Cent. Eur. For. J. 71 (2025) 224–235 sciendo DOI: 10.2478/forj-2025-0004
CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

Changes in the extent and structure of Norway spruce stands in the Ukrainian Carpathians based on forest survey data from 1988 to 2018

Vasyl Lavnyy[1]*, Petro Khomiuk[1], Mykola Gusti[1,3], Serhii Havryliuk[1], Mykola Korol[1], Oleksandr Matusevych[1], Volodymyr Savchyn[2], Christian Vonderach[4,5], Hans-Peter Kahle[4]

[1]*Ukrainian National Forestry University, 103 Gen. Chuprynky Str., UA-79057 Lviv, Ukraine*

[2]*Lviv State Forest Management Expedition of the Ukrainian State Forest Management Planning Association "UkrDerzhLisProekt", 17 Chaikovskoho Str., UA-79007 Lviv, Ukraine*

[3]*International Institute for Applied Systems Analysis, Schlossplatz 1, AT-2361 Laxenburg, Austria*

[4]*Institute of Forest Sciences, Albert-Ludwigs-University Freiburg, Tennenbacher Str. 4, DE-79106 Freiburg, Germany*

[5]*Forest Research Institute of Baden-Württemberg, Wonnhaldestr. 4, DE-79100 Freiburg, Germany*

Abstract

This study investigates dynamics of Norway spruce stands in the Ukrainian Carpathians in 1988–2018. Cultivation of Norway spruce has altered forest composition at the expense of site-adapted species. Climate change, with rising temperatures and altered precipitation has further impacted forest health and growth. Methods involve analyzing forest management databases from the Ukrainian State Forest Management Planning Association. Results indicate a decrease in Norway spruce stands area from 775.9×10^3 ha to 532.7×10^3 ha in 1988–2018, area-specific growing stock increased from 251 to 364 m^3 ha^{-1}. The share of mature and overmature stands increased from 35% to 52%, while for young and middle-aged stands the share decreased from 65% to 48%. The average potential wood production of fully stocked Norway spruce stands in the region is estimated to be about 9 m^3 ha^{-1} $year^{-1}$, while a considerable share of this potential may be lost due to mortality. For the survey periods 2011 and 2018 estimated gross periodic annual volume increment is larger than gross mean annual volume which is an indication that the analyzed stands in the average have not reached the age of biological rotation. The share of mixed Norway spruce – European beech forests increased from 10% to 25% of the total area. With ongoing climate change a further reduction in the share of Norway spruce is anticipated. However, actual potential for the use of Norway spruce wood in commercial Norway spruce forests is high. Conclusions highlight the need for adaptive forest management strategies to enhance the resilience and sustainability of site adapted Norway spruce stands amid environmental changes.

Key words: *Picea abies* [L.] H. Karst.; forest type; forest stand characteristics; age structure; climate change; forest management

Editor: Vladimír Šebeň

1. Introduction

Norway spruce (*Picea abies* [L.] H. Karst.) is one of the most widely cultivated and economically important conifer tree species in Europe (Caudullo et al. 2016; Kermavnar et al. 2023). Over the last three centuries, the distribution of Norway spruce in the Ukrainian Carpathians and other regions of Europe has significantly increased due to cultivation (Schmidt-Vogt 1977; Spiecker 2000). Currently, Norway spruce covers approximately 30 million hectares in Europe (Jansen et al. 2017), extending far beyond its native range (Jansson et al. 2013). Spiecker (2000) describes the causes and consequences of this expansion, attributing it primarily to the fast growth of Norway spruce and the high demand for wood. In the Ukrainian Carpathians, planted mono-species Norway spruce stands have often replaced native European beech (*Fagus sylvatica* L.) and Silver fir (*Abies alba* Mill.) dominated forests (Golubets 1978; Hensiruk 2007).

Climate change poses a serious threat to forests (Bolte et al. 2009; Spathelf et al. 2014). Local trends in annual temperature and precipitation may differ from global pat-

*Corresponding author. Vasyl Lavnyy, e-mail: *lavnyy@gmail.com*

terns (Struk et al. 2017). In 1990–2016, annual precipitation in the Prut River basin, a representative study area in the central part of the Ukrainian Carpathians, increased by 21–95 mm compared to the 1961–1990 norm, while average annual temperature rose by 0.5 to 1.1 °C (Kyyak et al. 2022). Based on the analysis of data from eleven meteorological stations in the Ukrainian Carpathians Vyshnevskyi & Donich (2021) did not find a significant change in annual precipitation during 1961–2019, whereas average annual air temperature increased from 5.6 °C (1961–1990) to 6.6 °C (1991–2019). Notable temperature changes occurred at the highest meteorological station in the Ukrainian Carpathians, on Mount Pozhezhevska (1,451 m a.s.l.), where average annual air temperature in 1991–2020 was 2.0 °C higher than in 1961–1990 (Kyyak et al. 2022).

In the recent past deteriorating sanitary conditions, and large-scale die-off of Norway spruce trees due to changing climatic conditions has been observed in several European countries (Rybníček et al. 2012; D'Andrea et al. 2023; Spiecker & Kahle 2023). Similar incidents have been reported for the Ukrainian Carpathians (Kramarets et al. 2009, 2018; Shvidenko et al. 2018; Shparyk et al. 2020).

The distribution and dynamics of Norway spruce forests have always been a focus of research in Ukraine and other European countries (Golubets 1978; Gerushynskyi 1996; Kahle et al. 2005; Synek et al. 2020). In Ukraine, several studies have concentrated on developing growth and yield tables, describing the distribution, and modelling the dynamics of forest stands (Golubets 1978; Tsuryk 1981; Gerushynskyi 1996). A number of studies aimed at assessing wood production, growth characteristics, and biomass accumulation of Norway spruce stands in Ukraine (Hensiruk 2007; Hrynyk & Hrynyk 2022).

With the extensive spread of Norway spruce stands in Central Europe, studies on their growth under changing climate have become important (Yue et al. 2016, 2023; Brandl et al. 2018; Krejza et al. 2021; Spiecker & Kahle 2023). Krejza et al. (2021) examined the growth responses of Norway spruce trees in Czechia to the drought in 2017–2018, finding a decrease in stem radial growth by 78–61% compared to the pre-drought level of 2016. Brandl et al. (2018) reported a decline in site index (H100) across large parts of Europe due to changes in temperature and precipitation. Similar findings were presented by Yue et al. (2016) for southwestern Germany (Baden-Württemberg). Spiecker & Kahle (2023) conducted a long-term analysis of growth and mortality patterns in Baden-Württemberg, demonstrating the significant influence of climatic conditions on the growth and mortality of Norway spruce forests.

Illés & Móricz (2022) emphasize the need to adapt forest management practices to anticipated climate changes, noting that European beech and Norway spruce stands may lose 58% and 40% of their area in Southern and South-eastern Europe, respectively. Impact assessments for the past period (1961–1990) and three future periods (2011–2040, 2041–2070, 2071–2100) support the feasibility of expanding forest areas of these main tree species to achieve climate neutrality, considering their potential distribution further north and at higher altitudes. Recently, studies on the impact of climate change in the Ukrainian Carpathians have evolved as well (Shparyk et al. 2020; Lavnyy 2021; Kyyak et al. 2022).

Aims of our study are to describe the current state of Norway spruce stands in the Ukrainian Carpathians, to analyze patterns in the dynamics of forest stand characteristics, and indicate the trends in area and growth of these stands in the study region. Previous investigations of Norway spruce resources in the Ukrainian Carpathians have been conducted over different periods (Golubets 1978; Gerushynskyi 1996; Hrynyk & Hrynyk 2022). However, these studies were typically focused on single mountain massifs or specific regions. An integrative analysis of Norway spruce resources for the entire Ukrainian Carpathians over the past few decades is lacking. Therefore, the objective of our study is to provide a comprehensive description and analysis of Norway spruce resources for the entire Ukrainian Carpathians, based on the five most recent state forest surveys.

2. Material and methods

The study on changes in the area and stand characteristics of Norway spruce forests in the Ukrainian Carpathians (Fig. 1) is based on forest management databases provided by the Ukrainian State Forest Management Planning Association (UkrDerzhLisProekt) for the years 1988, 1996, 2002, 2011, and 2018. These specific years were selected according to the orders of the Cabinet of Ministers of Ukraine, when the main characteristics of forests in Ukraine were compiled on the level of the forest enterprises during the "Periodic Basic Forest Management Survey and Planning" surveys.

More detailed analysis of Norway spruce forest stands characteristics for 2011 and 2018 was based on data from more than 110,000 forest stands. The database was queried to include only areas where Norway spruce is the main species, i.e. stands where forest management is oriented towards Norway spruce. The share of spruce in these stands is between 5% and 100%. An additional criterion of the query was location of the stands in the mountainous zone, as defined by the forest type zoning by Gerushynskyi (1996). When we use the term "Norway spruce stands" we refer to these forest stands. For each stand the following parameters were extracted from the database: forest category, stand composition (tree species share in %), stand origin (natural, planted), altitude (m a.s.l.), age (years), area (ha), site class, relative stand density, growing stock (m^3 ha^{-1}), mean annual increment (m^3 ha^{-1} $year^{-1}$).

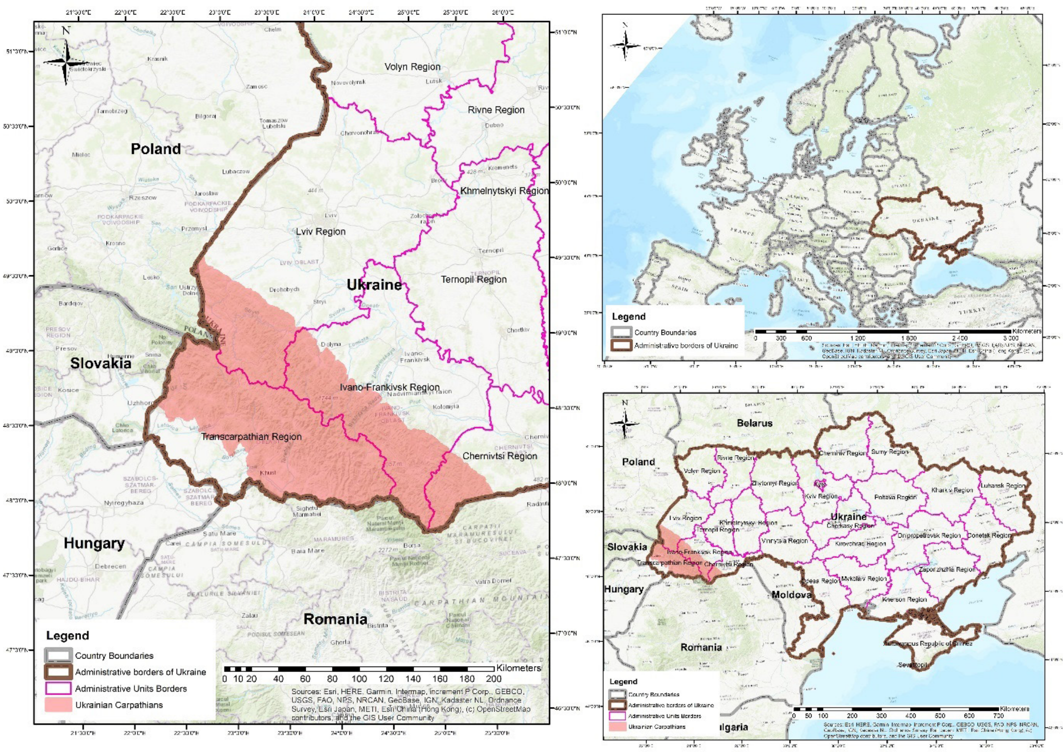

Fig. 1. Map of the study region with administrative regions (magenta) and the Ukrainian Carpathian region (salmon).

The methodology of forest management in Ukraine is set in the legislation and detailed in specific instructions (Cabinet of Ministers of Ukraine 1994, 2023, UkrDerzhLisProekt 2022). For the past few decades, the primary system of forest management was the age-class system, which sorts the forest stands into age classes (class width 10 years). Forest inventory in each management unit is primarily conducted using a visual forest inventory method. This method estimates key forest characteristics based on measurements of tree diameter, tree height, and stand basal area. Stand-level forest characteristics are then derived from these measurements or are estimated via site index using yield tables (Shvidenko et al. 1987; Strochynskyi & Kashpor 2010). The instructions specify the accuracy and peculiarities of measuring and estimating forest characteristics. In particular, for mature stands the mean tree diameter should be estimated with an error not exceeding 10%, and for mean tree height and growing stock 8% and 10% respectively. The method includes training the inventory experts in trial forest plots with the most typical conditions with measurements of the stand parameters. The visual method can be combined with the establishment of trial forest plots and additional measurements if it is necessary for achieving prescribed accuracy. The main characteristics, which are generated for forest-covered land include: species composition, origin of the stand, area, average diameter and height, absolute stand density (stand basal area) and relative stand density, growing stock, site class and forest type. Based on these characteristics, the stands are grouped into homogeneous forest sections and forest groups according to their main functions.

The classification of Ukrainian forests by their main functions is based on the Forest Code of Ukraine (Parliament of Ukraine 1994, Article 39). The code distinguishes ecological, social, and economic services, and classifies the forests into the following categories: protective forests (mainly providing water protection, soil protection, and other protection services); recreational and human health-improving forests (primarily providing recreational, sanitary, hygienic, and health-improving services); nature protection, scientific, historical, and cultural forests (forests providing special nature protection, aesthetic, and scientific services); commercial forests (mainly supplying timber and fuel wood for the economy). The distribution of Norway spruce forests in the Ukrainian Carpathians in 2018 is given in Table 1[1].

To characterize the management and growth conditions of forest stands, forests are further classified into different "forest types" and "forest site types". Six forest types dominated by Norway spruce or with a major share of Norway spruce are the most widely distributed and form the core of this study (the list refers to the year 2018 and shows the percentage of their area to the total area of spruce forests). Forests on moist relatively poor soils: pure Norway spruce forests 4.9%; on moist rela-

[1] The four main categories are divided into sub-categories depending on the main services they provide. For example, if the stand is close to a river band, the main function is protection of the river, so the subcategory will be "Forests along rivers, lakes, and basins".

Table 1. Area distribution of the forest categories in the Ukrainian Carpathians for Norway spruce – dominated forest stands in 2018.

Forest category	Area share (%)
Commercial forests	35.2
Protective forests:	
Anti-erosion forests	27.1
Forests along rivers, lakes, and basins	5.4
Other protective forests	0.7
Nature protection, scientific, historical, and cultural forests:	
National nature parks	14.8
Regional landscape parks	3.7
Scientific, historical, and cultural forests	8.8
Recreational and human health-improving forests	4.3

tively rich soils: mixed European beech-Norway spruce forests 6.0%; mixed European beech-Silver fir-Norway spruce forests 46.8%; pure Norway spruce forests 24.5%; mixed Silver fir-Norway spruce forests 4.6%; on moist rich soils: mixed European beech-Silver fir-Norway spruce forests 9.7%.

Site classes or productivity classes are established to assess site productivity of tree species and to compare growing conditions for different tree species. The associated yield tables describe the growth and wood production potential of specific stands under normal, i.e. equilibrium, growing conditions. In our case for Norway spruce the yield tables by Tsuryk (1981) were used (available in Shvidenko et al. 1987).

Stocking degree is used for assessing density of trees in the stand. The stocking degree values range from 1.0 to 0.1, with interpretations as follows. 1.0: represents a fully-stocked forest stand, utilizing all available space for tree growth. Less than 0.3: indicates understocked forests, where tree density is significantly lower relative to the potential. Relative stand density is used to estimate the current growing stock of forest stands and serves as an important information for the planning of silvicultural measures.

In Ukraine, the 10-year age classes of forests are gathered into the following forest age groups: young, middle-aged, premature, mature, and overmature forests. The main criterion for this grouping is the age at final cutting, which depends on the tree species and the category of forest. For example, for commercial Norway spruce forests the age at final cutting is currently set to be 81–90 years. The age groups are then defined as follows: young forests – first 4 age classes (stand age 1 to 40 years); middle-aged forests – all age classes between young and premature forest (in this case 41–60 years); premature forests – two age classes below the mature forests (61–80 years); mature forests – the age class at the final cutting and the subsequent age classes (81–120 years); overmature forests – all age classes above the mature forests (>120 years).

Tree species composition of forest stands is described by the share of the growing stock of each respective species to the total growing stock of the stand. For simplicity, the resulting values are rounded to integers so that the overall sum equals 10. If a species constitutes less than 5% of the growing stock, it is marked with a "+".

The potential wood production of forest stands is derived from yield tables and described using four key characteristics: growing stock, representing the total aboveground volume of wood per unit area within a forest stand, mean (gross) annual increment (MAI[2]), and current and periodic (gross) annual increment (CAI, PAI[3]) representing the total amount of wood per unit area and year that is produced in a certain year and in the average within a certain period, respectively.

To estimate gross CAI and PAI, we cannot refer to forest survey data, but need to estimate these characteristics from yield tables. Since the available yield tables (Tsuryk 1981) do not cover all site classes present in the considered area (relative site classes observed: I^d, I^c, I^b, I^a, I, II, III, IV, V, V^a, V^b; relative site classes in the yield tables: I^b, I^a, I, II, III), we extended the available yield tables by refitting a Chapman-Richards model to the yield table data (both for growing stock and total volume production), in such a way that the parameters of the model depend on the absolute site class (mean annual gross volume increment at age 100, MAI_{100}). Hence, we can evaluate the Chapman-Richards models for any absolute site class to predict growing stock and total volume production but also gross CAI, PAI and MAI. To apply the model in this analysis, we firstly scaled the observed growing stock per hectare to a stocking degree of 1.0 to achieve compatibility with the yield tables. Secondly, we estimated the absolute site class MAI_{100} from its relation to current growing stock in given age. Finally, we can calculate current, periodic and mean gross volume increment from the Chapman-Richards functions given MAI_{100} for the considered Norway spruce forests for both points in time.

3. Results

In Ukraine, as of 2022, Norway spruce (*Picea abies* [L.] H. Karst.) comprised 8% of the total forest area, making it the third most common forest tree species after Scots pine (*Pinus sylvestris* L., 35%) and European oak (*Quercus robur* L., 28%). Wood from planted Norway spruce stands accounted for 7.7% of the total harvested wood volume, amounting to 1,045.3 thousand cubic meters per year. Among coniferous species, Norway spruce accounted for 12.4% of the harvested wood (State Forest Resources Agency of Ukraine 2024).

[2] The mean net volume increment of a forest stand up to a given stand age. Unit: m_{ob}^3 ha^{-1} $year^{-1}$. MAI net can be calculated by dividing growing stock through stand age.

[3] The mean net annual volume increment of a forest stand in a certain year (CAI) or over a specific time period divided by the length of that period (PAI). In this study PAI is estimated for 10-year periods.

3.1. Forest area and growing stock

From 1988 to 2018 the area of Norway spruce stands in the Ukrainian Carpathians decreased by 31.4%, whereas the total growing stock does not show a clear trend (Tab. 2). The peak in absolute growing stock was in 2002, at 228.8 Mm^3, but it decreased by 34.7 Mm^3 in 2018. However, the average area-specific growing stock of Norway spruce stands has increased by 103 m^3 ha^{-1} from 1988 to 2018. These trends indicate a reduction in the total area of Norway spruce stands but an increase in the average growing stock per hectare over the period.

3.2. Forest types

Mixed stands composed of European beech-Silver fir-Norway spruce growing on moist, relatively rich soils, are considered to have higher productivity and higher resilience to climate changes compared to pure Norway spruce stands in the same growing conditions (Kramarets & Krynytskyi 2009; Lavnyy 2021). These stands belong to the I–I^a site classes. Typically, these forests grow at altitudes ranging from 800 to 1,400 meters above sea level (m a.s.l.), benefiting from adequate moisture and nutrient supply. The highest average growing stock within this forest type was observed in the "Rakhiv State Forestry Enterprise", reaching 1,017 cubic meters per hectare at an altitude of 950 m a.s.l. (in 2021). In comparison, pure Norway spruce stands, which are found at altitudes of 1,200–1,600 m a.s.l., generally have smaller growing stocks and primarily serve protective functions. Generally, the forests growing at altitudes between 800 and 1,100 m a.s.l., show an average growing stock of approximately 700 m^3 ha^{-1} and consist of high-quality stems. Most of these forests fall under the category of commercial forests and are predominantly middle-aged.

3.3. Area of stands by age groups and with different shares of Norway spruce in 2011 and 2018

The dynamics of the area of Norway spruce forests by age groups reveal a general trend: a decrease in young stands and an increase in the area of mature and overmature forests (Tab. 3).

Information on the tree-species composition of stands is based on the detailed database of forest management and is available only for 2011 and 2018. In 2018 39.4% of the area of Norway spruce stands in the Ukrainian Carpathians were pure Norway spruce stands (share of Norway spruce in the total stand growing stock 100%). From 2011 to 2018 the share of pure Norway spruce stands decreased by 3.1 percentage points (Fig. 2). Conversely, there was an increase in forest areas where the fraction of Norway spruce in the stand composition was between 50% to 80% (classes 5–8). This shift is due to the ongoing conversion of pure Norway spruce stands into mixed-species stands, following the extensive dieback of Norway spruce in recent decades.

Table 2. Area and area-specific growing stock of Norway spruce stands in the Ukrainian Carpathians according to the forest surveys between 1988 and 2018.

Parameter	1988	1996	Between 1988 and 1996		2002	Between 1996 and 2002		2011	Between 2002 and 2011		2018	Between 2011 and 2018		Between 1988 and 2018	
			10^3 ha^{-1} / m^3 ha^{-1}	%		10^3 ha^{-1} / m^3 ha^{-1}	%		10^3 ha^{-1} / m^3 ha^{-1}	%		10^3 ha^{-1} / m^3 ha^{-1}	%	10^3 ha^{-1} / m^3 ha^{-1}	%
Area, 10^3 ha	775.9	668.4	–107.5	–13.9	674.3	5.9	0.9	629.1	–45.2	-6.7	532.6	–96.5	–15.3	–243.3	–31.4
Growing stock, m^3 ha^{-1}	251	307	56	22.3	339	32	10.4	338	–1	–0.3	364	26	7.7	114	45.4

Table 3. Area of Norway spruce stands in the Ukrainian Carpathians by age groups according to the forest surveys of 1988 to 2018.

Age groups		Area of forests (10^3 ha per %) by year of survey				
		1988*	1996	2002	2011	2018
Young	10^3 ha	375.7	291.7	165.3	115.0	103.9
	%	48.4	43.6	24.5	18.3	19.5
Middle-aged	10^3 ha	233.5	216.9	310.6	281.4	239.0
	%	30.1	32.4	46.1	44.7	44.9
Premature	10^3 ha	110.7	79.3	88.3	95.9	83.3
	%	14.3	11.9	13.1	15.2	15.6
Mature	10^3 ha	56.0	73.3	98.1	109.2	80.9
	%	7.2	11.0	14.5	17.4	15.2
Overmature	10^3 ha	—	7.3	12.1	27.6	25.5
	%	—	1.1	1.8	4.4	4.8
Total	10^3 ha	775.9	668.4	674.3	629.1	532.6
	%	100.0	100.0	100.0	100.0	100.0

Note: *For the year 1988 the mature and overmature stands were gathered into one age group.

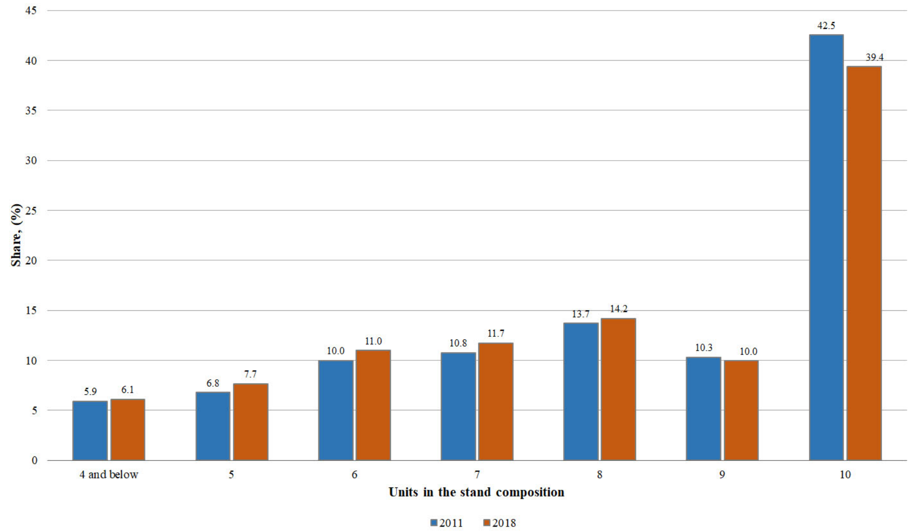

Fig. 2. Forest area shares by the fraction of Norway spruce in the stand composition of Norway spruce stands in the Ukrainian Carpathians according to the forest surveys in 2011 and 2018.

In the Ukrainian Carpathians, there is a general trend of decreasing areas of Norway spruce stands across all age groups (more than 96 × 10^3 ha for the period of 2011–2018; Tab. 3). However, the relative changes (in percent) show a different distribution. There is an increase in the fraction of all age groups except for the mature stands, which decreased by 2.2% from 2011 to 2018. This dissonance between absolute and relative changes is due to alterations in the area structure of the age groups of Norway spruce stands. The relative values provide a clearer picture of the age group distribution.

3.4. Area shares of Norway spruce stands by relative stand density and site classes in 2011 and 2018

From 2011 to 2018, there was a shift in the share of Norway spruce forests from medium (0.5–0.8) to the highest relative stand density classes (0.9–1.0) (Fig. 3), and changes in site classes distribution (Fig. 4). In 2018, the share of Norway spruce stands in the site classes very high (I^b and above) and very low (III and below) increased (Fig. 4). Conversely, the share of the prevailing intermediate site classes (I^a–II) decreased.

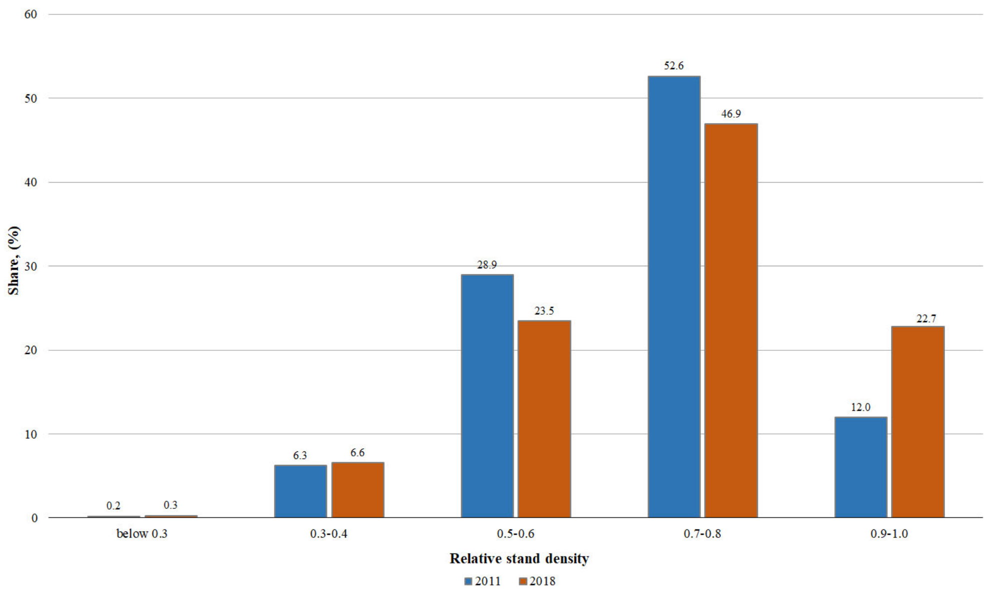

Fig. 3. Area shares of Norway spruce stands in the Ukrainian Carpathians by relative stand density according to the forest surveys in 2011 and 2018.

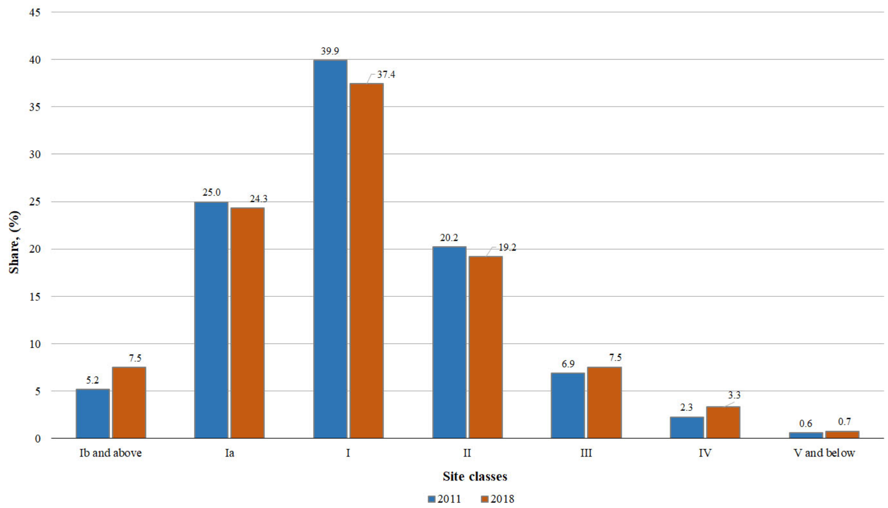

Fig. 4. Area shares of Norway spruce stands in the Ukrainian Carpathians by the site classes according to the forest surveys in 2011 and 2018.

The slight increase in the fraction of low productivity Norway spruce stands (site classes III and below, 0.1–1.0%) is explained by the expansion of Norway spruce stands to the upper edge of the forest, near the alpine tree line, where the site index is lower due to harsher growing conditions (Fig.5).

3.5. Area shares of Norway spruce stands by altitude in 2011 and 2018

There have been considerable changes in the distribution of Norway spruce forests by altitude (Fig. 5), while the total area across all altitudes decreased (Tab. 2). The shares at altitudes above 800 m a.s.l. have increased by 5.5%, while the shares at altitudes of 800 m a.s.l. and below have declined. The redistribution of the shares is rather a result of the shortage of Norway spruce forests at low altitudes.

3.6. Assessment of the Norway spruce production potentials in the Ukrainian Carpathians based on yield tables

Growing stock derived from the observation data reached 338 m^3 ha^{-1} at an average age of 66 years in 2011 and 364 m^3 ha^{-1} at age 69 in 2018. Hence, net mean annual increment (excluding mortality and removals) calculates to 5.1 m^3 ha^{-1} year^{-1} in 2011 versus the yield table-based

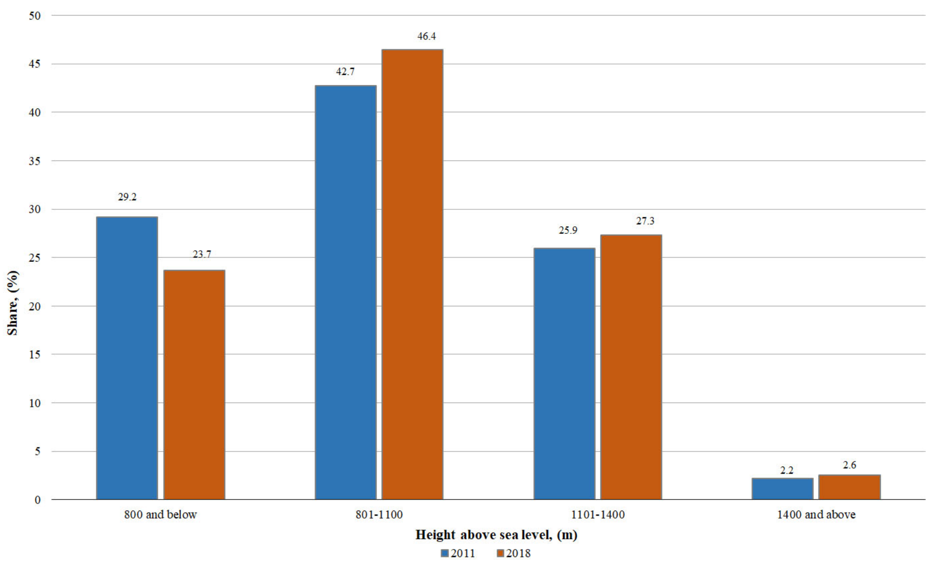

Fig. 5. Area shares of Norway spruce stands in the Ukrainian Carpathians by relative stand density according to the forest surveys in 2011 and 2018.

estimate for gross mean annual increment of 7.1 m^3 ha^{-1} $year^{-1}$. By 2018, net mean annual increment increased to 5.3 m^3 ha^{-1} $year^{-1}$, while the estimated gross increment increased to 7.3 m^3 ha^{-1} $year^{-1}$ (Table 4). From the estimated Chapman-Richards models, we can add information on the current and periodic increment. For the year 2011, a current and periodic gross increment of 10.0 m^3 ha^{-1} $year^{-1}$ is reached on average, considering stocking degree. Seven years later, values of 9.8 and 10.2 m^3 ha^{-1} $year^{-1}$ were achieved for the current and periodic gross increment, respectively (Table 4). These values give a more precise indication of the stands productivity than the net MAI alone could. According to the yield tables by Tsuryk (1981), the stands correspond on average to the relative site class I or the absolute site class MAI_{100} of 9.2 m^3 ha^{-1} $year^{-1}$ (2011: 9.22 and 2018: 9.15).

For the period from 2011 to 2018 the potential amount of available wood can be estimated by the change in growing stock (2011: 338 m^3 ha^{-1}; 2018: 364 m^3 ha^{-1}) together with the estimated gross periodic increment (weighted average of 2011: 12.7 m^3 ha^{-1} $year^{-1}$ and 2018: 12.6 m^3 ha^{-1} $year^{-1}$ for fully stocked forests, see Table 3 and Table 4). Respecting low stocking degree (0.7 in 2011 and 0.72 in 2018, translated into a reduced increment by a factor of 0.79 and 0.81, respectively, based on Albert et al. 2021), management intensity of different forest types (full use of increment in commercial forests, half use in protective forests; see Table 1) and conversion from standing wood to round wood (mobilisation of 70% of merchantable volume with bark), we estimate a potential roundwood production of 1.33 Mm^3 per year.

4. Discussion

The shift towards forming mixed-species stands in Ukraine's forest management strategy reflects a proactive response to external factors such as climate change, which has affected species distribution in recent decades. The increase in the share of Norway spruce stands with high relative stand density (0.9–1.0) suggests the development of forests with a higher relative stand density over the past seven years, which is promising for increasing productivity and a high-quality wood in the future.

The conversion of even-aged mono-species forest stands into uneven-aged multiple-species forests has ecological and economic advantages. For many sites in Western and Central Europe the conversion of pure Norway spruce stands into mixed-species stands with silver fir and European beech is recommended to increase resilience of the forests (Spiecker et al. 2004; Reventlow et al. 2021).

A strong decline in area and growing stock of Norway spruce stands was observed after 2002 (Table 2). In our opinion, these changes can be attributed to the extensive drought induced mortality of Norway spruce stands following the extreme drought in the summer of 2003, and widespread infestation of trees by trunk pests, most notably the European spruce bark beetle (*Ips typographus* L.) (Kramarets et al. 2009). This phenomenon was first identified in the Slavske State Forestry Enterprise, located in the Lviv region, prompting a field meeting of the representatives of the State Agency of Forest Resources of Ukraine in 2004, which involved the participation of scientists (Golubets et al. 1978; Krynytskyi 2005). Subsequently, there were numerous studies conducted on the issue of drought related damages in Norway spruce stands in the Ukrainian Carpathians, with publications by Hensiruk (2007) and Krynytskyi et al. (2006). The decreasing trends of area and growing stock of Norway spruce forests in the Ukrainian Carpathians coincide with similar trends in Slovakia (Moravčík et al. 2004).

In the period from 2002 to 2011, there was a notable expansion of overmature and mature Norway spruce stands in the Ukrainian Carpathians (Table 3). This trend is attributed to the increasing establishment of nature-protection areas in forests across Ukraine (FAO 2020; Poliakova & Abruscato 2023) and the absence of forest roads in extensive areas, making wood harvesting unfeasible. But in the last period from 2011 to 2018 the share of overmature and mature stands slightly decreased.

The observed changes in site index (Fig. 4) can be attributed to external factors affecting Norway spruce

Table 4. Potential wood production (average values) in Norway spruce stands in the Ukrainian Carpathians. MAI: Mean annual increment (average rate of wood production in a unit area of a stand during the whole life of the forest stand), CAI: Current annual increment (annual volume increment of a forest stand in a specific one-year-period, PAI: Periodic annual increment (mean annual volume increment of a forest stand over a specific time period divided by the length of that period).

Norway spruce forests	2011	2018	units
Growing Stock	338	364	m^3 ha^{-1}
Stocking degree	0.70	0.72	—
Age	66	69	years
Average relative site class	I	I	—
Average absolute site class (MAI_{100}*)	9.22	9.15	m^3 ha^{-1} $year^{-1}$
MAI (net, calculated from the observation data)	5.1	5.3	m^3 ha^{-1} $year^{-1}$
MAI_{yt} (gross, estimated from the yield table*)	9.0 / 7.1**	9.1 / 7.3**	m^3 ha^{-1} $year^{-1}$
CAI_{yt} (gross, estimated from the yield table*)	12.6 / 10.0**	12.1 / 9.8**	m^3 ha^{-1} $year^{-1}$
PAI_{yt} (gross, estimated from the yield table*)	12.7 / 10.0**	12.6 / 10.2**	m^3 ha^{-1} $year^{-1}$

Note: *yield tables by Tsuryk (1981), **corrected for stocking degree by a factor of 0.79 for 2011 and 0.81 for 2018 (based on Albert et al. 2021).

stands, such as deteriorating sanitary conditions due to climate change, changes in the age structure, and management interventions, which include the schemes of planting forests and thinning, as well as the expansion of Norway spruce to higher altitudes with harsher growing conditions. The transformation of pure Norway spruce stands into mixed-species stands can lead to a decrease in site class distribution because Norway spruce tends to have higher productivity site classes in pure stands than in mixed stands, where it is influenced by other species (Golubets 1978; D'Andrea et al. 2023). Concomitant tree species such as sycamore, birch, ash, Norway maple, elm, and rowan have lower productivity classes compared to Norway spruce. However, it is expected that the average sanitary conditions of Norway spruce will improve in the future due to an increase in the share of mixed-species Norway spruce stands (Krynytskyi & Kramarets 2009).

The share of Norway spruce stands at altitudes below 800 m a.s.l. significantly declined from 29.2% in 2011 to 23.7% in 2018, due to both ecological and anthropogenic factors (Fig. 5). A massive die-back occurred in planted Norway spruce stands, as they were growing outside their natural habitat (Kramarets et al. 2018). These stands were largely replaced by beech and silver fir, which are native to low altitudes in the Ukrainian Carpathians. The sharp decline at lower elevations was the primary reason for the increased share at higher altitudes in 2018. While the total area of Norway spruce stands decreased, the overall forest area increased due to the expansion of other forest types.

For our productivity analysis, we merged extended yield table information (Tsuryk 1981; Shvidenko et al. 1987) with the available stand data and derived different increment measures on total volume production. Although the used yield tables might be considered outdated with respect to changed environmental conditions and might therefore not reflect current growth, they still are a valuable tool to make a rough estimate on stand productivity, especially in lack of a repeated forest inventory data. In the absence of large calamities, decades old yield tables might underestimate current productivity, as was summarised e.g., by Pretzsch (2016). Hence, our presented results can be considered as conservative estimates.

By comparing net and gross mean annual increment, we estimate that for the survey periods 2011 and 2018 on average an amount of 2.0 m^3 ha^{-1} $year^{-1}$ of wood is removed from the growing stock, either by fellings or lost due to mortality. Compared to the commonly used mean net annual increment, we added information on current and periodic gross increment for the considered stands. With this information, a more precise estimate of the productivity of the stands is achieved. From the gross periodic increment we could additionally estimate potential availability of roundwood from forests accessible for wood supply. Here, we found a shortage of about 10–25% between our estimates and the roundwood recordings. It is yet unclear, where this difference can be attributed to, but likely reasons include losses due to mortality, little or even no thinning in many stands, and incomplete statistical recording on the production side. The fact that 10 years-periodic gross annual increment (PAI) is larger than MAI (10.2 m^3 ha^{-1} $year^{-1}$ versus 7.1–7.3 m^3 ha^{-1} $year^{-1}$) is an indication that the analyzed stands in the average have not reached the age of biological rotation. Of course, the process of stand-to-yield table mapping and calculation of expected roundwood production exhibits uncertainties, which include stocking degree, increment reduction, standing stock-to-roundwood conversion and the assumed harvest intensity. Nevertheless, we consider the estimates of potential wood production (wood removals) of 1.33 Mm^3 per year compared to recorded in forest statistics of 1.0 to 1.2 Mm^3 per year (State Forest Resources Agency of Ukraine 2024) for the period from 2020 to 2024 to be plausible and helpful in classifying and evaluating the Norway spruce forests in the Ukrainian Carpathians.

5. Conclusions

In this study, we considered Norway spruce forest stands in the Ukrainian Carpathians. Our analysis reveals a consistent decline in the overall area of Norway spruce forests. There have also been changes in the forest stand parameters: i) an increase in the area of stands with a greater share of Norway spruce in the stand composition (5–8 units); at the same time a decrease in the share of pure or close to pure stands (9–10 units); ii) an increase in the share of premature and overmature stands; iii) the share of Norway spruce stands with high site class indexes (I^b and above) increased, and with site indexes I^a, I and II – decreased; iv) a 5.5% increase in the share of Norway spruce stands located at altitudes over 800 m a.s.l. and higher and decline at lower altitudes; v) a shift of the areas of Norway spruce stands with an average relative stand density (0.5–0.8) to the highest relative stand density of 0.9–1.0; vi) an average potential productivity of Norway spruce forests, expressed as gross mean annual increment (MAI), in 2018 was 7.3 m^3 ha^{-1} $year^{-1}$, as compared to net MAI of 5.3 m^3 ha^{-1} $year^{-1}$, and the 10 years-periodic gross annual increment (PAI) was 10.2 m^3 ha^{-1} $year^{-1}$; vii) the difference between the potential gross (2011: 7.1, 2018: 7.3 m^3 ha^{-1} $year^{-1}$) and the observed net mean annual increment (2011: 5.1, 2018: 5.3 m^3 ha^{-1} $year^{-1}$) is indicative of high mortality in the forests; viii) the analysed stands on average have not reached the age of biological rotation as PAI is larger than MAI.

Our findings point to considerable dynamics of total area and growing stock as well as other characteristics of Norway spruce forests in the Ukrainian Carpathians in recent decades and highlight the necessity for adaptive forest management strategies that enhance the resilience and sustainability of Norway spruce forests. Transitioning from clearcutting to conversion cuts, promoting mixed-species forests, and implementing close-to-nature silviculture are recommended approaches to improve forest health and productivity. Furthermore, ongoing monitoring and research are crucial to understand the long-term impacts of climate change on forest ecosystems and to develop effective management practices that ensure the sustainability of these vital forest resources.

Acknowledgements

This study was undertaken within the framework of the "SURGE-Pro" project, which was financially supported by the Volkswagen Foundation (Germany, Az: 97 781).

References

Albert, M., Nagel, J., Schmidt, M., Nagel, R.-V., Spellmann, H., 2021: Eine neue Generation von Ertragstafeln für Eiche, Buche, Fichte, Douglasie und Kiefer [dataset]. Version 1.0. Zenodo. Available at https://doi.org/10.5281/zenodo.6343906. (In German).

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.-J., Schall, P. et al., 2009: Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scandinavian Journal of Forest Research, 24:473–482.

Brandl, S., Mette, T., Falk, W., Vallet, P., Rötzer, T., Pretzsch, H., 2018: Static site indices from different national forest inventories: harmonization and prediction from site conditions. Annals of Forest Science, 75:56.

Caudullo, G., Tinner, W., de Rigo, D., 2016: Picea abies in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (eds.): European Atlas of Forest Tree Species. Luxembourg, Publication Office of the European Union, e012300+ p.

D'Andrea, G., Šimůnek, V., Pericolo, O., Vacek, Z., Vacek, S., Corleto, R. et al., 2023: Growth response of Norway spruce (*Picea abies* [L.] Karst.) in Central Bohemia (Czech Republic) to climate change. Forests, 14:1215.

Gerushynskyi, Z. Y., 1996: Typology of forests of the Ukrainian Carpathians. Lviv, Piramida, 208 p. (In Ukrainian).

Golubets, M. A., 1978: Spruce forests of the Ukrainian Carpathians. Kyiv, Naukova dumka, 264 p. (In Russian).

Hensiruk, S. A., 2007: Causes of dieback of spruce forests of the Carpathians and measures to stop their degradation. Available at http://www.ntsh.org/node/54 01.04.2007 (In Ukrainian).

Hrynyk, G. G., Hrynyk, O. M., 2022: Growth and productivity of European spruce stands in the Ukrainian Carpathians depending on the topography: monograph. Lviv, Spolom, 252 p. (In Ukrainian).

Illés, G., Móricz, N., 2022: Climate envelope analyses suggests significant rearrangements in the distribution ranges of Central European tree species. Annals of Forest Science, 79:35.

Jansen, S., Konrad, H., Geburek, T., 2017: The extent of historic translocation of Norway spruce forest reproductive material in Europe. Annals of Forest Science, 74:56.

Jansson, G., Danusevičius, D., Grotehusman, H., Kowalczyk, J., Krajmerova, D., Skrøppa, T. et al., 2013: Norway Spruce (*Picea abies* [L.] H. Karst.). In: Pâques, L. (ed.): Forest Tree Breeding in Europe. Managing Forest Ecosystems, vol. 25. Dordrecht, Springer. Available at https://doi.org/10.1007/978-94-007-6146-9_3.

Kahle, H. P., Unseld, R., Spiecker, H., 2005: Forest ecosystems in a changing environment: Growth patterns as indicators for stability of Norway spruce forests within and beyond the limits of their natural range. In: Bohn, U., Hettwer C., and Gollub G. (eds.): Application and Analysis of the Map of the Natural Vegetation of Europe. Bfn-Skripten. Bonn, Bundesamt für Naturschutz, p. 399–409.

Kermavnar, J., Kutnar, L., Pintar, A. M., 2023: Ecological factors affecting the recent *Picea abies* decline in Slovenia: the importance of bedrock type and forest naturalness. iForest, 16:105–115.

Kramarets, V. O., Krynytskyi, H. T., 2009: Assessment and possible threats to the survival of the spruce forests of the Carpathians in connection with climate change. Scientific bulletin of the Ukrainian National Forestry University, 19.15:38–50. (In Ukrainian).

Kramarets, V., Matsiakh, I., 2018: The role of biotic factors in spruce decline in the Ukrainian Carpathians. Proceedings of the forestry Academy of Sciences of Ukraine, 17:121–132. (In Ukrainian).

Krejza, J., Cienciala, E., Světlík, J., Bellan, M., Noyer, E., Horáček, P. et al., 2021: Evidence of climate-induced stress of Norway spruce along elevation gradient preceding the current dieback in Central Europe. Trees, 35:103–119.

Krynytskyi, H. T., 2005: Critical situation in Norway spruce stands. Forest and Hunting Journal, 4:17–19. (In Ukrainian).

Krynytskyi, H. T., Kalutskyi, I. F., Havrusevych, A. M., Ivaniuk, A. P., 2006: The formation factors of windfalls and raising of biological resistance of stands in the zone of influence of recreational complex "Bukovel". Forestry, Forest, Paper and Woodworking Industry, 32:20-27. (In Ukrainian).

Krynytskyi, H. T., Kramarets, V. O., 2009: System of forestry measures on elimination of consequences of mass decline of spruce stands in beech-fir forests of Carpathians. Forestry and Forest Melioration, 115:256–260. (In Ukrainian).

Kyyak, V., Danylyk, I., Shpakivska, I., Kagalo, O., Lobachevska, O., Kanarsky, Y. et al., 2022: Conservation of biodiversity in mountainous and plain regions of Ukraine under climate change conditions. Lviv, Prostir-M, 189 p. (In Ukrainian).

Lavnyy, V. V., 2021: Silvicultural and ecological principles of primary stands regeneration on windthrow areas in the Ukrainian Carpathians. Lviv, Halytska Vydavnycha Spilka, 296 p. (In Ukrainian).

Moravčík, M., Dzian, M., Paluš, H., Parobek, J., 2024: Sustainable development: Evaluation and forecasting of Norway spruce production and growing stock in Slovakia in the context of bioeconomy. Central European Forestry Journal, 70:11–18.

Poliakova, L., Abruscato, S., 2023: Supporting the recovery and sustainable management of Ukrainian forests and Ukraine's forest sector. Bonn, Forest Europe, 67 p.

Pretzsch, H., 2016: Ertragstafel-Korrekturfaktoren für Umwelt- und Mischungseffekte. AFZ-DerWald, 14:47–50. (In German).

Reventlow, D. O. J., Nord-Larsen, T., Biber, P., Hilmers, T., Pretzsch, H., 2021: Simulating conversion of even-aged Norway spruce into uneven-aged mixed forest: effects of different scenarios on production, economy and heterogeneity. European Journal of Forest Research, 140:1005–1027.

Rybníček, M., Čermák, P., Žid, T., Kolář, T., 2012: Growth responses of *Picea abies* to climate in the Central Part of the Českomoravská Upland (Czech Republic). Dendrobiology, 68:21–30.

Schmidt-Vogt, H., 1977: Die Fichte. Hamburg, Berlin, Paul Parey, 647 p. (In German).

Shparyk, Y., Krynytskyy, H., Debryniuk, Y., 2020: Trends of dynamics in the site conditions types and species composition of the forest stands in the Ukrainian Carpathians caused by climate changes. Scientific bulletin of the Ukrainian National Forestry University, 20:82–92. (In Ukrainian).

Shvidenko, A. Z. et al., 1987: Normative materials of forest's inventory in Ukraine and Moldova. Kyiv, Urozhaj, 560 p. (In Russian).

Shvidenko, A. Z., Buksha, I. F., Krakovska, S. V., 2018: Vulnerability of Ukraine's forests to climate change. Monograph. Kyiv, Nika-Centre, 184 p. (In Ukrainian).

Spathelf, P., van der Maaten, E., van der Maaten-Theunissen, M. et al., 2014: Climate change impacts in European forests: the expert views of local observers. Annals of Forest Science, 71:131–137.

Spiecker, H., 2000: Growth of Norway spruce (*Picea abies* [L.] Karst.) under changing environmental conditions in Europe. EFI Proceedings, 33:11–26.

Spiecker, H., Kahle, H.-P., 2023: Climate-driven tree growth and mortality in the Black Forest, Germany – Long-term observations. Global Change Biology, 29:5908–5923.

Strochynskyi, A. A., Kashpor, S. M., 2010: Normative handbook for forest inventory. Kyiv, NUBIP, 283 p. (In Ukrainian).

Struk, T. V., Yaremko, O. Ie., Korchemliuk, M. V., Arkhypova, L. M., 2017: Global warming trends in Prykarpattia. Scientific and technical journal of the Ivano-Frankivsk National Technical University of Oil and Gas "Environmental safety and balanced resource use" 1:212–220 (In Ukrainian).

Synek, M., Janda, P., Mikoláš, M., Nagel, T. A., Schurman, J. S., Pettit, J. L. et al., 2020: Contrasting patterns of natural mortality in primary *Picea* forests of the Carpathian Mountains. Forest Ecology and Management, 457:117734.

Tsuryk, E. I., 1981: Spruce stands of the Carpathians (Structure and productivity): monograph. Lviv, Vyshcha Shkola, 182 p. (In Russian).

Vyshnevskyi, V. I., Donich, O. A., 2021: Climate change in the Ukrainian Carpathians and its possible impact on river runoff. Acta Hydrologica Slovaca, 1:3–14.

Yue, C., Kahle, H.-P., von Wilpert, K., Kohnle, U., 2016: A dynamic environment-sensitive site index model for the prediction of site productivity potential under climate change. Ecological Modelling, 337:48–62.

Yue, C., Kahle, H.-P., Klädtke, J., Kohnle, U., 2023: Forest stand-by-environment interaction invalidates the use of space-for-time substitution for site index modelling under climate change. Forest Ecology and Management, 527:120621.

Other sources

Cabinet of Ministers of Ukraine, 1994: Instructions for the forest inventory of the forest fund of Ukraine. Approved by the Decree of the Cabinet of Ministers of Ukraine of April 22, 1994 No. 234. (In Ukrainian).

Cabinet of Ministers of Ukraine, 2021: State Forest Management Strategy of Ukraine until 2035. Approved by the Order of the Cabinet of Ministers of Ukraine of December 29, 2021 No. 1777 (In Ukrainian).

Cabinet of Ministers of Ukraine, 2023: Procedure of the forest inventory. Approved by the Decree of the Cabinet of Ministers of Ukraine of February 7, 2023 No. 112. (In Ukrainian).

Food and Agriculture Organization of the United Nations (FAO), 2020: Global Forest Resources Assessment 2020. Report Ukraine. Rome, FAO, 54 p.

Parliament of Ukraine, 1994: The Forest Code of Ukraine. Available at https://zakon.rada.gov.ua/laws/show/3852-12?lang=en#Text.

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J. P., Sterba, H., Teuffel, K., 2004: Norway Spruce Conversion – Options and Consequences. EFI Research Report 18. Leiden, Boston, Köln, Brill, 320 p.

State Forest Resources Agency of Ukraine, 2024. Assortment structure of all types of cuttings, 2024: Approximate assortment structure of timber harvesting in 2022. Available at https://forest.gov.ua/en/areas-activity/use-forest-resources/assortment-structure-all-types-cuttings.

Ukrainian State Forest Management Planning Association (UkrDerzhLisProekt), 2022: Instructional and methodological guidelines on forest management. Irpin, 85 p. Available at https://lisproekt.gov.ua/fileadmin/user_upload/Instruktivno-metodichni_vkazivki.pdf (In Ukrainian).