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THE EFFECT OF ALTERNATIVE THINNING REGIMES ON GROWTH AND STABILITY OF SCOTS PINE PLANTATIONS IN SOUTHERN FOREST-STEPPE IN UKRAINE

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Abstract

The effect of selective and combination (row + selective) thinning of varying intensities on mensuration characteristics, differentiation, and productivity of middle-aged plantations of Scots pine was studied in southern Forest-Steppe in Ukraine. The experiment on thinning by combination method in planted Scots pine (*Pinus sylvestris* L.) stands was established in 1967 in 16-year-old pine plantations. The plantations were created in 1950 by one-year seedlings with 1.5 × 0.7 m spacing. The initial density of the stands was 9.5 thousand stems per ha. The experiment included five variants of different thinning regimes: selective thinning of moderate intensity; combination thinning with removal of every 4th row; combination thinning with removal of every 3rd row; combination thinning with removal of every 2nd row; combination thinning with removal of every 4th row at 16 years followed by combination thinning of middle rows at the age of 23. Thereafter, up to 40 years of age, the plantations were thinned twice using selective thinning from below of low and moderate intensity – 24 % by the growing stock volume. During the thinning, the plantations were kept to a specified density. 64-years-old planted Scots pine stands with a density of about 650 stems·ha^{-1}, in which thinning was carried out by selective method of moderate intensity and by combination (row+ select thinning) method of moderate and high intensities (with complete removal of trees in every 2nd, or 3rd, or 4th row) at the age of 17 and the subsequent selective thinning of moderate intensity, are scarcely different in mensuration characteristics. The best method was the combination thinning with the removal of each 3rd or 4th row; the method can be recommended for practice, given the high mensuration characteristics, productivity, and resistance of the thinned stands against a physical load.

Key words: combination thinning, stand density, production, stand resistance.

Introduction

One of the main instruments by which foresters can affect the production and quality of stands is improvement thinning. This issue is the subject of many scientific papers (Sennov 1984, 2001; Anonimous 1987; Shinkarenko and Izyumskiy 1989; Shinkarenko 1990; Golovashchenko 1993; Manoylo 2006; Tarnopilska and

Ponomarev 2008; Ryabokon 2010). Economic, environmental and social aspects of forest cultivation encourage seeking biologically allowable limits for increasing the intensity of the specific thinning and extension of the thinning period. They stimulate the development of methods and means of trees selection for cutting and the determination of thinning impact on the productivity of plantations, as well as on the environment and the residual trees.

The analysis of the studies devoted to the methods of improvement thinning revealed quite contradictory ideas. As a result of the increased mechanization and a higher workload during the thinning, there is a tendency to increase the intensity of cutting and decrease the number of interventions (Hokajärvi 2007, Nilsson et al. 2010, Tkach et al. 2010). For the same reason, as well as to reduce the labor intensity and cost of work, the technology of improvement thinning, based on row and combination (row + selective) methods of thinning, has spread to many countries in Europe and America (Granskog and Anderson 1980, Mitchell and Gallagher 2007, Ishii et al. 2008, Barlow and Dubois 2011, Tkach et al. 2010). Row and combination thinnings are widely used in overstocked row plantations of pine and other coniferous and hardwood species (spruce, poplar, pure oak, etc.) (Karr et al. 1987, Baldwin et al. 1989, Harrington 2001, Ishii et al. 2008).

During row thinning, trees are removed from the stand in alternate rows, without removal of trees in the residual rows. The combination thinning is a combination of both row thinning and selective thinning: alternate rows are removed and at the same time, individual trees are selectively removed from the residual rows. It is essential to determine in advance the intensity of thinning, which provides the remaining trees with an optimal living space (Izyumskiy 1980, Intermediate Treatments 2015).

The application of a particular regime of combination thinning depends on the distance between rows, the number of stems per hectare (Schönau and Coetzee 1989), the site quality (Stiff and Stansfield 2004), and the stand age and condition. In poor sites, in older stands with wide rows and low plant liveability, and especially if the thinning was not timely, more rows should be left in a strip. A large space between rows contributes to increased machine productivity rate (Granskog and Anderson 1980) and lower fuel consumption per harvested area. Row cutting is cost-effective until a certain time, but it can become unprofitable if the spacing becomes high rectangular, because the unused living space is remained between the rows after cutting. The close within-row spacing required for a wide distance between rows can also complicate the removal within the left rows without damage to residual trees. Wider rows had no significant effect on survival, growth, timber production and stem quality of the stand at a rectangular spacing up to the 1:3 (Sharma et al. 2002, Amateis et al. 2004). However, a more rectangular spacing can promote the development of trees with large branches and wider crowns (Sharma et al. 2002, Amateis et al. 2004).

Usually, row thinning is more often used as the first thinning in the rotation. It is difficult to perform row thinning twice since the distance between the left rows will become too large over time for closing of crowns. Also, as a result of late row thinning in the rotation, too many valuable dominant trees of large diameter can be removed, which would be better left until the end of the rotation. Often, a row thinning is followed by a thinning from below.

In practice, various schemes are used to cut the rows. It has been found that in steppe pine forests growing in the Left Bank zone of Ukraine, in 4–6-year-old sparse plantations with a row spacing of 2 m or less, the most effective method is removing alternating rows, followed by disc ploughing in the formed 3-meter row spacing until canopy closure. Row thinning in 8–15-year-old Scots pine plantations in dry and fresh poor forest site conditions can be used to maximize mechanization of subsequent forestry operations. Therefore, at the age of 10–15 years in stands with a row spacing of 2 m or less, every 7th or 9th row was recommended to be removed, and the remaining 6–8-row strips should be thinned from below. This would allow mechanizing the log skidding and minimizing the manual skidding distance. The intensity of thinning of such strips should be 40–50 % by the number of trees (20–30 % by the growing stock volume), provided that up to 3.5 thousand trees remain on the hectare (Tkach et al. 2010). The strips should be wider in plantations with a larger distance between rows and in worse site conditions, especially in the case of late thinning.

In the Volyn region, Ukraine, row thinning has been used since 1967. During this time more than ten thinning patterns have been investigated. In 13–19-year-old pine plantations with 1.5–2 m spacing between rows, every 4th, or 6th, 7th, 8th or 11th row is harvested. With 1 m spacing between rows, two rows are removed: 10th and 11th or 12th and 13th. According to the first pattern, every 8th row (8th, 16th, 24th, etc.) is cut in the first felling (10–12 years) with simultaneous selective removing in the adjacent rows. During the second felling, every 4th row (4th, 12th, 20th, etc.) is removed and in the third, the remaining even rows (2nd, 6th, 10th, etc.) should be harvested.

In Western Polissya, Ukraine, in planted Scots pine stands with the inter-row spacing of 1.25–1.5 m, every 4th row is cut in the first stage, with simultaneous selective removing with up to 20 % intensity in the left rows; in the second intervention, every 2nd row is harvested. If the distance between the rows is 2 m, each 4th row is cut in the first felling, and only individual trees are selectively removed in left rows during next thinnings (Sviridenko 1974).

For sandy soils of the Voronezh region, removing every 3rd row is advisable and in the northern regions of Kazakhstan, every 5th row is (Atrokhin and Ievin 1985). In the dense 15–20-year-old Scots pine plantations with 1.5 m distance between the rows, it is recommended to leave two-row unfelled strips and in older stands, to create corridors in 2 stages (first, the 6th or 9th row is harvested, then the central rows are cut) (Izyumskiy 1980).

The most common is the harvesting of every 3rd, 4th or 5th row. With the removal of every 3rd, 4th or 5th row of trees, the sum of basal areas is reduced by 33, 25 or 20 %, respectively (Adams et al. 1994).

Row and combination regimes of thinning have an indisputable technological advantage over uniform thinning, as it maximizes mechanization and reduces the cost (Lemmien and Rudolph 1964).

Individual trees accumulate more photosynthates and grow faster after thinning. There was a less growth of smaller-sized trees if row thinning was used in place of selective thinning from below, but the degree of this effect varies depending on the species (Baldwin et al. 1989).

For southern pines, early row thinning can be an effective insect attack mitigating factor for species like southern pine beetle due to reducing the density of a plantation

(Nebeker and Hodges 1983, Burkhart et al. 1986).

Row and combination methods of thinning have some silvicultural limitations, as follows: applicability only in dense plantations, limited selection of trees for growing, turf formation in the wide (3–4-meter) corridors, as well as branch spreading and *Aradus cinnamomeus* and *Melolontha* colonization (Izyumskiy 1980). Row and combination thinnings result in a removal of dominant trees and in a smaller increment as compared to selective thinning. They promote the growth primarily of smaller trees (Intermediate Treatments 2015). Intensive combination thinning of coniferous crops is recommended to be performed only up to 15 years (Varfolomeev 1983, Intermediate Treatments 2015). This is due to the fact that row and combination thinnings are not always beneficial. For example, intensive row thinning with the removal of every 4th, 3rd or 2nd row in overstocked pine forests in Polissya, Ukraine, can cause annosum root rot infection (Kiselevskiy et al. 1983). In the Voronezh region and in Poland, the removal of every 3rd or 4th row increased ice damage to plantations, and the diameter of the trees shifted towards the smaller ones (Fler 1974, Izyumskiy 1978, Galleger 1987).

During row and combination thinning, heavy equipment is used, which is moved through a significant part of the plantation area. For example, if cutting every 3rd row, this area can reach 40 %, making furrows on an area of up to 15 % if the thinning is performed on soft soil in wet weather (Karr et al. 1987).

Despite the deep and comprehensive knowledge of problems of thinning of pine stands planted in forest-steppe, several important issues are not investigated, including the impact of different regimes of intensive thinning on the growth and productivity of the stands.

Solving these problems will help to grow efficiently the high-yielding and resistant pine plantations, which will meet not only national economic requirements but also environmental ones. Scientific substantiation of methods, frequency, and intensity of thinning requires multi-year research, preferably on an experimental basis, the lifetime of which is comparable with the tending period (Fleming 1999, Sennov 2001). Such long-term observations will help to improve existing methods of forest cultivation and developing new ones, as well as modifying the existing regulations on thinning.

Therefore, the accumulation of experimental data on the basis of long-term experiments on thinning in different forest site conditions is necessary for scientific programming and simulation of stands development.

The aim of the study is to analyse and compare the peculiarities of formation of middle-aged artificial pine stands depending on the thinning of varying intensity conducted by row and combination methods.

Materials and Methods

The research area is located in the southern part of the Left-bank Forest-Steppe in Ukraine. According to the physiographic zoning, the research area is within the boundaries of the Kharkiv forest-steppe region of the western slopes of the Central Russian Upland of the Central Russian forest-steppe province of the Forest-Steppe Zone (Marinich et al. 1985).

The climate of the research area is moderately continental (A = (27–32) °C; T = (84–104) °C; W = (2.0–0.6) (Dubinskiy et al. 1971), where: A is an indicator of climate continentality, the algebraic difference between the mean temperature (°C) of the warmest (July) and coldest (January) months of the year; T is the sum of mean monthly positive temperatures (°C); W is the index of humidity, which is calculated according to the formula (1).

$$W = (R/T) - 0.0286 \cdot T \quad (1),$$

where: R is the total of the monthly precipitations for the months with a mean temperature above 0°C) (Lavrinenko 1972).

According to long-term data (Marinich et al. 1985), the mean air temperature in January is -8 °C, in July is +20 °C; the mean annual air temperature is about +6 °C. The winter period begins in mid-November. The period with a temperature below 0 °C lasts for about 135 days in the north-eastern part of the region. Weather conditions in winter tend to be mainly cloudy. The frost-free period lasts 155–160 days; the period with the mean daily temperature of above 5 °C is 195–200 days, above 10 °C – 155–160 days, above 15 °C – 110–115 days.

The mean annual rainfall is 538 mm, with one maximum in July and one minimum in February. Fluctuations of the annual values are quite significant – 340–880 mm. This is due to the drought typical for the studied region.

The territory of the Kharkiv region includes a number of rugged tablelands and small uplands, separated by deep and wide ravines cut into cretaceous rocks, and sometimes by gullies with slopes facing mainly southwest and southeast (Marinich et al. 1985).

In the region of the study, sod-podzolic soils (Placic Podzols) had been formed under pine forests on sandy terraces. Typically, such soils are formed at medium groundwater depth, and coniferous or mixed forests grow on them.

The forest-steppe was formed as a primary type of landscape with two equivalent types of vegetation, forest and steppe one.

Forest vegetation is represented by deciduous forests, the main areas of which are concentrated on a deeply rugged relief along the valley sides of rivers, and coniferous and mixed forests associated with sandy terraces (Alekseenko 1971).

During the fieldwork, mapping of sample plots and trees allocation, as well as dendrometric measurements (diameter at breast height D, height of a tree H, height to the first live branch, and diameter and projection area of a crown), were conducted using Field-Map technology developed by the specialists of the Institute of Forest Ecosystem Research (IFER, Czech Republic) (Field-Map 2018). Field-Map is a proprietary integrated tool designed for programmatic field data collection and management. It integrates various models of field computers, GPS, electronic compasses, laser rangefinders and inclinometers, electronic calipers and other advanced tools. The software combines a geographic information system (GIS) and a database management system (DBMS). The degree of differentiation of trees in plantations was estimated using the following Kraft's classification (Avery and Burkhart 2002) based on a tree's social position in the stand and its crown development: 1st class – predominant trees; their crowns extend above the general level of the canopy; they have the largest, fullest crowns in the stand and thicker trunks; 2nd – dominant trees; their crowns make up the general level of the canopy; generally, they are shorter than the predominant trees and have straight trunks; 3rd – subdominant trees; they have the same height as the dominant trees but are relatively weakly developed and restricted often with other trees, there are some signs of suppression; 4th – supressed trees, with crowns restricted on all sides or on two sides, or with one sided development; 5th class – dying and dead trees. Stands resistance against damage by the wind, glaze storm and sleet was assessed by the value of the relative height of plantations − the ratio of the mean height (*H*, cm) to the mean diameter (*D*, cm) − *H*/*D* (Medvedev 1910). The limit value of *H*/*D* of mean trees in the stand, indicating the resistance of the stand against the above-noted factors, is from 80 to 110 according to different sources (Franz 1983, Prien et al. 1985, Anonimous 1987, Shinkarenko 1990, Golovashchenko 1993, Manoylo 2006).

The diameters of trees were measured at a breast height (1.3 m) within the accuracy of 0.1 cm. The mean diameter was calculated using the mean cross-sectional area of trunks. The height of trunks in the field conditions was determined for 35 to 50 trees on each of the sample plots. The mean height was estimated according to the height curve, depending on the diameter of the given stand, which corresponds to the mean diameter of the trunks. Total basal area was determined according to the tables (Strochinsky et al. 2007). The total timber volume per hectare was estimated according to Strochinsky's tables (Strochinsky et al. 2007) for mensuration of young and middle-aged stands.

Processing and analysis of the results were carried out according to common methods of variation statistics (Baginskiy and Lapitskaya 2017). To characterize a homogeneous statistical population, the following values were calculated according to standard formulas: the mean statistical parameters for diameters and heights of the trees and for projected areas of their crowns (arithmetic mean (x), median (*Me*), mode (*Mo*)), their variation characteristics (minimal (min) and maximal (max) variants, sample variance (S_x^2), standard deviation (σ), sampling mean error (S_x), variation coefficient (C_v, %)), as well as skewness and steepness indices of the distribution curve (asymmetry (*As*) and excess (*Ex*)).

When comparing the arithmetic means, the null hypothesis testing was made: the arithmetic means of the general populations, from which the data samples were taken, did not differ by the Student's *t*-test (Fay and Gerow 2013).

If $t_{real} \geq t_{table}$, then the null hypothesis is rejected at the accepted significance level *p*; the difference between sample means is considered statistically significant. At $t_{real} < t_{table}$ the difference between sample means is not proven.

Experiments on improvement thinning in artificial Scots pine (*Pinus sylvestris* L.) stands were launched by Prof. P. Izyumskiy in Pivdenne Forestry (compartment 155) in 1966 and 1967 in 16-year-old pine plantations. The plantations were established in 1950 by one-year plantings after continuous tilling with the spacing of 1.5 × 0.7 m. The initial planting density was 9,523 stems·ha^{-1}. The type of site conditions was a fresh fairly fertile forest. The soil was soddy eluviated one on warp sands (Humic Podzol).

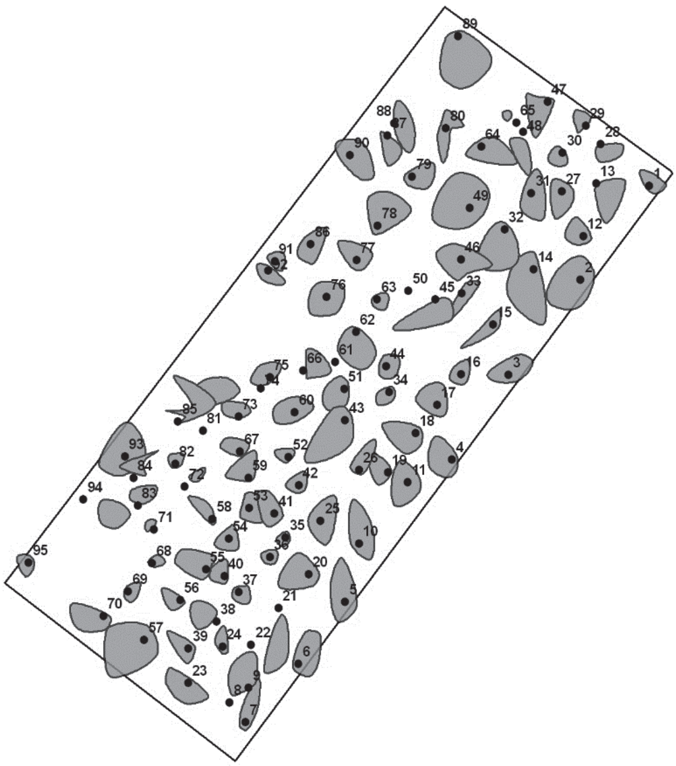
At the time of the experiment beginning, the plantation was a young dense stand having a mean height of 9.2 meters, a diameter of 9.6 cm, and growing stock of 182 m^3·ha^{-1}.

The experiment included six sections with different thinning regimes: Sections B and B-2 represented thinning of moderate intensity (controls); Section III − completely removed trees in every 4th row, and remaining stand was thinned in a moderate intensity; Section II − completely removed trees in every 3rd row, and remaining stand was thinned in a moderate intensity; Section I represented completely removed trees in every 2nd row, and remaining stand was thinned in a moderate intensity; Section IV were completely removed trees in the middle rows of three-row unfelled strips at a half of section III at the age of 23 years (Fig. 1).

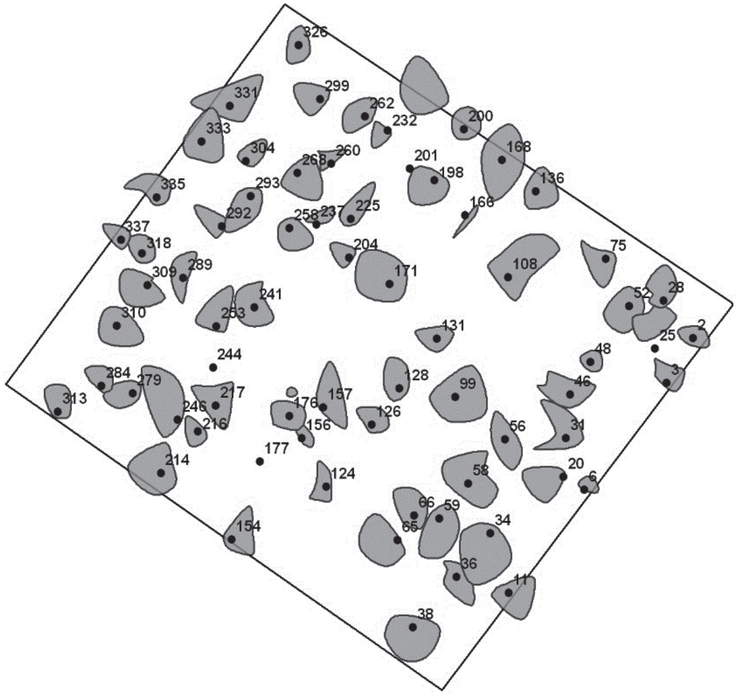
In the stands with row thinning at the Sections III, II, and I, in 1976 there was thinning from below of the low intensity: the removal of 1−7 % by the growing stock volume. In the sections with selective thinning (B and B-2), thinning of moderate intensity (11−24 % by the growing stock volume) was conducted in 1979.

In this experiment, the research was carried out in the stands aged 36, 40 and 56 years (Shinkarenko and Izyumskiy 1989, Shinkarenko and Tarnopilska 1993, Tarnopilska and Ponomarev 2008).

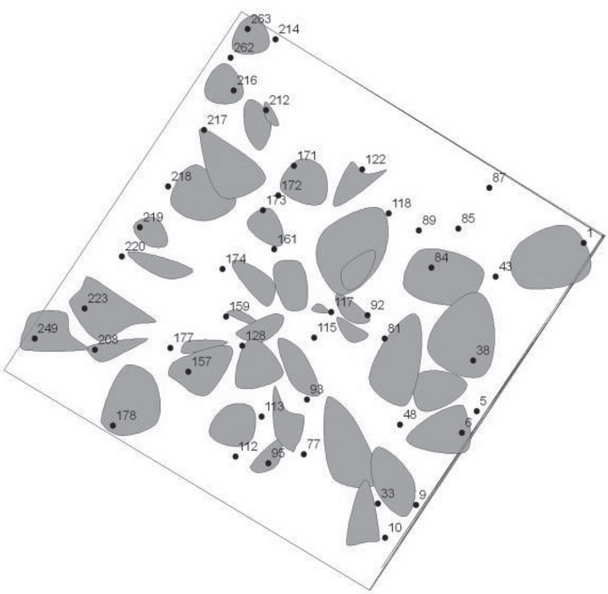
In 1990, 40-year-old stands of all sections were thinned with low and moderate intensity (6−17 % by the growing stock volume) with leaving stands of specified density on the plots, mostly 1,000 stems·ha^{-1} (Table 1).



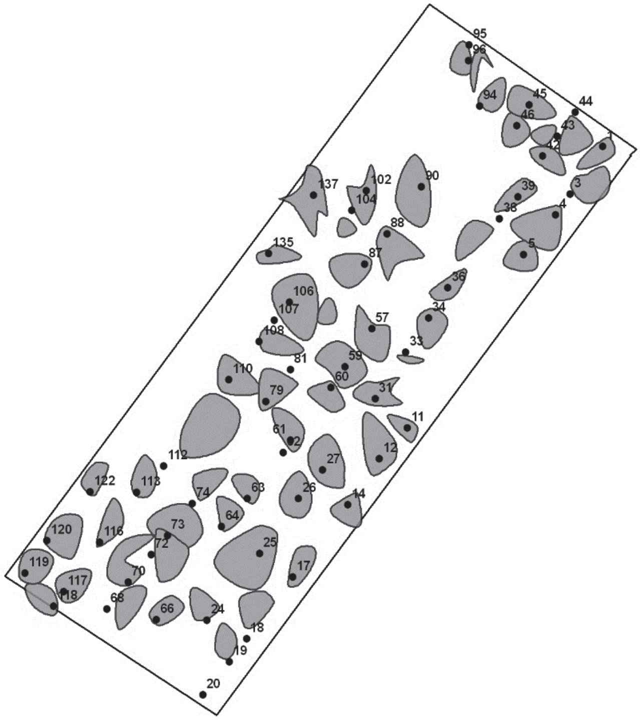
a) Section B-2, *N* = 900 stems·ha^{-1}



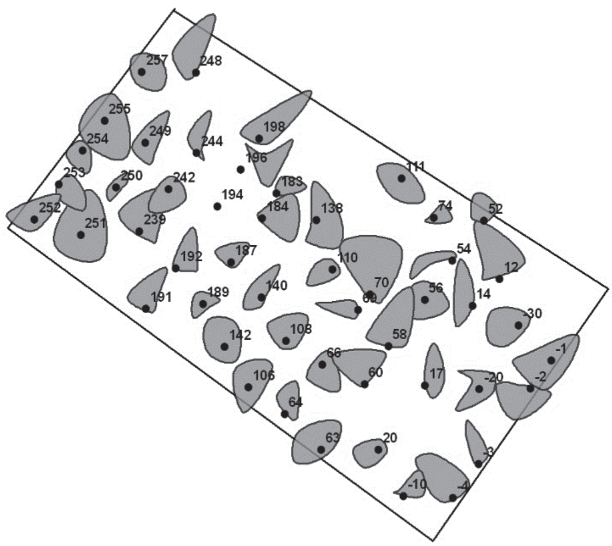
b) Section B, N = 640 stems·ha^{-1}



c) Section III, N = 875 stems·ha^{-1}



d) Section I, *N* = 656 stems·ha^{-1}



e) Section IV, *N* = 681 stems·ha^{-1}

Fig. 1. (a–e) Cartograms of the location of trees and projections of their crowns in 64-year-old pine plantations in the experiment on row and combination thinning (Pivdenne Forestry, compartment 155).

Table 1. Mensuration characteristics of 40-year-old pine plantations before and after the thinning (Danylivskyy Experimental Forest Economy, Pivdenne Forestry, compartment 155).

Characteristic	Section					
	B-2	B	III	II	I	IV
Before the thinning in 1990						
Density N, stems·ha^{-1}	2056	1920	2083	1181	1267	1236
Mean diameter D, cm	–	17.1	16.4	20.2	19.9	17.5
Mean height H, m	–	20.0	20.6	21.0	20.7	20.1
Growing stock, m^3·ha^{-1}	–	407	418	355	364	266
Thinned in 1990; age of the plantations is 40 years						
Density N, %	24.9	22.9	33.0	16.2	19.3	32.6
Growing stock, %	12.0	12.3	14.8	5.9	6.6	15.8
Left after the thinning in 1990; age of the plantations is 40 years						
Density N, stems·ha^{-1}	1544	1480	1396	990	1022	833
Mean diameter D, cm	18.6	18.2	18.6	21.1	21.1	19.2
Mean height H, m	20.7	20.5	21.2	21.2	21.2	20.7
Basal area, m^2·ha^{-1}	41	39	37	35	36	24
Growing stock, m^3·ha^{-1}	379	357	351	332	338	224

During the thinning both by selective and combination methods, attention had been given to the cutting the stands to a specified density. In the selection of trees that should be left for further growth, the "thinning by quality" principle had always been followed. Defective or diseased trees or specimens with thick branches were removed around high-quality trees. The preference had been made to the best trees, even if it would break the evenness of tree spacing in the area.

Results

After thinning in 1990, the density of 40-year-old stands in the experimental variants ranged from 833 to 1,544 stems·ha^{-1}. Note that growing stock volumes of the stands, the density of which varied within 990−1,544 stems·ha^{-1}, were similar (M = 332−379 m^3 per ha), and the difference between them was insignificant and did not exceed 12 %. The most thinned stand (N = 833 stems·ha^{-1}) of the variant with the combination thinning of high intensity (Section IV) had a somewhat smaller growing stock (224 m^3 per ha).

64-years-old pine stands had a high productivity (Table 2). In the variants, the stand density ranged from 900 to 640 stems·ha^{-1}, the mean diameter was 23.4−26.3 cm; the mean height was 25.5–26.8 m.

The density of the stand in the variant of moderate intensity thinning at a young age (Section B-2) was the largest; it was the lowest in the variant of thinning of high intensity (Section I). The mean diameter (23.4 cm) of the densest stand with a selective thinning of moderate intensity (Section B-2) was significantly lower compared to the variants of combination thinning of high and very high intensities (Sections I and II) (tables 2 and 3, Fig. 2).

Table 2. Mensuration characteristics of 64-year-old planted stands of Scots pine in the thinning experiment.

Kraft class	Density		Mean diameter D, cm	Mean height H, m	Basal area, $m^2 \cdot ha^{-1}$	Growing stock, $m^3 \cdot ha^{-1}$
	stems per ha	%				
1st	700	77.8	24.5	26.3	33	371
2nd	178	19.8	19.9	25.9	6	63
3rd	22	2.4	19.9	25.0	1	8
Total	900	100.0	23.4	26.2	40	442
1st	570	89.1	26.0	26.6	30	352
2nd	70	10.9	20.5	25.0	2	26
Total	640	100.0	25.5	26.5	33	378
1st	250	28.6	27.9	26.6	15	174
2nd	438	50.1	25.5	26.0	22	250
3rd	83	9.5	25.0	25.8	4	46
4th	63	7.2	20.2	24.3	2	21
5th	42	4.8	16.0	22.6	1	8
Total	875	100.0	25.5	26.0	44	499
1st	295	43.0	27.0	27.0	17	196
2nd	305	44.5	24.5	27.0	14	166
3rd	76	11.1	22.0	26.9	3	34
4th	10	1.5	24.0	26.5	0	5
Total	686	100.0	25.3	26.8	35	401
1st	533	81.3	27.2	26.4	31	350
2nd	89	13.6	21.4	24.8	3	35
3rd	33	5.0	20.2	24.5	1	11
Total	656	100.0	26.3	26.2	35	396
1st	208	30.5	27.7	26.3	12	141
2nd	181	26.6	27.4	26.2	11	119
3rd	139	20.4	22.9	24.9	6	62
4th	56	8.2	21.1	24.2	2	21
5th	97	14.2	17.1	22.6	2	23
Total	681	100.0	24.8	25.5	33	366

Table 3. The value of the actual Student's *t*-test for mean diameters of 64-year-old Scots pine plantations in different sections of the thinning experiment

Section	B-2	I	II	III	IV
I	3.52	–	–	–	–
II	2.97	0.76	–	–	–
III	0.76	1.00	0.33	–	–
IV	1.56	1.78	1.21	0.69	–
B	3.32	0.29	0.47	1.90	1.56

Note: t_{theor} = 1.96; P = 0.05.

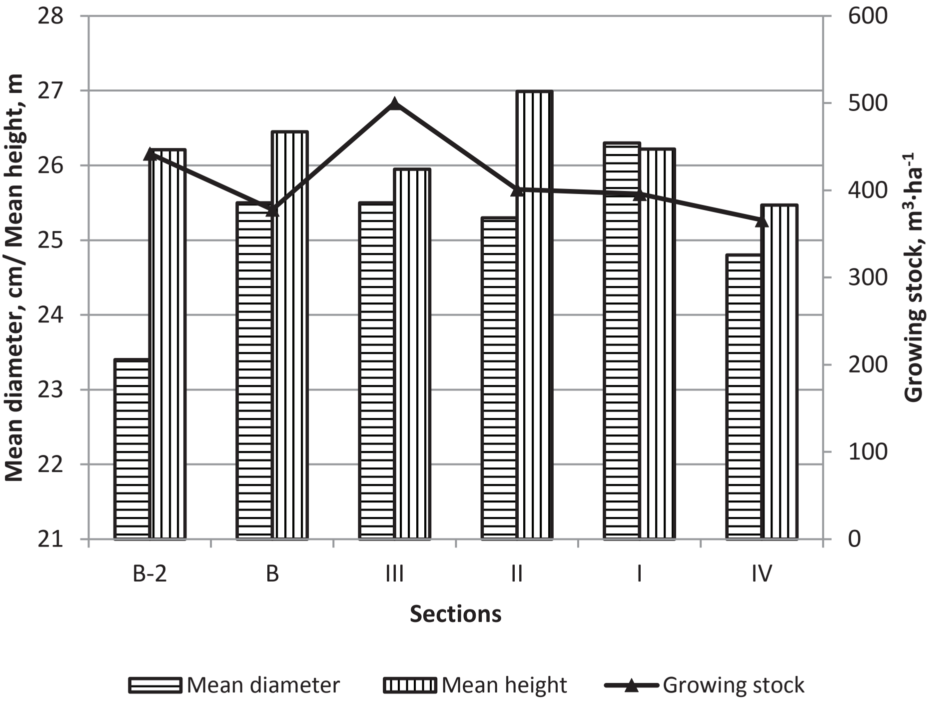


Fig. 2. Distribution of growing stock volume, mean diameter and mean height in 64-year-old planted stand of Scots pine by thinning regimes.

Let us consider the parameters of crowns and canopy of the plantations as an important component of the stand structure. The mean tree crown projections in 64-year-old plantations in different experimental variants ranged from 3.2 to 4.9 m^2 (Table 4). The mean crown projection in variants with selective thinning of moderate intensity (Section B-2) was the smallest (3.2 m^2) (Table 4, Fig. 3). It was significantly lower than crown projections in other variants (Table 4, Fig. 3). At Section B-2, due to the considerable density of the stand (900 stems·ha^{-1}), the crown projection area was smaller compared to the Section B, where the number of trees per hectare was 640. The variants with selective and combination regimes of thinning (Sections B, I, II, III, IV) did not differ in mean crown projections. Here, the mean crown projection area was in the range of 4.1−4.9 m^2 (Table 4, Fig. 3).

Table 4. The value of the actual Student's *t*-test for the mean crown projection areas in 64-year-old Scots pine plantations in the thinning experiment

Section	B	B-2	I	II	III
B-2	2.50	–	–	–	–
I	-1.57	-4.01	–	–	–
II	1.97	-2.36	0.36	–	–
III	-0.94	-2.93	0.31	1.50	–
IV	-1.75	-4.07	-0.25	1.76	0.50

Note: t_{theor} = 1.96; P = 0.05.

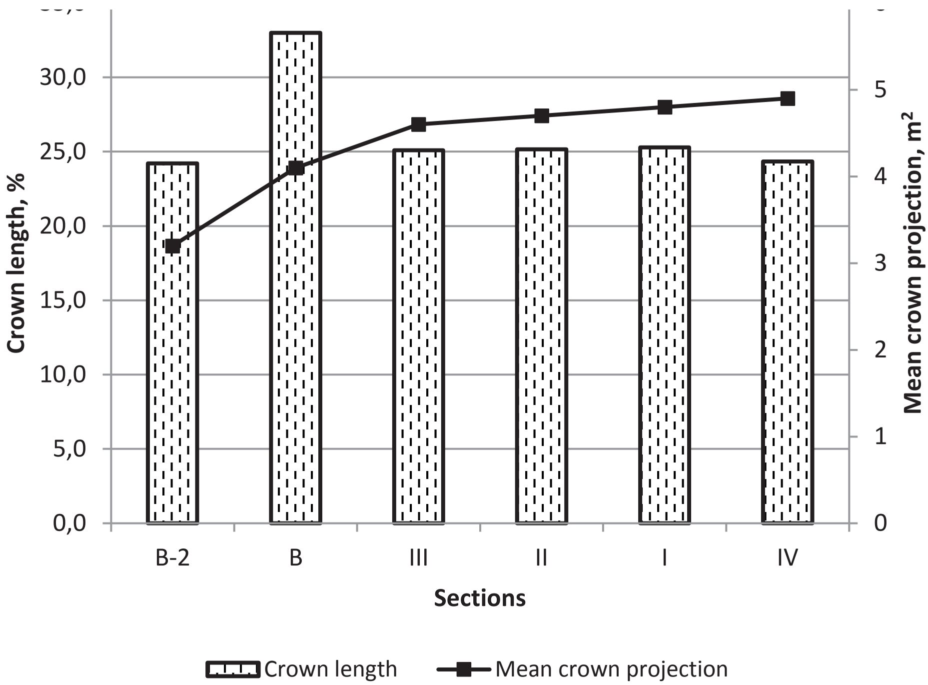


Fig. 3. The length of crowns and the mean crown projection for Scots pine by the thinning regimes.

Discussion

The analysis of the influence of different thinning regimes on the productivity of the plantations indicates that the growing stock depends on the stand density that is in accordance with the results of many researchers (Shinkarenko and Izyumskiy 1989, Sennov 2001, Intermediate Treatments 2015). Stands with highest density (about 900 stems·ha^{-1}) had the highest growing stock and largest total basal area. The best variants were Section III with the removal of every 4th row (the growing stock of the stand was 491 m^3 per ha and the basal area was 43 m^2 per ha) and Section B-2, i. e. the control with selective thinning (442 m^3 per ha and 40 m^2 per ha, respectively) (Table 1, Fig. 2). In this assessment, the combination thinning variant had the advantage in these indicators, although the difference between the best variants did not exceed 10 %. The plantation with the removal of every 4th row followed by thinning of middle rows in unfelled strips at the age of 23 (Section IV) had the lowest stock volume (343 m^3 per ha) and the least basal area (31 m^2 per ha). This variant was considerably exceeded in growing stock and basal area by the control (Section B-2) and the variant with every 4th row removed (Section III) – by almost 22 % and 30 %, respectively. The growing stock volumes and the basal areas of forest stands with a density of about 650 stems·ha^{-1} with combination thinning of every 3rd and 2nd rows (Sections II, I), as well as with selective thinning of moderate intensity (Section B) did not differ markedly. However, as many researchers have pointed out (Izyumskiy 1980, Schönau and Coetzee 1989, Tkach et al. 2010), a high density usually contributes to the greater productivity of plantations but, at the same time, to a decrease in the mean stem diameter and the mean area of crown projection within the stand, as each tree has less access to environmental resources. As a result, this leads to less cost effectiveness of the harvesting (Schönau and Coetzee 1989, Intermediate Treatments 2015). However, in the middle-aged plantations, nearly 50 years after the first thinning, not only the stand density but also the thinning regimes had affected the mean diameter. For example, a dense stand with selective thinning on the control (Section B-2) had a less mean diameter and a smaller crown projection (Table 1, figs 2 and 3). Such plantations need to be grown longer until the harvest is profitable (Intermediate Treatments 2015) due to the influence of the stand density on the diameter. Among combination thinning variants, the stand with the cutting of every 4th row and removal of middle rows in the left three-row strips 6 years after (Section IV) had a much smaller mean diameter (24.8 cm). Combination thinning of every 2nd row had the greatest impact on the mean diameter increase compared to other regimes (Table 2, Fig. 2). On the other hand, the difference between the mean diameters for plantations with every 4th and 3rd rows cut (Sections III, IV) and selective thinning of medium intensity (Section B) was not statistically significant (see Table 3). The plantations with a lower density despite a smaller total growing stock volume will be more cost-effective due to a larger mean diameter that is consistent with other studies (Schönau and Coetzee 1989, Shinkarenko and Izyumskiy 1989, Sennov 2001). These plantations can be thinned earlier because they reach the minimum required diameter more quickly since each tree has access to more site resources (Schönau and Coetzee 1989, Shinkarenko and Izyumskiy 1989, Sennov 2001).

Let's intercompare the variants of plantations with different regimes of initial density or thinning but with close values of the current density. Stands having the density of about 650 stems·ha^{-1} in variants with selective thinning of moderate intensity (Section B) and combination thinning with every 2nd row removal (Section I), every 3rd row removal (Section II) and every 4th row removal followed by cutting middle rows in three-row unfelled strips (Section IV) did not significantly differ in mean diameter, mean height, and growing stock. The difference in mean diameter and growing stock between the variants with selective thinning (Section B-2) and combination thinning with a removal of every 4th row (Section III) having the current density of about 900 stems·ha^{-1} was not significant.

Since at row thinning the trees are removed randomly, based on their spacing in the plantation, as a result, the mean stand diameter does not change (Intermediate Treatments 2015). For example, 33 % of small trees, 33 % of medium and 33 % of large ones are removed during the cutting every 3rd row. Thus, the ratio between the mean diameter of the removed trees and the mean diameter of the stand before cutting will always be equal to 1.00 for any row thinning. The stand density and the basal area will decrease in the same proportion as the number of cut trees will. For example, there were 450 trees per acre (1,111 stems·ha^{-1}) in the stand before thinning and the basal area was 11.15 m² per acre (27.55 m^2 per hectare). After removing every 3rd row in the stand, there will be

300 trees per acre (741 stems·ha^{-1}), and the basal area will amount to 7.43 m² per acre (18.4 m^2 per hectare) (Intermediate Treatments 2015).

Basal area is a common measure of stand density used to prescribe the intensity of thinning in the countries of Europe and the USA (Hokajärvi 2007, Nilsson et al. 2010, Intermediate Treatments 2015). For Loblolly pine (*Pinus taeda* L.) plantations, the stands are commonly thinned when they reach the basal area of 9.3–11.1 m² per acre (23.0–27.4 m^2 per hectare) or more (Intermediate Treatments 2015). Basal area is usually reduced to 6.57.4 m² per acre (up to 16.1–18.3 m^2·ha^{-1}) at each thinning. The targeting basal areas vary depending on the species, region, and objectives (Dickens and Moorhead 2015, Intermediate Treatments 2015).

Taking into account the high values of basal areas of the stands (33–45 m^2·ha^{-1}), as well as the presence of suppressed (4th Kraft class) and dead (5th Kraft class) trees, another improvement selective thinning should be carried out in the experimental sections. The intensity of the thinning should be moderate (up to 11–25 % by growing stock volume) or strong (26–30 % by growing stock volume). Such treatment will promote growth conditions for a high-quality part of the tree stand, as well as fast reaching the economically desirable tree size and income generation.

The stands thinned both by selective and combination methods were not significantly different in the mean height (Table 2, Fig. 2).

The combination method of thinning provides more site resources and living space to the residual trees not only between the rows but also within the rows, contributing to the formation of trees with spreading crowns (Fig. 3). This is consistent with the data of other authors (Izyumskiy 1978, Medhurst and Beadle 2001, Intermediate Treatments 2015). The variant of selective thinning of medium intensity had the largest crown length – 33 % of the bole height. In other variants, this value was about 25 % of the bole height (Fig. 3).

The purpose of thinning is the formation of high-quality and productive stand. The productivity is determined by a selection of the best trees that will be the basis of the stand price at the age of the final felling, which is emphasized by other researchers (Zasady hodowli lasu 2012). There are a number of requirements for the best trees to be selected. The trees must 20–30 % exceed the average tree in height and have straight full-boled stems, developed dense crowns and a good height increment. In addition, the uniform spacing of the best trees in the stand is desirable. The number of best trees to be selected is determined by the age of the stands and the forest site type. Our opinion on this issue is in line with the practice of selecting the best trees in Poland (Zasady hodowli lasu 2012). At the thinning stage, 500–600 best pine trees per hectare should be selected in poor sites and up to 300–400 trees per hectare in the rich ones. The trees can be selected also during the thinning in older stands (over 40 years) but their number should be less than during earlier thinning. For example, their number should be in the range of 350–400 stems·ha^{-1} in pine stands growing in poor forest sites and 250–350 stems·ha^{-1} in the rich sites, as in our case.

The dominant part of the stands of each variant accounts for over 50 % of all trees both by the number and growing stock (see Table 2). As the density of the stand increases, the proportion of trees of 1st and 2nd Kraft classes decreases.

The mean diameter and the mean

height in the dominant part (trees of the 1st and 2nd Kraft classes) of the stands, in which combination thinning had been conducted, were somewhat larger than those of stands with selective thinning (Fig. 4). The trees of 1st and 2nd Kraft classes in the variant with cutting out every 4th row and at the age of 23, with the removal of the middle rows in the three-row strips (Section IV) had a significantly larger mean diameter in comparison with the variant of selective thinning (Section B). The densest stand on the control (Section B-2) had a considerably smaller mean diameter of this part of the plantation as compared to all other variants ($t_{emp0.05}$ = 3.15…5.23, $t_{theor0.05}$ = 1.98). The differences between the diameters of the dominant part of the stands were not statistically significant for all combination thinning variants ($t_{emp0.05}$ = 0.30…1.87, $t_{theor0.05}$ = 1.98) (Table 2, Fig. 4).

The value of the relative height (*H*/*D* < 110) indicates insignificant degree of mutual suppression of trees in all sections.

The value of *H*/*D* mainly did not exceed 105 and indicates the resistance of the stands against the physical load. *H*/*D* value accounted for 113 only in the densest plantation of Section B and is indicative of trees' damage (Fig. 5).

The extreme limit of the *H*/*D* ratio is 126, according to Medvedev (1910). Our data, however, show that it is underestimated and may reach a larger value in planted stands than Medvedev's value indicated for natural forests. The relative height in the dominant part of the stands was much lower than in the dominated one in all variants. This confirms the correctness of Medvedev's statement

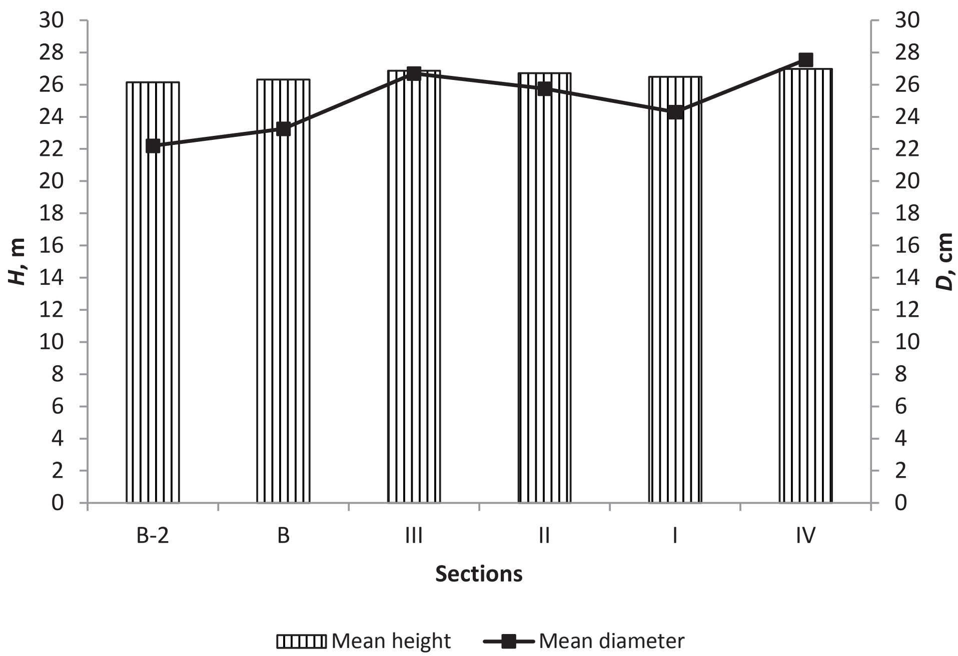


Fig. 4. Mensuration indices of the dominant part of the stands (trees of 1st and 2nd Kraft classes).

that *H*/*D* is a good indicator of tree suppression degree. At the same time, for the dominant part of the plantations with a higher density, especially for the trees of the 2nd Kraft class, the value of relative height has revealed a rather high degree of their suppression (see Fig. 5).

In our case, the storm in 1998 damaged significantly 48-years-old pine plantations of the experiment, causing a wind breakage and windfall. The results of the investigation indicated that the share of broken and blown down trees ranged from 1.4 to 22.2 % in different variants. The majority of the damaged trees in all variants belonged to the dominating 1st and 2nd Kraft classes (*H*/*D* > 110) as they overtopped the main stand canopy level. Their mean diameters varied in the range of 16.0−26.5 cm and the mean height, 23.6−25.6 cm. The amount of wind-damaged trees decreased with the increase of the stand density. This relationship was confirmed by statistically significant high coefficients of correlation r = 0.90 (t = -4.14 at p < 0.05) and determination r^2 = 0.81. However, we should note that windfall broken trees occurred mainly in the variant with the removal of each 2nd row (Section I). On the contrary, trees in the variants with the removal of every 4th row (Section III), every 3rd row (Section II) and every 4th row followed by cutting of middle rows in three-row unfelled strips (Section IV) remained undamaged. In these variants, the stand density ranged from 1,396 to 833 stems·ha^{-1} after thinning in 1990. Therefore, one can assume that the intensity and the nature of the damage depended not only on the strength and direction of the wind but also on the particular location of the sample plots towards the wind and on the structure of the stands. Analysis of the data on heavy

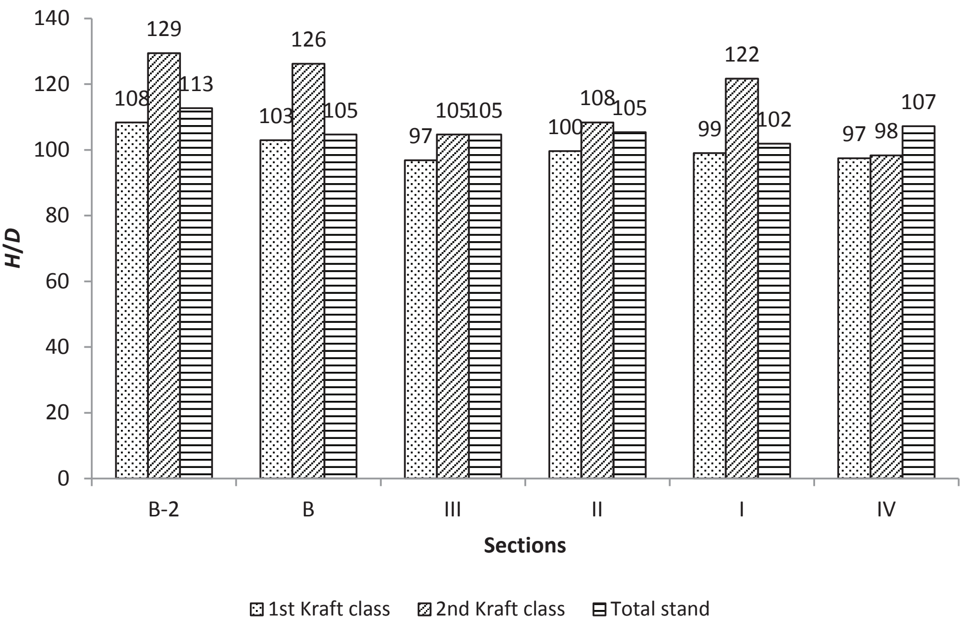


Fig. 5. Relative heights of forest stands and their dominant parts (trees of 1st and 2nd Kraft classes).

wind impact on the investigated stands allows asserting that in fresh fairly fertile forest site, the risk of wind damage to middle-aged pine stands increases with decreasing the stands' density and increasing the intensity of thinning, especially immediately after the thinning. This is due to the increase of crown opening and of wind load on the canopy and decrease of the protective effects of the surrounding trees. The best tall trees, which rise above the main stand canopy, are the most exposed to windfalls. For this reason, combination thinning with the removing every 2nd row in rich forest sites involves a certain risk of a windfall. On the other hand, the thinning may improve the stand stability due to long-term effects on growth and development of trees withstanding high winds.

The results of the experiment on combination thinning showed that the intensive cleaning by combination method with the removing of every 4th, 3rd, and 2nd row in planted pine stands in rich forest sites at the age of 15–18, followed by selective thinning of medium intensity 48 years after cutting, does not lead to a reduction in available growing stock compared to selective methods of thinning.

Thus, high mensuration characteristics and a significant number of dominant trees in the middle-aged artificial Scots pine plantations formed under the influence of thinning by combination method of moderate and high intensity indicate the possibility of use of such regime of improvement thinning in planted Scots pine stands up to 20 years of age, taking into account the simplicity of the technology and its economic benefits.

The results of our experiment also showed that in case of one intensive cleaning the second thinning is not necessary to be carried out in planted stands.

It is proposed to use the relative height (*H*/*D*) in the dominant part of the stand (trees of the 1st and the 2nd Kraft classes) when planning the intensity of late cleaning and thinning. Thinning of high and very high intensity can lead to an irreversible decrease in resistance and productivity of the stands if the relative height is above 110.

Conclusions

64-years-old planted Scots pine stands with the density of 650 stems·ha^{-1}, in which thinning was carried out by selective method of moderate intensity and by combination method of moderate and high intensities (with complete removal of trees in every 2nd, or 3rd, or 4th row), as well as the following selective thinning of moderate intensity, are scarcely different in mensuration characteristics.

The first thinning in planted Scots pine stands growing in the Ukrainian Left-bank Forest-Steppe in rich forest sites can be carried out up to 20 years of age by a combination method of moderate and high intensity with a complete removal of trees in every 3rd or 4th row. The combination thinning with the removal of every 3rd or 4th row is the best method that can be recommended to use in practice, taking into account high mensuration values, productivity, and resistance of the thinned stands to a physical load.

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