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Under-Canopy Regeneration of Scots Pine (*Pinus sylvestris* L.) as Adaptive Potential in Building a Diverse Stand Structure

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Abstract: Under-canopy natural regeneration of Scots pine (*Pinus sylvestris* L.) stand is able to create stands with a complex structure, which are characterised by greater resistance to extreme phenomena related to climate change. The main aim of the work was to analyse the potential of pine undergrowth, its role in the stand, and its usefulness in further breeding plans to create stands of various structure, with greater stability and tolerance to stress factors, including greater resistance to climate change. The study was carried out in north-eastern Poland, in pine stands thinned by strong (hurricane level) wind in 2002. The study area covers 225.2 ha and is located in 29 stands. Naturally regenerated pine saplings with a minimum height of 0.5 m, characterised by a high density, growing under the upper cover of the stand, with varying degrees of thinning, were qualified for the study. On average 7.820 pine saplings were recorded in the area of one hectare. Over 65% of the examined saplings were determined to be of very good or good quality, prognostic for further development and the creation of the main stand in the future. The principle of increasing the structural diversity of stands is the method of increasing the adaptability of forests to environmental changes.

Keywords: *Pinus sylvestris*; natural regeneration; climate change

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1. Introduction

Worldwide, climate change has posed a significant threat to forests due to the increasing heat and aridity, shifting rainfall patterns and extreme weather events [1]. The currently observed climate changes, especially sudden violent weather phenomena are major stressors for forests [2,3], reducing stability and resistance to harmful factors occurring in Central European forests [4]. Temperature variation, precipitation, and long-term changes in vegetation [5] are among the most important factors influencing forest stand structures [6–9]. The literature describes increased tree mortality in temperate forests [10,11]. Models of potential tree range changes indicate that the habitat conditions in most of Europe, including Poland, will become unfavourable for Scots pine (*Pinus sylvestris* L.), which may result in the withdrawal of this species from a significant part of its range in the near term. The main reasons for the potential tree range changes will be an increase in carbon dioxide concentration and an increase in the average global temperature [12,13]. In this situation, forest management faces a great challenge to develop methods of silviculture to maintain the health and vitality of forest ecosystems at a sufficiently high level [14,15], which will ensure the emergence of healthy, climate-resistant stands, which can be regenerate naturally.

Scots pine (*Pinus sylvestris* L.) is the most widespread conifer species in the world. It occurs in almost all coniferous habitats in the northern hemisphere, and its share in Europe is 29.6% [16,17]. In the past, this species was artificially renewed by planting on felling [18], but natural regeneration is now used to an increasing extent [19,20]. Planting/seeding dominates in annual regeneration in both north (71.2%) and central-east Europe (66%). In central-west Europe, natural regeneration is the most common regeneration type. For example, 74.7% of the annual regeneration in Germany, respectively 85.3% in Switzerland, is natural. In European forests average for natural regeneration is 68% [17]. However, natural pine regeneration under the canopy of other tree species is relatively rare [21,22]. It is difficult to create and maintain durable structures of different ages [23]. Under favourable conditions (considering the light requirements), the species can regenerate under the canopy of the parent stand [20,24,25]. The use of under-canopy natural regeneration promotes the formation of stands with a complex structure, characterised by greater stability and tolerance to stress factors [26], including stands characterised by greater resistance to climate change [27]. Currently, due to climate change, the need to maintain the continuity growing of forests on the smallest spatial scale is emphasised, and there is an underscoring of the reconstruction of the existing one-century monoculture stands [28,29], in line with the "Close to Nature" theory [30,31]. Natural regeneration is an important element in implementing an ecological management model [32], seeking to ensure the sustainability of the forest [33]. Properly shaping the stand structure is an important tool for mitigating future climate change in forests, especially drought [34], but also hurricanes, which more and more often cause damage to stands [35,36]. The gap made by strong winds can contribute to the creation of good conditions for under-canopy pine natural regeneration [37].

The currently small amount of pine under-canopy natural regeneration should encourage the use of local clumps (groups) of pine renewals. To date, there have been few studies that focus on under-canopy pine saplings [20,38,39]. The conducted study (a) analysed Scots pine under-canopy natural regeneration after hurricane winds, (b) analysed the role of saplings in pine stands and estimated the growth opportunities of a given tree, (c) analysed the use of a young forest generation to optimize further breeding plans and create stands with a diversified structure, and (d) looked for alternative methods of renewing Scots pine in a changing climate, in particular, strong winds.

2. Materials and Methods

2.1. Study Area and Sample Design

The study was carried out in north-eastern Poland, in pine stands of the Nowogród Forest District belonging to the Regional Directorate of the State Forests in Białystok (Figure 1). On 4 July 2002, a hurricane struck the central and northern areas of this forest district, causing forest damage. The study area was dominated by poor, dry habitats (86%). The dominant species (in terms of the area covered) was Scots pine, which formed mostly single-species stands with only a slightly diversified spatial structure (approx. 92% of the total forest area of the forest district). For this reason, they succumbed to the strong wind with ease.

Features characterizing the climate of study areas: the length of the growing season is approx. 210 days, the average temperature during the growing season–approx. 13.2 °C, the sum of rainfall during the growing season–approx. 455 mm, the average annual temperature—7.7 °C, annual rainfall—697 mm, relative air humidity—79% [40].

Following the suggestion of the Forest Service, the study analysed selected pine stands thinned by strong (hurricane level) winds, growing in a fresh coniferous forest habitat, aged 49 to 117 years. Tree stands in age classes 4 and 5 accounted for nearly 60% of the stands over the analysed saplings. The indicated stands were then surveyed on linear trails (every 15 m) to determine the location of pine regeneration under the canopy.

Naturally regenerated pine saplings with a minimum height of 0.5 m, characterised by a high density, were qualified for the study (Scheme 1). The edge of the tuft was established by delineating the outermost individuals in the tuft with saplings forming distinct clumps of growth cones. Thus, the young generation of saplings (at least 50 cm high) growing under the upper stand cover (giving hope for future stand establishment) was taken as saplings.The analysed saplings grew under the canopy of the stand with various thinnings (planting factors from 0.5 to 1.0, which corresponded to a specific density of the cover stand-value 0.5, there are wide gaps between the crowns, in which one can easily fit one or even two trees, 1.0, tree crowns are touching at the edges or partially overlapping). The study area was 252.2 ha and included 29 Scots pine stands.

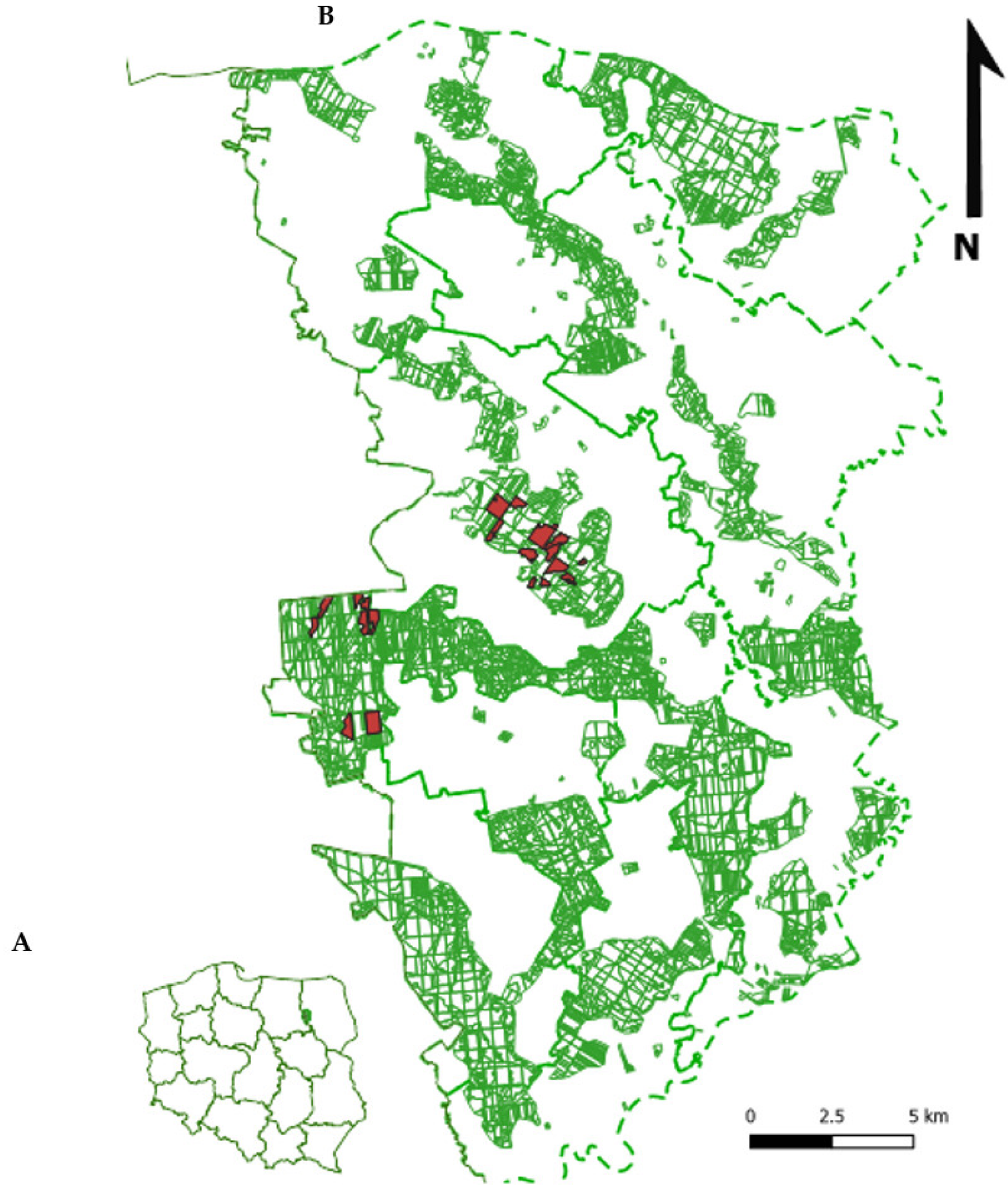


Figure 1. Location of (**A**) Nowogród Forest District in Poland, (**B**) the analysed stands in the Nowogród forest district (explanations of the colours on the map: brown—analysed stands, green—other stands in Nowogród forest district), green line—border of the Nowogród forest district.

Measurements were taken on 6860 individual pine saplings from sub-canopy natural regenerations. A total of 65 clumps of pine saplings were inventoried in areas ranging from 15 m^2 to 2.340 m^2. The average size of the clusters was 407.5 m^2 (Table 1).

Scheme 1. Under-canopy natural regeneration of Scots pine (Author: Anna Zawadzka).

Table 1. Basic characteristics of the research stands.

Sample Stands Number	Stand Area [ha]	Stand Age [Years]	Stand Height [m]	Planting Factor	Number of Clumps	Average Area of the Clump [m^2]
1	2.21	97	27	0.7	1	648
2	2.03	67	23	1.0	1	1350
3	0.94	67	19	0.7	2	479
4	10.91	87	23	0.8	1	340
5	7.17	77	20	0.6	3	143
6	9.25	87	23	0.8	4	412
7	1.51	72	18	0.9	1	65
8	32.93	83	21	0.7	2	296
9	9.59	102	26	0.7	2	460
10	6.65	102	25	0.8	2	582
11	6.77	47	18	0.5	1	2340
12	17.76	69	18	0.7	1	66
13	6.18	67	17	0.8	1	20

Table 1. *Cont.*

Sample Stands Number	Stand Area [ha]	Stand Age [Years]	Stand Height [m]	Planting Factor	Number of Clumps	Average Area of the Clump [m^2]
14	3.16	92	23	0.9	1	15
15	3.95	60	20	0.8	2	241
16	10.46	98	20	0.8	8	539
17	4.51	87	23	0.7	5	279
18	3.88	52	18	0.7	1	105
19	3.31	57	21	0.7	2	103
20	3.55	49	19	0.9	1	65
21	6.11	69	23	0.7	1	154
22	1.98	91	26	0.8	3	186
23	9.82	91	25	1.0	2	298
24	11.94	117	30	0.9	6	141
25	9.95	115	29	0.5	4	203
26	2.36	60	21	0.7	2	101
27	5.40	92	26	0.7	2	195
28	19.12	110	26	1.0	2	30
29	11.80	111	26	0.8	1	48

The study looked at pine clump shape and area, saplings height, and saplings development category. A visual assessment of the clump shape was performed according to the following criteria: regular clumps—oval similar to a circle or of a shape similar to a square (the diagonals did not differ significantly); strip clumps—rectangular in shape (one of the sides was longer than the adjacent side); irregular clumps—a lack of proportions between the sides, with many bends of the sides forming polygonal geometric figures. When determining the development category (tendency), the following criteria were taken into account: Category I—saplings with a positive prognosis for further development, no excess needles, no disease features, mechanical damage, or physiological damage; Category II—saplings stagnant in height with distinct features of a lack of light; trees with the possibility of promotion and strengthening of the main shoot, without any disease features or significant mechanical damage; Category III—saplings with a negative prognosis, with a damaged top, with a strongly crooked trunk, with mechanical damage, disease features, or strong defoliation with low breeding quality.

2.2. Data Analysis

A statistical analysis of pine saplings was performed using Statistica 13 software [41]. For measurable variables, arithmetic means, standard deviations, and the range of variability (extreme values) were calculated. The frequency of their occurrence (percentage) was also calculated for the qualitative variables. All of the quantitative variables were checked with the Shapiro-Wilk test to determine the type of distribution [42]. A comparison of qualitative variables between the groups was made using the chi-square test ($\chi 2$) [43]. The comparison of quantitative results between groups was performed using the Kruskal–Wallis test and a posthoc test (Tukey test). An analysis of Spearman's rank correlation between the selected variables was also performed [44]. The level of $\alpha = 0.05$ was assumed for all comparisons.

3. Results

Based on the results, pine saplings were divided into three development categories using data collected from 6860 individuals pine saplings, under-canopy natural regeneration, growing in 65 clumps.

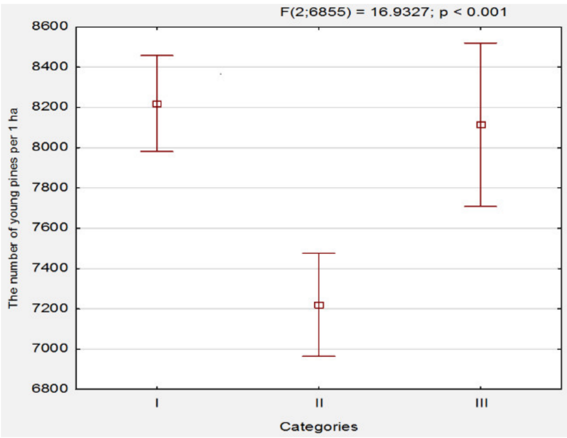
The average height of the stand above the clumps of saplings was 23.7 m. The average age of the stand was 91.3 years. There was an average of 7.820 pine saplings in one hectare, with at least 609 saplings per ha, and max. 40.714 saplings per ha (Table 2).

Table 2. Characteristics of the measured saplings and their division into development categories.

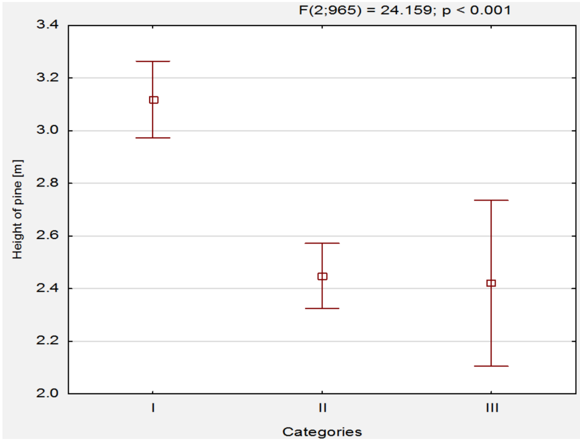
		Density [N·ha^{-1}]	Height of the Sapling [m]	Planting Factor	Stand Age [Years]	Stand Area [ha]	Stand Height [m]	Average Area of the Clump [m^2]
All saplings	Mean	7820	2.81	0.75	91.3	8.51	23.7	407.5
	min	609	0.75	0.50	47.0	0.94	17.0	15.0
	max	40,714	12.00	1.00	117.0	32.93	30.0	2340.0
	Sd	6774	1.54	0.14	19.7	5.98	3.9	458.6
Category I	Mean	8220	3.12	0.70	91.6	8.70	23.9	413.8
	min	609	0.80	0.50	47.0	0.90	17.0	15.0
	max	40,714	12.00	1.00	117.0	32.90	30.0	2340.0
	Sd	6863	1.70	0.14	20.5	6.40	4.1	502.0
Category II	Mean	7220	2.45	0.80	92.1	8.60	23.4	421.9
	min	609	0.80	0.50	47.0	0.90	17.0	15.0
	max	40,714	12.00	1.00	117.0	32.90	30.0	2340.0
	Sd	6679	1.19	0.13	18.3	5.60	3.8	413.9
Category III	Mean	8114	2.42	0.80	88.2	7.80	23.8	351.6
	min	609	0.80	0.50	47.0	0.90	17.0	20.0
	max	40,714	7.50	1.00	117.0	32.90	30.0	2340.0
	Sd	6634	1.46	0.14	20.4	5.80	3.7	420.9

The saplings in development category I were characterised by the highest abundance among the examined saplings. A difference in the number of saplings occurred between development categories I and III, and category II (which was the least numerous). The best quality saplings accounted for 34.9% of the total number of inventoried saplings (lower quality saplings accounted for 33.4% and stagnant saplings for 30.7%). The number of young pines per 1 ha of area varied among the development categories (Figure 2a).

The average height of pine saplings was 2.81 m, but differed depending on the development category (Figure 2b). The maximum and minimum average height differences were above 10 m for development categories I and II. The height of the category III saplings had the highest coefficient of variation (59.9%) and the category II saplings had the lowest (48.6%). The mean height value was 54.8% (Table 3).



(a)



(b)

Figure 2. (**a**) The number of young pines per 1 ha in each development category; (**b**) height of young pines in each development category.

The height of saplings included in the first development category decreased (rs −0.18) with increased numbers. Moreover, the forestation factor (−0.11) influenced the density of saplings (category II). For all categories, the age of the surrounding forest stand had a positive effect, and the number of saplings increased with the transition to older age classes (Table 4).

The growth of saplings in clumps (bio-groups) was also observed. During the measurements, a characteristic biosocial system was visible between the individual saplings in a clump. The tallest and relatively best quality saplings were usually in the centre of the clump, and the poorer quality saplings grew on the edges, often providing cover for trees inside the bio-group.

The mean sapling density differed between the clump shape categories ($p < 0.01$; F = 263.9; df = 2). In development categories I and II, the most numerous pine saplings were located in regular-shaped clumps (on average, 9680 saplings per ha). In turn, in category III, the highest pine density occurred with an irregular clump shape. In all development categories, the strip shape had the smallest number.

On average, 40% of the inventoried saplings had intermittent cover (planting factor 0.5–0.6) or full cover (planting factor 0.9–1.0), while 20% of pine saplings had moderate density cover (planting factor 0.7–0.8). For all development categories, a downward trend in numbers was noted along with an increase in the tree planting factor (to the value of 0.7–0.8). With the increase in the value of the planting factor (0.9–1.0), the sapling density also increased (by over 52%, on average).

A positive relationship was found between the number of saplings and the age of the upper stand. The smallest number was observed under the canopy in age classes 4 and 5 (on average, 5.615 per ha). As the parent stand progressed to the older development stages, the number of saplings increased, reaching the highest value under the age class 6 stand (on average, 12.934 saplings per ha).

Table 3. Pine saplings' density depending on the development category and the clump shape, planting factor, and age class.

	Overall Sapling		**Category I**		**Category II**		**Category III**	
Density [N·ha^{-1}]	7820 (6774)		8220 (6161)		7220 (6679)		8114 (6634)	
Height of the sapling [m]	2.81 (1.54)		3.12 (1.70)		2.45 (1.19)		2.42 (1.46)	
Stand height [m]	23.7 (3.9)		23.9 (4.1)		23.4 (3.8)		23.8 (3.7)	
Planting factor	0.75 (0.14)		0.70 (0.14)		0.80 (0.13)		0.80 (0.14)	
Stand age [years]	91.3 (19.7)		91.6 (20.5)		92.1 (18.3)		88.2 (20.4)	
Coefficient of variation in density [%]	86.6		83.5		92.5		81.8	
Coefficient of variation in sapling height [%]	5400200458		54.2		48.6		59.9	
	N·ha^{-1}	%	N·ha^{-1}	%	N·ha^{-1}	%	N·ha^{-1}	%
Clump shape:								
irregular	8014 (6985)	35.3	8550 (7270)	35%	7161 (6593)	30%	8342 (6753)	35%
rigger	5128 (4176)	22.6	5666 (4546)	37%	4699 (3794)	31%	4850 (4001)	32%
regular	9586 (7451)	42.2	9589 (7285)	35%	9770 (7926)	35%	8248 (6972)	30%
Planting factor								
0.5–0.6 (broken canopy closure)	11.847 (7906)	41.1	11.633 (8081)	32%	12.133 (7523)	34%	12.079 (8159)	34%
0.7–0.8 (moderate canopy closure)	5648 (3454)	19.6	5778 (3372)	33%	5197 (3316)	30%	6466 (3857)	37%
0.9–1.0 (full canopy closure)	11.356 (9951)	39.4	12.335 (9628)	37%	10.581 (10479)	32%	10.474 (9463)	31%
Age class:								
Age class III (41–60 years)	6891 (5370)	22.2	6239 (5398)	29%	7360 (5513)	35%	7643 (4951)	36%
Age class IV (61–80 years)	5832 (3406)	18.8	5744 (3079)	31%	5399 (3552)	30%	7145 (3628)	39%
Age class V (81–100 years)	5398 (3217)	17.4	5516 (3264)	33%	5019 (2912)	30%	6119 (3721)	37%
Age class VI (101–120 years)	12.934 (9321)	41.6	13.835 (8671)	36%	11.924 (9805)	32%	12.357 (9980)	32%

In parentheses standard deviation values.

Table 4. Intra-group correlations of selected characteristics of pine saplings in given developmental categories.

Development Category			Average Density [N·ha^{-1}]	Average Height of Sapling [m]	Planting Factor	Stand Age
Category I	Average density [N·ha^{-1}]	r_S	1	−0.18 *	−0.02	0.41 *
	Average height of sapling [m]	r_S	−0.18 *	1	0.01	−0.06
	Planting factor	r_S	−0.02	0.01	1	0.07 *
	Stand age [years]	r_S	0.41 *	−0.06	0.07 *	1
Category II	Average density [N·ha^{-1}]	r_S	1	−0.09	−0.11 *	0.29 *
	Average height of sapling [m]	r_S	−0.09	1	−0.05 *	0.02 *
	Planting factor	r_S	−0.11 *	−0.05 *	1	−0.05 *
	Stand age [years]	r_S	0.29 *	0.02 *	−0.05 *	1
Category III	Average density [N·ha^{-1}]	r_S	1	0.11	−0.03	0.24 *
	Average height of sapling [m]	r_S	0.11	1	−0.09	−0.02
	Planting factor	r_S	−0.03	−0.09	1	0.10 *
	Stand age [years]	r_S	0.24 *	−0.02	0.10 *	1

r_S—Spearman's correlation coefficient; *—correlation coefficients significant at the level of $p < 0.05$.

4. Discussion

Pine forests are an important component of the forest ecosystems of Central Europe, and they are usually located on poor and dry sandy soils. In these areas, climate change can result in even more extreme dry and warm periods during the growing season [20,45–47]. Warming climates also increase frequencies of catastrophic winds [48,49]. In Poland an increase in the frequency and amplitude of strong winds, with intense rainfall is expected [50–53]. The use of pine under-canopy natural regeneration is an activity conducive to forest management in the conditions of climate change and more frequent extreme weather phenomena at the local level. The increase in frequency and intensity of natural events [54] suggests large losses in future forest value [13]. Adapting forests to climate change is therefore one of the major challenges for forest management [55–58]. To mitigate climate change risks and reduce vulnerability of forests in the face of climate change, adequate adjustments to forest management are required [1,9]. Species diversity, tree height variability, and spatial diversity are among the main factors influencing stand resistance [20,48].

Natural regeneration of Scots pine under the canopy of other tree species is relatively rare [21,22,46] because it is an extremely light-requiring species [24,50]. However, the current study found that it can successfully regenerate naturally under the canopy of a stand. Some studies suggest that Scots pine seedlings cannot survive under a dense canopy, while others have found that they can survive for about 20–25 or even 45–60 years [24,51].

The study area was characterised by a large number of saplings (from 609 to as much as 40.714 per ha, with an average of 7820 per ha). Under forest management in Poland, the standard number of pine trees selected as good trees in a coniferous forest habitat is 500–600 trees/ha [59], aged about 20–40 years, depending on the site valuation [60]. Therefore, considering the number of measured saplings, they are useful in further plans, as such a high density allows the best specimens to be selected for further breeding. Although healthy and well-developed trees dominated, a relatively large share of saplings with features of insufficient light availability is an indication to improve insufficient light conditions. An excessively long period of growth under unfavourable conditions may significantly reduce the value of this layer. Trees left for further cultivation should usually have a straight trunk, a narrow, symmetrical crown, and growing without the upper cover of the stand (these elements are largely shaped by the features of the cover stand and the degree of density of the saplings themselves). The good quality of the inventoried saplings does not mean that they will become a valuable component of the next generation.

The reaction of the trees to full access to light will be of great importance since stunted saplings that remain under a large upper cover can accelerate growth after thinning the cover stand [37].

High light availability is a key factor in the growth and survival of understory seedlings [61]. In the current study, the smallest saplings were recorded under the canopy of a stand with a tree planting factor of 0.7–0.8. Andrzejczyk [37] found that it is necessary to thin a stand to a planting factor value of 0.4–0.5 to obtain successful regeneration under a pine canopy. This corresponds to the current study results (the highest density of young pines was recorded at planting factor of 0.5–0.6). However, this may have been due to the increased development of the herbaceous layer or slowing (or even suppressing) the emergence of seedlings by limiting seed contact with mineral soil [62]. The sapling density also increased with an increase in the planting factor (0.9–1.0) in the examined plots. This increase was probably, because a moderately dense canopy in dry places prevents the upper soil layers from drying out [63,64]. However, competition with parent trees may be a limiting factor, especially in dry and poor habitats [65–69]. According to Andrzejczyk [55], the cover stand should be thinned relatively early and heavily in areas with low rainfall.

The increasing frequency of random phenomena such as hurricanes, pollution, and insect plagues often contributes to a reduction of stand density which, in turn, influences the shaping of optimal conditions for the formation of under-canopy regeneration [70]. The gap dynamics are closely related to natural regeneration methods [24,71–73]. Close-to-nature management uses canopy gaps [74–76] to stimulate the natural regeneration process. Naturation regeneration can serve as an alternative or supplement both to conventional large-scale management and gap regeneration. In forests with significant non-production functions it can be used to increase their structural variability and resistance [77,78]. A high coefficient of variation in sapling height (approx. 50%), especially with a diversified height structure, is characteristic of pine saplings growing under a canopy [79]. Trees in stands with a different height structure are characterised by thinner branching, greater wood density, and less convergence of trunks [80,81]. The possibility of including pine saplings in further breeding planning could reduce the frequency of complete felling in favour of shaping stands with a more diversified spatial structure, thus increasing their naturalness and shortening the regeneration time [26]. Stands with a diversified structure are generally more resistant and thus show a greater adaptive potential to changes in the environment [82]. The ability of these stands to regenerate after disturbances and damage caused by, e.g., strong winds or harmful insects, is also usually greater than that of stands with a simplified vertical structure [83]. The abandonment of schematic cuts creates a richer ecosystem and diversifies the spatial structure of the forest, increasing the attractiveness of a forest complex for performing social functions.

Initiating the under-canopy natural pine regeneration requires extensive knowledge and observation of the processes taking place in the forest environment. Understanding the dynamics, patterns, and factors determining the success or failure of regeneration is now essential knowledge in forest management [84]. One of the most important goals of natural forest cultivation is to create multi-layered, multi-century stands [18]. "Close to nature" forest management has recently been gaining increasing interest as a way to increase the resilience of forests and their ability to adapt to climate changes [85–90].

5. Conclusions

Using under-canopy natural pine regeneration is a technique in forest management to maintain an appropriate level of health and vitality of forest ecosystems. The principle of increasing the structural diversity of stands is the method of increasing the adaptability of forests to environmental changes.

Conducted research concerned the analysis of natural regeneration of Scots pine resulting from hurricane winds, as well as the role of seedlings in pine stands and the assessment of the growth potential of a given tree. Moreover, the use of young forest generation was analysed in order to optimize further breeding plans and to create stands with a diversified structure. An important aspect of the conducted analyses was also the search for alternative methods of pine regeneration in a changing climate, especially in strong wind.

As a result of the analyses conducted, it was found that more than 65% of the examined seedlings were considered of very good or good quality, promising for further development, without disease traits and mechanical and physiological damage. Among the tested seedlings, the most numerous were those of developmental category I, which indicates the possibility of using pine seedlings in breeding plans for the creation of future stands. The specific density of the shelterwood stand affected the density of seedlings, while the age of the surrounding stand positively affected the transition to older age classes and increased the number of seedlings for all developmental categories. The highest number of regenerating pine seedlings under the canopy was found in stands with a canopy cover index of 0.5–0.6, while the number of seedlings increased (to nearly 13.000 per ha) in older developmental stages. The analysed pine seedlings may be taken into account in further breeding plans and in the future shaping of the main stand. Spontaneously arising pine saplings may also help to diversify the stand structure, further increasing its stability and resistance to climate changes.

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