

## Article

# Fine-Scale Spatial Variability of Stand Structural Features under Selection Management and Strict Protection: An Example from the Dinaric Mountains

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**Abstract:** Small scattered plots of a few hundred square meters well reflect structural variability at stand level, but not at small spatial scales as the data between plots is missing. Information about structural similarities between managed and unmanaged stands, especially based on large sample plots, is still scarce. Our first objective was to quantify and illustrate structural variability of a selection-managed stand and a corresponding old-growth (OG) stand at small spatial scales. The second goal was to find out if there is a positive autocorrelation among neighboring patches in these stands regarding tree density (N) and basal area (BA). Tree positions and their diameters were recorded in 1.5 ha plots. Structural variation was examined at scales from 0.01 ha to 0.36 ha. Spatial correlation of N and BA was examined by applying experimental semivariograms. The variability of N was similar in both stands, whereas it significantly differed regarding BA ( $\alpha = 0.05$ ). Semivariance did not detect positive spatial autocorrelation of BA, while adjacent plots appeared to be more similar (autocorrelated) regarding N in both stands. Despite statistical difference regarding BA variability, the selection-managed stand exhibited many structural similarities to the OG stand, which makes it potentially suitable for modulating, if needed, to bring it step closer to an old-growth structure.

**Keywords:** structural diversity; spatial analysis; selection system; old-growth



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## 1. Introduction

The analysis of structurally distinct patches at sub-stand level has been challenging for forest scientists, especially in old-growth forests [1], and it has not been until recently that the respective research has moved forward with rigorous spatial analysis that properly acknowledges the presence of trees of different ages or sizes within patches, whereby patch size is differently conceived and may range from 100 m<sup>2</sup> to over 1000 m<sup>2</sup> [2–4]. These newer studies have revealed that even-aged and/or even-sized patches are noticeably less common in European old-growth forests than previously thought. Old-growth forests are valuable carbon sinks and are known for their structural complexity and capacity to harbor rare animal and plant species [5–7]. They create micro-climates that slow global warming and represent an important part of our cultural heritage, providing people with aesthetic, symbolic, religious, and historical cues; moreover, large trees from old-growth forests control conditions that are essential for tree regeneration and host particular fungi with untapped medicinal potential [8]. However, these forests are scarce (<3% of forest land) and continue to disappear in Europe [9]. Thus, preserving them and emulating their structure in managed forests is becoming an urgent task in forest management planning. In this context, information from old-growth forests is highly valuable as a reference for close-to-nature silviculture [10]. However, the postulates relying on the creation of even-aged or even-sized patches in managed stands (including those composed of shade-tolerant species) have become deeply entrenched in the practice of European forestry [11–13].

Previous research that investigated managed forests and strictly-protected old-growth forests showed that there are large differences between them with respect to the amount and structure of deadwood per unit of area [14]. Significant differences also exist regarding structural features related to living trees [15–18]. These studies were mostly based on systematically or randomly distributed small plots. They are very valuable in providing information about the variability of a structural feature over larger areas (from a few up to several dozen hectares); however, in order to provide detailed insights into fine-scale structural variability without a loss of spatial information, tree-mapped sample plots  $\geq 1.0$  ha in size have been suggested [19,20].

The single-tree selection system is believed to emulate to a certain extent single-tree mortality that typically occurs in old-growth stands [21,22], so selection-managed stands may have a more similar structure to that of an old-growth stand compared with stands managed with other silvicultural systems (e.g., uniform shelterwood, clearcutting, etc.). However, it is still little known to what extent single-tree selection management really emulates old-growth structure, especially at fine spatial scales. Although during the last two decades forest studies have been employing ever more sophisticated methods to address research problems related to small-scale forest structure, some basic and straightforward information in the form of descriptive statistics has often remained unreported and is thus largely unavailable despite the rising number of published articles [3,4,10,23,24].

Consequently, our first research goal was to quantify and describe the structural variability among sub-stand patches in two stands: one subjected to the single-tree selection system, and the other retained officially for 70 years under strict protection (unofficially for over a century). For this purpose we examined explicable descriptive statistics (median, interquartiles, and coefficients of variation) regarding tree density, basal area, Gini coefficient, and the number of diameter classes (NDBH) at small spatial scales, gradually increasing from 0.01 ha to 0.36 ha. The second goal was to investigate whether there is a positive autocorrelation between neighboring sub-stand patches in any of the examined stands regarding tree density and basal area. Previous research on old-growth forests [24] showed a lack of spatial autocorrelation (stochastic variation, random pattern) for the horizontal distribution of basal area at fine spatial scales. We examine if this is true for an old-growth stand in South-Eastern Europe and set out to determine whether the application of semivariance analysis can detect the occurrence of similarly stocked adjacent and nearby plots (patches) in a selection-managed stand.

Instead of comparing managed and protected old-growth stands by looking only for similarities, we also focused on the differences between them as the scientific community and forest practitioners still need to know the degree to which a specific silvicultural system alters the natural stand structure. We are thereby aware of the fact that the structure of an old-growth forest can be variable, even among large plots [24], so we emphasize that in this study we use a typical example of a strictly protected core area of a Bosnian old-growth stand in which single-tree mortality has been a dominant disturbance pattern.

## 2. Materials and Methods

### 2.1. Study Sites and Data Collection

The research was conducted in the following locations:

- (1) The “Lom” old-growth forest stand, which has been strictly protected since 1954. The reason it was protected, apart from scientific purposes, was that it had not been subject to forest management prior to 1954. The core area of this reserve encompasses 55.8 ha. Our plot was established at its geographic center at 44°46' N, 16°47' E. This strictly protected core area is surrounded by a buffer zone of 297.8 ha in which only sanitary cuttings are performed. In the broader context, the Lom old-growth forest stand is located in the Dinaric Mountains of Bosnia and Herzegovina in southeastern Europe.
- (2) The “Drinić” selection (plenter) stand, which has been managed with single-tree selection silviculture, the prevailing management system in this part of South-Eastern Europe [25]. Its area amounts to 42.7 ha and its geographic center is located at

44°44' N, 16°51' E. It is approximately 4 km from the Lom reserve. The stands in Lom and Drinić are characterized by the same bedrock (limestone), soil type (brown soil), climatic conditions, and dominant tree species of European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), and Norway spruce (*Picea abies* (L.) Karst) (Table 1). The two stands are located at 1000–1400 m above sea level, with the terrain inclined from 3° to 10°, and the mean annual temperature and precipitation are 5 °C and 1600 mm, respectively. Selection management has been applied here since the early 20th century. Early on it was more traditionally oriented [26], but after World War II it was based on the principles of the control method [27,28]. Every tree with a diameter at breast height (DBH) >7 cm that is planned for cutting is marked in the field a few months before the actual cutting takes place. The regulation of species composition and tending below the inventory threshold (<7 cm DBH) was not performed, which means that the regeneration developed “freely”. The cutting intensity in this stand was typical for the selection system as it did not exceed 20% of the basal area in any ten-year period. All infected, deceased, and large trees (>80 cm) have been successively removed, while the trees from other DBH classes have been cut in a way that allows for maintaining a reverse-J structure [16].

**Table 1.** Basic characteristics of the analyzed stands (150 × 100 m research plots) expressed in absolute values, with percentages given in parentheses.

| Variable                                      | Stand      | Total | <i>Abies</i> | <i>Picea</i> | <i>Fagus</i> | Other Deciduous |
|---|------------|-------|--------------|--------------|--------------|-----------------|
| Tree density (trees ha <sup>-1</sup> )        | Selection  | 724   | 278 (38.4)   | 123 (17.0)   | 300 (41.5)   | 23 (3.0)        |
|   | Old-growth | 592   | 133 (22.5)   | 92 (15.5)    | 367 (61.9)   | 0 (0.0)         |
| Basal area (m <sup>2</sup> ha <sup>-1</sup> ) | Selection  | 40.4  | 22.6 (56.0)  | 6.1 (15.2)   | 10.8 (26.6)  | 0.9 (2.1)       |
|   | Old-growth | 69.3  | 20.9 (30.1)  | 31.5 (45.5)  | 16.9 (24.4)  | 0.0 (0.0)       |
| Mean DBH (cm)                                 | Selection  | 21.5  | 25.9         | 20.6         | 17.8         | 20.7            |
|   | Old-growth | 29.4  | 34.4         | 58.3         | 20.3         | -               |

Considering data collection, one sample plot of 1.5 ha (150 × 100 m) in size was located randomly in each of the two stands. In the data analysis for this study we first checked if the structure of our single plots corresponded to the structure at stand level. We decided to use single 1.5 ha plots from old-growth stand Lom and selection stand Drinić only after we made sure that they had the same DBH distribution shapes as the sample from previous research [16] that was composed of small systematically scattered plots across whole stands. Consequently, 1.5 ha plots faithfully represented the diameter distributions at stand level in both cases. For all living trees on these plots that exceeded the inventory threshold of 7.0 cm in DBH, the following information was recorded: tree species, DBH (calliper with 0.01 cm precision) and position of each tree (*x* and *y* coordinates) within the plot. For each tree the diameter was measured twice (in two perpendicular positions) at 1.30 m above the ground, and the average value of the two measurements was used in the analysis.

In the old-growth stand, trees with thicknesses ranging from 7.0 to 126.4 cm were measured, with a range for fir of 7.1–116.2, for spruce of 7.0–126.4, and for beech of 7.0–77.8. In the selection stand, the range of inventoried diameters was smaller, ranging from 7.0 to 92.5 cm, with a range for fir of 7.0–92.5, for spruce of 7.0–81.0, for beech of 7.0–61.0, and for other deciduous species of 8.3–46.7 (Table 1). The average characteristics are summarized in Table 1.

## 2.2. Data Analysis

The research was conducted using the following steps:

In the first step we provide descriptive statistics and DBH distribution shapes at the whole plot level of 1.5 ha for the studied stands. The shapes of DBH distributions were determined based on the computational approach described by Janowiak et al. [29]. In

the following part of the analysis, we divide these large plots into smaller spatial units to examine the fine-scale structural variability within and between stands. Namely, for plots gradually ranging from  $10 \times 10$  m (0.01 ha) to  $60 \times 60$  m (0.36 ha), the following stand variables were calculated: tree density per hectare (N), basal area per hectare (BA), Gini coefficient (GC), and the number of DBH classes (NDBH).

The Gini coefficient (GC) was computed with the following equation [30,31]:

$$GC = \frac{\sum_{j=1}^n (2j - 1 - n)ba_j}{\sum_{j=1}^n ba_j(n - 1)}$$

where  $j \in \langle 1; n \rangle$  is the rank of the tree in ascending order of DBH,  $n$  is the total number of trees in a plot and  $ba_j$  is the basal area ( $m^2$ ) of a tree with rank  $j$ .

The number of DBH classes was determined based on the proposal by Zenner et al. [3] for assessing the small-scale diversity of micro-neighborhoods (however, our study uses a priori determined plot sizes). The trees located within a plot were assigned to 10 cm DBH classes. If all trees within a plot belonged to one, two, or more DBH classes, then the plot was correspondingly classified as either even-sized, two-sized, or multi-sized, respectively.

For the investigated stand variables (N, BA, GC, NDBH), the median with interquartile ranges and coefficients of variation were computed, and described and presented graphically in order to obtain clear insight into the differences in fine-scale structure between the selection stand and the old-growth stand.

The observed changes in the coefficient of variation with increasing plot size were modeled using a power function  $y = b_0 \cdot x^{b_1}$ , where  $y$  is the coefficient of variation,  $x$  is the plot size, and  $b_0$  and  $b_1$  are parameters of regression [32]. In the first stage, independent models were developed for the examined characteristics and stands. The significance of the regression models was evaluated using the  $F$ -test,  $p$ -values, and coefficients of determination. Then, in order to assess the significance of the differences between the model obtained for the old-growth stand and the selection stand, the Chow test was applied [33] by computing an  $F$ -statistic for each regression pair compared, according to the following formula:

$$F = \frac{RSS_c - (RSS_1 + RSS_2)/k}{RSS_1 + RSS_2/n - 2k}$$

where  $RSS_1$  and  $RSS_2$  are the error sum of squares of residuals from the separate regressions,  $RSS_c$  is the error sum of squares from the single regression of the pooled data,  $k$  is the number of estimated parameters, and  $n$  is the total number of observations.

The  $F$ -statistic follows a  $F(k, n - 2k)$  distribution. Since the Chow test is designed for linear regression models, the power function used was first linearized by logarithmic transformation for its proper application in the test [32]. The Chow test indicates when a single regression is more efficient than two independent regressions. If the null hypothesis is not rejected, it means that the two regression models are not significantly different and can be replaced by one common regression model, otherwise the compared regression models are significantly different.

In addition, the spatial variability of structural variables among small-sized square plots was assessed by experimental semivariograms. For the analysis of the semivariograms, we determined the range of sample unit sizes prior to the analysis, as suggested by several authors [34,35], whereby square plot shapes were applied to avoid the artificial spatial anisotropy that often occurs in plots of irregular shape [35]. Following the proposal by Kral et al. [24], for an in-depth analysis of fine-scale spatial patterns, we used only small plot sizes of  $10 \times 10$  m and  $20 \times 20$  m for computation of the semivariograms. Since the detection of spatial autocorrelation in forest ecosystems requires extremely dense sampling [36], one-meter spacing was applied for these square-shaped plots, that is, sliding boxes were employed using the “moving window” approach [24]. The omnidirectional

semivariograms were computed by employing the estimator of the semivariance as defined by [37]:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i,j=1}^{N(h)} (z_i - z_j)^2$$

where  $N(h)$  is the number of pair observations  $(z_i, z_j)$  separated by a spatial distance  $h$ . The terms  $z_i$  and  $z_j$  are the attribute values of observations  $i$  and  $j$ , respectively.

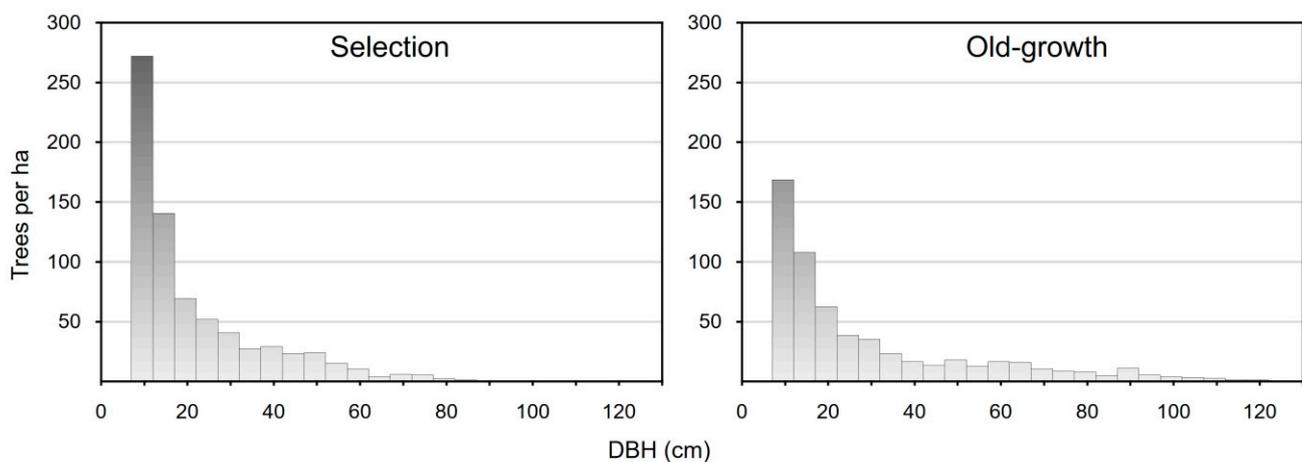
One third to one half of the diagonal of the total observation plot size (in our case  $150 \times 100$  m) is often suggested as the maximum distance to be included in the analysis [20,38], so we computed the semivariograms up to distances of 50 m. In addition, the initial parts of the semivariograms indicating spatial autocorrelation due to the effect of spatially overlapping plots (as a consequence of sliding boxes) were not considered for interpretation. Instead, the semivariograms were interpreted only from non-zero distances beginning at a distance equal to the size of the side of the square sample plot, so that only the autocorrelation beyond the plot overlap distance was taken into consideration.

The very dense sampling that resulted in detailed semivariograms allowed spatial patterns to be inferred without conventional model fitting. Consequently, the range, sill, nugget, and relative nugget (i.e., the ratio of nugget to sill as a percentage) were estimated from empirical omnidirectional semivariograms. A nugget represents variance of a structural feature between two adjacent plots, whereas a sill represents a maximum variance that occurs within a forest stand and is obtained based on comparing the variance among any two plots regardless of the distance between them. A pure nugget means that the ratio between nugget and sill variance amounts to 100%, that is, two adjacent plots are equally similar as any two respective plots being located at larger distances within a stand. More details regarding (semi)variogram analysis can be found in the specialized literature sources [20,38]. All statistical analyses were conducted in the program Statistica 14.

### 3. Results

#### 3.1. Diameter Distributions at the Stand Level

Despite a larger share of very thick trees in the old-growth stand and a larger share of young trees in the first DBH class in the selection-managed stand, we found that both stands were characterized by a rotated sigmoid-shaped DBH distribution, considering a plot size of 1.5 ha (Figure 1). In order to further describe the DBH distributions of the studied stands in a quantitative manner, we also computed skewness and kurtosis values (Table 2).



**Figure 1.** Diameter distributions of the studied stands at the spatial scale of 1.5 ha (whole plot size) for all trees above the inventory threshold of 7.0 cm.

**Table 2.** Skewness and kurtosis of diameter distributions in the differently managed stands.

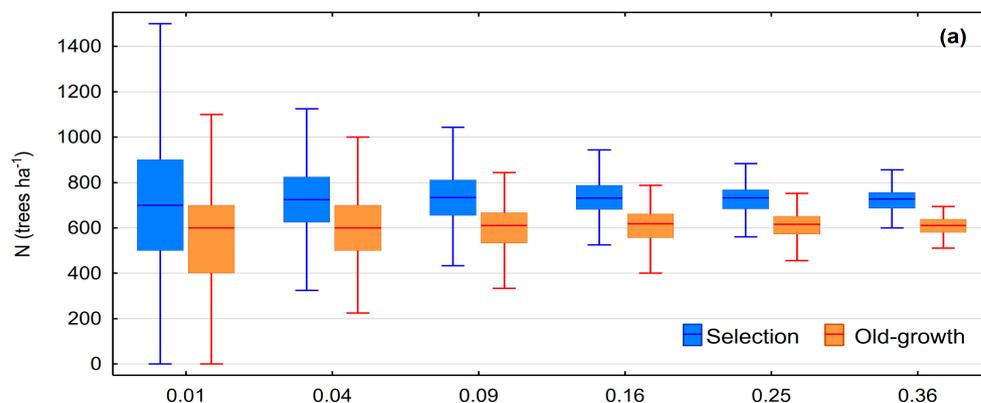
| Stand      | Skewness | St. Error | Kurtosis | St. Error |
|------------|----------|-----------|----------|-----------|
| Selection  | 1.536870 | 0.074227  | 1.920352 | 0.148318  |
| Old-growth | 1.472381 | 0.082061  | 1.396158 | 0.163939  |

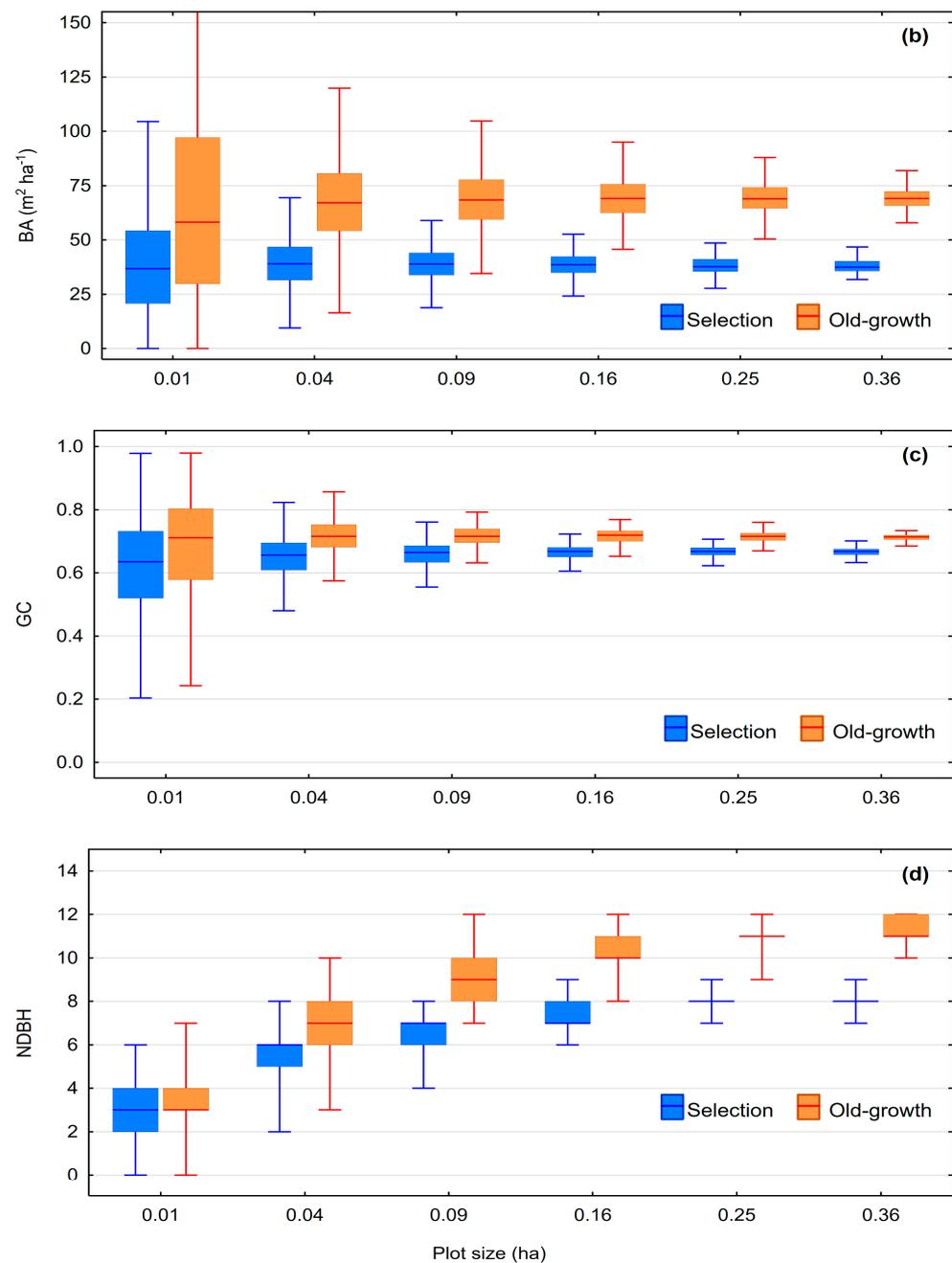
In both analyzed stands, the distributions are right-skewed, characterized by a long tail on the right side, which is confirmed by positive and similar values of skewness. Taking into account the value of kurtosis, the distributions in the stands can be described as leptokurtic, which means that a large number of observations occur within a narrow range of the analyzed variable, forming a peak of the distribution there [39]. The relationship between kurtosis and skewness also defines a family of theoretical distributions that can correspond to a given empirical distribution [40].

### 3.2. Median and Spread of Stand Variables with Respect to Changing Plot Size

Regardless of plot size, a higher median in terms of tree density was determined in the selection stand. This stand also had a larger span of this feature than the old-growth stand, but only at the smallest plot scale of 0.01 ha (Figure 2a). These statistics with respect to basal area were clearly greater in the old-growth stand (Figure 2b). The median values of the Gini coefficient (GC) differed between the stands, but not within single stands, with increasing spatial scale. Its greatest span was found at the smallest scale of 0.01 ha. In spite of large changes in the interquartile range and total range across different plot sizes, one outcome regarding the GC was common for all stands and for all plot sizes, namely, the median at the smallest observed scale of 0.01 ha remained virtually constant with increasing plot size up to the largest observed area of 0.36 ha (Figure 2c). The selection stand had GC values mostly between 0.6 and 0.7, while these values in the old-growth stand mostly ranged between 0.7 and 0.8. (Figure 2c).

The number of DBH classes at the smallest scale of 0.01 ha ranged between 0 to 6 and 0 to 7 in the selection stand and the old-growth stand, respectively. The median at this scale was two classes in both stands. However, as plot size increased further, the median number of DBH classes more noticeably grew in the old-growth stand than in the selection stand (Figure 2d). The selection stand and the old-growth stand had a maximum number of DBH classes that amounted to 9 and 12 DBH classes, respectively, while the minimum plot area required for all classes to occur in these stands was 0.16 ha. Although the number of DBH classes increased with increasing plot size, it should be noted that the plots with the highest number of DBH classes, even at the largest scale in this study, did not occur most frequently. For instance, the largest plots of 0.36 ha in the selection stand and the old-growth stand were most frequently characterized by 8 and 11 DBH classes, respectively (Figure 2d).

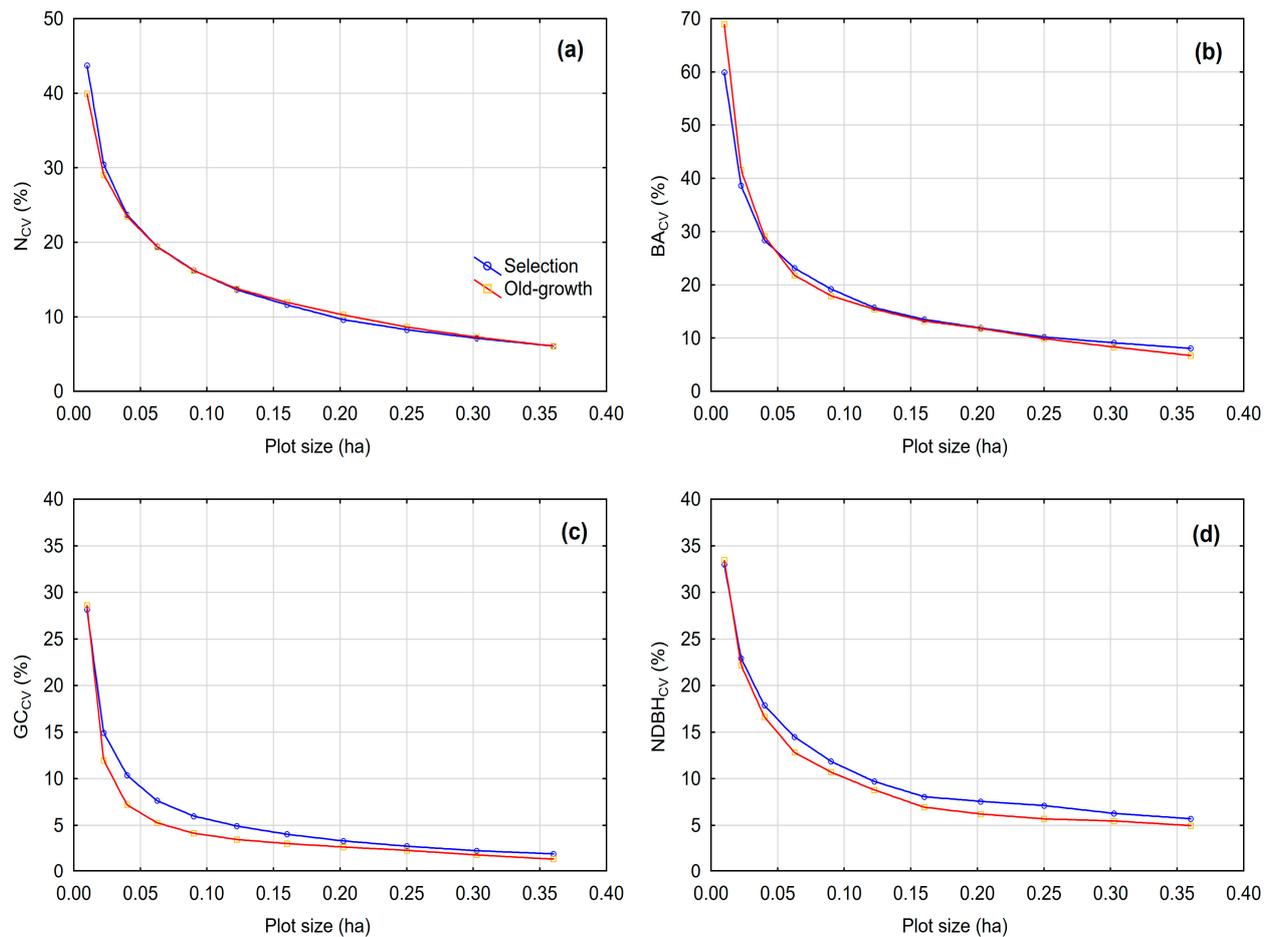
**Figure 2.** Cont.



**Figure 2.** Medians (horizontal lines), quartile ranges (boxes), and ranges of outlier values (whiskers) for tree density (a), basal area (b), Gini coefficient (c), and the number of DBH classes (d) at fine spatial scales in the strictly protected old-growth forest “Lom” and neighboring selection-managed stand “Drinić”.

### 3.3. Variation of the Studied Characteristics across Fine Spatial Scales

Slightly larger variation in tree density at the smallest scale of 0.01 ha was determined in the selection stand (43.7%) compared with the old-growth stand (43.0%) (Figure 3a). In both stands the change in the coefficients of variation of tree density with increasing plot size followed a power-law model, which in all cases was statistically significant at the  $\alpha = 0.05$  level. The observed power model for this feature in the selection stand did not significantly differ from the model found in the old-growth stand (Table 3).



**Figure 3.** Coefficients of variation for tree density (a), basal area (b), Gini coefficient (c), and the number of DBH classes (d) for different plot sizes in the old-growth stand and the selection-managed stand.

**Table 3.** Regression models ( $y = b_0 \cdot x^{b_1}$ ) of the coefficient of variation [%] related to changes in stand features with increasing plot size in differently managed forest stands. The  $F$  values of the pair-comparing Chow test are given in the last column. Parameters  $b_0$ ,  $b_1$  as well as regression statistics ( $R^2_{adj}$ ,  $F$ ,  $p$ ) and Chow  $F$  values were calculated on the basis of linear regression after logarithmic transformation of the original data.

| Feature               | Stand      | $b_0$ | $b_1$  | $R^2_{adj}$ | $F$    | $p$                   | Chow $F$ Values |
|-----------------------|------------|-------|--------|-------------|--------|-----------------------|-----------------|
| Tree density (N)      | Selection  | 3.995 | −0.543 | 0.981       | 527.5  | $2.7 \times 10^{-09}$ | 0.37            |
|                       | Old-growth | 4.311 | −0.511 | 0.970       | 328.9  | $2.1 \times 10^{-08}$ |                 |
| Basal area (BA)       | Selection  | 4.817 | −0.554 | 0.997       | 3790.6 | $4.0 \times 10^{-13}$ | 6.51 *          |
|                       | Old-growth | 4.063 | −0.617 | 0.993       | 1495.5 | $2.6 \times 10^{-11}$ |                 |
| Gini coeff. (GC)      | Selection  | 1.008 | −0.725 | 0.996       | 2566.6 | $2.3 \times 10^{-12}$ | 24.6 *          |
|                       | Old-growth | 0.704 | −0.766 | 0.983       | 573.5  | $1.8 \times 10^{-09}$ |                 |
| Number of DBH classes | Selection  | 3.467 | −0.498 | 0.996       | 2336.9 | $3.5 \times 10^{-12}$ | na              |
|                       | Old-growth | 2.730 | −0.551 | 0.995       | 2111.6 | $5.5 \times 10^{-12}$ |                 |

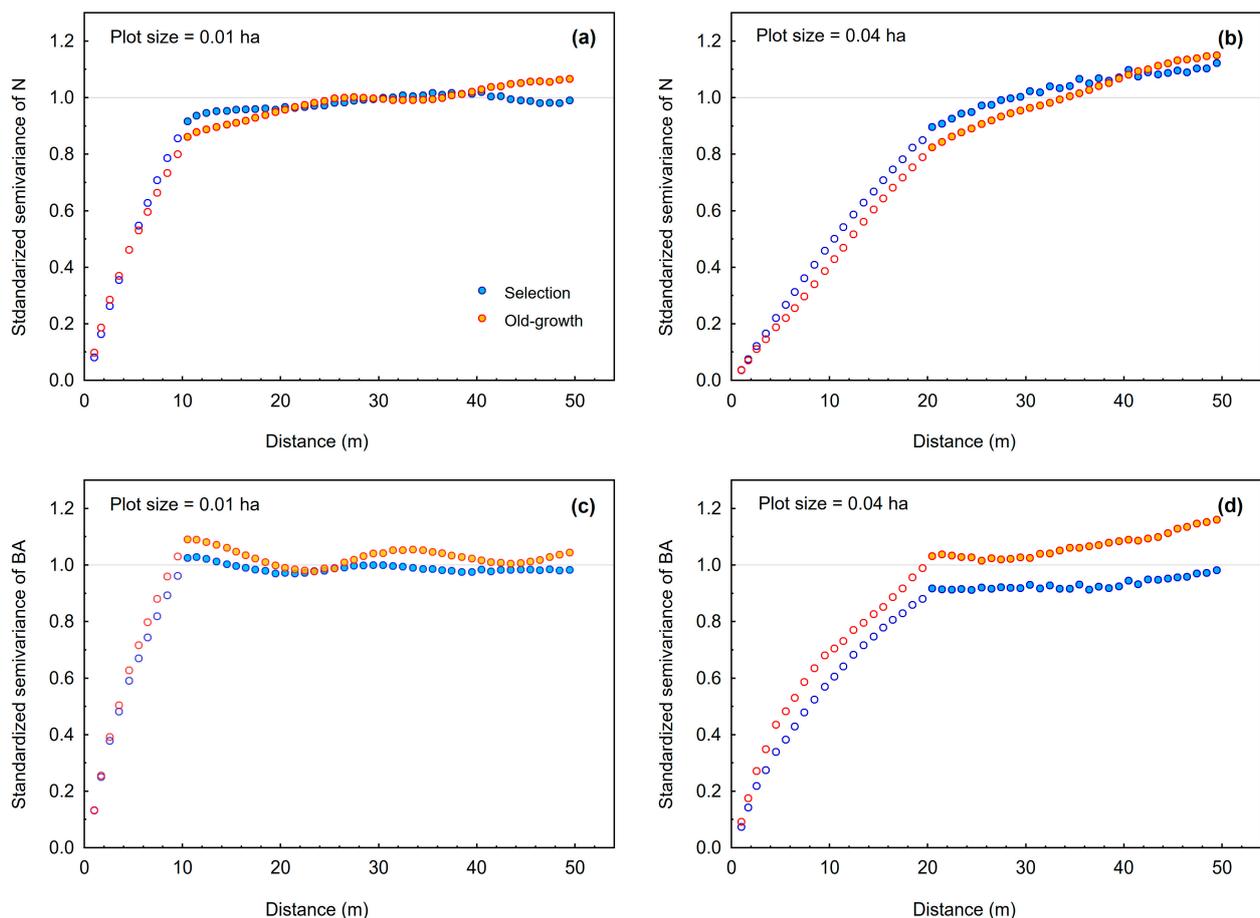
\* statistically significant at level  $\alpha = 0.05$ .

Similar to tree density, the variability of basal area fell sharply for both stands at the smallest spatial scales (more or less from 0.01 to 0.05 ha), after which it decreased gradually. At scales between 0.20 ha and 0.36 ha it still slightly decreased from 12% to 8% (Figure 3b). In contrast to tree density, the variation in basal area at the smallest scale of 0.01 ha was highest in the old-growth stand (69.0%), while the selection stand followed

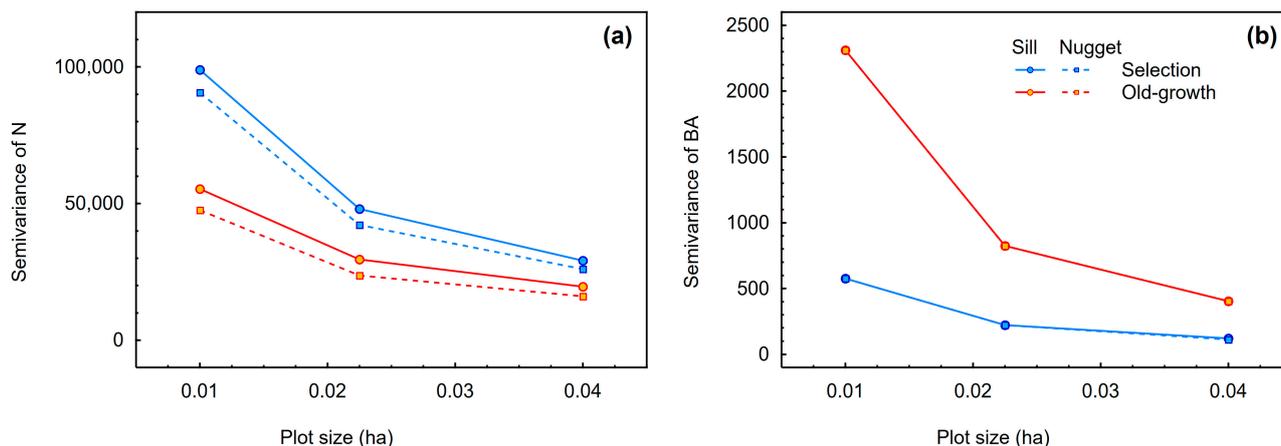
with 59.9%. Except for the spatial scales between 0.01 ha and 0.0225 ha, the variation lines of the old-growth stand and selection stand almost overlap, which indicates virtually identical variability in basal area at scales from 0.04 ha to 0.36 ha. However, in spite of the visual similarity of the curves describing changes in basal area variation, the Chow test revealed significant differences at  $\alpha = 0.05$  between these two stands. The adopted power models well described the changes in basal area variability in the analyzed range of plot sizes, since in both stands the fitted models were statistically significant, and the adjusted coefficients of determination ranged from 0.993 to 0.997. The Chow test confirmed also significant differences in the observed models of GC variation between the two studied stands (Table 3). Variation coefficients of GC and NDBH were also highest at the 0.01 ha scale, while the increase of scale (plot size) showed a gradual decrease in variability of these structural features (Figure 3c and Figure 3d, respectively).

### 3.4. Semivariograms and Spatial Autocorrelation

In the next step we focused specifically on the variance between adjacent (neighboring) plots and plots at short distances of up to 50 m. A moderate to weak positive spatial autocorrelation (similarity between adjacent and nearby 0.04 ha plots) was detected regarding tree density (Figure 4a,b), with relative nuggets ranging from 80% to 85% in the old-growth stand, and from 84% to 91% in the selection-managed stand (Figure 5a).



**Figure 4.** Empirical standardized semivariances for tree density (a,b) and basal area (c,d) observed at fine spatial scales of  $10 \times 10$  m and  $20 \times 20$  m in the studied stands. The empty circles relate to autocorrelation caused by spatial plot overlap (moving window with one meter spacing); the filled circles show autocorrelation of adjacent and more distant plots.



**Figure 5.** Empirical values of sill (solid lines) and nugget (dashed lines) observed for tree density (a) and basal area (b) at fine spatial scales in the stands under single-tree selection management and strict protection.

With respect to basal area, the computed semivariograms did not generally detect a positive spatial autocorrelation between adjacent plots or nearby plots since the relative nuggets (based on the nugget-to-sill relationship) in the studied stands were equal to or very close to 100% (Figure 4c,d). Although the investigated stands differed significantly regarding the variance between plots represented by sills and/or nuggets (Figure 5b) as well as coefficients of variation (Table 3), these dissimilarities were influenced by the different amounts of basal area and its spatial variation on small plots that were “moving” in all possible directions over the observed area. In spite of these differences, both studied stands exhibited one common feature—lack of a positive spatial autocorrelation—that is, the random (stochastic) spatial arrangement of basal area.

#### 4. Discussion

##### 4.1. Variability of Structural Features in Differently Managed Stands Depending on Plot Size

While it is generally known that significant differences occur between managed and old-growth forest stands regarding the distribution of structural features such as the presence of large sized trees, the amount of growing stock, and deadwood volume, much less attention has been given to the analysis of small-scale structural variability. Extensive studies in this regard have been conducted primarily in old-growth forests [2–4,41] and our results confirm the findings of the cited authors in that the small-scale structure of old-growth stands is much more complex than previously thought. However, still little is known about how much the small-scale structure of actively managed forests differs from that in old-growth stands.

Despite extensive literature exploration, we found only one study [42] recommended by Schütz [43], which explicitly showed that in Swiss selection forests at an area of 0.01 ha (100 m<sup>2</sup>) the variation coefficient of growing stock was approximately 60%. The study further indicated that this variation decreases with increasing sample plot size, whereby at plot sizes larger than 0.1 ha (1000 m<sup>2</sup>), only small changes take place. But even in these larger plots, the variation in Weidmann’s selection stand amounted to 15%–20%. Although we did not study growing stock (wood volume), we can partly confirm the findings of Weidmann, as the variation of basal area at a scale of 0.01 ha was also 60% in our selection stand.

On the other hand, the variability of tree density at this smallest scale was slightly greater in the selection stand, whereas across other scales the variation of this feature in the two examined stands was similar. Gini coefficient and number of DBH classes were virtually similar across all examined small spatial scales. Slightly greater variability in tree density at the smallest scale of 0.01 ha in the selection stand could be explained by

more intensive single-tree removals that allow somewhat larger penetration of direct and diffuse light to the understorey and midstorey, which facilitates survival of a larger number of young trees (e.g., from 7–17 cm DBH) compared with old-growth conditions where young trees have a harder time surviving deep shading [16]. In that case, dense groups of young trees in selection stands can occupy patches of more or less 100 m<sup>2</sup>, whereas their neighboring patches (virtually of the same size) seem to be typically occupied by a single mature tree with no or very rare advance regeneration directly below it. Such a spatial arrangement of trees results in large variation between neighboring patches. On the other hand, larger fine-scale variation of basal area was found in the old-growth stand. This outcome seems to be linked to the presence of differently sized trees, including very thick ones that are typical of old-growth forests [44].

For the most part, the variation of basal area in the old-growth stand was visually similar to that of the selection stand, except for the smallest scale of 0.01 ha where the difference was around 9%. Most likely for this reason, the Chow test indicated significant differences in basal area variation between the two stands. While this statistical outcome has to be respected, we also need to emphasize that the interpretation of results based purely on a cut-off level of  $\alpha = 0.05$  is sometimes criticized [45,46], so we suggest that readers also take into consideration the computed *F* values of the Chow test, which actually reveal the extent to which the variation in the basal area of the selection-managed stand deviated from that in the old-growth stand. The test results regarding tree density and Gini coefficient were similar to those of basal area, so they too should be interpreted in the same manner and with the same caution.

#### *4.2. Spatial Autocorrelation of Tree Density and Basal Area in Stands under Different Management Approaches*

Despite the general theory on spatial autocorrelation that assumes that close objects tend to be more similar compared with more distant ones, there is evidence that this tendency does not apply to basal area, at least in some forest types, as shown for instance in the case of Central European old-growth stands [24]. The results from old-growth stand Lom in this regard were expectedly in line with those from the abovementioned old-growth stands. Likewise, basal area in the selection-managed stand also exhibited a lack of spatial autocorrelation. Generally, we determined a positive spatial autocorrelation for tree density, but not for basal area, regardless of management approach. In this context, our results were congruent with the findings of a few other studies that have addressed similar research problems [24,47–49]. Moreover, these authors have additionally indicated that the outcomes of spatial autocorrelation may depend on the minimum inventory threshold and that the highest probability of detecting a positive autocorrelation occurs when the regeneration is included in the analysis.

Because we did not study the regeneration, we were not able to confirm if the statements of the above-cited authors also apply in our study area. However, we found that the inventory threshold indeed plays an important role in spatial analysis. In this context we refer to the study by Král et al. [24], who used a 10 cm DBH threshold in old-growth forests and found that plots of 0.04 ha in size should be used for computation of semivariograms, as smaller ones were often empty. Nonetheless, in our study we used a slightly lower threshold (7 cm), and only a few plots were empty at the 0.01 ha plot size. Consequently, it seems that apart from stand structural complexity and tree species tolerance to shade, the inventory threshold also strongly influences the outcomes of spatial analysis, or at least the outcomes of presence-absence data.

Since spatial autocorrelation regarding basal area was not determined in the studied stands, we may state that semivariograms, while sophisticated, may be a potentially overly sensitive analytical tool for the purpose of differentiation of even-sized or similarly stocked patches in forest stands. The concept of development patches (phases/stages) in old-growth forests was questioned by Paluch et al. [4]. However, some researchers and practitioners may still want to use this framework for practical or scientific reasons [50,51]. For the

time being, if one decides to do so, it seems most sensible to rely on the concepts that are not purely statistical but primarily ecologically meaningful and mathematically well defined [2,52]. In our opinion, the differing views among cited authors on the (non)-existence of phases/stages in old-growth forests should not be seen as an essential problem, but rather a methodological one, because a patch still represents the same “coin”, just observed from two different sides.

## 5. Conclusions

The presented study showed that the stand managed with the single-tree selection system differed significantly from the old-growth stand regarding basal area variation, while the variation of tree density was similar. Both stands exhibited large variability of structural features at fine spatial scales, which potentially may serve forest managers to diversify forest structure at sub-stand level. The analysis of semivariance did not detect a positive spatial autocorrelation of basal area at small spatial scales regardless of the management approach, while adjacent and nearby plots appeared to be more similar (autocorrelated) in terms of tree density in differently managed stands. If the outcome regarding basal area is confirmed in future studies, then perhaps more intuitive concepts rather than the purely statistical (such as semivariance) should be used for sub-stand patch classification.

The fact that basal area was stochastically distributed in both stands suggests that selection system fairly well emulates small-scale spatial distribution of this feature in old-growth forests. However, in order to confirm this statement, further research in at least several locations would be needed.

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