a particular tree and deserve more detailed attention in tree growth models and practice.

Keywords: Picea abies [L.] Karst.; competition; tree dimension; radial growth; tree increment; carbon sequestration; growing space

Highlights
- Tree size is an important indicator of relative radial increment.
- Tree social area is a better parameter than spatially-available area for estimating tree growth.
- The shape and orientation of tree social area play a significant role in tree growth dynamics.
- Trees with the lowest competition from the west showed the highest relative radial increment.

1. Introduction

Norway spruce (Picea abies (L.) Karst.) is an ecologically and economically important tree species in Western, Central [1], and Northern Europe [2]. However, Norway spruce stands are considered to be forests that have either a medium or high potential for risk
with regards to climate change [3–5]. Thus, an understanding of the factors that influence tree growth should be the basis of knowledge for maintaining and managing forests to not only cultivate environmental, social, and forest-based economic benefits but also to influence the vitality of trees [6–8].

In most forested settings, growth rates vary markedly from tree to tree [9]. Growth variation strongly influences tree mortality within certain forest stands [10]. Understanding what controls growth variation is critical for forecasting stand development and assessing community organization, as well as evaluating community resistance and resilience to environmental changes [11]. Moreover, variation in growth among trees within particular forest stands strongly influences stand development and leads to diversity in tree size and tree spatial patterns [10]. Tree growth, and even mortality, are strongly influenced by the spatial patterning of trees and competitive stress [12–14].

Factors like precipitation, air humidity, mean air temperature, and soil conditions (e.g., fertility) also influence tree growth [15]. Competition for resources is one well-studied source of variation in individual tree growth [16]. Typically, old-growth forests possessing a diversity of tree sizes, ages, vitality and mortality patterns, and growing conditions have fully-developed resource-use hierarchies [11]. Studies of neighborhood competitive interactions generally show that large, nearby neighbors exert higher competitive stress than small, distant neighbors [17]. On the other hand, there is not just competition between trees but also cooperation between trees [18]. Tree growing space is continuously changing due to artificial thinning and self-thinning [19–21]. Therefore, forest management practices should be implemented in a way that reduces their negative impacts on forest function and improves their sustainability [22–24]. Active management explicitly intends to reduce competition and subsequently to encourage tree growth [8,16].

There are many prior studies dealing with forest growth, forecasting and yield modelling that are fundamental to the study of forest development [25–29]. Competition is a fundamental driving force, alongside predation and mutualism, that creates a functional web between the organisms in living systems [30]. Tree competition consists of many interactions and it is difficult to separate particular effects from microsite conditions or climatic and genetic variations [31,32]. In the data evaluation process, competition index is an independent variable in growth models [33]. To provide descriptive power, competition indices must be strongly correlated with the actual competitive stress experienced by a tree [34]. According to the required data input, the respective index formulas can be divided into (i) distance-independent that aggregates tree size and number without spatial information, (ii) distance-dependent that also aggregates the locations of neighboring trees [35], and (iii) semi-distance-independent in which indices are computed independently at each subsampling plot surrounding a subject tree [34,36].

Previous studies have employed different variables, but tree size itself is the best predictor of growth because it is an integration of the trees’ competitive history [29,37]. Most competition indices are independent of the directional distribution of competing trees [35]. This means that the horizontal distribution of competing trees has no effect on the resulting indices and we cannot evaluate the effects of specific directions of the highest or lowest competition in detail.

As used here, the term social area (AS) can be commonly characterized as the area where a particular tree realizes its growth and supplies its growth demands [38,39]. The shape and orientation of AS result from the competitive strength of neighboring trees; thus, using tree AS allows researchers to estimate the apparent competitive environment surrounding a tree. A slightly different approach could be Voronoi tessellation, which does not consider tree size in its original design [40–42].

As was stated by Conterars et al. [36] and Teissier et al. [43], light availability and the possibility of light interception are forms of competition; other forms of competition include growing space availability, nutrient availability and water availability [44]. The spatial distribution of trees can lead to shading among crowns and can lower the amount
of incident light reaching some leaf layers [45–47]. Additionally, the shading effect of neighboring trees is more pronounced than self-shading [48].

We dealt with stem radial increment as stem is the largest tree biomass compartment, thus the largest pool of stored carbon in tree body and its growth integrate the influence of biotic and abiotic conditions on every single tree. The main objective of the study was to evaluate and quantify the influence of the orientation of social area on the radial increment of particular Norway spruce trees and to identify differences of these growth patterns between three various tree classes—dominant, co-dominant and sub-dominant. The observation compared individual tree AS in terms of its shape as well as its spatially-available area (AA). We hypothesized that the directional distribution of competitors would have an effect on tree radial growth. Finally, the tree radial growth would be dependent on the size and directional distribution of neighboring trees.

2. Materials and Methods

2.1. Study Sites

The subjects of this investigation were nine permanent sites located in pure Norway spruce stands in 3 locations in the Czech Republic (Table 1, Figure 1). The studied stands are permanently monitored by the Department of Forest Ecology, the Department of Silviculture (both under Mendel University in Brno) and CzechGlobe (The Global Change Research Institute CAS). According to the natural vegetation of Europe [49], the chosen study sites are situated within a temperate zone in hemiboreal forests and nemoral coniferous and mixed broadleaved—coniferous forests.

Figure 1. Geographic location of the 3 study sites in the Czech Republic (A). An example of three dimensional (B) and two dimensional (C) spatial representation of a sample tree and the closest neighboring trees with spatially-available area (AA) marked with a light grey and social area (AS) marked with a dashed line and light red.
Norway spruce stands (sites 1 and 2) at the stage of pole stands are situated in the Ecosystem station Bílý Kříž (ES Bílý Kříž) in the Beskydy Mountains (Figure 1). The locality is moderately cold and wet with an annual mean temperature of 5 °C, an annual mean humidity level of 80% and 1100–1400 mm of annual precipitation. The growing season is around 190 days [50]. The soil type is classified as Ferric Podzol with a depth of 60–80 cm lying on sandstone.

### Table 1. Site characteristics used for evaluating social area shape, n1 represents the number of trees growing in the study site, n2 the number of trees used for computing tree social area, N—number of trees per hectare, SDI—stand density index.

| Locality | Site | Area (ha) | Age (years) | n1 | n2 | DBH (cm) Mean ± SD | Height (m) Mean ± SD | N [ha⁻¹] | SDI * |
|----------|------|-----------|-------------|----|----|---------------------|----------------------|----------|------|
| Bílý Kříž | 1    | 0.05      | 35          | 64 | 41 | 17.6 ± 2.83        | 14 ± 1.02            | 1268     | 721.9|
|          | 2    | 0.05      | 35          | 73 | 47 | 17.5 ± 3.28        | 15.5 ± 1.31           | 1184     | 667.9|
| Kněhyně  | 3    | 0.24      | 79          | 51 | 20 | 28.9 ± 4.46        | 19.1 ± 1.33           | 639      | 806.5|
|          | 4    | 0.21      | 89          | 39 | 16 | 42.5 ± 7.62        | 23.7 ± 3.51           | 325      | 761.6|
|          | 5    | 0.2       | 66          | 49 | 25 | 28.2 ± 4.61        | 19.6 ± 2.07           | 767      | 930.2|
|          | 6    | 0.19      | 66          | 44 | 18 | 23.9 ± 6.30        | 19.2 ± 1.91           | 1100     | 1023.4|
|          | 7    | 0.19      | 71          | 39 | 15 | 30.8 ± 5.24        | 20.4 ± 1.26           | 650      | 908.5|
| Rájec–Němčice | 8 | 0.05 | 39          | 69 | 41 | 15.3 ± 3.55        | 16.1 ± 2.31           | 2032     | 924.0|
|          | 9    | 0.05      | 39          | 90 | 56 | 14.4 ± 5.27        | 13.8 ± 3.92           | 1808     | 745.9|

* SDI according to Reineke [51].

Five forest stands (sites 3, 4, 5, 6 and 7) at the stage of (semi-)mature stands are situated on Kněhyně Mountain with a mean annual temperature of 5.5 °C and annual precipitation of 1200–1400 mm. The growing season is around 190 days [50]. The soil is a Leptic Podzol and the parent rock is Cretaceous sandstone.

Forest stands (sites 8 and 9) at the stage of advanced pole stands are part of the intensively monitored Rájec–Němčice station in the Drahanská Highlands. The region is moderately warm and moderately dry, with an annual mean temperature of 6.5 °C, an annual mean humidity level of 85% and annual precipitation of 600–800 mm. On average, the growing season lasts 215 days [50]. The soil type is oligotrophic cambisol formed on acid granodiorite.

The research sites in Rájec–Němčice are nearly flat (with a maximal slope up to 3°). However, the research sites at Kněhyně and Bílý Kříž can be characterized with a slope of up to 10° and orientation towards the west and south-west, respectively. All three research locations were artificially established with an initial number of samplings ranging between 5000 and 6000. and were managed using the classical forest tending approach (i.e., 1 intervention every 10 years). This treatment applies mostly (semi-)moderate silvicultural measures in sub-dominant tree stratum of the crown layer and is the prevailing type of commercial forest management in the Czech Republic. No intervention was applied in the research sites for the last 7 to 10 years.

### 2.2. Field Measurements

The dataset was collected in 9 sites with areas ranging from 0.05 to 0.24 ha and ages ranging from 35 and 89 years (Table 1). All trees had their diameter at breast height (DBH) and height (H), crown projection (CP), and spatial position (x–y coordinates) measured using a Field-Map system (IFER, Czech Republic); diameters were measured using Diameter Measuring Tape.
2.3. 5-Year Radial Increment at DBH

Five-year radial increments were obtained from routine measurements (from 2008 to 2012). To compare 5-year radial increments of all sample trees, a value of relative radial increment was used. Each tree relative 5-year radial increment ($I_{5r}$) was obtained by:

$$I_{5r} = \frac{I_{5a}}{\overline{I}_{5j}}$$  \hspace{1cm} (1)

where $I_{5a}$ represents the absolute radial increment of the tree $a$ for 5 years and $\overline{I}_{5j}$ is the mean of the 5-year radial increments of all trees growing in site $j$.

Using Equation (1), particular tree growth was classified related to the mean growth of the forest stand on a particular site. The study postulated that all growing conditions had no variability within a particular Norway spruce stand (i.e., site) and that the variability of growth was the result of competition and tree size.

2.4. Tree Social and Spatially-Available Area

Social area is an aspect of stand area associated with a sample tree that accounts for its size and the size of neighboring trees as well as the available surrounding space [38,39]. Thus, each tree has its own growing area shaped by the trees surrounding it [52]. This assumption was also used in this study when the area available for each particular tree to supply its demands was acquired from two different viewpoints: (i) spatially-available area (AA) and (ii) social area (AS).

AA quantified the polygonal areas around the sample trees up to the nearest neighbors, where only distances ($D$) were used to calculate AA. Distances between the sample tree and its neighboring trees were directly measured using the Field-Map system. The six nearest neighboring trees were used to calculate social and spatially-available area according to Krejza et al. [42]. AS is the share of the stand area associated with a particular sample tree accounting for its size and the available surrounding space. AS was calculated as a polygonal area (Figure 1B,C), where distances between the sample tree and the neighboring trees were weighted by the dimensions (basal area) of the neighboring and sample trees [53]. AA is not simply an area measurement but also the distance- and direction-dependent area around a sample tree, while AS is a distance-, direction- and dimension-dependent characteristic (Figure 1). In total, 518 trees were measured; AA and AS were calculated for 279 of these trees. The reason for the reduced number of trees with a calculated AA and AS was missing positions (and dimensions) of the closest neighboring trees surrounding the experimental sites to calculate both area types for trees situated on the border of the site. Thus, all trees used both for calculation of AA and AS were surrounded by measured and position-oriented trees.

Ninety-degree sectors in the directions towards the north (N), north-east (NE), east (E), south-east (SE), south (S), south-west (SW), west (W) and north-west (NW) were then defined (Figure 2) and the relative portion of the $k$th sector of social area—$AS_{sk}$—was obtained by:

$$AS_{sk} = \frac{AS_k}{AS}$$  \hspace{1cm} (2)

where $AS_k$ is the social area of the sample tree in the $k$th sector and $AS$ represents the whole social area of the sample tree. Two different systems of sector determination were distinguished. The first approach was the N-W sector definition; second was the NE-NW sector segmentation (Figure 2). Each of the two neighboring sectors (of two different sectors’ determination approaches) overlap in 50% of their surfaces.
It was necessary to divide the trees into groups by size due to trees of separate classes differing in their growth response to variations in sources of nutrients and light, as has been shown in many eco-physiological studies [54,55]. Trees were divided into three classes: dominant, co-dominant and sub-dominant trees. To categorize the clustering of trees into three classes, the following algorithm was used to express $DBH_r$—relative DBH:

\[
DBH_r = \frac{DBH_a}{DBH_{(j)}}
\]  

(3)

where $DBH_a$ is diameter at the breast height of a tree $a$ and $DBH_{(j)}$ is the mean of diameters at breast height of trees growing in site $j$. Relative height ($H_r$) was calculated in the same way. However, due to the strong relationship ($R^2 = 0.83$) between relative height and relative DBH, DBH was used as the only parameter for tree size stratification (Figure 3). Tree size classes were defined as 0-1/3 percentile of relative diameter (sub-dominant trees), 1/3–2/3 percentile (co-dominant trees) and 2/3-1 percentile (dominant trees).

**Figure 2.** Two systems [N-W (A) and NE-NW (B)] of social area segmentation used for detecting the largest and smallest relative sector of tree social area (AS). The black points with different size represent each tree and its’ dimension. AA represents spatially-available area for a particular tree.

2.5. Tree Size Groups

Figure 3. Relative diameter at breast height versus relative height for all analyzed trees. The dotted line indicates the 1/3 percentile and the dashed line the 2/3 percentile of relative diameter, which separates tree size classes (dominant, co-dominant and sub-dominant).
2.6. The Orientation of Tree Social Area and Data Analysis

Within this topic, the study is primarily focused on the influence of the orientation of the largest and smallest relative sectors of AS. The relationship between the smallest and largest relative sectors of AS shows the regularity or irregularity of AS. Trees with the highest regularity of AS lie in the right lower part of the cloud of points in Figure 4, while the highest irregularity of AS is in the left top part of the points. Trees were grouped into three bands according to their degree of ir-/regularity of AS and, within all of these bands, the trees were clustered into three tree classes with regards to their DBHr (Equation (3)).

Three types of tree filtering were used to capture all possible extremes of the AS (Figure 4, Appendix A); thus the shape of AS was sometimes peculiar for groups chosen by all of three filtering approaches. The first approach for tree grouping was targeted at creating the set of trees that could be characterized as the third of all trees with the lowest competition coming from one particular sector (i.e., the largest portion of AS in this sector). The second approach (Figure 4, approach 2) created the set of trees characterized by the highest competition coming from one particular sector. Therefore, these trees are growing under the highest competition from one particular sector of AS. The third approach created the set of trees simultaneously characterized by the highest competition coming from one particular sector and the lowest competition coming from another sector of AS; thus, these trees could be labelled as the trees with the highest degree of irregularity of AS (Figure 4, approach 3).

For all approaches, the following issues were studied: (i) the effect of the direction of the largest $AS_{rk}$ on $I_5r$ and (ii) the effect of the direction of the smallest $AS_{rk}$ on $I_5r$.

Total values and portions of social and spatially-available areas were calculated in MS Excel 2010 using general worksheet functions. The data were then analyzed in the
3. Results

In the monitored Norway spruce stands, diameter distribution ranged from 5 to 55 cm and was dominated by the 15 to 20 cm class. The range of the relative 5-year radial increment (I5r) was 0.04–2.87. Most of the trees were in the 0.8–1.0 and 1.0–1.2 classes.

3.1. Tree Social and Spatially-Available Area

The highest quantity of tree social area (AS) was in the 0–10 m² interval and the highest quantity of spatially available area (AA) was seen in the 10–20 m² intervals. The mean AS was 6.54 m², the smallest AS was 0.06 m² and the largest AS was 43.04 m². The mean AA was 26.40 m², the smallest AA was 6.77 m² and the largest AA was 142.50 m².

The dependence of the I5r on AAr of the trees was low (Figure 5; R² = 0.16). This outcome caused us to stop analyzing the effect of the largest and smallest relative area sector on I5r. The correlation of I5r to ASr was R² = 0.66 (Figure 5); this parameter was used to evaluate the effect of the orientation of AS on tree radial growth (i.e., in terms of the orientation of the part with the lowest competition extreme and with the highest competition extreme).

![Figure 5. Relative 5-year radial increment (I5r) versus the relative spatially-available area of the tree (AAr) and relative tree social area (ASr).](image)

3.2. The Orientation of the Tree Social Area Extremes

We observed that trees had mostly an irregularly-shaped and irregularly-oriented AS with less competition from one direction and high competition from another (Figure 6). The trees in the left upper part of this figure were trees with less competition oriented towards one cardinal point and simultaneously, high competition was oriented towards one other cardinal point. On the other side of this figure were trees with a relatively regularly-shaped and regularly-oriented AS. The median of the smallest relative segment of tree social area (smallest ASrk) was nearly the same for both segmentation systems [N-W (0.11) and NE-NW (0.12)], (Table 2). The median of the largest relative value of social area (largest ASrk) was 0.41 for the N-W tree social area segmentation and 0.39 for the NE-NW segmentation.
In general, the same growth reactions to direction of largest \( \text{AS}_{rk} \) and direction of smallest \( \text{AS}_{rk} \) were observed for all tree classes. Dominant trees are the most sensitive to orientation of \( \text{AS}_{rk} \) (Figure 7). Dominant trees were positively influenced when the direction of largest \( \text{AS}_{rk} \) was oriented towards a south-west direction and negatively influenced when the direction of largest \( \text{AS}_{rk} \) was oriented towards east or south-east. The pattern was more evident with increasing shape irregularity of AS (from approach 1 to approach 3). A similar pattern of reaction was observed in case of co-dominant and sub-dominant trees but with significantly lower \( I_{5r} \) growth response of sub-dominant trees.

The effect of the highest competition orientation (Figure 7, 1S, 2S, 3S) was fairly analogous for all three tree social classes. For sub-dominant trees, we found significantly lower \( I_{5r} \) for the trees experiencing competition from south-west or west than for trees with competition from south-east. Co-dominant trees were significantly suppressed in \( I_{5r} \) by competition from south-west, north and north-east compared to competition coming from east. A similar effect was evident for dominant trees, which sustained a significant decrease of \( I_{5r} \) when competition was coming from west and north-west yet showed a significantly higher \( I_{5r} \) (and thus the lowest negative impact of competition) when the competition was coming from south-east.

Finally, the Pearson’s correlation coefficients of linear regression between the orientation of the largest \( \text{AS}_{rk} \) and \( I_{5r} \) were calculated (Figure 8) from the full dataset (\( n = 279 \)). The results showed a significantly positive correlation for sub-dominant trees when the largest part of AS was oriented around the west (south-west and north-west) sector that was significantly higher than trees having the largest part of AS oriented to east (south-east and north-east). The highest positive correlation was reached when more than 55% of the AS was oriented towards the west \( (R = 0.60) \); the highest negative correlation was achieved when more than 55% of the AS was open to east \( (R = -0.57) \) in sub-dominant trees. A similar effect was found in dominant trees, but this trend was evident only in trees with more than 50% of the AS oriented towards some cardinal point. The highest positive correlation \( (R = 0.79) \) was found around the south orientation of AS (south-west) and the highest negative correlation was found around the north-east orientation of AS \( (R = -0.52) \) in the dominant tree class. A specific set of correlation coefficients was reached in co-dominant trees. This tree cohort showed a negative correlation with the lowest competition coming from south (south-east), while a positive correlation was reached for all other directions.

Figure 6. Graphically established tree growing space according to the orientation extremes of tree social area (AS). The smallest \( \text{AS}_{rk} \) represents the lowest relative value of the ninety-degree sector AS. The largest \( \text{AS}_{rk} \) represents the highest relative value of the ninety-degree sector of AS.
Table 2. Observed median and extremes of relative tree social area segments (\(AS_{rk}\)), \((n = 279)\).

| Parameter                                      | Median | Smallest Value | Largest Value |
|------------------------------------------------|--------|----------------|---------------|
| Smallest \(AS_{rk}\) of the tree (N-W segmentation) | 0.11   | 0.01           | 0.22          |
| Smallest \(AS_{rk}\) of the tree (NE-NW segmentation) | 0.12   | 0.01           | 0.22          |
| Largest \(AS_{rk}\) of the tree (N-W segmentation)  | 0.41   | 0.28           | 0.69          |
| Largest \(AS_{rk}\) of the tree (NE-NW segmentation) | 0.39   | 0.27           | 0.72          |

Figure 7. The means of relative 5-year radial increments (I_{5r}) with a 95% confidence interval. The black bolt numbers 1–3 in the figure follow the filtering approaches in Figure 4 (i.e., 1—trees having some large part of AS; 2—trees having some scheme. 3—trees having both large and small parts of AS). L represents an evaluation of the growth according to the direction of the lowest competition and S represents an evaluation of the growth according to the direction of the highest competition in relative ninety-degree social area sectors. Different letters denote significant differences \((p < 0.05)\) between the orientation of \(AS_{rk}\) (within tree size classes) using Tukey's post-hoc test.
in co-dominant trees. This tree cohort showed a negative correlation with the lowest competition coming from south (south-east), while a positive correlation was reached for all other directions.

**Figure 8.** The Pearson’s correlation coefficients ($R$) of linear regressions between relative 5-year radial increments ($I_{5r}$) and the orientation of the largest relative sector (largest $AS_{rk}$) for dominant (A), co-dominant (B) and sub-dominant trees (C). The numbers 1–3 indicate the significance of the correlation on a significance level of $\alpha = 0.10$ (1), $\alpha = 0.05$ (2) and $\alpha = 0.01$ (3).

4. Discussion

The suitability of relative spatially-available area of a tree ($AA_r$) and relative tree social area ($AS_r$) as parameters for explaining relative 5-year radial increments of the stem ($I_{5r}$) have been compared. Previously, Krejza et al. [42], Butler et al. [52] or Čermák et al. [53]...
used AA to calculate AS. However, they did not use spatially-available area in relation to competition or stem radial increment. The results of this study confirmed that AA had a very low correlation with \( I_5 \) due to disregarding the size of neighboring and sample trees. On the other hand, as a parameter that uses the dimension and distance between neighbors to express competition, AS is a good tool for explaining current tree radial increment. In addition, calculating AS for a sample tree, according to Čermák et al. [38,39], presumes that basal area at breast height is the best variable for tree size expression and for weighting distances between trees in a mutual tree competition evaluation. The weighted distances were solved by Krejza et al. [42] and Pelz [57] and their results confirmed our finding that basal area is the best criterion to express tree dimension in competitive environment observations. However, to obtain valuable information about the expansion of AS, the sample tree must be surrounded by neighboring trees. If not, the maximal distance influencing tree growth must be stated in the direction of competition absence. The main advantage of the method presented here is its simplicity. It uses easily-obtained equipment (a compass and a measuring tape, or any recording position device) and commonly known trigonometric functions. Moreover, social area is very suitable for evaluating belowground competition as observed by Butler et al. [52] and Čermák et al. [53].

Our results confirmed the finding published by Boivin et al. [58] that tree class (dominant, co-dominant, sub-dominant) is an important indicator for \( I_5 \). Nevertheless, current DBH remains a valid predictor of future radial increment in the absence of silvicultural treatments or other interferences leading to a change of stand structure [58,59]. This additionally highlights the need to avoid extrapolating radial increment rate much beyond the sampled DBH range. The use of DBH as a radial increment predictor is limited in long-term forecasting models and other information like the influence of competition on tree growth is needed.

To the best of our knowledge, no previous study has evaluated local tree growing space with respect to the direction of competition strength for Norway spruce trees. Only the study by Duduman et al. [60] states that neighboring competitors from the north do not adversely affect the radial growth of silver fir. This corresponds well with our results because the highest degree of competition from the northern direction does not result in any significant growth reaction for Norway spruce, which has ecological demands similar to the silver fir. Some authors have dealt with slope aspect at the stand level increment evaluation (e.g., [61,62]), but no one has studied an analogous effect at the single tree level or the effect of tree social area orientation as was studied here.

Each individual tree has its own available growing space within a stand [63]. Ground level is considered as the boundary of the growing space if we do not incorporate the belowground competitive environment, which has not been thoroughly investigated. If a certain tree is not shaded or overtopped by other trees, the growing space is not limited upwards. However, there is clear competition from the side by neighbors in even-aged forest stands with homogenous structure [64]. Growing space is the most limited around sub-dominant trees, less intensively limited around co-dominant trees, and marginally limited around dominant trees [65]. The results of this study clearly confirmed the latter statement that dominant trees have no observed expected growing reaction on low thinning in terms of not sufficient reduction of competition pressure. This is because growing space is slightly limited within the upper part of the canopy. This kind of growing reaction was only observed in cases of intensive competition reduction around the dominant trees, specifically when the reduction from a particular side \( AS_{rk} > 0.5 \) (expressed by the relative sector of social area—\( AS_{rk} \)). The orientation of \( AS_{rk} \) had a slight influence on growing reaction \( (I_5) \) towards the lowest competition in co-dominant trees. However, the growing reaction for this class was slightly different compared to the other two tree classes. The radial increment limitation was found when the lowest competition was oriented to the south and south-east. A significant \((p = 0.05)\) relationship between the \( I_5 \) of co-dominant trees and the azimuth of the lowest competition was found. As Pulkkinnen and Pöykkö [65] stated, sub-dominant trees are under the highest competition stress because of
the limited growing space in the crown layer; that was also clearly observed in our study. A significantly positive correlation was found when the sub-dominant trees had the lowest competition from the north-west, west and south-west, whereas a negative correlation was observed when the lowest competition was from the south-east, east and north-east.

The results generally demonstrated that the direction of the largest AS\textsubscript{rk} influences the relative radial increment. It is favorable to have a low competition from a particular side and high competition from another side due to temperature and water status variations within the tree crown. This issue was studied by Špulák and Souček [66], who investigated temperature conditions around the crown of young Norway spruce individuals. Their results showed that most extreme temperatures are on the side from the south to the east of the spruce crown. Furthermore, they found the highest temperature fluctuation occurred both during warming and cooling phases. In contrast, the western to the northern sides of the spruce crown showed a positive effect on reducing temperature extremes in their study. The results by Špulák and Souček [66] support our findings for all tree classes in which there was a positive growth response to protection (provided by competition of other tree) from south-east to east sector if we suggest that reduced microclimate extremes promote radial increment whereas unhindered microclimate extremes suppress growth. Intensive and significant differences in growth response of sub-dominant trees on shape and orientation of SA was evident (Figure 8). The growth is influenced by the synergic effect of the dominant drivers of photosynthesis (water, light and temperature) [67]. We can assume that the less competition from the west brings favorable coincidence of amount of incoming radiation and temperature (in daily course perspective).

Nevo [68,69] stated that southern slopes potentially receive six times more radiation than northern slopes. Thus, south-facing areas have warmer, drier and more variable microclimates than north-facing areas, although both areas belong to the same macroclimatic zone. Jones et al. [70], added that water pressure gradients and water loss would be much greater on south-facing slopes. Although we did not determine the influence of slope on I5\textsubscript{r}, the analogy to the azimuth of the release of a tree is evident. If a particular tree has low competition from the south, the microclimate conditions are changed to warmer and drier. Norway spruce require humid, water-saturated and cooler conditions [71,72]. These ecological demands indicate that the growth suppression observed in our research could be a result of the change of microclimate towards warmer and drier conditions. This issue is partially connected to the effect of shading and radiation, especially during sunny days. As was investigated by Roderick et al. [73], most of the radiance on those days comes from a single direction. Therefore, the microclimate conditions on the southern and south-eastern parts of the crown where there is the lowest level of competition (and thus the open social area to this side) from these cardinal points could be even more disadvantageous on sunny days and have a negative impact on the whole individual. This was highly proved by our results, mainly by the positive influence of protection (by competition) from this sector found in all tree cohorts and also by negative effect of large AS\textsubscript{rk} oriented to south-east sector and east sector as we proved for co-dominant and sub-dominant trees, respectively. Bednář [74] found different radial increments of mature Norway spruce trees growing around gap felling. The radial increment of the trees growing on the eastern border (i.e., the lowest competition from the west) of the gaps showed a significantly higher radial increment than the individuals growing on the northern border (i.e., the lowest competition from the south). This finding clearly also corresponds with the observations seen in this study.

5. Conclusions

Tree growth potential can be predicted using social area (AS). However, potential available area (AA) is not an accurate parameter for making this estimation. As this study showed, individual variation in the orientation and shape of tree social area is an important variable of competition and plays a considerable role in tree growth dynamics. Our analyses of the social areas of 279 trees showed that trees usually have somewhat
irregularly shaped social areas. Low competition from the east in particular causes a negative impact on radial growth of individual trees, regardless of the size class of trees. This impact was especially evident in the case of sub-dominant trees. A positive correlation between radial growth and the direction of low competition was observed in the case of ca. western direction. This trend was observable in all three tree classes but was especially consistent for sub-dominant trees. This set of findings can be effectively used to optimize biomass production and also to maximize carbon sequestration and tree vitality under global change using proper tending approaches. This novel approach how to evaluate the effect of neighboring trees and the orientation of tree social area on stem radial increment was tested in pure Norway spruce stands. Challenges for future research could be testing presented approach for other tree species (softwood and hardwood) and in rich-structure forests. Therefore, this issue deserves greater attention in tree growth models and forest practice.

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Appendix A

Table A1. Summary of data evaluation procedure.

| Tree Grouping According to Irregularity of AS | Social Status of Tree | Description | Link to Results (Figure 7) |
|---------------------------------------------|-----------------------|-------------|----------------------------|
| Band 1 (approach 1)                         | dominant              | evaluation of the growth according to direction of the highest competition | 1S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 1L |
|                                             | co-dominant           | evaluation of the growth according to direction of the highest competition | 1S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 1L |
|                                             | sub-dominant          | evaluation of the growth according to direction of the highest competition | 1S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 1L |
| Band 2 (approach 2)                         | dominant              | evaluation of the growth according to direction of the highest competition | 2S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 2L |
|                                             | co-dominant           | evaluation of the growth according to direction of the highest competition | 2S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 2L |
|                                             | sub-dominant          | evaluation of the growth according to direction of the highest competition | 2S |
|                                             |                       | evaluation of the growth according to direction of the lowest competition | 2L |
| Tree Grouping According to Irregularity of AS | Social Status of Tree | Description | Link to Results (Figure 7) |
|---------------------------------------------|----------------------|-------------|--------------------------|
| Band 3 (approach 3)                         | dominant             | evaluation of the growth according to direction of the highest competition | 3S |
|                                             | co-dominant          | evaluation of the growth according to direction of the lowest competition  | 3L |
|                                             | sub-dominant         | evaluation of the growth according to direction of the highest competition | 3S |
|                                             |                      | evaluation of the growth according to direction of the lowest competition | 3L |
|                                             |                      | evaluation of the growth according to direction of the highest competition | 3S |
|                                             |                      | evaluation of the growth according to direction of the lowest competition | 3L |

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