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Close-to-Nature Forestry Measures in East Polissia Region of Ukraine

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ABSTRACT

The article discusses close-to-nature forestry measures for the natural regeneration of pure and mixed pine forests. It is shown that successful natural regeneration of high value tree species takes place after uniformly gradual logging and progressive strip felling as final cutting operations in pure pine forests in fresh or moist oak-pine forest stands on sandy soil, resulting in the development of natural young pine forests with mixed composition. The article analyzes the state of natural regeneration after the first cycle of transformation felling operations in pure even-aged pine stands aimed at converting them into mixed pine forests of natural origin. Systems of close-to-nature silvicultural measures for restoration, development, improvement and regeneration of forest stands in the process of continuous cover forestry have been elaborated.

Keywords: felling; natural regeneration; development of mixed uneven-aged forest stands; biodiversity

INTRODUCTION

Close-to-nature forestry (CNF) is a system of organizational and forest management activities aimed at regeneration and development of natural forests. Natural forest stands are formed in accordance with forest types of the original stands with authentic seed origin, which is in accordance with the European Forest Management Strategy aimed at preserving continuous cover forestry (Mason et al. 2021).

For the regeneration and development of forest stands that are close to the original natural forests in terms of their species composition, age and spatial structures, forestry operations should involve environmentally-friendly technologies that contribute to preserving biotic diversity (Chernyavskiy et al. 2006, Krynytskyi et al. 2014).

Preservation and increasing species diversity is one of the fundamental principles of close-to-nature forestry that enhances forests' capacity to adapt to climate change and boosts their regeneration after the extreme negative impact of abiotic environmental factors (Schütz 1999, Garcia-Güemes et al. 2014, Spathelf et al. 2015).

The natural regeneration of high value species occurs after clear, gradual and selective final felling operations (SFMCU 2010).

In the pine forests of North-East Germany, close-to-nature silviculture measures include uniformly gradual, group-selective felling and strip and wedge clearcutting (Lavnyy and Spathelf 2016).

Clearcutting (CC) is followed by the formation of mainly even-aged and temporary uneven-aged stands. The success of the process of natural regeneration is mainly influenced by the following factors: the area of the logging site, its width, the availability of seeding sources within the deforested area, as well as microclimatic, soil and hydrological conditions, cluttering with logging residues, condition and types of ground cover (Pogrebniak 1968, Vedmid et al. 2008, Lavnyy and Spathelf 2016, Zhezhkun 2021). In order to follow the principles of close-to-nature forestry, the maximum area of clear-cutting sites should be restricted. The maximum area allowed for clearcutting varies between European countries, with Germany, Austria, Italy and the Czech Republic restricting clearcutting to 1 ha and below, Poland (2 ha), Slovakia, Romania (3 ha) and

Bulgaria and Estonia up to 5 ha (Zasady 2003, Kravets and Kremenetskaya 2008, Lavnyy and Spathelf 2016).). In Ukraine, the area of clear felling is limited in pine forests up to 3 ha, and in oak forests up to 5 ha (SFMCU 2010). In the fresh and moist pine and pine-oak stands on sandy soil and clay soil in the eastern part of Polissia region of Ukraine, successful seed production leads to a satisfactory natural regeneration of Scots pine (*Pinus sylvestris* L.) and other valuable species with logging sites up to 70-80 m wide (Zhezhkun 2021).

Gradual and selective final felling systems belong to the selective form of forest management (Krynytsky et al. 2012). After the uniformly gradual felling (UGF) in pine stands we can trace an increase in tree species diversity and structural diversity. Also, genetic intraspecific variability of trees is preserved and increased, and tree resistance to adverse biotic and abiotic factors (stresses) is enhanced, which corresponds to the principles of close-to-nature forestry (Brang et al. 2014, Krynytskiy and Chernyavskiy 2015). In the fresh and moist pine forest stands on sandy soils in the eastern part of Polissia effective results have been achieved in case of two-stage UGF and implementation of the soil cultivating measures aimed at supporting natural regeneration of Scots pine if carried out before seeding in a year of high seed production (Zhezhkun 2021). Gradual felling interventions aimed at the natural regeneration of high value tree species are carried out mainly in even-aged stands. In uneven-aged stands the communities of over-mature, mature, ripening, middle-aged and young forest generations grow on the same site. In order to maintain the dynamic balance and promote a developing multi-aged structure, selective felling operations with the removal of over-mature and mature trees are carried out (Tichonov et al. 2000, SFMCU 2010, Krynytsky et al. 2012).

In recent years, against the backdrop of global climate change and increasing anthropogenic pressure, the sanitary condition of the forests has been deteriorating. Artificial forest stands and monocultures are characterized by low biotic stability, which leads to a decrease and suspension of growth processes, as well as to the weakening and drying-out of pine stands under the current conditions (Gilliam 2016, Meshchkova, Borisova 2018, Hlasny 2019, Klein 2020, Reuna et al. 2020, Zhezhkun et al. 2021).

In artificial pure even-aged stands, selection cutting (SC) is used to transform them into stable uneven-aged stands (Cabinet of Ministers of Ukraine 2007). In mountain conditions, the secondary forest stands of spruce, fir and beech are subject to transformation with a gradual shift to original fir-spruce-beech forest stands (Chernyavskiy et al. 2006, Krynytskyi et al. 2014). In even-aged artificial pine stands of homogenous composition in Eastern Polissia, the selective felling operations by forming small-scale forest logging sites and gaps ensure successful natural regeneration of Scots pine and common oak (*Quercus robur* L.), as well as other high-value tree species (Zhezhkun and Porochniach 2017).

In uneven-aged oak forests, selective felling operations are offered among the close-to-nature silvicultural measures with the aim to reduce the canopy closure in parental forest stands, strip felling of undergrowth in a mast year, soil mineralization, and additional sowing of acorns (Chernyavskiy et al. 2006). Experiments have been conducted on regenerated common oak stands' transformation into the forest stands of naturally regenerated or planted origin (Tkach 2010). Reproduction of natural pine stands in the steppe pinewoods of Ukraine is not linked to the final felling operations, so preservation of their biodiversity and genesis is carried out by complex felling methods, mainly by progressive felling in groups (Tkach et al. 2015).

Tending measures in the even-aged forests are carried out prior to the transformation felling in order to convert these forest stands into uneven-aged ones. In natural forests, tending begins with thinning, but is focused on fostering the target trees for the future (Krynytskyi et al. 2014, Lavnyy and Spathelf 2016).

To reduce the impact on natural environment during logging and other close-to-nature forestry activities, safe, environment-friendly logging technologies have been used (Vedmid et al. 2008, Krynytskyi et al. 2014, Lavnyy and Spathelf 2016). In the process of felling, fireless methods of cleaning the felling sites are used to avoid burning of the felling residues (Krynytskyi et al. 2014).

Thus, close-to-nature forestry includes a system of organizational and forestry tools for the restoration and formation of resilient, multi-age, complex-structured, mixed composition stands of natural origin. Felling and other forestry activities should be carried out using safe and sustainable technologies. Formation of uneven-aged stands with a multi-layered vertical structure accommodates the nature of shade-tolerant tree species; therefore, such an approach is widely practiced in mountain forests. In the region's lowland forests, experimental logging has started to be carried out for the natural regeneration of valuable tree species and the formation of native stands, which currently determines the scientific novelty and relevance of the research.

The purpose of the research is to study the results of experimental uniformly gradual felling and transformation felling operations to ensure a continuous forest cover and to develop a system of close-to-nature forestry measures in the Eastern Polissia region of Ukraine.

MATERIALS AND METHODS

The study was conducted in the forest reserves of state-owned forestry enterprises in the Eastern Polissia region of Ukraine (Chernihiv and Sumy regions) in the following types of forest ecological conditions: fresh and moist forest stand on sandy soil. In Ukraine, forest ecological conditions have a following trophic types: bor (pine or other coniferous forests, also mixed forests with a predominance of pine on very poor soils with oligotrophic vegetation), subor (types of forest ecological conditions characterized by relatively poor soils, close to "bor", but with an increased forest-vegetation effect), sugrud (types of forest vegetation conditions, combining relatively fertile soil conditions; the upper tree layer is formed by pine, oak, beech, spruce, fir, black alder and others), and grud (types of forest vegetation conditions that combine the most fertile habitat conditions; the upper layer is formed by oak, spruce, black alder, and less often beech and fir). Forest ecological conditions' typology by humidity includes: dry, fresh, moist, humid, wet (Pogrebniak

1968). In mature pine stands, gradual and continuous final felling operations were carried out for the natural restoration of Scots pine and other valuable tree species. Gradual felling was performed in two steps, and repeated every 3-5 years. In clearcuttings, the width of the logging sites ranged from 40 to 100 m, while the area of the logging sites was around 0.5–2.5 ha. The trees were felled with chainsaws and skidded in the form of debarked tree trunks or 4–6 m long segments using wheeled tractors along the skidding lines. Undergrowth of Scots pine and common oak was preserved on the logging sites after the gradual or continuous felling operations. After the first stage of gradual felling under the pine canopy which had been thinned down to the density of 0.4, and in the clearcutting sites the natural regeneration was promoted by cultivation of soil with disk cultivators or by making furrows with plows. The share of soil mineralization was 50–70% of the sites' area.

The transformation felling operations were implemented to convert even-aged pure pine stands into the mixed uneven-aged ones. The research plot with an area of 10 hectares is located in compartment #9 of the Slobidske Experimental Forest Unit of the Novhorod-Siversk Forest Research Station (Chernihiv region). A stand of artificial origin with the following characteristics was selected for transformation logging: stand composition – 9 PiSy1BePe, age – 66 years, average pine tree height – 24 m, average diameter – 28 cm, density – 0.60, standing volume – 300 $m^3 \cdot ha^{-1}$, forest type – fresh oak-pine subor. In the composition of the forest stand, the figures indicate the presence of each tree species (1 unit corresponds to 10% of the forest standing volume) and the abbreviated name of the tree species (PiSy – *Pinus sylvestris* L., BePe – *Betula pendula* Roth.). The sample plot is divided into 5 sections (2 hectares each) (Table 1). It was planned to carry out the transformation logging operations in 4 steps, repeated every 5-7 years with the transformation cycle of 15-20 years.

The experiment was designed in a way that the cycle of transformation felling involved removing part of the stand in small plots – from 0.045 to 0.25 ha within 1 ha logging site. In the first felling cycle two plots of 50×50 m each with an area of 0.25 ha were felled within 2 hectares of Section 1. On other sections, 1-5 gaps of different dimensions were formed evenly over the area. In subsequent felling cycles, two plots of 0.25 hectares were cut down within Section 1, and the gaps were expanded in other sections.

At each section, measures were tested to promote the regeneration of high value species (Table 2). For part of the logging site no interventions were implemented to promote natural regeneration (NR) and used for further comparison with the previously held measures. In the nomenclature of experiments, the number of the section and the measure to promote the regeneration were indicated (for example: 1-C).

Table 1. Parameters of the gaps formed as a result of transformation felling operations on the sample plot.

Section	Logging cycle (No.)	Gap dimensions (m)	Number of gaps per 1 ha	Area of gaps (ha)	Width of the forest regeneration site (thinning down to 0.4 density) (m)
1	1	50×50	1	0.25	-
	2	50×50	2	0.50	-
	3	50×50	3	0.75	-
2	1	diameter (D) 24*	5	0.23	-
	2	D 36	5	0.51	-
	3	D 44	5	0.76	-
3	1	D 36*	2	0.20	-
	2	D 42	2	0.28	-
	3	D 48	2	0.36	-
4	1	D 24*	3	0.14	12
	2	D 36	3	0.31	8
	3	D 44	3	0.46	5
5	1	D 36*	1	0.10	18
	2	D 44	1	0.15	22
	3	D 66	1	0.34	33

*Initial diameter of the gap after the first felling cycle: 24 m – 1 x stand height, 36 m – 1.5 x stand height

Table 2. Measures to promote regeneration of tree species.

Method of soil treatment	Depth of treatment (cm)	Mechanisms for soil treatment	Planting of seedlings (species, trees $\cdot ha^{-1}$)	Variant code
Cultivation	5-7	Disc cultivator	-	R
Ploughing	10-12	Two-blade plough	-	B
Ploughing	10-12	Two-blade plough	PiSy -5,000 QuRo – 2,100	K

Inventory of self-sown seedlings (age – 1-2 years) and young trees (3-15 years) was held on the reference strips 2.5 m wide and 20 m long each. Those were 5-10 reference strips evenly distributed across the plot. The inventory was held for 2-5% of the plot surface. In the process of accounting for undergrowth and self-sown trees, the species composition, origin, age, viability, density, and success of natural regeneration were determined according to the current scales (Pasternak 1990, Forester's Manual), amended and restated (Zhezhkun 2021). In particular, for the natural regeneration of 4-8 years old Scots pine, the amount of viable undergrowth (trees per 1 ha) is divided into following categories: "good" – more than 6,000, "satisfactory" – 3,000-5,999, "insufficient" – 1,000-2,999, "bad" – less than 999 (Table 3).

Permanent sample plots were laid in accordance with the requirements (Sample plots of forest inventory 2006) after the canopy in regenerated young stands got closed. The determination of taxation specifications of the stands within the permanent sample plots was carried out using officially adopted manuals and guidelines (Kashpor and Strochynskyi 2013). In the composition of stands, the admixture of arboreal species (3-5% of the standing volume) was marked with a "+" sign, and the admixture of 1-2% of the standing volume was marked with the "unit" index. The research materials were processed by applying mathematical and statistical methods using software Microsoft Excel (2019). We determined the probability of differences in the average amounts of undergrowth and self-sown individuals of tree species by experimental variants, and compared the amount of undergrowth and self-sown trees with the standards provided in the rating scale for assessing the success of natural regeneration.

RESULTS

The first cycles of gradual felling in pine stands were carried out in the period 2009–2014. The intensity of the first stage of GF was 122–223 $m^{3}\cdot ha^{-1}$ (30–52% of standing volume). The density of pine stands was reduced to 0.3–0.4. Given a successful mast seeding of Scots pine in the first year, 10,000–35,000 trees·ha^{-1} regenerated. For 4–5 years, the density of pine undergrowth was 8,000–20,000 trees·ha^{-1} and 2,000–9,000 trees·ha^{-1} of 1–2-year self-sown trees. The frequency of pine undergrowth occurrence was 73–84%, and the placement on the plots was uniform. During the final stage of GF, the preservation of undergrowth was 71–96%. The composition of young stands formed after gradual felling was dominated by Scots pine (Table 4). The canopy closure was 0.26–0.4, which indicated the formation of special forest environment (Shvidenko and Ostapenko 2001). The largest number of pine trees was observed on the experimental plots No. 2, No. 4 and No. 5 in dense bio-groups.

The share of deciduous species in young forest stands was 10–40%, which was sufficient for the formation of mixed stands of natural origin.

Table 3. Rating scale for natural regeneration success of tree species (Zhezhkun 2021).

Success category	Quantity of viable seedlings and saplings per 1 ha by age				
	1 year old	2 years old	3 years old	4-8 years old	0-16 years old
I. Good	> 40001	> 20001	> 12001	> 6001	> 4001
II. Satisfactory	26001 - 40000	10001 - 20000	7001 - 12000	3001 - 6000	2001 - 4000
III. Insufficient	15001 - 26000	6001 - 1000	3001 - 7000	1001 - 3000	501 - 2000
IV. Bad	< 15000	< 6000	< 3000	< 1000	< 500
Conversion factor to 4-8 years old	0.2	0.3	0.7	1.0	1.5

Table 4. Forestry and taxation indicators of young stands of natural origin formed after gradual and final clearcutting.

Plot No.	Felling type	Stand composition*	Average age (years)	Average height (m)	N (trees·ha^{-1})		Canopy density
					Total	Pine	
1	UGF**	7PiSy1PoTr1BePe1QuRo	5	1.0	11,700	7,600	0.30
2	UGF	8PiSy1BePe1QuRo	6	1.4	15,700	12,900	0.34
3	UGF	6PiSy3BePe1QuRo	7	1.8	6,300	4,600	0.26
4	UGF	7PiSy2BePe1PoTr+QuRo	7	1.7	25,900	17,900	0.40
5	UGF	9PiSy1BePe+QuRo	7	1.8	17,500	15,700	0.36
6	CC***	5PiSy3PoTr2BePe+QuRo	5	0.7	11,400	5,400	0.40
7	CC	10PiSy+BePe,1Potr	6	1.0	11,400	10,000	0.30
8	CC	7PiSy3BePe, 1QuRo	7	1.4	7,100	4,900	0.30

* BePe – *Betula pendula* Roth., PiSy – *Pinus sylvestris* L., PoTr – *Populus tremula* L., QuRo – *Quercus robur* L.
** UGF – uniformly gradual felling
*** CC - clearcutting

Satisfactory regeneration of Scots pine occurs after final clearcutting with soil mineralization of 50–60% of the plot area (plot 6). The proportion of deciduous species increases up to 50% from the density of a 5-year-old stand. Pine trees are suppressed by common aspen *(Populus tremula* L.*)* and silver birch *(Betula pendula* Roth.*)*, and this situation requires tending interventions. On the plots 7 and 8, most of the natural regeneration of pine (83–92%) is located in former plough furrows, 1.4 m wide, laid at a distance of 2.5 m. The availability of deciduous species among the young stand composition will enable to form natural pine stands of mixed composition.

Intensity of the stage of transformation logging cycle carried out within the sections in 2009–2010 was made up from 53 to 105 $m^3 \cdot ha^{-1}$ or from 16.8 to 40.2% of the standing volume. On average, the felling intensity compared to the standing volume on the plot was 71.2 $m^3 \cdot ha^{-1}$ or 24.1%, which corresponded to the standard provided by the Regulations on Improving the Quality Composition of Forests (CMU 2007). Given the average yield of Scots pine mast in the first year, 3,300 to 60,500 seeds$\cdot ha^{-1}$ of self-sown trees regenerated in the gaps. Even in the variant that does not involve assistance to natural regeneration in Section 1, the density of 1-year old self-sown pine was 11,600 trees$\cdot ha^{-1}$, which was explained by partial mineralization of the soil during felling operations. In variants that involved planting of pine and oak trees during the first year, the survival ability was 77–94%.

Over the next 5 years, the density of natural regeneration of Scots pine on the plots with furrows was 9,500–21,000 trees$\cdot ha^{-1}$. In variants where the soil was leveled with a cultivator, the density of natural pine regeneration was slightly lower than 7,500–18,100 trees$\cdot ha^{-1}$. On the plots without assistance to natural regeneration, the success rate of natural pine regeneration was satisfactory as well (2,500–6,000 trees$\cdot ha^{-1}$). In the variants that envisaged planting of pine and oak trees, the density was 3,400–6,900 trees$\cdot ha^{-1}$ and the natural regeneration of pine was 1,100–9,600 trees$\cdot ha^{-1}$.

The most successful natural regeneration after the first cycle of transformation logging operations was observed within the gaps whose diameter is equal to the stand's height (Section 2) and on one height of the stand with thinning on the forest regeneration site (0.5 of the gap diameter) with the density of 0.4 (Section 4). On such plots, subject to partial tending of the soil with furrows, the amount of natural regeneration of pine when applying the conversion factor to 4 - 8 years old amounted to 14,100–21,300 trees$\cdot ha^{-1}$, and in case of cultivation with the cultivator, 11,100–12,000 trees$\cdot ha^{-1}$.

Stands in the Sections 2, 3, and 5 were damaged by heavy wind storms in the summer of 2014. It should be mentioned here that the most significant increment and the smallest die-off compared to the standing volume was observed during 5 years after the first cycle of transformation logging on the Sections 2 and 4 (respectively: 37.4 $m^3 \cdot ha^{-1}$ and 43.0 $m^3 \cdot ha^{-1}$, and 15.9 $m^3 \cdot ha^{-1}$ and 0 $m^3 \cdot ha^{-1}$), compared to Sections 3 and 5 with the gap size of 1.5 of the average stand height (26.7–32.9 $m^3 \cdot ha^{-1}$, and 21 and 18 $m^3 \cdot ha^{-1}$). In Sections 3 and 5, the mortality exceeded the indicators of the current periodic change in the standing volume after the 1st felling cycle. Therefore, in order to maintain the biotic stability of pine stands intended for transformation felling, the diameter of a gap should be limited to one average height of the stand. Dead trees were removed by selective sanitary felling in 2014.

The regeneration of tree species occurs not only in the gaps formed in the first cycle of transformation felling, but also between the gaps and under the stand canopy (200–600 trees$\cdot ha^{-1}$). Reforestation in the sections took place not only with Scots pine, but also with tree species that were not desirable for restoration (common aspen (*Populus tremula* L.), goat willow (*Salix caprea* L.), silver birch (*Betula pendula* Roth.) and others). To improve the vegetation conditions for the pine trees in previous years, grass cover and unwanted tree and bush species were cut down with a bush cutter.

The second cycle of transformation felling was implemented in 2016, and the measures to assist regeneration were carried out in the spring of 2017. The felling intensity in the sections was 52–105 $m^3 \cdot ha^{-1}$ or 21–37% of the pine stands' standing volume. Simultaneously with the clear-cutting elements, the undergrowth and young tree stands were thinned on the plots where the previous felling cycle had been held. All undesirable trees and shrubs that shaded the Scots pine and common oak trees were removed. During the period 2017–2020, the standing volume increment decreased to 7–15 $m^3 \cdot ha^{-1}$ (mortality - 1–2 $m^3 \cdot ha^{-1}$) compared to the period after the 1st cycle of felling, which was explained by a decrease in the density of thinned stands. The amount and success of regeneration within the sections during 2017–2020 was different (Table 5).

Section 1 with plough furrows is dominated by natural regeneration of pine trees aged 4-8 years. The regeneration of 1-2-year self-sown trees took place. Therefore, the success rate of regeneration is good. In the variant that envisaged cultivation of soil with a disk cultivator (1-C), the density of pine is slightly lower than in the variant 1-F. A certain obstacle to regeneration and growth of self-sown pines is competition with abundant ground cover. The success rate of natural regeneration of Scots pine is satisfactory.

In Section 2, in the variant with the creation of forest plantations (2-P), the success rate of regeneration has improved over 5 years and is estimated as good (see Table 4). Other variants were also characterized by the improvement in regeneration success (mostly up to the satisfactory rate). In the variant with thinning operations held at a wrong time (2-C), regeneration is rated as insufficient. In the variant with natural regeneration 2-NR (without any human assistance), its success rate has somewhat improved, but is still insufficient.

In Section 3 during 5 years after the 2nd cycle of transformation felling operations, the regeneration progress has mostly been insufficient. Only in the section with the furrows (3-F) it is rated as satisfactory. The deterioration in regeneration success was due to a decrease in the amount of thinning and the dieback of Scots pine (especially in variant 3-NR without measures aimed at assistance to regeneration).

In Section 4, the regeneration progress is rated as satisfactory, except for the option 4-C with cultivation of the soil with a disc cultivator. Deterioration in the regeneration success also occurred due to insufficient treatment for high value species.

In Section 5, with the largest diameter of gaps, the regeneration progress is rated as satisfactory given all the needed assistance and control. This fact is explained by preserving the pine undergrowth, which appeared in the

Table 5. Number of trees of natural and artificial origin that regenerated after the second cycle of transformation felling in 2017-2020.

Section and variant No.	Amount of natural common pine regeneration by age (trees·ha^{-1})					Density of artificial regeneration (trees·ha^{-1})		Regeneration rating
	1	2	3	4-8	Total	Pine	Oak	
1-C	–	670	260	3,970	4,900	–	–	satisfactory
1-F	200	4,000	510	8,900	11,610	–	–	good
2-P	–	–	210	4,850	5,060	2,800	–	good
2-NR	–	–	250	1,510	1,760	–	–	unsatisfactory
2-F	260	510	1,030	4,870	6,670	–	–	satisfactory
2-C	–	500	250	2,000	2,750	–	–	unsatisfactory
3-C	670	–	670	2,000	3,340	–	–	unsatisfactory
3-F	7,810	2,500	1,090	1,870	13,270	–	–	satisfactory
3-NR	5,000	–	–	400	5,400	–	–	unsatisfactory
3-P	670	1,330	130	400	2,530	130	–	unsatisfactory
4-F	2,870	1,380	1,250	3,500	9,000	–	–	satisfactory
4-C	750	–	500	2,000	3,250	–	–	unsatisfactory
4-P	960	340	–	1,580	2,880	1,230	620	satisfactory
5-P	2,420	1,900	530	100	4,950	3,210	–	satisfactory
5-F	4,500	1,400	900	2,800	9,600	–	–	satisfactory
5-C	1,670	–	–	4,000	5,670	–	–	satisfactory
5-NR	1,670	–	–	4,000	5,670	–	–	satisfactory

C – cultivation, F – Ploughing, P – plantations, NR – natural regeneration

regeneration strip after the first cycle of transformation felling. With an increase in the amount of pioneering regeneration and its preservation after the second cycle of felling, the amount of regeneration of softwood species decreases, which contributes to the successful growth of pine.

Thus, the best results of regeneration after the second cycle of transformation felling were obtained in the sections with the largest gap dimensions (1.5–2 height of the stand). The success of regeneration may deteriorate due to untimely thinning of pine and other valuable species.

The third stage of transformation felling was held in 2021. The logging operations intensity in the sections was 65–94 m^3·ha^{-1} or 28–45% of pine standing volume.

The first stage of transformation felling in 2009 resulted in the formation of 11-year-old mixed pine stands on the plots (Table 5). It is worth noting that in 2016, the second stage of restocking felling was followed by thinning of the young stands regenerated in the gaps from the first felling cycle. During the thinning operations, all the viable trees of Scots pine, common oak, European spruce, small-leaved lime were left untouched. The unwanted specimens of marginal species (silver birch, goat willow, aspen, and common hazel) were cut down. Individual specimens and groups of silver birch trees were left only in places where more valuable species did not regenerate. Therefore, the composition and structure of the newly formed young stands were somewhat different and depended on the success and abundance of regeneration with Scots pine and common oak, as well as on timely thinning.

11-year-old mixed pine young stands were formed on the plots after the first cycle of transformation felling operations carried out in 2009 (Table 3). It is worth mentioning that in 2016 in young stands regenerating in the gaps left from the first cycle of felling the thinning measures were implemented after the second cycle of transformation felling. During these thinning interventions all viable individual trees of Scots pine, common oak, Norway spruce (*Picea abies* (L.) Karsten), and small-leaved lime (*Tilia cordata* Mill.) were left. The unwanted trees of marginal species (silver birch, goat willow, aspen, common hazel (*Corylus avellana* L.) were removed. Individual silver birch trees and its groups were left intact only in the places without regeneration of more valuable species. Therefore, the composition and structure of the newly formed young stands were somewhat different and depended on the success and abundance of regeneration with Scots pine and common oak, as well as on timely applied thinning interventions.

In Section 1, with the removal of trees in the logging sites with the dimensions of 50×50 m (0.25 ha), Scots pine prevails in young stands in the variant with no assisted regeneration (1-NR). On some of the plots, the birch trees exceed the pines in height, which required regulating their interconnection by thinning. In a young stand characterized with high rates of standing volume, common oak trees (836 trees·ha^{-1}) are inferior in average height to almost all the other species (difference of 0.4–1.0 m or 21–52%). To form a mixed oak-pine stand with an admixture of small-leaved lime in a fresh oak-pine subor (forest on relatively poor soils, but with an increased forest-vegetation effect), it is necessary to undertake cutting of unwanted species. As a measure of treatment, the trees of marginal species that shaded common oak and Scots pine were removed during thinning.

Table 6. Forestry and taxation indicators of mixed pine stands formed after the 1st cycle of transformation felling operations.

Variant code	Composition*	Age (years)	Average height (m)	Average diameter (cm)	Sum of cross-sections (m²·ha⁻¹)	Density	N (trees ·ha⁻¹)	Standing volume (m²·ha⁻¹)
1-F	3PiSy6BePe1QuRo, singly PoTr, TiCo, AcPl	11	2.0	1.1	2.39	0.78	20 100	7.4
1-C	2PiSy6BePe1QuRo1PoTr	11	2.1	1.5	1.72	0.37	9 800	5.4
2-P	Forest crops 9 PiSy1QuRo Natural regener. 8 PiSy2 BePe, singly SaCa, QuRo, PoTr	11 11	2.7 2.8	2.3 2.5	1.20 2.47	0.31 0.48	3 620 21 377	3.3 7.1
2-NR	7QuRo1PiAb1PiSy1SaCa, singly PoTr, BePe	11	3.0	3.5	1.73	0.26	4 697	4.1
2-F	5PiSy4BePe1QuRo, singly SaCa, AcNe, PoTr	11	2.8	2.4	5.60	0.91	21 043	17.2
2-C	3PiSy4BePe3PoTr, singly QuRo, SaCa	11	1.6	0.8	0.63	0.17	11 500	2.0
3-1C	3PiSy5BePe1QuRo1SaCa, singly PoTr	11	2.2	1.7	1.61	0.43	10 856	4.8
3-2F	10BePe+QuRo, singly SaCa, PiSy, PoTr, MaSy	11	3.6	2.4	3.75	0.47	8 879	13.3
3-NR	4PiSy6BePe+ QuRo, singly PiAb, MaSy,PoTr, RoPs	11	2.6	2.1	2.69	0.38	5 434	8.5
3-P	Forest crops 9PiSy1QuRo Natural regener. 7BePe2QoRo1PiSy, singly PoTr	11 11	3.5 2.7	3.5 1.4	1.52 2.43	0.18 0.41	2 915 11 574	4.5 7.5
4-F	3PiSy3QuRo4BePe, singly PiAb, SaCa, PoTr	11	2.4	1.9	3.23	0.58	16 819	9.4
4-C	5PiSy3BePe1QuRo1SaCa, singly PoTr	11	2.3	1.8	2.21	0.52	10 715	6.9
4-P	Forest crops 10PiSy+QuRo Natural regener. 5PiSy3BePe2QuRo+SaCa, PoTr	11 11	3.5 2.8	3.6 2.4	2.96 2.06	0.33 0.39	3 968 12 221	7.7 5.8
5-P	Forest crops 8PiSy2QuRo Natural regener. 7BePe2PiSy1QuRo, singly PoTr	11 11	3.5 2.3	3.5 1.0	0.80 0.32	0.09 0.08	1 081 3 243	1.8 1.1
5-F	5PiSy5BePe+SaCa, singly QuRo, PoTr	11	3.2	3.0	2.10	0.38	9 257	5.7
5-C	6PiSy3BePe1QuRo+SaCa, singly PoTr	11	3.1	2.8	6.39	0.99	15 500	19.8
5-NR	7BePe1PiSy1QuRo1SaCa+PoTr, singly PyCo	11	4.8	4.0	6.24	0.79	7 332	22.3

* AcNe – *Acer negundo* L., AcPl – *Acer platanoides* L., BePe – *Betula pendula* Roth., MaSy – *Malus sylvestris* Mill., PiAb – *Picea abies* (L.) Karst., PiSy – *Pinus sylvestris* L., PoTr – *Populus tremula* L., PyCo – *Pyrus communis* L., QuRo – *Quercus robur* L., RoPs – *Robinia pseudoacacia* L., SaCa – *Salix caprea* L.. TiCo – *Tilia cordata* Mill.

In variant 1-F (assistance to natural regeneration by furrowing), the average height of Scots pine is 0.2 m (10%) less than that of birch. Birch (15,200 trees·ha^{-1}) and aspen (200 trees·ha^{-1}) trees inhibit the growth of Scots pine trees (3,900 trees·ha^{-1}) and common oak (500 trees·ha^{-1}). In order to regulate the interconnection between the trees in the stand, purging treatment is recommended.

In variant 1-C (cultivation of the soil with a disc cultivator), the share of Scots pine amounts to 22% of the young forest standing volume. Pine density (2200 trees·ha^{-1}) remains sufficient for the formation of pine with an admixture of common oak (800 trees·ha^{-1}). The dieback of pine trees has been detected (100 trees·ha^{-1}) due to the suppression of birch and aspen trees that require improvement felling.

In Section 2 with the size of gaps of 24 m in diameter, the highest rated regeneration progress was observed in the variant 2-P where pine and oak plantations were created. The number of pine trees of natural origin is 1.6 times higher than the density of planted stands with the same species, and not inferior in average morphometric indicators of height and diameter. Oak trees of both artificial (1 000 trees·ha^{-1}) and natural (520 trees·ha^{-1}) origin are inferior in average height to other species, and are suppressed by them. Thinning is recommended to regulate the interconnection between the trees. In the variant 2-F with furrow lying, the Scots pine also dominates in the composition of young stands. The share of Scots pine is somewhat small (30% of the stock) in the variant with soil cultivation (2-C). The interconnection between pine, oak and soft-leaved trees should be regulated via selection logging operations.

In Section 3 with a gap size of 36 m after the first felling cycle in the variant with soil cultivation (3-C), pine is inferior in terms of standing volume (31%) to birch (45%). The difference in the average height of the compared species is insignificant (0.2 m or 9% for birch), which is explained by timely maintenance. However, in the adjacent gap (3-F), birch is completely dominant. Pine showed poor regeneration success and died in the first years due to oppression by birch. The site also demonstrates the consequences of untimely treatment of high-value species (pine and oak density: 0.09 and 0.17 thousand pcs. ha-1, respectively). Even in the 3-NR variant which included natural regeneration (without any assistance to regeneration, but with partial removal of litter during skidding), the share of pine in the composition is 37% of the standing volume. The average height of a birch tree (5.5 m) is more than twice that of a pine tree, so tending logging operations are recommended. As in Section 2, the best composition in terms of high value species was found in the variant where pine and oak plantations were created (3-P). The availability of an admixture of pine and oak trees of natural origin in the composition of the young stands enables the formation of a stand of highly valuable composition and combined origin.

In Section 4, due to the size of gaps of 24 m in the diameter and the thinning operations held in the regeneration strip for all the variants, there is predominance of 11-year-old young stands of Scots pine and common oak. The largest number of pine trees of natural origin was preserved in variants with furrowing as a measure to assist the regeneration process (4-F) and in plantations (4-P). Timely held tending (improvement) felling may lead to the formation of young mixed pine stands of natural and combined origin.

In Section 5 with the diameter of gaps of 36 m and thinning being held in the regeneration strip for 11 years since the first cycle of restocking felling, the predominance of Scots pine in the composition of young stands was revealed in the variants with assisted regeneration using furrows (5-F), cultivation with a cultivator (5-C) and by establishing plantations (5-C). In this section, the average height of pine trees of natural origin is the highest compared to other sections. Only in the variant 5-NR without any assistance to regeneration, but with the partial removal of litter during skidding, the share of Scots pine is 11% of the standing volume. The composition is dominated by silver birch, which exceeds the average height of pine by 1.7 m (55%) and suppresses its growth. Therefore, assistance to the natural regeneration of Scots pine and common oak *(Quercus robur* L.*)* is the most important measure for the reproduction of high value forest stands.

Thus, during the period of 11 years after the first cycle of transformation logging, young pine forest stands of mixed composition both of natural and combined origin were formed on the sections. The standing volume of young stands ranges from 2 to 22 $m^3 \cdot ha^{-1}$, and the average increment is 0.2-2.0 $m^3 \cdot ha^{-1}$. The density of young stands is different, ranging within 0.17–1.03, which is explained by different rates of regeneration progress and preservation status of the trees of the main forest-forming species, as well as timely held felling treatment aimed at forest stand improvement.

After the second cycle of transformation felling, pine and oak regeneration progress in the variants with assistance to natural regeneration and establishing plantations is mostly satisfactory, and in the sections without assistance it is insufficient. The success of the main forest-forming species preservation and forming young forest stands will also depend on the timely held tending operations - improvement felling.

After the third cycle of the transformation felling, the best rate of the natural regeneration was observed in Section 1 in the variant with natural regeneration (1-NR). As of 18 October 2021, the density of annual self-seeding of Scots pine was 10,800 trees·ha^{-1}, aspen – 10,000 trees·ha^{-1}, and goat willow – 6,000 trees·ha^{-1}. Individual common oak and white birch were found in the admixture. Regeneration success rate was good. In other variants an additional clearing of logging sites, combustion of logging residues, implementation of measures to promote the restoration of pine and oak were ongoing during the study.

Until the final fourth stage of restocking felling is carried out, the increment will increase for the young stands on the sections used in the previous cycles. Gradual regeneration will enrich the age diversity and preserve the biotic diversity. The combination of elements of final felling for the older generation of pine stands and the improvement felling operations for the valuable tree species of the new generation meets the principles of comprehensive logging.

Comprehensive transformation logging gradually converts an artificial even-aged weakened pine stand into a stable uneven-aged mixed pine forest stand of natural origin, which is coherent with the principles of close-to-nature forestry. After the completion of the transformation logging cycle, it is recommended to recreate a stand with the following structure: 70–80% of Scots pine, 10–20% of common oak, 10–20% of associated species, aged 3–20 years, with a cascade profile of the canopy (due to gradual regeneration within the gaps), and homogenous distribution of the trees within the site.

DISCUSSION

Forest management should ensure the continuous existence of forest cover. In the mature forest stands in Ukraine, four systems of final felling are currently utilized (State Forest Management Committee of Ukraine 2010) (Figure 1).

The most common is the final clearcutting system. Gradual felling may be carried out in the pine stands on 20–30% of their area (Vedmid et al. 2008, Zhezhkun 2021). Selective felling operations are carried out in uneven-aged stands (Tichonov et al. 2000, Krynytskiy et al. 2012), but their area in the Polissia region of Ukraine is restricted (Hensiruk 2002, Vedmid et al. 2008). The combined logging system that unites different types of final felling is rarely used (Tokarieva 2021).

When implementing different felling systems, one should apply fireless methods of clearing felling sites. In particular, in dry and fresh hygrotopes, it is advisable to shred the logging residues and coat the soil to provide shade from the direct light, and in wet and damp hygrotopes – to leave them to decay. Fire safety measures are used to prevent fire. It is allowed to process large-sized felling residues into technological chips for further sale, but the thin branches should be left to decay so that the soil fertility and biodiversity are ensured.

After logging and purging activities are carried out, measures are taken to promote the regeneration of high-value species. The viable undergrowth of Scots pine, Norway spruce (*Picea abies* (L.) Karst.), common oak, common ash (*Fraxinus excelsior* L.) and other species has to be preserved. To facilitate the natural regeneration process of the valuable species, the soil is mineralized prior to the mast year by cultivation with disk cultivators and harrows, and by plowing furrows. According to the studies, the share of soil mineralization for a successful natural regeneration should be more than 60% of the site area. In the years with poor seed yield, seeds of the main forest-forming species are sown (in particular, common pine – 1 kg·ha^{-1}). In case of

Felling systems	Cleaning the logging sites from felling residues	Measures to assist forest regeneration	Forest regeneration system
• Gradual • Selective • Clearcutting • Combined	• Soil crushing and covering with soil • Retention for decay • Processing and removal	• Undergrowth preservation • Soil mineralization • Soil cultivation • Artificial sowing of tree seeds	• Natural forest regeneration • Artificial forest regeneration • Combined forest regeneration

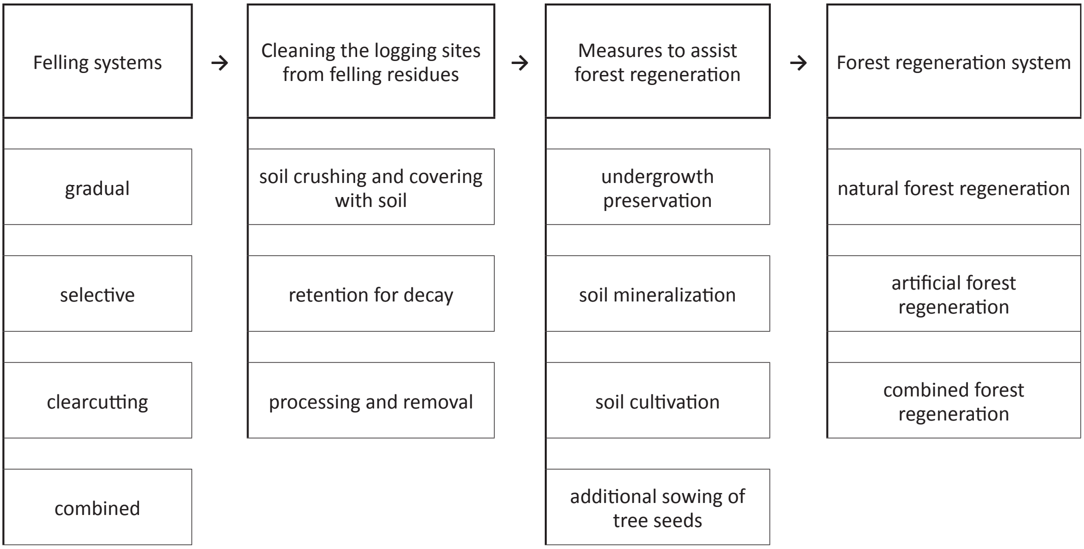

Figure 1. Final felling and forest regeneration systems for close-to-nature forestry.

the impossibility to ensure natural regeneration, the soil is cultivated for artificial reforestation.

In the pine forest stands, the most effective measures to ensure natural regeneration are as follows: the uniformly-gradual logging, gradual logging in strips, gradual felling in groups, and clearcutting in strips. In the pine forests of fresh and wet subors (on poor soils), after the double-stage uniformly-gradual logging, from 8,000 to 20,000 trees·ha^{-1} of 4–5 year-old Scots pine trees are regenerated, which is sufficient to form the high-value forest stands. During the 4–5 year cycle of the uniformly-gradual logging operations, the undergrowth is preserved, so the pine and other species regenerate simultaneously, which contributes to the formation of relatively uneven-aged stands (Figure 2).

After the strip-shaped gradual logging and clearcutting on the logging sites up to 80 m wide, the successful regeneration of Scots pine (density of 5,000–10 ,000 pcs.·ha^{-1}, which allows to schedule the adjacent logging sites for felling in 4–5 years) has been ensured. However, in the context of close-to-nature forestry, the scope of clear-cutting should be reduced, in accordance with the studies (Tokarieva 2021), and the area of the logging sites should be limited to 0.5–1 ha. If the undergrowth is unevenly distributed, then successful natural regeneration process occurs after three rounds of gradual felling by groups (Zhezhkun 2021). In addition to Scots pine, the natural regeneration involves common oak, silver birch, and small-leaved lime trees, which will facilitate the onset of the mixed stands with high biotic stability and productivity.

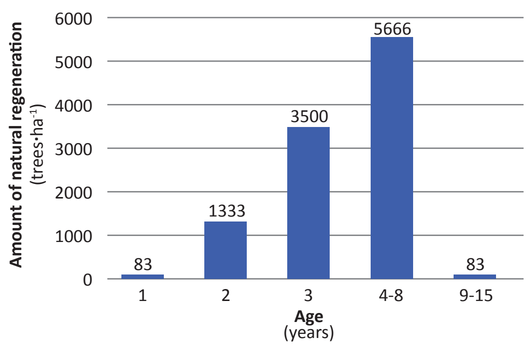

Figure 2. Age structure of the undergrowth and self-sown trees of Scots pine 2 years after the final stage of UGF (compartment 40, sub-compartment 10 of the Horodnianske Forestry Unit, Chernihiv region).

Artificial regeneration is carried out only in case of poor natural regeneration of high-value tree species. The development of forest cultures is carried out by planting trees or sowing seeds of either principal or related species to form mixed biologically resistant stands.

Given the partial retention of trees from natural regeneration of the forest, the vacant areas within the plots are planted or sown with trees for the combined forest stands' regeneration process.

In the process of stand development, the internal relations between the trees are regulated by tending felling operations (Figure 3).

Improvement felling is carried out in order to shape the species composition, regulate the density, enhance the ecological conditions for the chosen trees, increase sprouting, as well as improve marketability, and other quality indicators of the remaining trees (Cabinet of Ministers of Ukraine 2007). In particular, canopy opening interventions are carried out in young stands up to 10 years of age to create the desired composition and density of the stand. Early thinning is carried out in young forests of 11-20 years of age to ensure the composition and homogeneous distribution of the main forest-forming species of trees over the site, to shape the optimal structure of the future forest stand, and to regulate the quantitative ratio of individual tree species. In the middle-aged stands, thinning is carried out to maintain the shape of the trunk and crown of the finest trees, while severance felling is conducted to increase the increment of the best trees, improve their marketability, and enhance the resilience of the stands.

Depending on the age, composition, and density, moderate or high intensity improvement felling operations are performed. Untimely maintenance or poorly-performed improvement logging leads to the development of secondary stands with the predominance of species that do not meet forest vegetation conditions or, conversely, stands of homogenous composition characterized by low biotic stability originate. It is possible to correct the secondary and low-value young forest stands by reconstructive logging: introducing the main forest-forming species into their composition and maintaining them using the developed technologies (Zhezhkun 2021). It is important to note that in previous years, the research area was dominated by the development of pure monocultures of Scots pine, Norway spruce, common oak, etc. (Zhezhkun 2021).

The resulting mono-dominant even-aged stands have low biotic stability and in years with unfavorable factors are affected by pests and diseases. They are also subject to massive drying-out and decline. The transformation of pure even-aged cultures into mixed stands of diverse age groups is carried out via transformation logging. At the age of maturity of such stands, the forest restoration felling is carried out.

To ensure timely recovery of the forest stands, the removal of the trees freshly invaded by pests and the placement of trapping trees is applied. In particular, placement of trapping trees is carried out by cutting down and leaving seriously weakened trees of a certain species on the site, which are used as traps for bark beetles, and then removing them from the forest. In case of stand disruption due to the damage caused by squally winds, snow storms, fires, etc., felling is carried out to localize and eliminate the consequences of the disasters. In particular, logging of large burnt areas refers to logging on sites with an area of more than 5 hectares, where stands were destroyed by a forest fire.

Close-to-nature silviculture in forests of different functionality and purposes has its own peculiarities. In forests of high nature conservation value, the system of measures of close-to-nature forestry should be aimed at strengthening the conservation functions of reserves, sanctuaries and other protected areas. In the case of protective forests, it should be aimed at improving water-regulating and soil-protective properties. In recreational forests, the aim is to increase the attractiveness of forest and park landscapes while maintaining the biotic stability

Tending logging systems	Sanitation felling systems	Transformation and reforestation felling systems	Felling systems to mitigate the consequences of calamities
Canopy opening	Felling of the trees with early signs of pest invasion	Transformation felling	Logging of windthrow / windstorm sites
Clearing (?)	Laying trapping trees	Transformation felling	Salvage logging and clearance on wildfire sites
Thinning	Selective sanitary felling	Reconstructive felling	Felling of the stands destroyed by forest pests and diseases
Severance felling ?			

Figure 3. Felling systems for the development, improvement and regeneration of forest stands.

of the stands. In commercial forests, the close-to-nature forest management should be aimed at ensuring high productivity, preserving the biotic stability of the stands and their habitat-forming functions. Felling and other activities are carried out with the least interference of machinery and mechanisms in the forest ecosystems. To maintain biodiversity, it is necessary to leave some old trees with a long lifespan, individual dead trees, and forest litter to mimic the processes in natural forests.

CONCLUSIONS

The research was conducted by means of experimental felling operations and other activities related to close-to-nature forestry; the most effective variants were identified, and the following conclusions were reached.

- Close-to-nature forestry includes a system of institutional and forestry activities aimed at restoring and developing resilient, multi-age, complex forest stands with a mixed composition both of natural and combined origin.
- In mature pine stands, after the first round of uniformly gradual felling with a decrease in density up to 0.3–0.4 (* ratio of the sum of tree crown projections to the occupied area) and measures to promote natural regeneration, within 4–5 years, the density of pine undergrowth was 8,000–20,000 trees·ha^{-1} and there were additionally 2–9 thousand units ha^{-1} of 1–2 year old self-seeding trees with uniform distribution on the plots. During the final cycle of uniformly gradual felling, the preservation of the undergrowth was 71–96%. At the age of 5–7 years, the mixed relatively uneven-aged pine young forest stands are developed.
- After stripped-coupe felling in pine stands of fresh and moist pine forests on sandy soils as well as after soil mineralization, the natural regeneration of Scots pine is satisfactory, and during 5–7 years the mixed young stands of pine are developed with the canopy closure of 0.3–0.4. (* ratio of the sum of tree crown projections to the occupied area).
- Conversion of artificial, even-aged and weakened pine stands of pure species composition into resilient mixed relatively uneven-aged forest stands is carried out by means of transformation logging operations with gradual removal of individual trees and their groups to create proper conditions for the regeneration of high value species and development of the next forest generations.
- After carrying out the two cycles of transformation felling (complete course – 4 cycles) in the maturing artificial weakened pine stand of fresh oak-pine subor, repeated every 6 years, the mixed young pine stands of natural and combined origin have been developed after 11 years. In the gaps after the first cycle of transformation felling and implementation of restoration measures, the 11-year-old young mixed pine stands were formed with a share of Scots pine reserves from 2 to 9 trees in the composition. Somewhat worse regeneration was observed in the variants without any assisted regeneration (e.g. no sowing or planting), and provided that tending felling was not carried out in a timely manner. In 4-5 years after the second cycle of transformation felling, the regeneration performance was from 2,000 to 19,000 trees·ha^{-1} of undergrowth and self-sown pine trees (the success rate of regeneration is estimated as good and satisfactory).
- To ensure the continuous forestry cover, it is advisable to use the final felling systems for the forest cover restoration, as well as felling systems aimed at improvement, regeneration and regeneration of the forest stands in the context of close-to-nature silviculture and sustainable forest management.

Author Contributions

AMZ: study conception and design, data collection and processing, models derivation, data analysis, writing of the manuscript (original draft). SK: data collection and processing, methodological discussions, writing of the manuscript (editing). IP: data collection, writing of the manuscript (editing). IK: writing of the manuscript (editing). TM: data collection and processing, checking and editing the references.

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Conflicts of Interest

The authors declare no conflict of interest.

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