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Change in the productivity of stands of the spruce (*Picea abies* L.) mountain Carpathian forests district over a 70-year period

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Abstract

The state and comparison of stands of the spruce mountain Carpathian forests district, which involves a significant portion of the forest fund of the State Enterprise 'Rakhiv Experimental Forestry', are analysed based on materials of forest management. The analysis examines changes in the area covered by forest vegetation, the formation peculiarities of the main inventory indicators of forest stands and their evolution over an almost 70-year period of forest management activities in the region. The aim of this study is to analyse the forest management materials of the spruce mountain Carpathian forests, focusing on the forest vegetation area and the main management indices of tree stands over a 70-year period. It highlights the intensive economic impact on stands, evidenced by a decrease in average relative completeness. Sustainable forest management necessitates a comprehensive understanding of the ecosystem, encompassing biological, ecological and socioeconomic aspects. Long-term regional studies and modern forest management approaches are crucial for informed decision-making. In addition, involving local communities, stakeholders and experts in decision-making ensures socially acceptable, economically viable and environmentally sound management practices. It is suggested that mitigating the negative impacts of climate change on natural ecosystems involves forming native stands of rational structure and composition in the mountainous Carpathians, recognising the potential benefits of integrating conifers into beech stands and vice versa.

Key words

forest management, site conditions, climate change, European spruce stands, silver fir, European beech

Introduction

The analysed part of the spruce (*Picea abies* L.) mountain Carpathian forests district occupies the highest forest belt in the Ukrainian Carpathians, covering the uppermost slopes of the Gorgany, Chornohora, Chivchynsky, Marmarosky and Hrynyavsky mountains, according to the geobotanical zone scheme (Fig. 1) (Golubets 1978). A large area of the study area is occupied by the forest stands managed by the State Enterprise 'Rakhiv Experimental Forestry'.

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Forests, due to their ability to perform numerous diverse functions, have significant importance, both for the region where they are located and for adjacent territories (Myklush 2011). Mountain forests are especially important for carrying out protective and ecological functions, but due to their elevation, they are particularly sensitive to the consequences of climate change, which affects the competitive ability of tree species and the nature of their growth and stand structure (Beniston 2003; Debrynyuk 2010; Scherler et al. 2016). Mixed mountain forests are particularly vulnerable to climate change that occurs in areas with suboptimal conditions for their viability (Hilmers et al. 2019). Climate change affects the ecological conditions of forest areas; in particular, increased temperature leads to drought and intensifies the development of insect pests and pathogenic microorganisms, which affects the stability of stands (Porta et al. 2008; Seidl et al. 2014) and their reforestation (Hartl-Meier et al. 2014; Pretzsch et al. 2015).

Long-term studies on the structure, growth and productivity of pure and mixed mountain forests in the Ukrainian Carpathians (Khodot 1959; Shvidenko 1980; Molotkov 1972; Tsuryk 1981; Hrynyk and Hrynyk 2022) are primarily based on one-time measurement data. Therefore, to ensure sustainable forest management, it is necessary to make management decisions based on long-term regional studies and take into account modern approaches and extensive experience in forest management. Hence, for solving current problems of management in mountain forests and ensuring effective forest management, information on the growth and productivity of stands over a long period of their formation and use is crucial. One of the elements of information support for making informed decisions should be an analysis of changes in the forest fund structure, its species composition and the productivity of forest stands, which can be identified by comparing forest inventory materials that were carried out in different age periods and covered several decades. Materials with an

Figure 1. The analysed part (pink colour) of the spruce mountain Carpathian forests district (Google Maps 2024, Golubets 1978)

age difference that covers the rotation of harvesting of the main tree species should be of particular value. It is also relevant to identify the reasons that cause changes in the main forestry and inventory indices that can occur under the influence of climate change and forestry measures taken.

Material and methods

In the data provided by forest management materials, the main forestry indices were established following the requirements of forestry instructions and regulations on forest management (Myklush et al. 2022). To determine forest typological units, the classification by D.V. Vorobiov (1953) was used, and data from lists of forest types specific to mountain forests were analysed (Pohrebniak 1963; Molotkov 1972; Gerushinsky 1996). Stand site index classes were determined using the forest inventory site index scale developed by M.M. Orlov (Shvidenko et al. 1987).

The climate in the area where the forest enterprise is located is moderately continental, with humidity prevailing in the mountainous forest zone, and it is moderately warm and humid in the Tisa River valley. The area exhibits specific microclimate features that depend on the altitude above sea level, the exposure of the slopes and the relief.

According to the materials of the forest management plan (The project… 1952), based on data from the weather station in the town of Rakhiv in 1951, the average annual air temperature was 6.8°C (maximum +35°C, minimum -32°C) and the average annual precipitation was 1167 mm. According to data from open sources, in the vicinity of Rakhiv, the average annual air temperature in 1952 was 7.2°C, and in 2021 it was 8.2°C. The forest management plan materials indicate that in 2020, the average annual air temperature was +6.9°C (maximum +30.7°C, minimum -29.4°C) and the average annual precipitation was 1176 mm (Explanatory note… 2021).

Based on the forest inventory of 1951–1952 and the materials from the State Enterprise 'Rakhiv Experimental Forestry' as of 1 January 2021, it is evident that the most common soils in the region are brown mountain forest soils, characterised by varying thicknesses and significant amounts of gravel, sand and stones. Furthermore, the materials indicate that steep slopes predominate in the region, ranging from 21° to 30° on southern slopes and from 21° to 35° on northern slopes.

Research conducted over a 70-year period allowed for an analysis of changes in the distribution of forest-covered areas by tree species. The study also examined the specific characteristics of the main inventory indicators of silver fir (*Abies alba*) stands and their productivity. Detailed results of the research are presented in the materials of the forest inventory and the Explanatory Note of the State Enterprise 'Rakhiv Experimental Forestry' in 2021 (Explanatory note… 2021).

Results

Based on the forest inventory data from 1951 to 1952, the area covered by forest vegetation in the 'Rakhiv Forestry Enterprise' was 41,230 ha (Project… 1952), while according to the forest inventory data as of 1 January 2021, the area covered by forest vegetation in the 'Rakhiv Experimental Forestry' was 35,358.2 ha (Explanatory Note… 2021). The total area of the enterprise and, consequently, the area covered by forest vegetation have decreased due to the restructuring of forest management in the region and the formation of a nature conservation area.

According to the requirements of the relevant regulations in force in 1951–1952 and to fulfil the functions of the forests, four economic sections were identified during forest management planning: the special forestry unit, the production part along the railway tracks, the protective grazing forests and the green forestry unit. Grazing refers to forest stands or areas that are located at a distance of approximately 300 m from the meadow, which are high mountain meadows or pastures where livestock graze. Such forests usually have an uneven composition and low productivity compared to other types of forests. Since grazing forests are located on mountain slopes, they may be subject to soil erosion and avalanche hazards. These forests are of great importance for preserving biodiversity and protecting water resources.

At the same time, in the materials of forest management planning as of 1 January 2021, within the categories of forests by their priority function, six economic sections were identified: forests for nature conservation,

Table 1. Distribution of areas covered with forest vegetation by tree species

Tree species	The area as of 1952, ha	Area share, %	The area as of 2021, ha	Area share, %
Common pine (*Pinus sylvestris* L.)	–	–	1.1	–
European spruce (*Picea abies*)	33,682.0	81.7	26,372.4	74.6
Silver fir (*Abies alba*)	395.0	1.0	61.9	0.2
European larch *(Larix decidua*)	3.0		20.2	0.1
European beech (*Fagus sylvatica* L.)	7146.0	17.3	8547.9	24.2
Carpathian walnut (*Juglans regia* L.)	3.0	–	–	–
Common oak (*Quercus robur* L.)	1.0	–	2.5	–
Northern red oak (*Quercus rubra* L.)	–	–	13.7	–
European hornbeam (*Carpinus betulus*)	–	–	247.4	0.7
European ash (*Fraxinus excelsior* L.)	–	–	5.4	–
Sycamore (*Acer pseudoplatanus* L.)	–	–	23.3	0.1
Scots elm (*Ulmus glabra*)	–	–	0.7	–
Eurasian aspen (*Populus tremula*)	–	–	4.2	–
Grey alder *(Alnus incana*)	–	–	45.2	0.1
Small-leaved lime *(Tilia cordata*)	–	–	7.3	–
Crack willow (*Salix fragilis*)	–	–	0.8	–
Swiss pine (*Pinus cembra*)	–	–	0.5	–
Douglas fir (*Pseudotsuga menziesii*)	–	–	3.7	–
In total	41,230.0	100.0	35,358.2	100.0

scientific, historical and cultural purposes, recreational forests with unique and limited use regimes in the mountains, protective forests with unique and limited use regimes in the mountains and production forests. In addition, virgin and quasi-virgin forests were identified in the forest fund of the forestry enterprise, covering an area of 696.0 ha.

According to the distribution of forest-covered areas (Tab. 1), European spruce stands predominate, occupying almost 75% of the area. As of 2021, the area of spruce stands has significantly decreased compared to the data of the forest management plan of 1951–1952, when their area exceeded 33,000 ha and the share of forest-covered areas exceeded 81%.

The decrease of almost 6000 ha in the area of fir and spruce stands, which were primarily designated to the special production unit, was due to their transfer to the nature conservation object. Simultaneously, over the analysed period, the area of beech stands increased by almost 1.4 thousand hectares. The increase in the area of beech stands could have been even more significant. Seventy years ago, according to the requirements of the current instruction for forest management, areas of ash, maple and other deciduous tree species were not separately classified due to their small size and were instead grouped under beech stands.

In the absence of growth and productivity standards for stands in the mountainous conditions of the Carpathians, experimental yield tables for the main tree species were developed based on site index classes during their management in the 1950s. From the fragment of standards for the I site index for spruce stands (Tab. 2), it can be observed that at 20 years of age, natural spruce stands on average reached a height of 6.5 m and had volumes of over 100 m^3/ha, while at 100 years and older, the average heights exceeded 38 m and volumes reached 1000 m^3/ha. It should also be noted that according to the research yield tables, the height of spruce stands increased almost four times compared to 20-year-old stands and the volume increased by more than five times. From 50 to 100 years of age, the average height and sum of cross-sectional areas increased by 1.5 times, while the volume doubled.

Table 2. A fragment of the research yield table for spruce stands of the site index class I

Age	Height, m	The sum of cross-sectional areas, m^2/ha	Volume, m^3/ha
20	6.5	26.2	101
40	20.0	34.3	359
60	30.0	45.5	661
80	35.0	57.6	944
100	38.0	61.9	1062
120	39.5	65.8	1168
140	40.5	66.9	1211

According to the findings of the forest inventory conducted during 1951–1952, the average stand indices of the predominant tree species exhibited variations across distinct management units (refer to Tab. 3), indicating discrepancies in age and productivity. The most substantial growing stock volumes were observed in a 3-ha stand comprising artificially established European fir trees, situated at an elevation of 1000 m near Rakhiv. At 130 years of age, the stand demonstrated an average height of 38 m, an average diameter of 56 cm and a growing stock volume of 640 m^3/ha. Considering that within the specialised forestry unit, with an average age of 103 years, fir stands typically have an average growing stock of 610 m^3/ha, it becomes apparent that in certain areas, the growing stock of fir stands surpassed 700 m^3/ha.

Drawing upon the compiled research tables and the growth dynamics tables of closed Carpathian fir stands (Khodot 1959), alongside those depicting the growth dynamics of fully coeval fir stands in the Ukrainian Carpathians (Tsuryk 1981), it is evident that the growing stock volumes of mature fir stands aged 120–140 years attain 1200 m^3/ha. The growing stock volumes of spruce stands at this age were commensurate. In comparison to coniferous stands, beech forests retained more than two times less growing stock.

Table 3. Average management indices of forest stands of 'Rakhiv Forestry Enterprise' based on the materials of 1951–1952

The dominant tree species in the stand	Average indicators				
	Age, years	Site index, class	Completeness	Volume, m^3/ha	Average volume change, m^3/ha
Special forestry unit					
European spruce	57	I^a, 4	0.76	363	6.2
Silver fir	103	I^a, 2	0.69	610	6.2
European beech	107	I, 8	0.69	218	2.6
The production part along the railway tracks					
European spruce	27	I, 0	0.81	123	4.5
European beech	84	I, 9	0.66	246	3.4
Protective grazing forests					
European spruce	133	II, 0	0.64	489	3.7
Silver fir	111	I, 7	0.73	492	4.8
European beech	138	II, 5	0.6	264	1.9
Green forestry unit					
European spruce	87	I, 1	0.71	281	5.7
Silver fir	70	I^a, 7	0.66	427	6.1
European larch	130	I^a, 0	0.6	640	4.9
European beech	50	I, 8	0.68	134	2.9
On average per enterprise					
European spruce	68	I^a, 7	0.75	377	5.8
Silver fir	90	I^a, 7	0.68	502	5.9
European larch	130	I^a, 0	0.6	640	4.9
European beech	102	I, 9	0.61	152	2.5

The average growing stock volume of stands in the economic sections mostly correlates with their age. The oldest stands were found in the protective grazing forests, where the main tree species have an average age of over 110 years, and the average volumes of fir and spruce reached almost 500 m^3/ha. Beech stands have the highest average volume of 264 m^3/ha in this economic section, characterised by the highest average age and the lowest relative completeness compared to others.

Both in individual forest sections and on average across the forestry enterprise, beech stands were characterised by the lowest average volumes, which ranged from 134 m^3/ha in a young forest section with an average age of 50 years to 264 m^3/ha in protective grazing forests with an average age of 138 years.

The forest inventory data from 1951 to 1952 reveals that the stands of the primary tree species were shaped under substantial management influence. Notably, spruce stands exhibited the highest average relative completeness, reaching 0.75, with only those along railway tracks, averaging 27 years in age, surpassing this with a relative completeness exceeding 0.8. Remarkably, spruce stands within designated management units, covering 2281 hectares, exhibited markedly higher relative completeness, achieving 1.0, while those spanning 9744 hectares attained a completeness of 0.8. Beech stands in the area showcased a broad spectrum of relative completeness, ranging from 0.3 to 1.0. However, they displayed the least variability in relative completeness among management units, aligning closely with the average relative completeness of 0.61 (refer to Tab. 3).

It is common for coniferous tree species to exhibit a greater change in volume compared to beech stands, surpassing the latter by 2.4 times in managed forests. Within the special management unit, the change in volume of beech stands closely approximates the average value across the forestry enterprise. Notably, the average change in volume of spruce stands displays significant variability across forestry units, ranging from 6.2 m^3/ha in the special management unit to 3.7 m^3/ha in the protective grazing forests, which harbours stands with the highest average age.

The highest age and one of the lowest average site index class indices, as noted by M.M. Orlov (Shvidenko et al. 1987), were observed in grazing forests. Specifically, spruce stands with an average age of 133 years are characterised by an average site index class II and a relative completeness of 0.64, whereas forests in the specialised forestry unit with an average age of 57 years exhibit an average site index class Ia.4 and a relative completeness of 0.76.

According to the site index classes of stands as per the forest management materials of 2020 (Table 4), circuitously, the productivity of all tree species has increased over the past 70 years. Thus, over the 70-year period, the average site index class of spruce stands increased from $I^a.7$ to $I^b.9$, larch trees from $I^a.7$ to $I^b.3$, fir trees from $I^a.7$ to $I^a.2$ and beech trees from I.9 to I.2. The main reason for the increase in the average values of the site index class might be climate change, particularly an increase in the average air temperature (Hartl-Meier et al. 2014; Pretzsch et al. 2014).

The forest vegetation conditions at the enterprise are favourable for the formation of productive stands dominated by conifers. Therefore, the stands with Douglas fir trees domination are characterised by the highest value of site index class I^b, which, with low relative completeness, reached a volume of 424 m^3/ha.

With an average age of 78 years, larch stands exhibit an average site index class of $I^b.3$ and a volume of 287 m^3/ha. Within the enterprise's conditions, silver fir stands demonstrate superior volume and average age characteristics.

The average age of fir stands on the enterprise has remained almost unchanged (increased from 68 to 70 years) despite intensive management, but the average volume has increased by almost 50 m^3/ha (up to 423 m^3/ha) (Fig. 2). Over the analysed period, while the average age of spruce stands increased from 90 to 126 years, their average volume remained almost unchanged. The average volume of beech stands increased the most from 152 to 307 m^3/ha. The volume of mature stands of the main tree species was 5–11% higher than their average values, and the highest average volume of mature stands (namely 559 m^3/ha) was characteristic of spruce stands, which were mostly concentrated in nature reserves. As a result of regeneration of fir stands, their average volume decreased by more than two times.

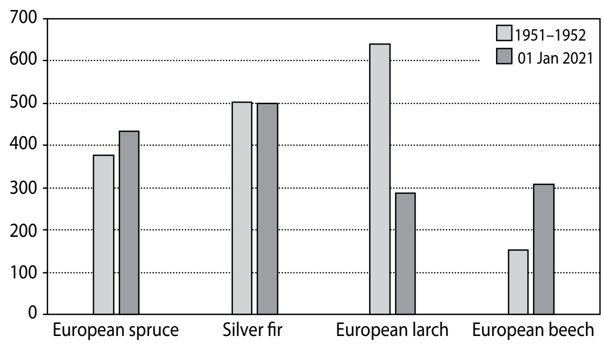

Figure 2. Average growing stock volumes of stands of the main tree species

Table 4. Average management indices of forest stands of 'Rakhiv Experimental Forestry' as of 1 January 2021

The dominant tree species in the stand	Age, years	Site index class	Relative completeness	Volume per 1 ha, m^3		The average change in volume per 1 ha of areas covered with forest vegetation, m^3
				Areas covered with forest vegetation	Mature and overmature stands	
European spruce	70	$1^b.9$	0.71	433	459	6.2
Silver fir	126	$1^a.2$	0.63	501	559	4.0
European larch	78	$1^b.3$	0.54	287	518	3.7
European beech	111	1.2	0.63	307	325	2.8
European hornbeam	36	2.8	0.66	80	153	2,2
Grey alder	32	1.5	0.6	97	167	3.0
Douglas fir	110	$1^b.0$	0.38	424	424	3.8
In total	80	$1^a.2$	0,69	399	416	5.0

At the highest average age of spruce stands, according to the 2021 forest inventory, they were characterised by a lower average change in growing stock volume by 1.9 m^3/ha than according to the 1951–1952 forest inventory, when the average volume change was 4.0 m^3/ha (Fig. 3). Along with the increase in average volumes of spruce and beech stands, the values of their average volume change also increased.

According to the 2020 forest inventory, spruce stands are characterised by the highest value of relative completeness, namely 0.72, but this indicator is lower than 70 years ago. At the same time, it should be noted that according to the 1951–1952 data, relative completeness of 0.7–0.9 was relevant for 75.6% of the area of spruce stands, and according to the latest forest inventory, this number is 78.8%.

In spruce stands, there was a decline observed in the average relative completeness, decreasing from 0.68 to 0.63 over the analysed period. Conversely, in beech stands, there was an increase noted in relative completeness (rising to 0.63).

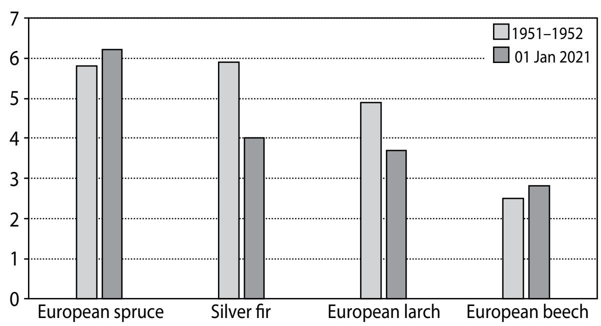

Figure 3. Average change in growing stock volume per 1 ha of the main tree species, m^3

According to the forest inventory conducted between 1951 and 1952, the largest proportion of beech stands, accounting for 38.0%, exhibited a relative completeness rating of 0.7. Meanwhile, stands with a relative completeness rating of 0.7 and above comprised 55.4% of the total. In contrast, as per the 2020 forest inventory, the prevalence of beech stands with a completeness rating of 0.7 remained the highest, albeit with a reduction exceeding 10%. Moreover, the proportion of stands with a completeness rating of 0.7 and above decreased to 46.8%.

It is noteworthy that over the analysed 70-year period, the share of highly completed stands, rated between 0.9 and 1.0, dwindled from 15.7% to 4.7%, marking nearly a threefold decrease. This decline underscores the pronounced impact of intensive forestry practices on the stands. In addition, there has been a decrease in the average relative completeness, declining from 0.74 based on the 1951–1952 data to 0.69 as recorded in the forest inventory as of 1 January 2021. This reduction in relative completeness has implications for the available wood volumes, which averaged 399 m^3/ha according to the 2020 forest inventory data.

Discussion

Among the main reasons for changes in the area, structure and productivity of stands, along with the level of management intensity, researchers (Bolte et al. 2010; Trotsiuk et al. 2014; Dulamsuren et al. 2017; Albrich et al. 2020) cite the influence of climate change, increase in air temperature and decrease in precipitation. Climate change can affect not only the forest conditions, survival and regeneration of tree species, formation of plantation or stand structure, but also the degree and intensity of transformation processes in forest stands (Dale et al. 2001). Warming and increased risk of drought and storms, additional biotic threats due to changes in pathogen and pest development regimes, are reflected in the loss of timber volume in coniferous stands in Europe, particularly in fir forests due to bark beetle infestations (Dobbertin and DeVries 2008). The decrease in the area of fir and spruce stands with a simultaneous increase in the area of beech stands in mountainous conditions of enterprises may confirm that the main reason for such changes is the impact of climate. Obviously, climate change has contributed to an increase in the diversity of introduced tree species under enterprise conditions, including the Douglas fir and red oak, as well as an increase in the area of European larch and common oak stands.

The areas of tree species that were absent from the accounting materials 70 years ago provide grounds for noting that the enterprise continued to search for ways to increase the productivity of stands, including through the creation of stands with introduced species such as red oak and Douglas fir, as well as the expansion of European larch stands. However, the presence of over 240 ha of common hornbeam stands and more than

20 ha of maple-ash stands, which formed on the site of beech stands as noted in the 2020 forest management materials, indicates the need to review approaches to forestry activities in beech stands to prevent the formation of less-productive hornbeam and maple-ash stands.

Different forest species react differently to climate change. For example, Bolte et al. (2010), on analysing the change in structure of mixed forests in the semi-natural ancient spruce–beech forest in Smaland (the 'Siggaboda' reserve in southern Sweden), note the increase in competitiveness of the beech forest compared to spruce at its northern range in Scandinavia due to climate change. Dulamsuren et al. (2017) indicate the characteristic growth and development features of beech forests under the influence of climate change, depending on the altitude, in the federal state of Baden-Württemberg in southwestern Germany. According to dendroecological studies of beech forests, researchers have found that a decrease in annual tree growth of beech at altitudes of 110–300 m above sea level is caused by low rainfall in April–May, low summer temperatures at an altitude of 1230 m and average values at an altitude of 640 m. Therefore, with further warming and a decrease in precipitation, beech may suffer in lower mountainous areas of Central Europe due to a decrease in viability and productivity, while warming may have a positive effect on the upper mountainous part. Thus, the general increase in temperature gradually affects the change in forest vegetation conditions, which are more favourable for the growth of beech forests in mountainous conditions than for spruce forests, which are common in the forest areas located at higher altitudes. The change in forest vegetation conditions was also evidenced by the fact that the forest management plan of 2020 allocated rich forest types under enterprise conditions. This allocation contrasts with the forest management plan of the 1950s, which only addressed relatively rich forest vegetation conditions. This aspect largely explains the increase in productivity and average values of site index class of the analysed forests.

In the realm of climate change mitigation, one strategy to bolster the protective and ecological functions of forests and sustain ecosystem services involves the establishment of mixed forests. A plethora of studies underscore the predominantly positive impact of tree diversity on the resilience and ancillary advantages of forest stands in response to climatic shifts (Boeck et al. 2018; Neuner et al. 2015). The silver fir and the Douglas fir emerge as potential substitutes for Norway spruce, which is vulnerable to extreme conditions, owing to their purported greater resistance to biotic and abiotic stressors (Vitali et al. 2017). Moreover, it is anticipated that under the influence of climate change, the European beech will outcompete the European spruce beyond its native range (Bolte et al. 2010). Bosela et al. (2016) posit that the productivity of beech in mixed mountain forests will either remain stable or marginally increase.

Research findings by Hilmers et al. (2019) on mixed stands of beech, European spruce and silver fir reveal that productive mixed mountain forests in Europe did not experience diminished productivity over a 30-year period (1980–2010) despite climate change; however, tree species exhibited varied responses to climatic shifts. Specifically, while the growth of European spruce declined, that of silver fir increased, and beech growth remained relatively steady. Nevertheless, a comparison of average values of site index classes and completeness in mountainous regions of the Carpathians suggests an augmentation in beech, silver fir and European spruce stands established as the dominant tree species. Discrepancies between forest inventory data and mixed forest studies (Hilmers et al. 2019) may also stem from the fact that in the climatic conditions of the Carpathians, only indicators of one predominant tree species in pure and mixed forests were analysed, such as the advantages of beech, silver fir or European spruce. Hartl-Meier et al. (2014) identify a number of advantages of mixed mountain forests, including their ability to better adapt to temperature increases caused by climate change. Pretzsch et al. (2010) and Pretzsch and Forrester (2017) reported that mixed mountain forests are 20% more productive than adjacent pure stands. Mina et al. (2018) found that mixed mountain beech forests with spruce and fir are more resilient and productive. According to forest management data for 2021, mature spruce forests have an average growing stock of 130 m^3/ha, which exceeds the average growing stock of mature beech forests. Therefore, including a certain proportion of spruce and fir in beech forests will increase their overall growing stock.

To enhance the productivity and resilience of Carpathian mountain forests, it is crucial to recommend the establishment of indigenous forests characterised by an optimal structure and composition tailored to each forest type. Recognising that incorporating a certain proportion of conifers into beech forests can augment productivity, and vice versa, integrating beech into spruce or fir forests can bolster biotic resilience. Such management strategies not only mitigate the risks associated with monoculture forests, but also facilitate diversified resilience.

These resilient and productive mountain forests serve as effective shields, performing crucial protective functions and delivering essential ecosystem services. When establishing mixed stands, forest managers must consider local forest conditions, accumulated experience and regional management nuances to minimise the adverse impacts of climate change on forest resilience and productivity. This approach ensures the sustained functionality of forest ecosystems.

Consequently, for the effective management of mountain forests, comprehensive knowledge regarding stand growth and productivity dynamics influenced by economic factors and undergoing long-term changes is indispensable.

Conclusions

The primary factor driving enhanced productivity in spruce, fir and beech stands, alongside the expansion of beech stands within mountainous enterprise conditions, likely stems from climate influences. Climate change may have furthered the amelioration of forest vegetation conditions, facilitating the proliferation of introduced tree species, notably Douglas fir and red oak, and the expansion of European larch and common oak stands, alongside various deciduous and coniferous species.

Due to economic activities and regulatory changes pertaining to the allocation of economic sectors, the diversity of tree species within distinct economic sections of the enterprise's forest reserve has expanded during the analysed period. Notably, species such as red oak, Douglas fir and European larch, alongside various hardwood and softwood species including common hornbeam, common ash, maple-sycamore, aspen and small-leaved lime, have witnessed increased representation. Over a 70-year period between forest management plans, several noteworthy changes have been observed:

a) There has been a discernible increase in the area of productive fir stands alongside an elevation in the average site index class of the primary tree species. Specifically, the average site index class of fir stands has risen from $I^a.6$ to $I^b.8$. Concurrently, spruce stands have seen an ascent from $I^a.7$ to $I^a.2$, larch stands from $I^a.0$ to $I^b.3$ and beech stands from I.9 to I.2.
b) Moreover, there has been a notable augmentation in the average growing timber volume of the principal tree species, namely European fir and beech. Particularly significant is the 15% increase in the average growing stock of fir stands and more than a twofold increase in beech stands.
c) There has been a decrease in the average relative density of coniferous tree species. The average relative completeness in fir stands decreased from 0.75 to 0.71, and in spruce stands, it decreased from 0.68 to 0.65. According to the latest forest management plan, beech stands are characterised by an average relative completeness of 0.63, which is 0.02 higher than in the 1951–1952 data.

To enhance the productivity and resilience of mountain forests in the Carpathians, it is recommended to establish indigenous stands with an optimal structure and composition tailored to the specific forest type. This practice is recognised for its efficacy in reinforcing stand vitality and resilience. It entails strategic integration of coniferous species within beech-dominated forests to augment productivity, and likewise, the inclusion of beech species within spruce or fir-dominated forests to enhance their resilience.

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