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Conversion of low-value stands by corridor method in Left-Bank Forest-Steppe, Ukraine

Mykola Vedmid[1], *Volodymyr Luk'yanets*[2], *Oksana Tarnopilska*[2], *Maksym Rumiantsev*[2], *Oleksii Kobets*[2], *Iryna Obolonyk*[2] ✉, *Svitlana Pozniakova*[1], *Sergiy Musienko*[2]

[1] State Biotechnological University, Kharkiv, Ukraine

[2] Ukrainian Research Institute of Forestry and Forest Melioration named after G. M. Vysotsky, Kharkiv, Ukraine, phone: +380503008864, e-mail: obolonik@uriffm.org.ua

Abstract

The aim of the study was to identify the influence of different widths and cardinal directions of felled corridors on the condition and mensuration characteristics of the English oak trees planted there during the conversion of low-value young stands using the corridor method. The study was carried out in oak forests in the forest-steppe zone at a permanent sample plot. The experiment included the conversion of a low-value 8-year-old stand to improve its species composition. The sample plots were laid out in a fertile hardwood forest site. The conversion was realised by felling corridors of various widths (6, 9 and 12 m) and directions and planting English oak trees (*Quercus robur* L.) within them in rows. For the planted oaks, tending felling was carried out three times: weeding (8 years), cleaning (13 years) and thinning (32 years). A comparative analysis of mensuration characteristics (average height, diameter, growing stock, radial increment, health condition, etc.) was carried out for 32-year-old oak trees grown in the corridors and a part of a low-value stand in the unfelled strips after the tending felling. It was found that the average height and diameter at breast height of oaks in the 6, 9 and 12 m wide corridors of different cardinal directions did not differ significantly. The difference in oak stocks within 6 and 9 m wide corridors of different cardinal directions was also insignificant. The stock differences were statistically significant for 6 and 12 m wide corridors as well as for 9 and 12 m wide ones. The article made recommendations on the width of felled corridors and unfelled strips to effectively convert low-value young stands by the corridor method.

Key words

corridor direction, felled corridor width, *Quercus robur* L., stand diameter, stand health condition, stand height, unfelled strips

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Introduction

Low-value stands arise in large areas after clear felling of indigenous stands or as a result of other anthropogenic and natural impacts. They include planted and natural stands, the composition and structure of which do not allow to grow highly productive and resistant stands in certain ecological conditions (Gvozdev 2017; Vedmid et al. 2019).

The total area of low-value oak forests in left-bank Ukraine is over 360,000 ha or 70% of the forests growing in fertile hardwood site type. In particular, the area of low-value stands within the Ukrainian Left-Bank Forest-Steppe is 51,300 ha (Vedmid et al. 2019). Such stands usually have low yield; they are often overstocked and weakened, and therefore susceptible to damage by pests and diseases. So, they are not sufficiently effective in their protective role.

Increasing the productivity of low-value forests, changing their species composition, improving their timber quality, as well as enhancing water conservation and soil protection functions of forests can be achieved through the conversion of such stands. In Ukraine, the issues of low-value stand conversion began to be actively addressed in the 1950s (Havrylenko et al. 1993; Vedmid and Ugarov 1993; Vedmid 2001; Vedmid et al. 2008; Brodovich et al. 2014; Levchenko 2018).

In different European and American countries, the conversion of low-value stands is interpreted differently. Some authors, including us, consider it as a set of forestry interventions aimed at basic changes in the composition and structure of low-value young stands to obtain more valuable ones that correspond to forest site conditions. Such changes are made by introducing missing main species into low-value stands (Pavlenko 1967; Izyumsky 1978; Krachkovsky 2014). Others meant a set of measures to transform even-aged single-layer stands into uneven-aged multilayer ones (Loewenstein 2005; Kerr et al. 2010; Dupont-Leduc et al. 2020; Schneider et al. 2021). Still others identified the conversion as an improvement of the stand resilience by introducing other valuable species into the pure stand (Heinze et al. 2000; Fonder 2007; Felton et al. 2010, 2016; Dobrowolska et al. 2021).

Depending on the way of introduction of valuable species into the composition of low-value young stands, different conversion methods can be applied, which are as follows: continuous and corridor felling and gap creation (Izyumsky 1978; Deryabin 1981; Levchenko 2018, Yakimov et al. 2020). Conversion interventions should be started as early as possible because the younger the stand is, the easier it is to improve. Also, early conversion enables better results to be achieved less expensively.

According to Jaszczak et al. (2011), 43% of the forest area in Poland corresponds to the forest site conditions in terms of species composition; 38% partially correspond and 19% do not correspond to them and require conversion. In the country, preference is given to a continuous method of conversion. In the Republic of Belarus, conversion comprises 11–14% of the total area of reforestation. Oak, pine and spruce were the main species used for reforestation by the conversion method (Zelensky et al. 2016).

According to Savushchik et al. (2003), the proportion of low-value stands in Ukraine is 14%. Therefore, the improvement of low-value stands through reconstruction is an urgent forestry problem for Ukraine.

The aim of the study was to evaluate the influence of different widths and cardinal directions of the felled corridors on the condition and mensuration characteristics of the English oak trees planted there during the conversion of low-value young stands using the corridor method.

Material and methods

The study was carried out in the north-eastern part of Ukraine (Kharkiv Region, Derhachi District) in September 2019. The experiment was started in 1987; it included the conversion of a low-value 8-year-old stand to change its species composition. The conversion was realised by felling corridors of various widths (6, 9 and 12 m) and directions and planting English oak trees (*Quercus robur* L.) within them in rows. For planted oaks, tending felling was carried out three times: weeding (8 years, 1995), cleaning (13 years, 2000) and thinning (32 years, 2019).

The influences of the width and direction of the corridors on the health condition and mensuration characteristics of planted English oaks were investigated. The oaks were planted in the corridors within a low-value stand with 3-year planting stock in 1987, after felling corridors over an area of 3.2 ha. The composition of the low-value stand included 60% of field maple (*Acer campestre* L.), 20% of small-leaved lime and 20% of Norway maple. The low-value stand was 8 years old; the average tree height was 5 m and the diameter averaged 4.1 cm. The experiment consisted of four variants. Depending on the variant, two or three corridors of different widths (6, 9 and 12 m) were felled in the stand and one, two or three rows of oaks were planted in each of them (Tab. 1). Unfelled strips of the low-value stand, 3- and 6-m wide, were left between the corridors (strip felling). The direction of the corridors was latitudinal in sample plots 1, 2 and 3 and longitudinal in sample plot 4. In-the-row spacing for oak was 1 m in all variants. Field maple, Norway maple and small-leaved lime trees adjoining corridors and suppressing oak trees were cut down from the unfelled strips during thinning. Only suppressed and damaged oak trees were cut down in the corridors.

Table 1. Variants of the experiment on low-value stand conversion

Sample plot number	Number of corridors	Corridor width (m)	Corridor direction	Width of unfelled strips (m)	Number of planted oak rows in the corridors
1	3	6	latitudinal	3	1
2	3	12	latitudinal	6	3
3	2	9	latitudinal	6	2
4	2	12	longitudinal	6	3

Figure 1. Location of the study site

The sample plots were laid out in the experimental sites where conversion felling was carried out, in fresh maple-lime oak forest type (according to the Ukrainian forest typology system (Ostapenko and Tkach 2002)). Geographical coordinates of the sample plot centre were the following: 50°11′12″ N; 36°19′41″ E (Fig. 1).

The climate in the study area is classified as temperate continental. The average annual temperature ranges from +21°C in summer to –7 °C in winter. The length of the growing season is 190 ± 5 days on average. The average annual rainfall is 492 mm, of which 280 mm falls during the warm season. The height of the snow cover is 18–28 cm (Ecological passport of Kharkiv region 2021). Deciduous forests predominate. The most widespread forest-forming species is the English oak (*Quercus robur* L.). Oak-dominated stands cover more than 84% of the forest area of the region. The next most common tree species in the region's forests are Scots pine (*Pinus sylvestris* L.), common ash (*Fraxinus excelsior* L.), Norway maple (*Acer platanoides* L.), small-leaved lime (*Tília cordata* Mill.), silver birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.) (Ostapenko and Tkach 2002). Soils are clay chernozems (Ecological passport of Kharkiv region 2021).

Stand mensuration characteristics are shown in Table 2 (for sample plots 1 and 2) and Table 3 (for sample plots 3 and 4).

Table 2. Stand mensuration characteristics in sample plots 1 and 2

Composition	Age (years)	Average		Stand basal area ($m^2 \cdot ha^{-1}$)	Stand density ($stems \cdot ha^{-1}$)	Growing stock per 1 ha ($m^3 \cdot ha^{-1}$)	Health condition index	Stem quality category	Height (m)	
		height (m)	diameter (cm)						to dead knot	to living branch
Sample plot 1, stand in the corridor before felling										
100% Eo	32	13.5	14.1	7.08	454	51.4	2.5	2.0	4.6	7.0
Stand in the corridor after felling										
100% Eo	32	14.3	16.9	6.35	285	47.2	1.4	1.7	4.9	7.5
Unfelled strip in sample plot 1 after felling										
56% Fm	30–40	14.2	19.6	4.9	162	33.9	1.4	–	–	–
29% Sll		17.4	29.5	2.1	31	17.6	1.1	–	–	–
15% others		14.3	19.7	1.4	46	9.5	1.2	–	–	–
Total in unfelled strip		–	–	8.4	239	61.0	–	–	–	–
Total unfelled strip + corridor 44% Eo, 31% Fm, 16% Sll, 9% others		–	–	14.75	524	108.2	–	–	–	–
Sample plot 2, stand in the corridor before felling										
100% Eo	32	13.4	15.1	11.89	665	84.5	2.0	1.8	4.5	7.0
Stand in the corridor after felling										
100% Eo	32	14.0	17.1	10.92	470	79.0	1.3	1.6	5.0	7.5
Unfelled strip in sample plot 2 after felling										
52% Fm	30–40	12.8	14.5	3.2	193	19.8	1.4	–	–	–
14% Cp		13.2	23.8	0.8	19	5.3	1.5	–	–	–
13% Nm		14.2	21.0	0.7	21	4.9	1.3	–	–	–
21% others		12.9	22.0	1.6	40	8.1	1.2	–	–	–
Total in unfelled strip		–	–	6.3	273	38.1	–	–	–	–
Total 67% Eo, 17% Fm, 5% Cp, 4% Nm, 7% others		–	–	17.22	743	117.1	–	–	–	–

Note: Cp = common pear (*Pyrus communis* L); Eo = English oak (*Quercus robur* L.); Fm = field maple (*Acer campestre* L.); Nm = Norway maple (*Acer platanoides* L.); others = other species; Sll = small-leaved lime (*Tília cordata* Mill.).

Table 3. Stand mensuration characteristics in sample plots 3 and 4

Composition	Age (years)	Average		Stand basal area ($m^2 \cdot ha^{-1}$)	Stand density ($stems \cdot ha^{-1}$)	Growing stock per 1 ha ($m^3 \cdot ha^{-1}$)	Health condition index	Stem quality category	Height (m)	
		height (m)	diameter (cm)						to dead knot	to living branch
Sample plot 3, stand in the corridor before felling										
100% Eo	32	13.5	14.6	8.93	535	64.6	2.0	1.8	4.8	7.3
Stand in the corridor after felling										
100% Eo	32	14.2	17.0	8.14	360	60.1	1.2	1.5	5.2	7.8
Unfelled strip in sample plot 3 after felling										
51% Fm	30–40	13.6	17.5	4.6	190	29.8	1.3	–	–	–
20% As		17.2	22.2	1.6	40	11.8	1.1	–	–	–
16% Sll		13.9	14.5	1.3	80	9.2	1.1	–	–	–
13% others		15.0	22.6	1.1	30	7.4	1.2	–	–	–
Total in unfelled strip		–	–	8.6	340	58.2	–	–	–	–
Total 51% Eo, 25% Fm, 10% As, 8% Sll, 6% others		–	–	16.74	700	118.3	–	–	–	–
Sample plot 4, stand in the corridor before felling										
100% Eo	32	13.8	15.5	12.7	672	91.6	2.1	2.0	5.2	7.4
Stand in the corridor after felling										
100% Eo	32	14.2	17.4	11.7	482	85.8	1.4	1.8	5.5	8.0
Unfelled strip in sample plot 4 after felling										
40% Fm	30–40	12.8	15.4	2.6	143	16.5	1.4	–	–	–
33% Sll		16.2	20.3	1.7	53	13.5	1.1	–	–	–
27% Nm		14.3	18.6	1.6	58	11.2	1.3	–	–	–
Total in unfelled strip		–	–	5.9	254	41.2	–	–	–	–
Total unfelled strip + corridor 67% Eo, 13% Fm, 11% Sll, 9% Nm		–	–	17.6	736	127.0	–	–	–	–

Note: As = aspen (*Populus tremula* L.); Eo = English oak (*Quercus robur* L.); Fm = field maple (*Acer campestre* L.); Nm = Norway maple (*Acer platanoides* L.); others = other species; Sll = small-leaved lime (*Tília cordata* Mill.).

The sample plots were laid out in such a size that there were at least 100 oak trees on a plot depending on the corridor width. Trees were recorded by species, listing trees by diameters, health condition categories and stem quality categories. Tree diameters were measured at a breast height using a Codimex S-1 caliper within the accuracy of 0.5 cm (Neretin et al. 2006). The average diameter was calculated through the average cross-sectional area of the stems. The average diameters of all species were determined according to the calculated cross-sectional area of the average tree. Stem heights were measured for 35–45 trees in each sample plot with a Haglöf Electronic Clinometer (HEC) hypsometer in field conditions. The average height was determined by a graph of height variance depending on the average diameter of a specific stand (Hrom 2010). The heights to a dead knot and a living branch were measured.

The stem quality category was evaluated using a 3-point scale: 1 point corresponds to trees with high-quality stems without any defects (crooks, large knots, damage and diseases); 2 points correspond to the trees with stems of satisfactory quality (defects make no more than 40% of the stem); 3 points correspond to the trees with stems of poor quality (defects account for more than 40% of the stem).

The health condition of the stand was characterised by the health condition index I_c that was evaluated by Equation (1) (Voron et al. 2011):

$$I_c = \frac{K_1 n_1 + K_2 n_2 + \ldots + K_6 n_6}{N} \quad (1)$$

where:

$K_1, \ldots, K_6$ – refers to the category of the health condition of the trees (from 1 to 6),

$n_1, \ldots, n_6$ – indicates the number of trees of the given health condition category and N refers to the total number of recorded trees in the sample plot.

We estimated the health condition of the trees using six categories as follows: first – trees without signs of damage, second – weakened trees, third – severely weakened trees, fourth – dying trees, fifth – standing dead trees died over the present year and sixth – standing dead trees died over recent years (Tab. 4).

Table 4. Scale used to determine the stand health (Voron et al. 2011)

Health condition index range	Stand damage degree	Health status of the stand	Average health condition category
1.00–1.50	none	healthy trees	1
1.51–2.50	light	weakened trees	2
2.51–3.50	moderate	severely weakened trees	3
3.51–4.50	severe	dying trees	4
4.51–5.00	very severe	dead trees	5
5.51–6.00	very severe	standing dead trees died over recent years	6

The stand basal area was defined as the sum of the cross-sectional areas of the trees in a stand per hectare. The relative density of stocking was calculated as the ratio of the stand basal area to the basal area of the 'normal' stand (Shvydenko et al. 1987). The growing stock was estimated as the volume of all living trees per unit area, and the stand density as the number of living trees per unit area (Hrom 2010).

Cores of model trees were taken at the breast height (1.3 m) in sample plot 2 (latitudinal corridor direction) and sample plot 4 (longitudinal corridor direction), 15 model trees in each of the two sample plots, with the Haglof increment borer to study the radial increment. The model trees represented different thicknesses (12, 14, 16, 18, 20 cm), three trees from each thickness.

Statistical analyses

Normality tests, summary statistics, one-way analysis of variance (ANOVA) and Tukey HSD (honestly significant difference) test with a significance level of $p < 0.05$ were performed for raw data (Tab. 5–7).

Table 5. The average radial increment of oak trees in different variants of the experiment

Year	Sample plot number		F	p
	2	4		
1991	3.3 ± 0.15^a	3.5 ± 0.21^a	1.59	0.23
1992	2.8 ± 0.19^a	3.2 ± 0.20^a	1.40	0.25
1993	2.8 ± 0.12^a	3.4 ± 0.18^b	8.33	<0.01
1994	2.4 ± 0.19^a	3.0 ± 0.22^b	4.96	0.03
1995	2.1 ± 0.18^a	2.5 ± 0.19^a	2.86	0.10
1996	3.0 ± 0.06^a	3.1 ± 0.14^a	0.03	0.86
1997	3.1 ± 0.12^a	3.3 ± 0.11^a	0.46	0.50
1998	2.6 ± 0.13^a	2.7 ± 0.13^a	0.005	0.94
1999	2.3 ± 0.11^a	2.1 ± 0.10^a	0.62	0.44
2000	2.2 ± 0.17^a	2.1 ± 0.11^a	0.07	0.79
2001	2.4 ± 0.15^a	2.2 ± 0.13^a	0.62	0.44
2002	2.4 ± 0.17^a	2.5 ± 0.11^a	0.01	0.93
2003	3.1 ± 0.10^a	3.4 ± 0.16^a	1.16	0.29
2004	3.0 ± 0.13^a	3.2 ± 0.15^a	0.16	0.70
2005	3.0 ± 0.13^a	3.4 ± 0.19^a	1.19	0.29
2006	2.6 ± 0.09^a	3.1 ± 0.14^a	1.84	0.19
2007	2.7 ± 0.09^a	3.3 ± 0.14^a	3.88	0.06
2008	2.1 ± 0.17^a	2.2 ± 0.15^a	0.001	0.99
2009	1.8 ± 0.14^a	2.0 ± 0.15^a	0.23	0.63
2010	1.9 ± 0.15^a	2.3 ± 0.16^a	0.26	0.62
2011	1.9 ± 0.15^a	2.1 ± 0.16^a	0.08	0.78
2012	1.7 ± 0.11^a	2.0 ± 0.14^a	0.20	0.66
2013	2.4 ± 0.11^a	2.6 ± 0.16^a	0.005	0.95
2014	2.0 ± 0.09^a	2.2 ± 0.15^a	0.14	0.71
2015	1.4 ± 0.10^a	1.6 ± 0.18^a	0.02	0.88
2016	1.6 ± 0.08^a	1.5 ± 0.16^a	0.89	0.36
2017	1.8 ± 0.10^a	1.5 ± 0.17^a	2.38	0.14
2018	2.1 ± 0.14^a	1.7 ± 0.20^a	3.44	0.08
2019	1.2 ± 0.09^a	0.9 ± 0.13^b	4.48	0.04

Note: Different letters indicate significant difference between variants ($p < 0.01$, Tukey's pairwise ANOVA). ANOVA = analysis of variance

Table 6. The average radial increment of oak trees before and after tending felling

Sample plot number	Before tending felling, 1995	After tending felling, 1996	F	p	Before tending felling, 2000	After tending felling, 2003	F	p
2	2.1 ± 0.18[a]	3.0 ± 0.06[b]	20.63	<0.01	2.2 ± 0.17[a]	3.1 ± 0.10[b]	5.24	0.03
4	2.5 ± 0.19[a]	3.1 ± 0.14[b]	8.20	0.04	2.1 ± 0.11[a]	3.4 ± 0.16[b]	11.75	0.02

Note: Different letters indicate significant difference between variants ($p < 0.01$, Tukey's pairwise ANOVA). ANOVA = analysis of variance

Table 7. Heights of the self-pruned stem sections and crown lengths of oak trees

Sample plot number	Height to dead branches (m)	Stem section with dead branches (m)	Crown length (m)
1	4.9 ± 0.10[a,b]	2.6 ± 0.09[a]	6.8 ± 0.14[a]
2	5.0 ± 0.09[a,b]	2.5 ± 0.06[a]	6.5 ± 0.11[a]
3	5.2 ± 0.15[a]	2.6 ± 0.08[a]	6.4 ± 0.16[a]
4	5.5 ± 0.17[a,c]	2.5 ± 0.11[a]	6.2 ± 0.18[a]
F	2.98	0.59	2.39
p	0.04	0.62	0.07

Note: Different letters indicate significant difference between variants ($p < 0.01$, Tukey's pairwise ANOVA). ANOVA = analysis of variance

The Box–Cox transformation was used to transform the data to the normal distribution, stabilise group variances and meet the homoscedasticity condition (Hammer et al. 2001). After data transformation, the F-test ANOVA was used to find statistically significant differences between variants (Hammer et al. 2001).

Results

The average radial increments of oak trees in sample plots 2 and 4 (12 m corridors of different cardinal directions) varied synchronously within 3.5–0.9 mm during 1991–2019. The differences between them were insignificant from year to year (0.1–0.6 mm or 3–20%) (Tab. 5). The average sum of radial increments over this period was 7% higher (by 4.9 mm) in sample plot 4 compared to sample plot 2 and was also insignificant (Tab. 5, Fig. 2). Tending felling in the stands in 1995 and 2000 led to a gradual increase in the average radial increment of oak trees (Tab. 6, Fig. 2) on both sample plots due to the improvement of light and nutrition conditions and increase in the tree growing space. As a result of tending felling in 1995, the average radial increment of oaks increased significantly the following year: by 30% in sample plot 2 and by 21% in sample plot 4 (Tab. 6). In the second year after thinning (1997), this variable reached the same value as in the first one, which was also significantly higher than before felling (Tab. 6). The average radial increment of oak gradually decreased in the third to fifth years after felling (1998–2000). The difference between its values before and after felling was minimised.

The average radial increment reached a maximum (about 3.0 mm) in both sample plots in the third year (2003) after the tending felling in 2000 and remained at this level for 5 years, until 2007 (Tab. 5, 6). During

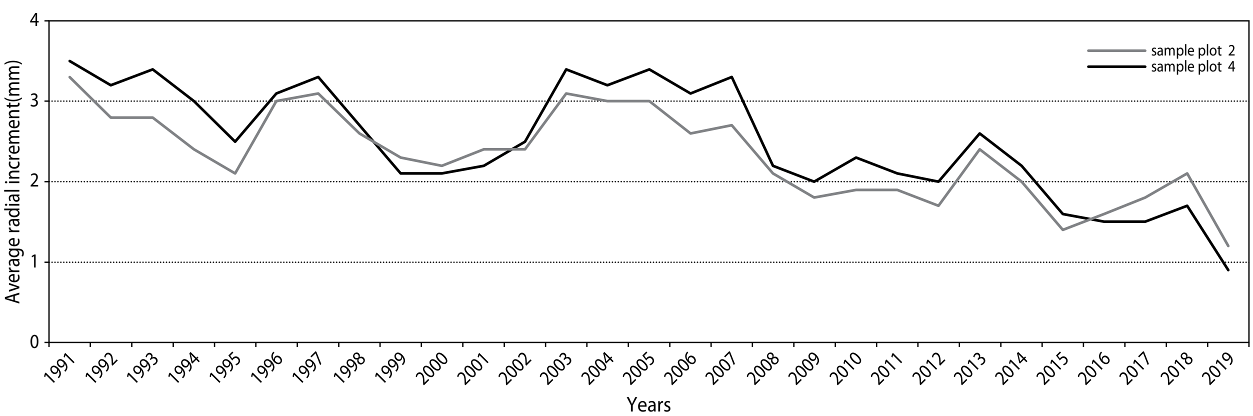

Figure 2. Average radial increment of oak trees in sample plots 2 and 4

this period, it increased by 32–38% compared to 2000, which was statistically significant. The current oak increment evenly decreased over 2008–2019. This indicates that the oak trees in the corridors are suppressed by the trees of the unfelled strip, so further thinning of the unfelled strip is required.

Before thinning (32 years, 2019), the poor health condition of oak trees in the corridor (I_c from 2.0 to 2.5) also indicated their suppression. The oak trees in 6 m corridors (sample plot 1) had the worst health condition; at the same time, the health condition was the best in 12 and 9 m corridors (sample plots 2 and 3, respectively). In 12 m corridors, regardless of their cardinal direction (sample plots 2 and 4), the health condition of oaks was the same (I_c was 2.0 and 2.1, respectively). After felling, the health of oaks improved significantly in all variants of the experiment. The trees were characterised as healthy, regardless of the width of the corridors and their geographical direction (I_c was 1.2–1.4). In sample plots 1 and 4 with the worst health condition (I_c = 1.4), the stem quality category after thinning was also the worst, accounting 1.7 and 1.8 points, respectively (Fig. 3).

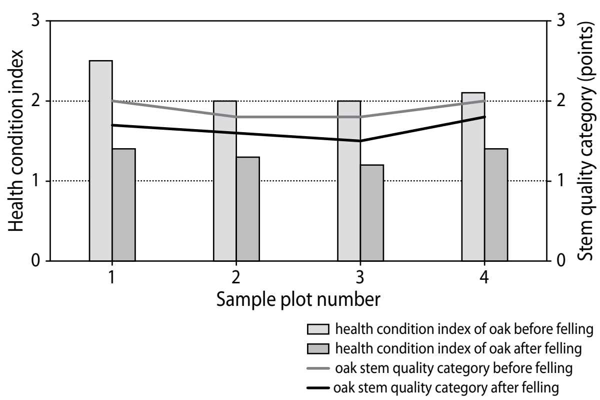

Figure 3. Health condition index and stem quality category of English oak before and after thinning (32 years, 2019) in the sample plots

After thinning, the average height of the oak trees in the corridors increased by 3–6% and the average diameter by 11–17% in all sample plots. The difference between the average heights of oaks did not exceed 2%, and the difference between the average diameters was not greater than 3% in all sample plots and was insignificant (F = 1.139, p = 0.3346). Therefore, the width and direction of the corridors in the experiment did not significantly affect the average height and diameter of oak trees (Fig. 4).

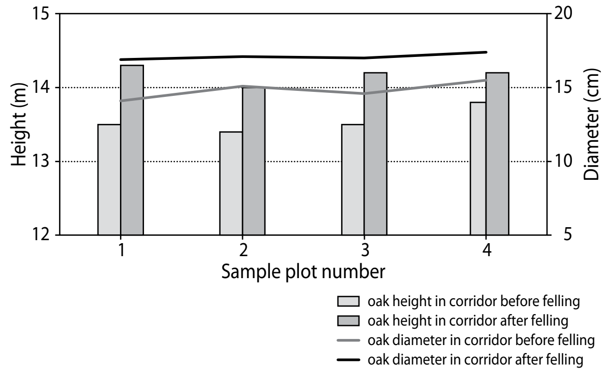

Figure 4. Average heights and diameters of the oak trees in the sample plots before and after thinning (32 years, 2019)

The difference between growing stock volumes of less than 15% is considered insignificant (Anuchin 1982). A significant difference in oak growing stocks in the corridors was found between sample plots 1 and 2 (35%), 1 and 4 (40%), 2 and 3 (24%) and 3 and 4 (30%). This was because one to three rows of oaks were planted in the corridors depending on their width. Therefore, the number of oak rows increased with the width of the corridors and, accordingly, the oak growing stock rose. The difference between the oak growing stocks in 6 and 9 m wide corridors (sample plots 1 and 3) was insignificant (14%). The difference between these indicators (8%) in the 12 m corridors of latitudinal (sample plot 2) and longitudinal (sample plot 4) directions was also insignificant. Therefore, the direction of the cor-

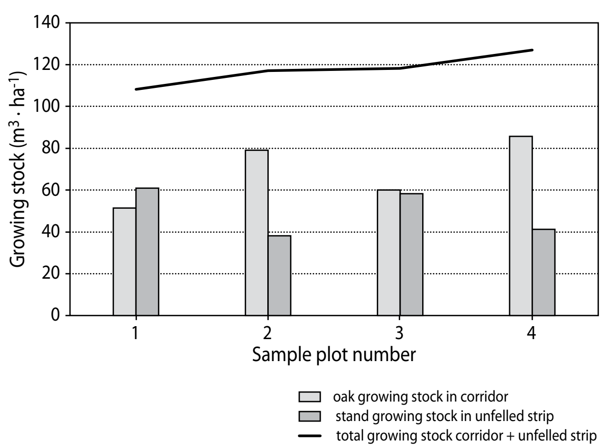

Figure 5. Growing stock in the sample plots after felling

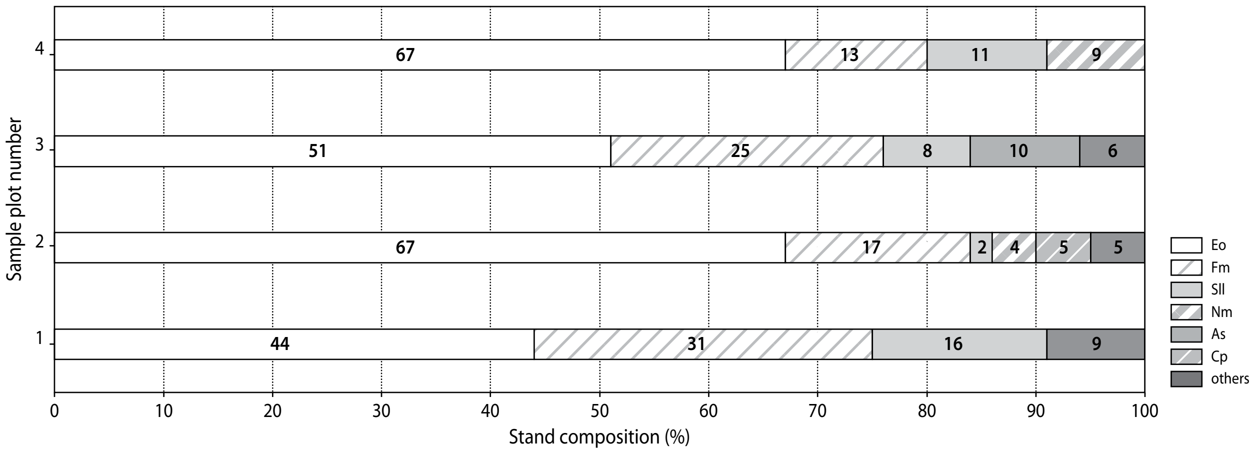

Figure 6. Stand composition in the sample plots after felling. As – aspen (*Populus tremula* L.); Cp – common pear (*Pyrus communis* L); Eo – English oak (*Quercus robur* L.); Fm – field maple (*Acer campestre* L.); Nm – Norway maple (*Acer platanoides* L.); others – other species; Sll – small-leaved lime (*Tílіa cordata* Mill.)

ridors did not influence the oak stocks within them. The stand growing stock in the unfelled strip was found to decrease with an increase in the stock of oaks within the corridor in all sample plots (Fig. 5). At the same time, both the significance and insignificance of the differences in the growing stocks for unfelled strips (29–38% and 5–8%, respectively) were detected between the same sample plots as for the corridors. However, the differences between the total stocks of oaks within the corridor and the stand in the unfelled strip among all sample plots were insignificant and varied from 1% to 15% (Fig. 5).

In the first year after felling, the proportion of oak in the stand with 12 m wide corridors of different cardinal directions (sample plots 2 and 4) was the same and accounted for 67% by growing stock. The difference between the oak proportions in the stands with corridor width of 6 and 9 m (sample plots 1 and 3) was also insignificant (14%). The oak proportion differed significantly in the 6- and 12-m-wide corridors (sample plots 1 and 2, 4) by 34%, as well as in the 9 and 12 m wide corridors (sample plots 3 and 2, 4) by 24% (Fig. 6).

One of the indicators that characterise the state of the stand is self-pruning. The study showed that the trees in the stand with a 12 m width corridor of the meridional direction (sample plot 4) were the best in self-pruning, while in the stand with a 6 m width of the corridor of the latitudinal direction (sample plot 1), self-pruning was poor. The difference between the average heights of the self-pruned stem sections among these sample plots (5.5 and 4.9 m, respectively) was significant – 11% (Tab. 7). First, the density of oaks before and after felling was higher in sample plot 4 compared to sample plot 1. More shading of the lower branches promoted more intensive self-pruning. Second, at noon, when the sun is most active, the sun's rays are directed along the rows of oaks at the longitudinal direction of wide corridors (sample plot 4). As a result, each tree in the row shades the adjacent one and thus contributes to the death of the lower, most shaded branches. At the latitudinal direction of the corridors, the sun's rays at noon are directed perpendicular to the rows of oaks. Only one oak row bordering the unfelled strip to the south was shaded by it at noon. In the other two rows, every tree got intense light at noon, reducing self-pruning. Among other sample plots, the difference in the average heights of the self-pruned stem sections was insignificant, 2–9% (Tab. 7). The crown length was insignificantly influenced by the width and direction of the corridors (Tab. 7).

Discussion

For the successful transformation of low-value stands into economically valuable ones, the technological parameters of conversion felling, such as the width of corridors and unfelled strips and their cardinal direction, are essential. They mainly influence the ecological environment of the converted stands (light, temperature and soil moisture). This, in turn, determines the further growth and health status of plants. So far, related studies were focused primarily on the impact of the width of corridors and unfelled strips on the average height and diameter, cross-sectional area and growing stock of planted trees. In addition to these variables, this work is the first to investigate the dynamics of the average radial increment of planted oak trees, their stem quality category, the height of the self-pruned stem section, the crown length and the health condition index before and after felling in permanent research plots with a long observation period of 32 years.

The corridor method of stand conversion is considered the most promising (Vedmid et al. 2008; Reshetnikov 2013; Yakimov et al. 2013, 2020; Krachkovsky 2014; Reshetnikov and Storozhishina 2016). It has long been used in oak forests in Latvia (Kronit 1968), Belarus (Krachkovsky 2014; Gvozdev 2017; Yakimov et al. 2020), Moldova (Kichuk et al. 2014) and Ukraine (Izyumsky 1978; Vedmid et al. 2008). Compared to the continuous method, it has undoubted advantages in forestry and environmental sense. On the one hand, significant cost savings (Gvozdev 2017) and the possibility of mechanisation of main technological operations are achieved (Zubov 1971; Yakimov et al. 2010). On the other hand, the forest environment is not significantly disturbed (Yakimov et al. 2020). Also, the application of the method creates favourable conditions for the cultivation of resilient and highly productive mixed oak stands (Izyumsky 1978).

There is no consensus regarding the width of the corridors and their direction. Some studies provide evidence for the longitudinal direction (Murzov et al. 1986; Reshetnikov 2013). However, most consider the latitudinal direction of corridors to be preferred (Pavlenko 1967; Kachan 1980; Bugaev and Gladysheva 1991; Vedmid 2001; Yakimov et al. 2010; Brodovich et al. 2014). The argument is that the latitudinal direction of the corridors, compared to the longitudinal one, provides better lighting and more uniform distribution of light in the corridor throughout the day. The corridors of the longitudinal direction are more intensively illuminated by direct sunlight during noontime. Although the intensity of such sun rays is highest during the day, their physiological value is lower than the rays in the morning. Furthermore, the more intense illumination of the corridors at noon leads to a noticeable increase in air and soil temperatures, a decrease in relative humidity and even a decrease in soil moisture (Vedmid 2001).

The studies at permanent research sites indicate that the highest survivability and growth characteristics of planted oak (Vedmid et al. 2008) and spruce trees (Yakimov et al. 2013) were observed in the latitudinal direction only at the initial stages of growth (up to 15–20 years). With aging, the differences in these characteristics became insignificant. The canopy of the unfelled strip is crucial, shading the corridors and creating root competition for the planted trees. At this stage of stand development, timely felling of trees growing within the unfelled strips and hindering normal growth and development of trees planted during conversion becomes a determining factor.

Narrow corridors have been proposed by many authors (Zubov 1971; Izyumsky 1978; Deryabin 1981; Bugayev and Gladysheva 1991; Reshetnikov and Storozhishina 2016) for the conversion of low-value stands, with a corridor width ranging from half to one height of a low-value young stand. In the first years of life (up to 7 years), in the absence of top shading, oak is known to grow better in narrow corridors (2–3 m) than in wide ones, where the effect of side shading is less (Deryabin 1981; Bugayev and Gladysheva 1991). However, narrow corridors of half the height of the low-value young stand must be excluded. Assuming the height of the low-value stand is 4 m, the width of the corridor should be 2 m. In our view, such width of the corridors is impractical, since the growth rate of a low-value young stand in the direction of the corridor is 0.5 m per year (Alentiev 1990). Therefore, to ensure the normal growth and development of the oaks until they reach the height of the young stand, which is to be converted, tending felling in the unfelled strip is necessary every 2 years.

More authors propose using wide corridors with a width of one to two heights of the low-value young stand (Pavlenko 1967; Alentiev 1990; Vedmid and Ugarov 1993; Vedmid 2001; Vedmid et al. 2008; Yakimov et al. 2013; Gvozdev 2017). Pavlenko (1967) and Vedmid (2001), unlike others, set the corridor width by calculation. For example, the study of the duration of oak lighting in the 3, 6, 9 and 12 m wide corridors having latitudinal and longitudinal directions at the height of the low-value young stand of 3, 6 and 12 m confirmed that the latitudinal direction of the corridors for up to

15-year-old stands was the best (Vedmid 2001). Based on the minimum allowable duration of the oak lighting in the corridors, it has been found that 3 m is the appropriate width of the corridor in the latitudinal direction when the height of the low-value young stand is up to 3.5 m, 6 m is appropriate for a height of 7.5 m and 9 and 12 m are suitable for a height of up to 12 m. Corridors of the longitudinal direction with a width of 3 m at the height of the low-value young stands above 3 m should not be used due to their insufficient lighting. The corridor width of 6 m should be used for the height of the low-value young stands up to 5 m, 9 m width for the height of 8 m and 12 m width for the height of 11 m. The unfelled strip width depends on the presence of the main and accompanying species as well as the height of the low-value stand. The unfelled strip width can be increased depending on the number of trees of the main species in the composition of the low-value young stand. At this, the number of trees of the main species should be no less than 1500 per 1 ha (Vedmid 2001).

Havrylenko et al. (1993) investigated 2, 3, 6 and 9 m wide corridors of longitudinal and latitudinal directions for the planted English oak trees within Right-Bank Forest-Steppe in Ukraine. One row of oaks was planted in 2- and 3-m-wide corridors, while two oak rows were planted in 6 m width corridors and three rows in 9 m width corridors. The oaks were planted on a cut-over site reafforested with European hornbeam (*Carpinus betulus* L.). The results indicated that 23-year-old oaks planted in 6 and 9 m wide corridors with the latitudinal direction had better health and growth rate; however, this difference was not significant. In our opinion, 2 and 3 m wide corridors are ineffective due to poor lighting. That is also the view of other researchers (Alentiev 1990; Bugaev and Gladysheva 1991; Yakimov et al. 2020).

Conclusions

The corridor method of stand conversion is the most promising because its application does not significantly disturb the forest environment. For successful conversion of low-value stands, the best width of corridors is 9 or 12 m. Two oak rows should be planted within 9 m width corridors and three oak rows within 12 m width corridors. The width of the unfelled strip should not be greater than the width of the corridor and less than half its width.

The study of the impact of different strategies on the growth of planted oak stands, which were converted using the corridor method, showed that the width and direction of the corridors did not significantly affect the height and diameter of planted oaks after felling at the age of 32 years.

The health status of the stands was almost identical in the corridors of different cardinal directions and different widths. However, the worst health and stem quality categories were detected for oak trees after felling in 6-m-wide latitudinal corridors and 12 m wide longitudinal ones.

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