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MODELLING OF SECONDARY EVEN-AGED NORWAY SPRUCE STANDS CONVERSION USING THE TREE GROWTH SIMULATOR *SIBYLA*: SE "RAKHIV FORESTRY" CASE STUDY

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Abstract: *The multifaceted phenomenon of climate change and increased human activities of the Anthropocene induce significant losses. Especially, the ecological resilience of secondary even-aged Norway spruce and require of their conversion into mixed uneven-aged ones. This study modelled and analyzed conversion of such stand under conditions of the State Enterprise "Rakhiv Forestry", Transcarpathian region, the Ukrainian Carpathians, using the tree growth simulator SIBYLA. The analysis of collected data showed that application of only two of the four proposed conversion strategies (S3 and S4) allows us to get a target tree species composition with a sufficient height and diameter diversity. That was confirmed by a set of indicators for tree species and structural diversity of the study forest plot.*

Keywords: *forest conversion, secondary even-aged Norway spruce stands, State Enterprise "Rakhiv Forestry", tree growth simulator SIBYLA.*

1. Introduction

The multifaceted phenomenon of climate change poses forest ecosystem at threat and forces us to reexamine the effectiveness and efficiency of a forest decision-making in the past. As time has gone by, the secondary even-aged Norway spruce (*Picea abies* (L.) Karst.) forests, established in the 19th century for economic reasons across Europe on the sites that were previously naturally dominated by broadleaved- or coniferous-broadleaved forests, has turned out to be less resistant to ambient conditions as compared to their natural predecessors [20], [38]. Under the synergy of changing natural conditions and increasing

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anthropogenic pressure, the replacement of natural mixed forests by spruce monocultures led to a degradation of these forest stands, loss of forest functions and ecosystem services, biodiversity and, as a result, worsening the welfare of forest-dependent communities [41]. Complex nonlinear behavior of forest ecosystems, which causes their weak response until these systems transgress the thresholds and their collapse becomes obvious and unavoidable [32], aggravates the situation and puts the conversion dilemma into a focus of adaptive forest management [26].

In the Ukrainian Carpathians, more than 1800 km^2 of even-aged spruce forests were established on the sites naturally dominated by beech (*Fagus sylvatica* L.) and mixed coniferous-broadleaved forests [37]. The first signs of these forests decline appeared over the last two decades [15]. Currently, a massive dieback is observed on the area of 193 km^2 (or 10.5% of the total area of the secondary forest stands in the Ukrainian Carpathians) with a timber volume of nearly 6 million m^3 [27]. Therefore, to create biologically stable and productive forest ecosystems, to strengthen their ecological and social functions, it is necessary to carry out a set of changes in the tree species composition and age structure, using principles of close-to-nature forestry [15], [22-23].

Conversion of such modified forest ecosystems into mixed uneven-aged ones is internationally thought as an urgent and imperative measure [1], [22-23], [27]. Spiecker et al. (2004) [38] advanced two main arguments which confirm the need for secondary spruce stands conversion. Firstly, with a growth of life quality for a long time, society is becoming more and more interested in the numerous and diverse ecosystem services. Secondly, forest management practices applied in the secondary spruce forests in the past decades have currently become unacceptable, as they face serious threats in terms of increasing the risks of natural disasters and the spread of pathological processes. Comparative evaluation of forest ecosystem service flows also revealed that mixed forests are thought to be providers of better and richer flows of ecosystem services compared to the flows generated by spruce monocultures [42]. Although the conversion of spruce monocultures is a research topic of increasing relevance in the Anthropocene era, only little is known about its long-term ecological and economic consequences, preferable conversion regimes and strategies on the territory of the Ukrainian Carpathians.

In scientific literature, two terms are used to define the process of change tree species composition and age structure: "conversion" and "transformation" [13], [24-25], [38]. We conduct our research considering secondary even-aged Norway spruce stands conversion as changes in the tree species composition like natural stands and change of the age structure from even-aged to uneven-aged.

Rapid development of software tools for forest ecosystem modelling [8], [14], [40] allows us to predict a broad range of stand parameters after the application of different types of forest cutting and, thus, to choose the best strategy for forest management that will satisfy the target goal. However, the search for the literature on the conversion of forest stands has revealed only a few studies [2], [5], [24], [26], [35], [39-40] which use the software for a simulation of the conversion processes. No data have been found about similar research in the Ukrainian Carpathians. However, these quantitative data are essential for adaptive management of secondary spruce stands and further economic analysis of forestry activities related to their conversion.

The objective of this study is to develop and test four strategies for secondary even-aged Norway spruce forests conversion into mixed uneven-aged ones under conditions of the SE "Rakhiv Forestry" (SERF), Transcarpathian region, the Ukrainian Carpathians using tree growth simulator SIBYLA [8]. The paper consists of three main parts. In the first part, the design of conversion regime and strategies was performed. In the second part, calibration of SIBYLA to minimize the differences between the simulated and observed value in the SERF was done. In the end, the conversion strategies were tested using silvicultural, economic and ecological diversity criteria to choose the best one for application under the SERF conditions.

2. Materials and Methods

2.1. Study Area and Data Collection

The study area (SERF) is located in the Transcarpathian region, in the Ukrainian Carpathians. The SERF occupies 39.183 ha mainly in a mountain rural area which is represented by the slopes of different exposures and inclinations. The elevations range from 500 to 1800 m. The area of the SERF is divided by narrow valleys formed by the Chorna (Black) and the Bila (White) Tysa rivers into three mountain ranges:the Svydovets, the Chornogora, and the Maramorosh. The forests on the territory of the enterprise are represented mainly by highly productive stands of Norway spruce (*Picea abies* (L.) Karst.), European beech *(Fagus sylvatica* L.*)*, Silver fir *(Abies alba* Mill.*)* and in mixture with valuable species such as Sycamore maple *(Acer pseudoplatanus L.)*, Elm *(Ulmus glabra* Huds.*)*, European Ash *(Fraxinus excelsior* L.*)* and others. 78.5% of the total forest area belongs to different categories of protection zones and 21.5% belongs to the commercial forest category. The average growing stock of forests is 370 m^3 / ha with an annual increment of 6.0 m^3 / ha / year.

The climate is temperate with a moderate continental influence. The average annual precipitations range between 750-1500 mm and the average temperature is from +20 °C to 6 °C in summer and from -3 °C to -10 °C in winter.

Currently, 600 ha of the SERF is damaged by *Heterobasidion annosum*. Therefore, foresters focus their attention on the conversion of these secondary stands into similar to natural mixed ones, with the goal to increase the productivity, resilience and resistance of these stands to climate change and destructive human praxis.

Initial data on the study forest plot were collected using the forest-inventory database of the SERF. The plot with an area of 1 ha is located at elevation 650 m. In the initial stand state dominated by a 62-year-old spruce (90%) and the rest a scattered natural regeneration of 10-year-old fir (160 trees), beech (113 trees), and sycamore (113 trees).

The stem distribution has a wide diameter range of the class between 16 and 32 cm and has a form similar to a bell-shaped distribution. The density of the plot is 0.6 with a growing stock of 302 m^3 / ha. The mean height is 23 m and the mean diameter – 23 cm. The number of stems is 740 / ha with a basal area of 29.7 m^2 / ha.

According to the inventory data of the SERF, a 15% of all spruce trees are die-back. The existing tree species composition of the site does not correspond to the natural one, which is considered as 70-75% of spruce and 25-30% mixture of beech, fir and sycamore.

2.2. Design of the Conversion Regime and Strategies

We modelled the conversion process combining two silvicultural procedures – selective thinning (ST) and target diameter harvest (TDH) (Table 1) – to achieve uneven-aged (heterogeneous vertical structure) mixed stand (heterogeneous horizontal structure) relying on natural regeneration.

ST was modelled for promote natural regeneration (160 future trees for fir and 113 for beech per ha) using the factor A as a proportional factor fixing the intensity of thinning. The A-value defines an intensity of a competition of a central tree through a defined neighboring one by means of measured data (distance among the trees, their height, and diameter). The smaller value of A, the more intensive thinning and more space to grow will be given to the selected future trees [8]. The A-value was set to 4, representing an intensive thinning.

Procedures for a secondary Norway spruce stands conversion Table 1

Procedure	Action	Control-parameters	Value
ST	future crop trees favoured using the A-value	A-Value N future crop trees	4 160 / ha for fir 113 / ha for beech
TDH	a defined percentage of trees that has reached the fixed target diameter is cut	Target diameter Maximum cutting rate	40-45 cm 70%

The second procedure is a method of TDH (rotation dimension). For every tree the score of existence and target removal percentage were calculated. The principle of this variant calculation is that the percentual number of trees $(\%d\max)$ with the diameter greater than or equal to $d\max$ should be felled. Hence, the treatment intensity (Np) depends on the number of trees that reached or exceeded the target diameter $d\max$ $(n(di \geq d\max))$ and the percentage of removed trees $(\% \approx \max)$:

$$Np = \frac{\% d\mathrm{max}}{100} \times n\left(di \geq d\mathrm{max}\right) \tag{1}$$

Afterwards, all trees were divided into two groups. The first group consisted of the trees with the diameter smaller than $d\max$, while the second – greater than $d\max$ [8]. The trees in the second group were ranked according to the value of existence score. The required number of the trees with the lowest score was removed from the simulation model. The application of variable TDH procedures for different periods of the conversion provides a vertical differentiation within the simulation stand. The diameter of the harvested trees was fixed on 40 cm at the beginning of the simulation and 45 cm was applied at the end of the conversion.

Combining proposed procedures in Table 1 and based on a hierarchy of conversion objectives proposed by Schutz (2001) [34] and the conversion approaches proposed by Hanewinkel and Pretzsch (2000) [14], Hanewinkel (2001) [13] four conversion strategies were developed (Table 2). Also, recommendations of Krynytskyy and Chernyavskyy (2014) [22] for conducting secondary spruce stands conversion in the Ukrainian Carpathians were used, namely: (1) such conversion can last for 60-80 years; (2) ST for fir and beech should be carried out at the age of 30-50 years; (3) during ST a predominantly moderate degree of thinning (16-25% for the stock) should be practiced; (4) ST needs to be combined with TDH.

Conversion strategies for the SERF case study Table 2

Period of conversion (age of spruce)	Conversion strategies $Si_{(i=1:4)}$			
	S1	**S2**	**S3**	**S4**
1 (62)	TDH 40 cm for spruce			
2 (72)	TDH 40 cm for spruce			
3 (82)	ST for beech and fir for all strategies TDH 40 cm for spruce			
4 (92)		TDH 45 cm for spruce		
	TDH 40 cm for sycamore			
5 (102)				
6 (112)				TDH 45 cm for spruce
7 (122)				
8 (132)			TDH 45 cm for spruce	
	TDH 40 cm for sycamore			
9 (142)	The end of conversion			

From the very beginning (from the 1st to the 3rd simulation periods) for spruce trees the TDH of 40 cm was applied in all strategies. Later on, from the 3rd to the 7th simulation periods, for all the conversion strategies we applied ST for 30-year-old beech and fir trees to promote a natural regeneration of these tree species. For all the conversion strategies we also applied TDH for sycamore 40 cm in the 5th and in the 8th conversion periods.

For the conversion strategy S1 any other conversion procedure was not applied. In the conversion strategy S2, TDH of 45 cm for spruce in the 5th simulation period was applied. For the conversion strategy S3, the TDH for spruce 45 cm was applied in the 5th and 8th simulation periods. And for the conversion strategy S4, TDH for spruce was applied in the 7th simulation period. The duration of a simulation period is 80 years.

2.3. The Tree Growth Simulator SIBYLA

For modelling and analyzing the conversion strategies $Si_{(i=1:4)}$, during the conversion of the study forest plot, the tree growth simulator SIBYLA [18] as an empirical, individual-tree-based, distance-dependent forest growth and yield model was applied. This model is built on the SILVA 2.2 modelling principles [29], but it has more advantages of thinning model compared to the SILVA model [9] and allows modelling of even-aged and uneven-aged stands, pure as well as mixed stands with variable stand structures [10].

The SIBYLA model requires input data at the level of individual trees, but also allows application of stand data with an aid of effective structure generator [8]. The data on the mean diameter, mean height and basal area, or the stock for individual tree species were used in the case study of the SERF as a minimal set of input data. Input data at the level of individual trees are needed to achieve simulation accuracy, but averaged information about the forest stand is also suitable for operational practice [10].

2.4. Calibration of SIBYLA for the Case Study in the Ukrainian Carpathians

An incremental model of forest growth simulator is based on ecological site classification [19] which relies directly upon the climatic and soil characteristics of a site: the content of CO_2 and NO_x in the atmosphere, supply of nutrients in the soil, the length of vegetation period, average temperature during the vegetation period, annual temperature amplitude, total amount of precipitation during the vegetation period, relative soil moisture content and aridity index. These factors enter the dose and response functions. They are constructed based on ecological studies. The results of the functions are reduction factors which are aggregated into a nutritional, thermal and humidity indices [10]. For adapting the increment functions of the simulation model to real conditions of the SERF, eight abovementioned factors in LOCALIZER module of SIBYLA were adjusted for simulation of the study forest plot.

Annual data on climate conditions were obtained from the Rakhiv meteorological station. Tree diameter and height data from the yield tables, developed for the Ukrainian Carpathians [12], were used for calculation of correctors for diameter and height increments in CALIBRATION module of SIBYLA. These model calibrations allowed us to ensure the accuracy of the simulation and minimize the differences between the simulated and observed data on the study forest plot.

2.5. Criteria for Choosing an Optimal Conversion Strategy for the Study Area

To choose the best of four proposed conversion strategies under SERF conditions, three criteria which reflected silvicultural, economic and ecological parameters were selected. Appropriate indicators have been chosen for these criteria which the SIBYLA model provides.

The silvicultural criterion of the conversion process was described by desirable tree species composition, dynamics of stand volume and stem distribution.

To follow an economic criterion, such indicators were selected as a stand volume, an assortment structure and the total costs for a stand thinning.

In SIBYLA model, the total direct costs (F) for thinning include total payroll (Fp), material (Fm), and social welfare costs (Fs):

$$F = Fp + Fm + Fs = NC \times V \times T + Vy \times \times NC \times KJMP \times M \times Vr + NC \times V \times T \times \times KMOSP, \text{ [Eur/ha]} \quad (2)$$

where: NC – final man-time; V – tree species volume, m³; T – wage tariff, EUR/h^{-1}; Vy – yarded volume; $KPMG$ – man-time of the given activities is reduced by the reduction coefficient of compensation for the chain-saw; M – multiplied by the material costs per man-hour; Vr – realized volume; $KMOSP$ – coefficient of funds contribution.

The ecological criterion includes the set of indicators to show the change in biodiversity, which is measured by a species and structural diversity (Table 3) and a total diversity index.

Set of indicators for measuring changes in biodiversity Table 3

Indicator, source		Essence	Formula	The value range
Set of indicators to measure a species diversity				
Species richness:	- Index $R1$	derived from the number of tree species (m) and the number of trees per ha (N)	$R1=\frac{m-1}{\ln(N)}$	The value ranges from 0 to 1: 0 – stands with the minimum tree species diversity; 1 – stands with the maximum tree species diversity
	- Index $R2$	calculated using the number of tree species (m) and the number of trees per ha (N)	$R2=\frac{m}{\sqrt{N}}$	
Species heterogeneity:	- Index lambda λ	calculated from the basal area proportions of individual tree species (Wi)	$\lambda=1-\sum_{i=1}^{m}Wi^2$	
	- Entropy H	calculated from the basal area proportions of individual tree species (Wi)	$H'=\frac{-\sum_{i=1}^{m}\left(Wi\times\ln(Wi)\right)}{\ln(10)}$	
Species balance:	- Index $E1$	depends on entropy (H) and the number of tree species (m)	$E1=\frac{H'\times\ln(10)}{\ln(m)}$	
	- Index $E5$	depends on the indices lambda and entropy (H)	$E5=\frac{\frac{1}{1-\lambda}-1}{g^{H*\ln(10)}-1}$	
Set of indicators to measure a structural diversity				
Vertical structure:	- "Arten profil' index APi	calculated using the basal area of the tree species in the stand layer (pij)	$APi=\frac{-\sum_{i=1}^{m}\sum_{j=1}^{z}\left(pij\times\ln(pij)\right)}{\ln(3\times m)}$	The value ranges from 0 to 1: 1 – better value
	- Diameter differences TMd	ratio between the larger and the smaller diameter of all nearest neighboring trees in the plot ($rdij$)	$TMd=\frac{1}{n}\sum_{i=1}^{n}\left(1-rdij\right)$	The value ranges from 0 to 1: <0.3 – small; 0.3-0.5 – medium; 0.5-0.7 – high; > 0.7 – very high differentiation
	- Height differences TMh	ratio between the larger and the smaller height of all nearest neighboring trees in the plot ($rhij$)	$TMh=\frac{1}{n}\sum_{i=1}^{n}\left(1-rhij\right)$	

Note. * Compiled by authors using the Tutorial for tree growth simulator SIBYLA [8]

To estimate a change in forest stand biodiversity, Jaehne and Dohrenbusch (1997) [18] proposed to use the total diversity index (ε) which is calculated as a sum of tree species diversity (α), diversity of vertical structure (β), diversity of tree spatial distribution (χ) and diversity of crown differentiation (δ).

$$\varepsilon=4\times\alpha+3\times\beta+\chi+\delta \quad (3)$$

The maximum index value higher than 9 means that stand structure is very diverse, between 8-8.9 – a diverse structure, between 6-7.9– an uneven structure, between 4-5.9 – an even structure and the values below 4 – a monotonous structure.

3. Results

3.1. Silvicultural Aspects of the Conversion Process

The main aim of the proposed conversion strategies was to achieve the target trees species composition (70-75% of spruce and 25-30% of beech, fir and sycamore) and uneven-aged structure of the study forest plot based on the new generation. The simulation of the strategies S1 and S2 resulted in a share of nearly 80% of spruce, which mismatches the target proportion. The target share of spruce was reached only after applying the strategies S3 (75%) and S4 (73%).

All the conversion strategies started from the same stand volume (305 m³ / ha) which increased to 437 m³ / ha in the 5th period for each of the strategies (Figure 1).

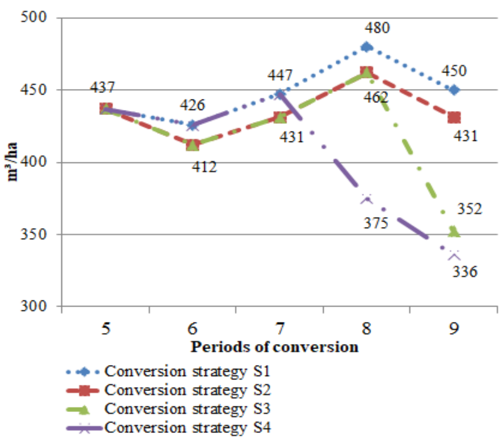

Fig.1. *Simulated dynamics of the stand volume (remaining stand)*

The maximum stand volume among all the conversion strategies was reached with 480 m³ / ha in the 8th simulation period for the strategy S1. Further accumulation of standing volume was interrupted by a TDH for sycamore and the stand volume decreased to 450 m³ / ha. For the conversion strategy S4 the decrease in the standing volume started a bit earlier, in the 7th period and achieved the minimum value of 336 m³ / ha at the end of the conversion period.

The maximum for this strategy was around 447 m³ / ha. The conversion strategies S2 and S3 reach their maximum standing volume of 462 m³ / ha in the 8th period. After this period, the stand volume decreased to 431 m³ / ha and 352 m³ / ha, respectively because of application of TDH for spruce and sycamore in the 8th period.

Stem distribution up to the 5th simulation period is identical for all the conversion strategies due to identical conversion regimes and begins to take the form of a reverse J-sphere. New stems appeared in the diameter class of 4-12 cm for 75 to 213 trees per ha. At the end of the simulation the stem distribution for all the conversion strategies reaches the reverse J-shaped distribution, which characterizes the stand as an uneven-aged.

The stem distributions of all the conversion strategies $Si_{(i=1:4)}$ in the 9th simulation period almost identical and have the reverse J-shaped distribution form. The highest amount of new regeneration appeared after the application of the conversion strategy S3 (around 436 trees per ha in the diameter class 4-12) compared with the other three strategies. Trees in the diameter class 52 cm appeared at the end of the modelling period in all the conversion strategies.

3.2. Economics of the Conversion Process

The conversion strategies S3 and S4 reach the target tree species composition, have reverse J-shaped distribution form of stem distribution, but have a bit higher total direct costs (by 18.39% on average) for stands thinning compared with the other two ones.

The volume of timber in the assortment class I-IIIB decreased for all the conversion strategies compared to the initial state. Application of the conversion strategy S1 allows getting 64.66% of the I, II and III assortment classes of timber (Table 4).

Other strategies allow us to get a bit lower percentage of such a timber quality. This is especially noticeable after application of the strategy S4: the timber volume of the I, II and III assortment classes are lower by 32.6 m^3 / ha compared to the initial state (on average by 14.4% lower). Consequently, the volume of timber in classes V, VI and higher increased. It caused an overall increase in the value of the assortment structure compared with the initial stand state (17922 EUR / ha).

Table 4

Distribution of assortment volume before / after the conversion process

Conversion strategies	Units	Assortment volume classes*				Total
		I-IIIB	V	VI	rest	
Initial stand	m^3 / ha	216.04	85.6	3	0.2	304.84
	%	70.87	28.08	0.98	0.07	100
S1	m^3 / ha	290.84	125.4	31.92	1.64	449.8
	%	64.66	27.88	7.10*	0.36	100
S2	m^3 / ha	270.44	125.16	33.32	1.76	430.68
	%	62.79	29.06	7.74	0.41	100
S3	m^3 / ha	205.56	114.12	31.04	1.6	352.32
	%	58.34	32.39	8.81	0.45	100
S4	m^3 / ha	183.44	117.96	32.84	1.68	335.92
	%	54.61	35.12	9.78	0.50	100

Note. *Timber class system is represented by Slovak classification system

The highest value increase was observed after the application of the strategy S1 up to 27944 EUR / ha (by 55.92%), the least – after implementation of the strategy S4 - to 19318.8 EUR / ha (by 7.79%).

3.3. Changes in Biodiversity during the Conversion Process

To measure the quality of biodiversity (a species and structural diversity), resulted from the application of the simulated strategies, used a set of indicators, presented in Table 3 was used. All the strategies started from the same point, this implies that in the beginning all the parameters have the same value under different strategies.

From the very beginning, indexes of tree species richness R1 and R2 were characterized by a rather low initial value (by 0.152 and 0.075, respectively) and showed a small change during the conversion period. Only at the very end of the period, the obviously advantageous was the strategy S1 (by 0.397 and 0.091). Similar, but slightly lower trend was demonstrated by these indexes for the conversion strategies S3 and S4 (by 0.393 and 0.088). A set of species heterogeneity indicators characterize a higher tree species diversity of the study plot (Figure 2) after the conversion.

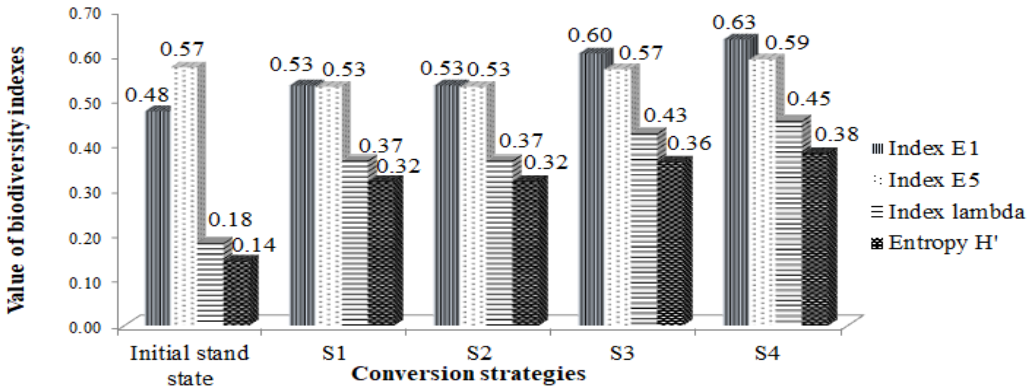

Fig. 2. *Indexes of species balance and heterogeneity before / after the conversion process*

Analyzing the values of the indexes one can see that the changes were relatively small compared with the initial stand state. However, the most noticeable change was found for the strategy S4. The conversion strategy S3 showed a bit lower value of the applied indexes compared with the strategy S4. The simulation of the conversion strategies S1 and S2 showed the same values for all the analyzed set of indicators for measurement of species diversity.

In general, after the application of all the conversion strategies $Si_{(i=1:4)}$, the value of indexes of a species balance and heterogeneity was increased for all the analyzed indicators, except the value of Index E5. Namely, after application of the conversion strategies S1 and S2, the value of the Index E5 decreased to 0.53 compared with the initial stand state value of 0.57.

Analysis structural diversity indicators of the study forest plot after application of the conversion strategies $Si_{(i=1:4)}$, show that the conversion strategy S4 is the best one and it represents higher vertical structure diversity in the study forest stand (Figure 3).

The Arten-profil index revealed a weak sensitivity to the simulated conversion process. The highest value of this index was obtained after application of the strategy S4 (0.66) that indicate the most diverse vertical structure of the study forest stand.

The biggest change in values was shown by the diameter and height differences index. The initial stand state for these indexes was characterized by the value of 0.29 and 0.18, respectively, which indicated rather small structural differentiation. After the modelling of all the conversion strategies $Si_{(i=1:4)}$, these indexes get the value in the range from 0.6 to 0.64 for Diameter a (medium level of diversity) and from 0.42 to 0.46 for Height differences (a high level of diversity).

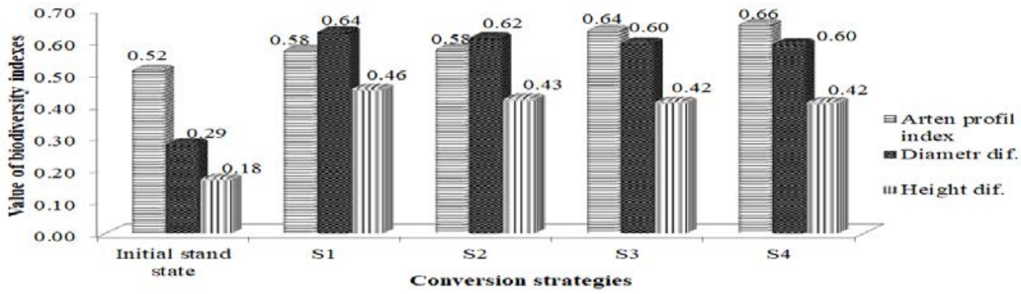

Fig. 3. *Indexes of structural diversity before / after the conversion process*

All the conversion strategies started from the value of Jaehne and Dohrenbusch index of diversity (1997) [18] of 4.91, which characterizes the study forest plot as an even-aged stand structure. Till the 5th simulation period the value of Jaehne and Dohrenbusch index gradually increased to 7.681 (Figure 4).

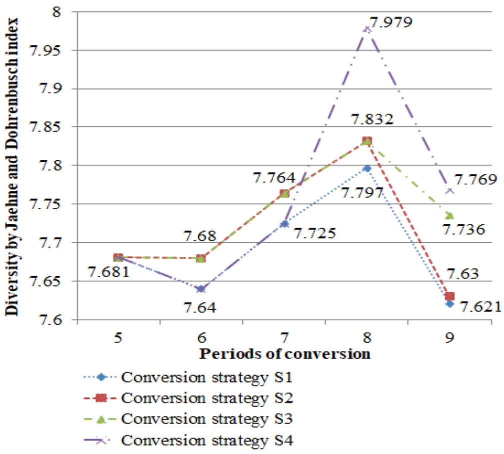

Fig.4. *Simulated dynamics of the Jaehne and Dohrenbusch index of diversity (1997)*

The highest value of biodiversity (7.979) was achieved in the 8th simulation period due to implementation of the conversion strategy S4. But during the next period, it decreased to 7.769 because the TDH 40 cm for sycamore was applied in this period. The conversion strategy S1 had the same values till the 7th period (7.725), but after that, it increased only to a level of 7.797 and in the final period dropped to 7.63, the lowest value of the Jaehne and Dohrenbusch index for the last conversion period. The dynamics of the index value for the conversion strategies S2 and S3 were identical till the 8th simulated period due to the identical application of the conversion regimes. Only at the very end of the simulation, the conversion strategy S3 showed a bit higher increase in the index value up to 7.736.

As can be seen from the Figure 4, the final value of the Jaehne and Dohrenbusch index of diversity varies from 7.621 for the conversion strategy S1 to 7.769 for the conversion strategy S4. It means that after the application of all the conversion strategies $Si_{(i=1:4)}$, we obtained an uneven-aged stand structure, a heterogeneous stand structure with a more diverse vertical structure, a tree spatial distribution, a crown differentiation and a tree species diversity.

4. Discussion

4.1. General Consideration of the Modelling Obstacles

As in many other studies on modelling the conversion process [2, 5, 14, 35, 40] in this study the tree growth simulator SIBYLA was used to depict growth and yield of the study forest plot during the simulated conversion process. Therefore, all the results, that are presented here, are subject, firstly, to the limitations of the applied tree growth model.

Secondly, it is hard to presume the change in climatic conditions during the simulated period. The results of modelling a future forest landscape of the Ukrainian Carpathians by Kruhlov et al. (2018) [21] show that spruce stands dominance will decline under climate change during the next 500 years. Predicted changes in soil water conditions accompanied by increasing air temperatures are the most detrimental factor for a decrease in spruce widespread. Thus, Shvidenko et al. (2017) [36] predict that in the Ukrainian Carpathians, a territory with extra-humid climate will shrink significantly by 2031–2050 and almost disappear by the end of the century (2081–2100), remaining just over the highest peaks. Similarly, Hlásny et al. (2016) [17] predict a strong increase in the number of cumulative dry days and a significant decrease of precipitations during a growing season. These prognosticated changes in soil water conditions and air temperatures will be the most detrimental factor and will lead to a more restricted zone with conditions favorable for spruce. For the Ukrainian Carpathians, these conditions can bring a high uncertainty about the quality of forest regeneration which is crucial for the successful conversion of the secondary spruce forests. Considering these factors, the obtained research results need to be interpreted with caution and cannot be extrapolated to other forest plots which need to be converted.

4.2. The Start and Duration of the Conversion Regime

According to Krynytskyy and Chernyavskyy (2014) [22], the optimal age period to start the forest conversion with the participation of the main forest-forming tree species of the Ukrainian Carpathians – beech, oak, fir, and spruce - is 60-70 years. These considerations are consistent with Lavnyy and Schnitzler (2014) [23] findings which showed that the start of the conversion felling in secondary spruce stands aged of 60-70 years allows providing the necessary uneven-aged and diverse vertical structure of the future mixed stands. In our study, the investigated forest plot was dominated by the 62-year-old spruce (90%).

Considering economic and ecological dimensions of the conversion from even-aged to uneven-aged stands, Buongiorno (2001) [3] proposed the duration of the time span needed to reach the target stand state up to 5 periods of 10 years, i.e. duration of the transformation period up to 50 years. Lavnyy and Schnitzler (2014) [23] substantiate that the duration of the conversion felling depends on the sanitary conditions of spruce trees from the upper layer and prove that duration of the conversion usually lasts 30-50 years. Krynytskyy and Chernyavskyy (2014) [22] argue that the conversion of pure, single-storied spruce stands in the Ukrainian Carpathians can last 60-80 years or more with the cutting time every 5-10 years and continue until the point when the next generation reaching the upper layer. In general, the initial structure of the stand decisively influences the conversion duration. In our case, the aim of the conversion was to achieve mixed tree species composition and uneven-aged stand. We went on with the simulation up to the point when this goal was reached, and, based on the reaching of this state, we derived the duration of conversion to be 80 years.

4.3. Silvicultural Effects of the Conversion Process

Application of the conversion strategies S3 and S4 allow us to get the desired tree species composition with enough height and diameter diversity. This forest stand might be better adapted to drier climate conditions compared to initial state [21, 36]. The obtained results show that the achievement of the target tree species composition of the forest area through proposed conversion regimes (Table 1) is possible but restricted because it is accompanied by a large loss of standing volume at the site. These coincide with the results of Hanewinkel and Pretzsch (2000) [14] which showed that the possibilities of achieving uneven-aged structures in single-layered, even-aged stands through "structuring measures" during thinning or target diameter harvesting are very limited. The success of the conversion depends mainly on the success of the regeneration during the conversion process.

One of the main benefits of the conversion process is the possibility of receiving an increase in productivity and biomass of the stands in the future. In particular, the studies by Piotto (2008) [28] and Pretzsch et al. (2010 and 2014) [30-31] showed that the currently dominant tree species in European forest - Norway spruce and European beech - show much faster height growth (+ 32-77%) and growth in volume (+ 10-30%) compared to 1960 and in mixed stands of spruce and beech the productivity increases on average by 20% compared with pure stands of the same tree species.

Standing volume that characterizes stand development and estimates quality of silvicultural practices, increased through the simulation run due to the conversion strategies implementation. Only application of the conversion strategies S3 and S4 did show some decrease of this parameter due to application of TDH measure in the last simulation period. But in the future, we predict an increase of this parameter while having a good and stable new generation (more than 300 trees / ha in diameter class of 4 cm) – which is the main factor of the conversion success. Availability of these generations, gradually over the time, can reduce the costs of reforestation. With an increase in the amount of forest conversion, there will be no need for artificial regeneration, which will lead to a reduction in the cost of the final product.

4.4. Economic Effect of the Conversion Process

Conversion activities cause significant operational and investments costs which are quite explicit and depend on a range of factors: the level of technology, the organization of production and labor, the techniques applied, the slope of the area, the average volume of stem, stand volume, presence of forest roads network, use of production and material capacities, structure and quality of products, etc. These costs, as Schulte and Buongiorno (1998) [33] indicate, can increase due to maximizing tree-size diversity or tree-species diversity among softwoods, soft hardwood, and hard hardwoods. These considerations are consistent with our analysis of the conversion strategies which showed that the total cost for stand thinning was higher for the conversion strategies S3 and S4, which enable us to reach the required level of the tree species composition, compared with the other two.

These strategies (S3 and S4) had the smallest percentage of I-IIIB assortment class in the assortment structure (58.34% and 54.61%, respectively). This may be explained by the fact that these strategies had a larger volume of timber cutting to get the target tree species composition and age structure than two other strategies. In such forests, there is a high proportion of broadleaved timber which has a lower timber price and conifer trees have longer crowns, which also reduces a timber quality. That is contrary to the common requirements of the timber industry: a high amount of saw timber which means coniferous trees with no branches and little crowns. On the other hand, such mixed uneven-aged forests can reduce financial risks due to a timber products diversification and may help to buffer fluctuations in market prices [16].

Macdonald et al. (2009) [24] note, that the economic returns of forest conversion will depend on the availability of the equipment required for harvesting and processing larger trees. That depends on the financial ability of the forestry enterprises. According to Dudiuk and Pelyukh (2013) [6], only 61% of the forestry enterprises in Lviv region of the Ukrainian Carpathians have enough level of financial stability that could allow them to modernize their facility and equipment, to train their staff to gain knowledge and skills for conversion forest planning and implementation. The same situation is in the financial ability of the SERF.

4.5. Impact of the Conversion Process on Biodiversity and Forest Ecosystem Services

Comparative evaluation of forest ecosystem services accomplished by forest scientists and staff of forest enterprises of the Ukrainian Carpathian region and results of many researches revealed that mixed forests are thought as providers of better and richer flows of the ecosystem services compared to the flows generated by spruce monocultures [42]. After the conversion process, the recreational value of forests increases as well. According to Edwards et al. (2012) [7], the most important structural attributes of forest for recreational value are greater variation in tree size; the presence of large trees; limited or no clear cutting; and a greater variation in spacing. In the current study, the values of indicators of tree species and structural diversity increase, which characterizes the derived forest plot as recreationally more attractive. According to the results of a meta-analysis of 32 studies conducted for European mountain forests, the willingness to pay for walks in a broad-leaved forest is 4.36 EUR, while in the mixed forest – it amounts to 17.01 EUR [11]. This fact can increase the flow of tourists to the Bogdan village (surroundings of the study area) and improve the well-being of the local forest-depended communities and the financial position of SERF.

In the current study the values of the Jaehne and Dohrenbusch index of diversity (1997) [18], after modelling the conversion strategies $Si_{(i=1:4)}$, range from 6.0 to 7.9 and characterize the obtained stand as a heterogeneous stand with a higher diversity of the vertical structure, tree spatial distribution, crown differentiation and a tree species diversity. These results match those observed in earlier studies [4, 22] showing that the conversion process contributes to an enhanced biodiversity.

5. Conclusion

New developments in tree growth simulation software can support multicriterial forest decision-making process. Such models potentially integrate a wide range of system knowledge and test different scenarios of variables important for any management decision.

Emerging interest in social and cultural values of forests, biodiversity and the expected increasing risks related to climate change have awakened an interest in mixed, uneven-aged forests in the Ukrainian Carpathians. The assessment of the impact of the simulated strategies of secondary even-aged spruce stands conversion into mixed uneven-aged ones in the territory of SERF by the tree growth simulator SIBYLA shows that the conversion strategy S4, which consists of the combination of ST in 3rd-7th simulation period, TDH for spruce in the first two (40 cm) and 7th (45 cm) periods and TDH for sycamore (45 cm) in the 8th period is the best one. Despite the fact that this strategy involves an intensive thinning and harvesting, which causes a large loss in the stand volume, and, therefore, is more expensive in implementation and reduces the volume of high assortment class wood in the site in comparison with the others, the strategy S4 allows obtaining the target (similar to natural) tree species composition with the heterogeneous vertical structure. That was confirmed by a set of indicators for tree species and structural diversity of the study forest plot.

The simulated results should be integrated into forest decision-making in the SERF with the aim to improve the vitality and stability of the secondary spruce stands; their resistance to increasing pressure of human practice and uncertainty of climate change. Such integration of the obtained results will contribute to formation of responsible long-term economic activity and adequate forest policy, contribute to adaptive forest management based on ecosystem services approach. Considering that an individual approach is required for each site that needs to be converted, these findings also must be interpreted with a caution to other plots in the Ukrainian Carpathians. This means there is a need for further study on the best management practices of declined secondary spruce stands in this region.

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