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Differentiation of the Forest Structure as the Mitigation Action of Adverse Effects of Climate Change

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Abstract

For several decades, the attention of societies has been focused on potential environmental changes due to climate change. Although climate change is not a new phenomenon, in the recent two decades, there has been a growing interest of scientists trying to determine scenarios of trends and their potential impact on forest ecosystems and forestry. Despite the uncertainties of climate change and the response of forest ecosystem to change, the forest management must deal with these uncertainties. There is no single prescription on how to manage forest resources under climate change in order to fulfill all demands from society. Various strategies in forest management are developed to counteract the adverse effects of climate change on forests and forestry. The future forest management should implement the following three main strategies: create forests which are resistant to change, promote their greater resilience to change, and enable forests to respond to change. It is expected that the more the structured forest, the higher the adaptive capacity is expected. Experiment focused on the influence of different silvicultural procedures on the structure of Scots pine in Poland is presented. Achieved results indicated that the process of stand structure conversion is a long-term process and different structural elements can be modified to different extents.

Keywords: stand structure, adaptive management, stand diversity, adaptive silviculture, *Pinus sylvestris*

1. Forests and forestry under climate change

For several decades, the attention of societies has been focused on the information about potential changes in our environment due to the changing climate system. Although the climate change is not a new phenomenon, in the recent two decades, there has been a growing interest of scientists trying to determine trends in climate change and their potential impact on a number of areas of human life. The impact of these changes is also studied in the context of forest ecosystems and forestry [1–3].

As the Intergovernmental Panel on Climate Change (IPCC) reports indicate, one of the significant reasons for the observed climate change is the increasing content of greenhouse gases in the atmosphere and the human activity attributed

to them. Apart from determining the causes of the increasing content of these gases and their origin, the increase in average air temperature, changes in precipitation regimes, and changes in the natural disturbance regimes observed in recent years raise concern among scientists dealing with forest ecosystems as well as foresters and forest owners [4].

In addition to the uncertainty of the scale and rate of climate change and the different nature of these impacts on forest ecosystems, the response of forest ecosystems to these changes is subject to high uncertainty too [1, 5]. This problem is not easy to solve because it must be underlined that the projections derived from global circulation (climatic) models and ecological models are not predictions of future climate conditions, but they are rather description of possible conditions resulting from certain scenarios [4, 5]. In other words, climate models represent the range of probable features of the future environmental conditions, and here we are dealing with uncertainties. Therefore, the forest management under climate change must deal with uncertainties. Up to now, there is no single prescription on how to manage forest resources under climate change in order to fulfill all the demands from society.

Due to the growing concern about the future of the forests around the world, various strategies in forest management are developed to counteract the adverse effects of climate change on forests and forestry [4, 6]. Novel environmental conditions resulting from climate change might result in changes of forest tree species distribution (change in natural ranges) through changes in forest productivity and the economic value of managed forests [3, 7].

Up to now, different paradigms of forest management are suggested as the potential solution, that is, close-to-nature forestry, adaptive forestry, systemic forestry [8–11]. It is expected that the future forest management should implement the following three main strategies [6, 12]:

- create forests which are resistant to change,
- promote their greater resilience to change, and
- enable forests to respond to change.

Adaptive management can be defined as a systematic and iterative approach for improving forest resource management by learning from management outcomes. It can be done by exploring alternative ways to meet the management objectives [13].

Modern forest management, taking into account the multifunctionality of forests and uncertainty of future climate conditions, will then require the introduction of innovative ways of management to ensure all services provided by forest ecosystems under the future unpredictable environmental conditions. Different approaches of short-term and long-term strategies are assumed to be required [13].

Three ways of adaptation strategies concerning forests are indicated [14, 15]. The so-called *business as usual* (no intervention) relies on today's practices and management targets. It is based on the assumption that forests themselves can adapt to changing environmental conditions as they did in the past. The second strategy called *reactive adaptation* takes place in the moment just after the fact. This strategy takes in account salvage cutting, updated harvest scheduling, recalculating allowable cuttings, etc. The third strategy is called *planned adaptation*, and it involves redefining goals and practices in advance taking into consideration climate change risk and uncertainties. This strategy will require new thinking of foresters taking into account the considerations of the global implications of local operations. Of

course, the planned adaptation for climate change involves greater uncertainty and novel risk. Among the activities related to planned adaptation strategy, one can consider the planting of new provenances or species capable of growing in environment under projected climatic conditions, reaping the benefits of new products from forests (i.e., carbon sequestration). It is expected that the adaptation strategy will increase the resilience of the forests while simultaneously decreasing their vulnerability. Other operations within planned adaptation include the silviculture of mixed stands, use of clones better suited for novel conditions, modification of thinning regimes, etc.

Bolte et al. [12] indicated three other strategies in adaptation of forest ecosystems to change to meet the management goals: *conservation of forests structure*, *active adaptation*, and *passive adaptation*. The first can be treated as business as usual and it relies on the maintenance of the structural consistency independently on the pressure due to environmental change. Active adaptation means the use of silvicultural methods to change the structure of the stand in a way that the resulting forest is better adapted to a new climatic condition than it would happen by natural succession. Passive adaptation uses spontaneous adaptation processes in terms of natural succession and natural species migration.

2. Different silvicultural tools for increasing adaptive capacity of forests to change

To understand the importance of silviculture, it is worth to recall its goals. They are defined as related to creating and maintaining the forest that will best fulfill all objectives of both owner and society. As they stated, the wood production is neither the only nor necessarily the dominant goal. At present the benefits of the forest are manifold, and all of them, for example, recreation, esthetics, or habitat protection, must be taken into account in modern forestry. The biggest problem, however, in modern silviculture, is getting the owners and society to define the management objectives which should aim to ensure all services and functions provided by the forest for a long time despite the impact of the potential climate change.

While the priority of timber production was clearly seen in the past, one can observe that the forest management focused mainly on the providing economic benefits is no longer possible. Ecological and cultural services seem to be more and more desirable by society even when their provision is mostly possible due to the timber harvesting. Therefore, it is obvious that protection and production functions of the forest are both important to society and the conflict between these two functions must be avoided or, at least, mitigated [16, 17].

The changing needs of society also require a change in forest management which must provide more services than wood production. In Europe, such management, called *continuous cover forestry* (CCF) is only one option for that, and it is now successfully implemented in practice in many countries [18–20]. The concept of CCF mostly relies on close-to-nature silviculture (CTNS) or natural silviculture [21, 22]. Different aspects of the implementation of CTNS to increase the stability of forest ecosystems can be recommended: avoidance or limitation of clear-fellings, promotion of highly structured forests, and promotion of native tree species and selective individual tree silviculture are among the most important. Two basic principles of CTNS should be implemented: (1) reducing silvicultural risk and (2) reducing its spreading. Both are extremely important to mitigate the potential adverse impact of climate change on forests and forestry as well. Under the first principle, the following activities should be promoted [23, 24]:

- full use of genetic diversity of forest tree species (natural regeneration promoted),
- species composition adapted to the local site conditions,
- tending treatments aiming at the increase of tree vitality and ensuring better use of growing space, and
- forest site cultivation.

Among activities within the second principle, the most important is associated with the promotion (creation) of complex forest structure in terms of their species composition (mixed stands), vertical profiles (multilayered and multicohort stands), and horizontal patterns (patchy stands) [25, 26].

3. Which adaptation strategy is better? A case study from Scots pine (*Pinus sylvestris* L.) stands in Poland

Why forest structure matters? Shortly—it is a key to the forest ecosystem, its function, and diversity [27, 28]. Understanding the forest structure dynamics allows us to better understand the history, functions, and future of the forest ecosystem. The stand structure of the stand can be described by lots of elements, for example, species composition, tree age, tree size, and dead wood amount. If we manage the forest structure, we will affect the forest functions. Potential benefits and limitations of different silvicultural regimes on the structuring forest stand are presented here on the base of the experiment in Scots pine (*Pinus sylvestris* L.) forests in Poland.

Forests cover in Poland ca. 9,200,000 hectares (29.6% of area) and *P. sylvestris* is the most economically important tree species in Poland. In Poland, this tree species has optimal climatic and site conditions within its Euro-Asiatic natural range. While conifers dominate the species structure of Polish forests, pine accounts for 58% of the area of forests. It also accounts for 56.5% in the volume structure of timber resources [29]. Most Scots pine forests in Poland are managed according to even-aged silviculture, and thus they represent rather structurally homogenous stands in terms of species composition, vertical and horizontal structures. The Department of Silviculture, Faculty of Forestry of the Poznan University of Life Sciences, has been involved for decades in research projects aiming at finding opportunities to change the even-aged silviculture of pine forest into more complex management, for example, shelterwood cuttings or selection cuttings [26]. One example of such studies is presented below.

3.1 Methodological considerations of the experiment

Experiment has been established in three stands where *P. sylvestris* shares 90% or more in abundance. Admixture tree species is silver birch (*Betula pendula* Roth.). Till the initialization of experiment in the 1980s of the last century, each stand (experimental object) has been managed according to even-aged silviculture and they could be characterized as monocultures, even-aged and single-layer stands. Three experimental objects, reflecting different status of silvicultural treatments, has been applied: control (C), experimental (Ex), and economic (E) of sizes 35.78, 37.88, and 41.01 ha, respectively. In the control object, no logging operation has been allowed and it represents *passive* adaptation strategy. In case of the

experimental object, only selective thinning has been allowed and it can be treated as the *active* strategy of adaptation. In the economic object, a *business as usual* strategy has been planned and conducted according to the low thinning rules indicated in the management plan elaborated for this forestry district.

In 1988, the net of permanent circular measurement plots of size 0.05 ha each was laid out in the nodes of the rectangular grid of size 100 × 50 m. On each plot, the stem diameter at 1.3 m (dbh, cm), total tree height (*H*, m) of 2–3 trees, and polar coordinates (*x*, *y* calculated from the azimuth and distance to each tree from the plot center) were measured. Also, tree species and tree status (dead, live) were recorded. The first survey was done in 1988 and the second after 15 years, in 2003. The mean stand parameters (tree density, tree diameter, and basal area) coupled with spatially explicit structural indices (**Table 1**) describing different aspects of the stand structure were calculated. Tree diameter and basal area distributions were checked for their normality using Shapiro-Wilk test of normality. If the distributions were not significantly different from the normal distribution ($\alpha = 0.05$), the analysis of variance (ANOVA) was applied to analyze the differences among treatment means in terms of both characteristics. If these differences are significant, the *post hoc* Tuckey’s range test is applied to find out which treatments differed significantly from each other.

Spatial pattern of tree distribution was evaluated on the basis of the Clark-Evans (CE) index. For random distribution of trees, the index gets the value of 1.00. If $CE < 1.00$, trees are distributed in smaller or larger clumps while if $CE > 1.00$, they are more or less regularly dispersed in the stand. The significance of the departures from unity is estimated using the standard *z*-test value [30].

Size differentiation indices TD (for tree diameter) and TH (for tree height) are calculated for each tree in the plot in relation to three neighbors. The higher the value of the index, the more is the diversity in terms of tree size observed. Apart from the mean value of these indices, it is possible to analyze the distribution of them in five differentiation classes [30]: very low (<0.20), low (0.20–0.40), moderate (0.40–0.60), large (0.60–0.80), and very large (>0.80) differentiation among the nearest neighbors. Small value of size differentiation index means homogenous in size group of trees, and large value indicates heterogeneous groups of trees.

Index	Formulation	Explanations
Aggregation index, CE	$CE = \frac{r_A}{r_E} = \frac{\frac{1}{N} \sum_{i=1}^N r_i}{0.5 \cdot \left(\frac{A}{N}\right)^{1/2} + 0.0514 \cdot \frac{P}{N} + 0.041 \cdot \frac{P}{N^{3/2}}}$	<i>r_A</i> —Observed mean distances between trees <i>A</i> —Area (m ²) <i>N</i> —Total number of trees <i>P</i> —Circumference of the plot
Mingling index, SM	$SM = \frac{1}{k} \sum_{i=1}^k v_{ij}$	<i>k</i> —Numbers of nearest neighbors <i>v_{ij}</i> = 1, if reference tree and neighbor are different species, otherwise <i>v_{ij}</i> = 0 <i>n</i> —Number of neighbors (<i>n</i> = 3)
Size differentiation index, <i>T</i>	$T = \frac{1}{n} \sum_{i=1}^n \sum_{j=1}^3 \left[1 - \frac{\min(\text{size}_i, \text{size}_j)}{\max(\text{size}_i, \text{size}_j)} \right]$	<i>size_i</i> —Diameter or height of <i>i</i> th tree <i>size_j</i> —Diameter or height of <i>j</i> th tree <i>n</i> —Number of neighbors (<i>n</i> = 3)

Table 1.
Structural indices calculated in each of the objects analyzed.

Species mingling (SM) is calculated for each tree in the plot and their three nearest neighbors. The lower the value of the index, the more is the homogeneous group of trees in terms of their species. In the case of three neighbors, the index can take four values: 0.0, 0.3, 0.7, and 1.0, indicating no mingling, low mingling, large mingling, and full mingling, respectively [30].

All structural indices were calculated for plots with the number of trees ≥ 10 .

Afterward, the change in stand structure over the 15-year period of the stand development was evaluated. To find out the differences in structural diversity between objects (C, Ex, and E), the Kruskal-Wallis nonparametric test followed by the Dunn's multi-comparison test were applied to test significant differences ($\alpha = 0.05$).

Statistical calculations were done in R environment [31] and Siafor 1.0 software [32].

3.2 Results

3.2.1 Stand parameters

Scots pine was the dominant tree species in the stand independently on the experimental object. In 1988, the average number of trees per plot was for the control object 44.5 (SD = ± 8.4), experimental—35.3 (SD = ± 7.3), and economic—34.3 (SD = ± 8.0). After 15 years, the density decreased in each object and, in 2015, the average number of trees per plot was reached in the control object 38.3 (SD = ± 7.5), in experimental—23.8 (SD = ± 4.7), and in the economic—21.0 (SD = ± 6.1).

The highest number (on average) of individuals (per 1 ha) of this tree species was observed in the control object, where no logging was conducted. Experimental and economic objects showed similar number of trees of Scots pine. In case of birch, the highest number was observed in the economic object and the lowest in the control one (Table 2). Similar trend was observed in terms of basal area—Scots pine was the dominant tree species reaching the share by more than 90% in each of the object analyzed. In absolute numbers, however, the highest basal area was observed in 1988 in the economic object and the lowest in the control one (Table 2). In 2003, the highest basal area was obtained in the control object and the lowest in the economic one. The share of birch at the beginning of the experiment was the highest in the

Year	Pinus sylvestris		Betula pendula		Picea abies		Robinia pseudoacacia	
	N (%)	BA (%)	N (%)	BA (%)	N (%)	BA (%)	N (%)	BA (%)
Control object								
1988	817 (92)	25.4 (91)	50.4 (6)	1.8 (6)	6.3 (1)	0.3 (1)	12.4 (1)	0.5 (2)
2003	709 (93)	35.3 (92)	41 (5)	2.1 (5)	6 (1)	0.4 (1)	5 (1)	0.4 (1)
Experimental object								
1988	638 (90)	26.8 (91)	68 (10)	2.6 (9)			—	
2003	432 (92)	29.9 (92)	37 (8)	2.4 (8)				
Economic object								
1988	610 (89)	27.7 (92)	76 (11)	2.4 (8)			—	
2003	383 (92)	28.8 (94)	33 (8)	2 (6)				

Table 2. Average tree number ($N\ ha^{-1}$) and basal area ($BA\ ha^{-1}$) and the corresponding percentage (in brackets) of tree species present in the objects in 1988 and 2003.

economic object and the lowest in the control one. After 15 years, this trend was still observed (**Table 2**). Other tree species, that is, Norway spruce (*Picea abies* (L.) Karst.) and black locust (*Robinia pseudoacacia* L.) were present only in the control object and both are excluded from the further analysis.

Figure 1 shows that the mean diameter of living trees was the highest in the economic object, followed by the experimental one. The lowest dbh was observed in the case of the control object. Similar trend can be observed for the basal area.

Coefficient of variation calculated for dbh was similar in all objects, however, it was slightly higher in case of the economic object (25.7%) than in the others.

The diameter distribution of living trees and their basal area were not different significantly from the normal distribution (data not shown). Analysis of variance, followed by Tukey's *post hoc* test, revealed that the mean tree diameter and basal area were significantly different in the analyzed objects in 1988 and 2003 ($\alpha = 0.05$, **Figure 2** for tree diameter).

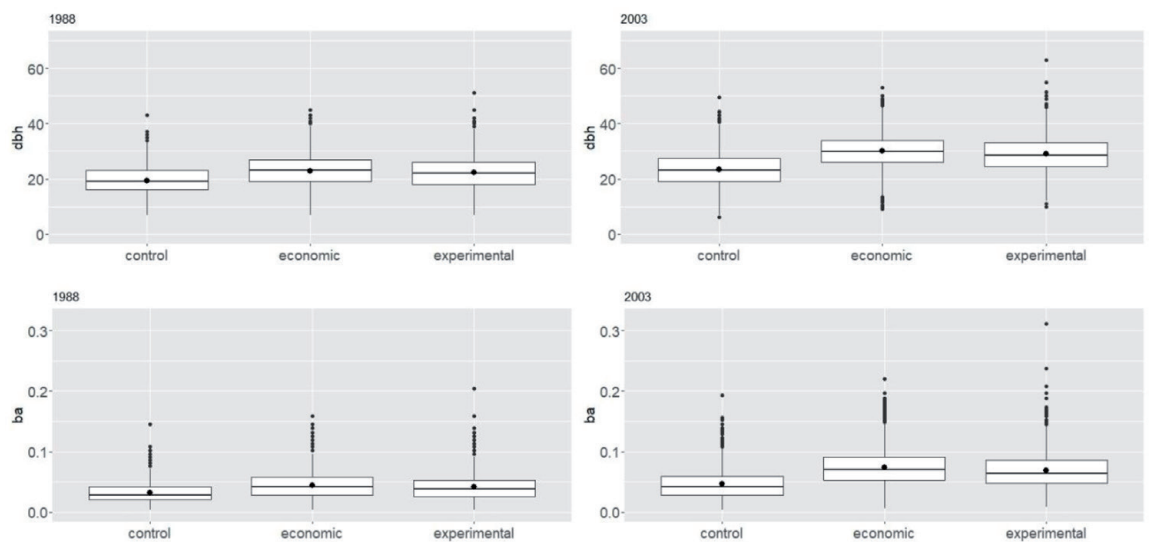


Figure 1. Boxplots (mean, median, min, max, outliers, and first and third quartiles) for tree diameter (dbh) and basal area (ba) in the objects in two inventories.

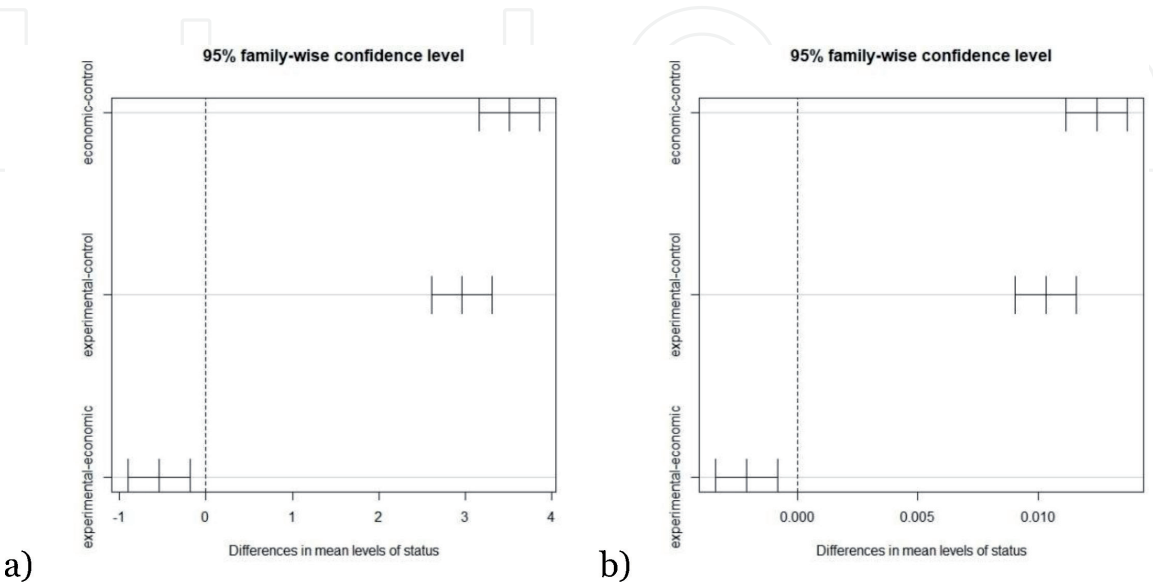


Figure 2. Differences in the mean of dbh between objects in 1988 (a) and 2003 (b). If the confidence level does not include 0 value, then two means are significantly different at $\alpha = 0.05$.

3.2.2 Structural parameters

3.2.2.1 Control object

3.2.2.1.1 Spatial distribution

The average value of the CE index for the object at the beginning reached the value of 1.14 and was significantly different from the random expectation. The index ranged from 0.81 to 1.35 with its variation among plots at the level of 8% (**Figure 3**). There were 32 plots (51% of all plots) in the control object on which trees showed regular pattern of their distribution ($CE > 1.0$) and only on one plot in this index was significantly lower than $CE < 1.0$, indicating clumped distribution of trees. On the rest of the plots (48%), the deviations from the random expectation were not statistically proved and trees were randomly distributed. After 15 years—in 2003—the mean value of CE index did not change ($CE = 1.14$). The value of this index varied among plots between 0.83 and 1.30. The number of plots on which the index was significantly higher than 1.0 indicating regular pattern decreased to 23 (36%). No plot indicating clumped distribution of trees was observed. Therefore, the random pattern was still dominant in 2003 and this type of tree distribution was observed on 40 plots (63%).

3.2.2.1.2 Tree size diversity

Just after the initialization of the experiment, in 1988, the mean value of diameter differentiation index, TD, in the case of the control object reached $TD = 0.19$. This index ranged from 0.00 to 0.54 depending on the plot (**Figure 3**). Coefficient of variation for TD index between plots was large ($cv = 50\%$). The mean index showed that, in general, the variation in dbh among neighboring trees was low. This was confirmed by the distribution of the index in differentiation classes (**Table 3**). The dominant classes were these of very low and low diameter differentiation, which indicates that the diversity in diameter between the nearest neighbors was lower than 40%. After 15 years, the situation did not change much. The average TD index took the value of $TD = 0.20$ with much smaller range: 0.17–0.31 than in 1988. The variation of TD among plots clearly decreased to 20%. Again, the distribution of TD index in diameter differentiation classes confirmed that trees were mostly similar in their diameter at the small spatial scale (**Table 3**).

In the case of tree height differentiation, the mean value of the TH index was much smaller than for tree diameter and it reached $TH = 0.10$. The index ranged from 0.06–0.16 (**Figure 3**) depending on plot, and the coefficient of variation between plots was 28%. This indicates that neighboring trees were very similar in their height (**Table 3**). Homogenous groups of trees are indicated also by the share of trees belonging to the lowest differentiation class (92.9% of trees). After 15 years, the mean value of the TH index did not change ($TH = 0.10$), with the range varying between 0.06 and 0.15. The share of trees in the lowest differentiation class increased to more than 95% (**Table 3**).

3.2.2.1.3 Species mingling

In 1988, the species mingling index, SM, reached the mean value of $SM = 0.08$, indicating very homogenous conditions, on average, in terms of species diversity at the small spatial scale. The index ranged from 0.00 to 0.54 and its variation between plots was at very high level, $cv = 103\%$ (**Figure 3**). There were 17 plots (27%) in the control object on which the index was equal to 0.00, indicating the

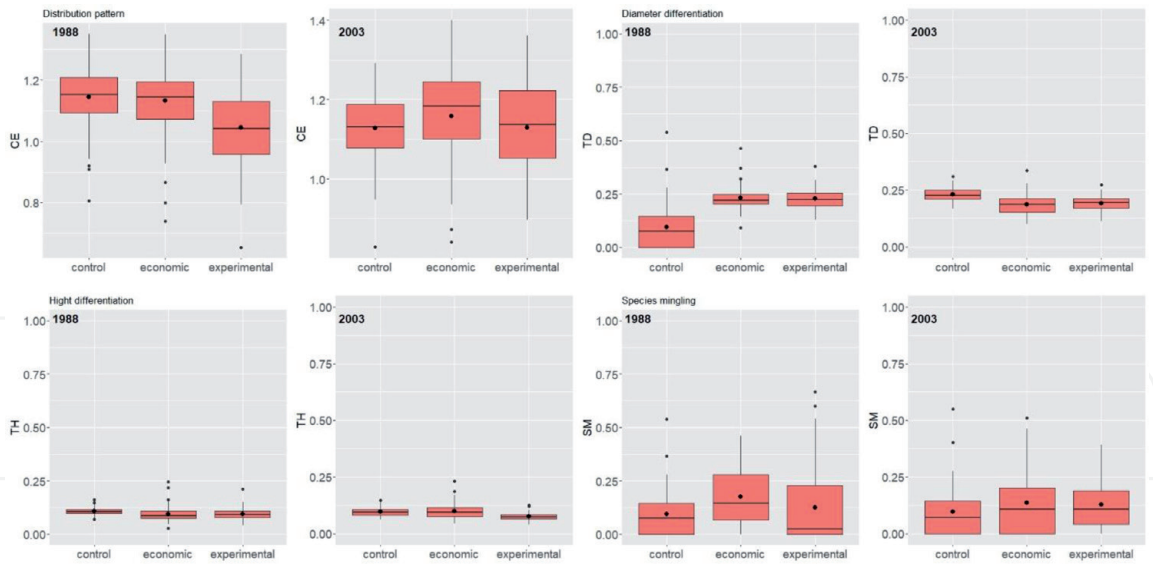


Figure 3. Statistical characteristic (mean, median, max, min, outliers, and first and third quartiles) of structural indices describing spatial pattern (CE), tree size differentiation (TD), and species mingling (SM) in the experimental objects in 1988 and 2003.

Index	Year	Differentiation classes				
		Very low	Low	Moderate	Large	Very large
TD	1988	45.5	48.5	5.8	0.18	0
	2003	44.8	48.0	6.6	0.46	0.12
TH	1988	92.9	6.98	0.04	0	0
	2003	95.5	4.14	0.33	0	0

Table 3. The share (%) of diameter (TD) and height (TH) differentiation classes in the control object.

lack of species mingling at all. On other plots, the mingling index varied from low to moderate. Analysis of the index distribution in mingling classes pointed out that the neighborhood of most trees in the control object was homogeneous (83% of trees). Only in the case of 9% of trees, their neighborhood was more heterogeneous in terms of species, meaning that 1–2 neighbors were different in species. In 2003, the mean SM index increased to $SM = 0.12$ and ranged from 0.00 to 0.55 depending on the plot. The coefficient of variation between plots in the control object decreased slightly after 15 years and got the value of 97%. On 19 plots (30%), the index value was equal to 0.00, indicating the lack of species mixture. Again, the dominance of very low mingling class can be observed on most plots in the object (84% trees). Both tree species showed the opposite behavior (**Figure 4**). Scots pine formed large homogenous groups of trees, while silver birch was present in the stand mostly as a single mixture.

3.2.2.2 Experimental object

3.2.2.2.1 Spatial distribution

In 1988, the mean CE index for the experimental object took the value of $CE = 1.18$, indicating regular pattern in tree distribution. The value of the index ranged from 0.65 to 1.28 and the coefficient of variation among plots reached the

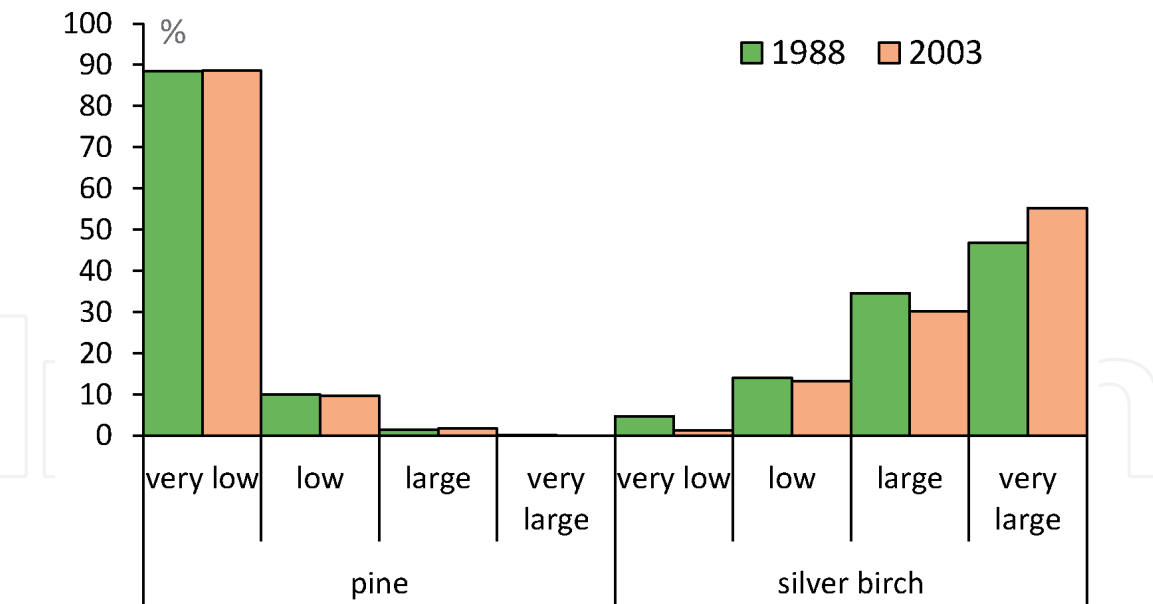


Figure 4.
Spatial mingling of Scots pine and silver birch in the control object in two inventories.

level of 12% (**Figure 3**). In the case of 19 plots (25% of all plots), the value of the index was significantly larger than that for the random expectation and on the others the distribution pattern was random. After 15 years, in 2003, the mean value of the CE index increased to $CE = 1.22$ and it varied from 0.89 to 1.29 depending on the plot. The coefficient of variation among plots was at the level of 8%. In the case of 26 plots (35%), the value of this index was significantly different from the randomness, indicating clear regularity in the spatial distribution of trees.

3.2.2.2.2 *Tree size diversity*

In 1988, the mean value of the diameter differentiation index, TD, was $TD = 0.23$ which pointed to the low diversity in diameter of trees at small spatial scale. This index ranged in this object from 0.12 to 0.38, and the variation on it among all plots was at the level of 20% (**Figure 3**). Most trees in the experimental object could be characterized by very low and low differentiation (95% of all trees), which confirmed that trees were similar in their diameter at the nearest-neighbor spatial scale (**Table 4**). In 2003, the average value of the TD index decreased to $TD = 0.19$. The lowest value of the index was 0.14 and the largest was 0.31. Coefficient of variation of the index among plots decreased to the level of 15%. Up to 97% of trees were characterized by very low and low differentiation in diameter at small spatial scale (**Table 4**). At the beginning of the experiment, the mean index describing the differentiation of tree in terms of their height took the value of $TH = 0.10$. It pointed to a large similarity of trees in tree height. The index ranged from 0.04 to 0.21 with the coefficient of variation among plots at the level of 28%. Up to 96% of trees showed similarity in height with their nearest neighbors (**Table 4**). In 2003, the mean value of the TH index decreased to $TH = 0.07$, with the minimum value of 0.05 and maximum one of 0.15. Variation in the TH index among plots was at the level of 21%. The share of trees which showed large similarity in their total height with the nearest neighbors increased to 98% (**Table 4**).

3.2.2.2.3 *Species mingling*

In 1988, the mean value of the species mingling index got $SM = 0.13$, indicating rather low species mixture in the experimental object. The value of this index varied

Index	Year	Differentiation classes				
		Very low	Low	Moderate	Large	Very large
TD	1988	43	52	5	0.3	0
	2003	60	37	2	0.4	0
TH	1988	96	3.5	0.3	0	0
	2003	98	1.5	0.5	0	0

Table 4.
The share (%) of diameter (TD) and height (TH) differentiation classes in the experimental object.

among plots from 0.00 to 0.60 (**Figure 3**) and the coefficient of variation was very high, $cv = 78\%$. Species homogenous neighborhood, expressed by the index $SM = 0.00$, was observed in the case of 28 plots (39%), and the others showed higher mingling level. After 15 years, the mean value of the index was almost the same like in 1988— $SM = 0.12$. The minimum value of SM was 0.00 and the highest one was 0.55, with variation among plots reaching the level of 89%. The number of plots with the index $SM = 0.00$ decreased in 2003–2018 (25%), that is a 34% decrease. Similar to the control object, Scots pine and silver birch showed opposite behavior (**Figure 5**). Homogenous neighborhood was observed in the case of Scots pine, while birch was present most often as a single mixture.

3.2.2.3 *Economic object*

3.2.2.3.1 *Spatial distribution*

At the beginning of the experiment, the mean value of CE describing the spatial pattern of living trees in the economic object took the value $CE = 1.21$, pointing to a clear regular pattern. The lowest value of the index was $CE = 0.74$ and the highest was $CE = 1.35$ (**Figure 3**). The coefficient of variation between plots for this index was low—10%. The index differed significantly from randomness ($CE = 1.00$) in the case of 33 plots (43%). The dominant spatial pattern of living trees was therefore a random pattern. No clumping was observed on any plot. After 15 years, in 2003, the mean value of the index increased to $CE = 1.27$. In the object, the index ranged from 0.84 to 1.40 depending on the plot, with the coefficient of variation at the level of 11%. The number of plots with the CE index significantly larger than 1.0 was 34 (48%). The dominance of the random pattern was still observed in this object.

3.2.2.3.2 *Tree size diversity*

In 1988, the mean value of diameter differentiation index reached $TD = 0.23$, indicating rather low diversity in tree diameter among the nearest neighbors. The index ranged from 0.09 to 0.47 (**Figure 3**), with the coefficient of variation among plots at the level of 22%. Most trees showed very low or low diameter differentiation at the small spatial scale (92% of trees) and only few (7.8%) showed larger variation in diameter (**Table 5**). In 2003, the mean value of the index decreased to $TD = 0.19$, varying between 0.10 and 0.34 depending on the plot. The variation of the index among plot was at the level of 23%. After 15 years of stand development, the number of trees in the lowest two classes of diameter differentiation clearly increased (**Table 5**). As much as 97% of trees belonged to both these classes.

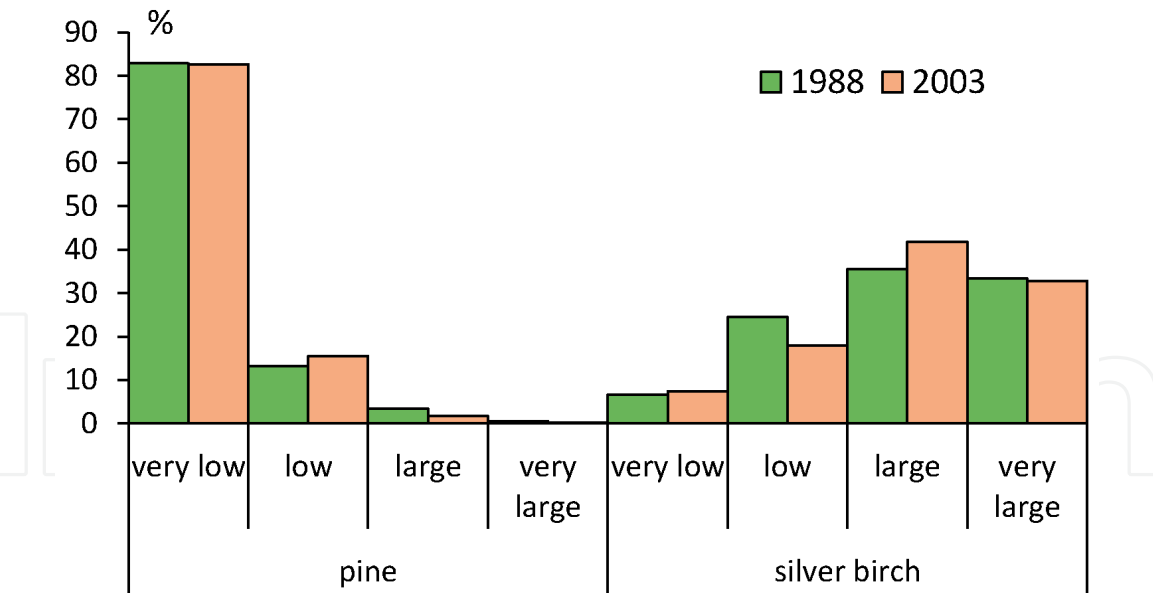


Figure 5.
Spatial mingling of Scots pine and silver birch in the experimental object in two inventories.

Index	Year	Differentiation classes				
		Very low	Low	Moderate	Large	Very large
TD	1988	45.6	46.4	7.0	0.8	0
	2003	63.9	32.9	2.6	0.6	0
TH	1988	93.2	6.2	0.7	0	0
	2003	93.9	4.9	1.1	0.1	0

Table 5.
The share (%) of diameter (TD) and height (TH) differentiation classes in the economic object.

The height differentiation of trees in the economic object was clearly lower than the diameter. The mean value of the index, TH, was 0.10 and it ranged from 0.03 to 0.25, with $cv = 35\%$. Up 93% of trees showed very low differentiation in height among their neighbors (**Table 5**). In 2003, the TH index reached the same mean value as in 1988 ($TH = 0.10$). The index varied from 0.05 to 0.23 depending on plot, and the coefficient of variation of TH index among plots was at the level of 32%. Again, the most abundance class was the one indicating very low height differentiation (**Table 5**).

3.2.2.3.3 *Species mingling*

In 1988, the spatial mingling index, SM, reached the mean value of 0.17, with its range from 0.00 to 0.46 (**Figure 3**). The coefficient of variation for the index was at the level of 74%. The relative low mean value of the index pointed to rather homogenous neighborhoods in terms of tree species. In the case of eight plots (10%), the index showed no mingling and in the case of the others, the species diversity was slightly higher. The low species mingling in the economic object was also confirmed by the distribution of this index in the mingling classes. Trees belonging to the lowest mingling class accounted for 68.8%, but 6.4% belonged to the mingling class showing very large mingling. In 2003, the mean value of SM index dropped to 0.13, varying between 0.00 and 0.51 among plots ($cv = 97\%$). The abundance of very low mingling class increased to 75.8% at the expense of the classes of higher species

mingling. Both tree species showed more complex situation in terms of spatial mingling comparing to the other objects (**Figure 6**). However, Scots pine formed large homogenous groups of trees, while silver birch was mixed in the form of groups or a single mixture.

3.2.3 Difference in structural diversity of the stand between objects

3.2.3.1 Spatial distribution

At the beginning of the experiment, the analyzed stands in the control, experimental, and economic objects showed significant differences in terms of spatial distribution of trees ($\alpha = 0.05$). It was indicated by the Kruskal-Wallis test (KS) ($\chi^2 = 27.6787$, $P = 0.00$). The Dunn's test, applied to find out which objects differed, showed that such significant differences were observed between the control and experimental objects ($P = 0.00$) as well as between the experimental and economic ones ($P = 0.00$). No significant difference in terms of spatial pattern was observed between the control and economic objects ($P = 0.57$). In 2003, the KS test confirmed the significant differences between the objects ($\chi^2 = 5.8092$, $P = 0.05$). However, the Dunn's test indicated the only significant differences between the control object and economic one ($P = 0.02$). No differences have been observed between other pairs of the objects.

3.2.3.2 Tree size diversity

In 1988, the differences in the diameter differentiation index between the objects have been statistically proven by the KS test ($\chi^2 = 87.6834$, $P = 0.00$). They have been observed in the case of economic and control objects ($P = 0.00$) as well as the experimental and the control ones ($P = 0.00$). The experimental and economic objects were not different in terms of diameter differentiation of trees at the neighborhood spatial scale ($P = 0.96$). After 15 years, these differences were still significant ($\chi^2 = 52.4553$, $P = 0.00$) and they were observed in the case of the same pairs of

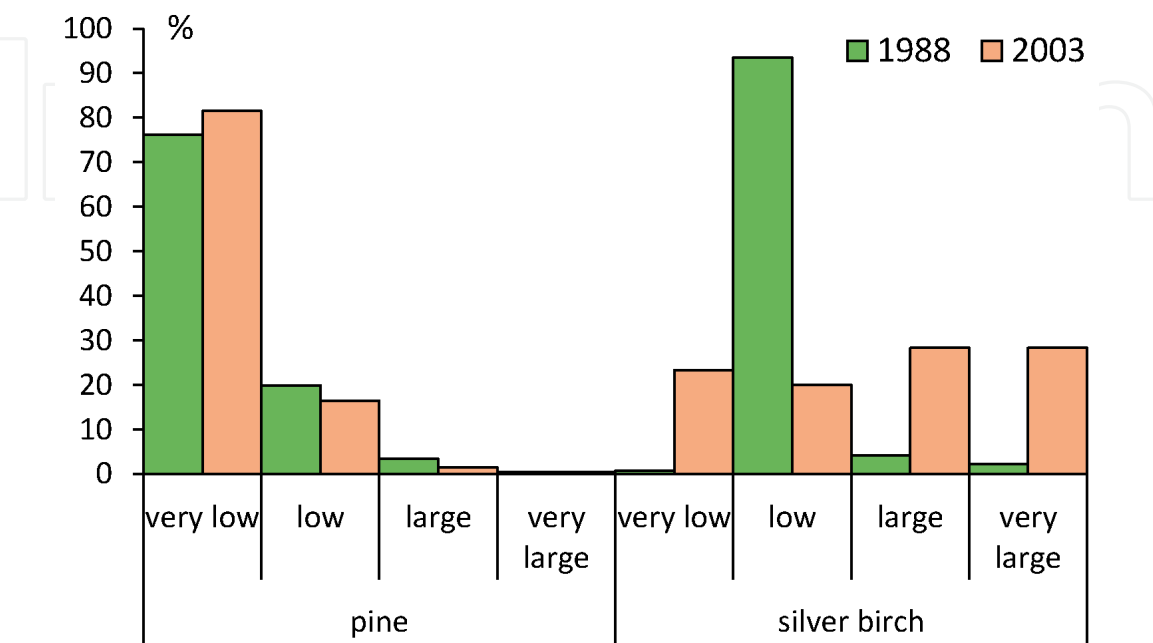


Figure 6.
Spatial mingling of Scots pine and silver birch in the economic object in two inventories.

objects. In 1988, the differences in tree height differentiation between objects were statistically significant ($\chi^2 = 20.5312$, $P = 0.00$). Dunn's test proved the significance of the differences between the control and economic objects ($P = 0.00$) as well as for control and experimental objects ($P = 0.001$). Trees in the economic object and experimental one were not significantly different in terms of total tree height ($P = 0.81$) at the beginning of the experiment. While the KS test showed significant differences between the objects after 15 years, the pairs of them for which Dunn's test pointed out the significant differences were different. No significant differences in tree height at the small spatial scale were confirmed for the economic and control objects ($P = 0.66$), but in the case of the other pairs of objects they were significant ($P = 0.00$).

3.2.3.3 *Species mingling*

Species diversity expressed in the form of species mingling index showed that the objects differed significantly ($\chi^2 = 28.6449$, $P = 0.00$) but only at the beginning of the experiment (in 1988). The Dunn's test showed that such differences could be observed between the control and economic objects ($P = 0.004$) and between the economic and experimental ones ($P = 0.01$).

4. Conclusion

The structure of Scots pine stands has been shaped by the historical management system, that is, even-aged silviculture. This system results in the homogenous stand structure what is confirmed by the analysis of the stand structure based on different structural metrics. Just after the initialization of the experiment with different silvicultural strategies and their impact on the stand structure, the common stand parameters (dbh, basal area) were quite similar in each of the objects being analyzed. Fifteen years after, these parameters changed clearly, and the objects differed significantly. The highest mean tree diameter was reached in the economic object followed by the experimental one. The lowest was in the case of the control object. The total stand basal area was the highest in the control object.

While the spatial pattern of tree distribution was regular, on average, the silvicultural strategies influenced clearly in the number of plots for which the regularity was statistically proved. Active strategy led to the increase of regularity and passive strategy favored the random pattern occurrence in the stand.

The previous even-aged silviculture favored low diameter differentiation of trees in each of the object. Fifteen years of the experiment, passive and active silvicultural strategies resulted in more differentiation between objects. Each of the strategies led to a lower tree diameter diversity, but business as usual strategy favored diameter homogeneity to much more extent than other strategies. Passive strategy supported higher diversity of tree diameter. In the case of tree height diversity, all strategies considered here were associated with decreasing of tree height diversity. There was no clear impact of any strategy on creating tree height diversity in Scots pine stands.

The dominance of Scots pine in the stands was confirmed by the structural metrics in each of the object. Species homogenous plots were favored by two strategies: passive and business as usual. The share of homogeneous plots decreased after 15 years of experiment only in case of the experimental object.

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