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RECEIVED 23 February 2026

REVISED 21 April 2026

ACCEPTED 30 April 2026

PUBLISHED 15 May 2026

CITATION

Šilinskas B, Linkevičius E, Beniušienė L,
Aleinikovas M, Konstantinavičienė J and
Vikšniauskas R (2026) Enhanced
productivity in mixed stands of Norway
spruce, Scots pine, and silver birch
in Lithuania.
Front. For. Glob. Change 9:1815758.
doi: 10.3389/ffgc.2026.1815758

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Enhanced productivity in mixed stands of Norway spruce, Scots pine, and silver birch in Lithuania

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Mixed-species forests are increasingly promoted in Europe due to their potential to enhance productivity, resilience, and ecosystem functioning compared with pure stands. However, empirical evidence quantifying productivity differences among common boreal and hemiboreal species mixtures under Lithuanian conditions remains limited. This study evaluated stand volume in pure and mixed stands of three dominant tree species in Lithuania—Scots pine (*Pinus sylvestris* L.), Norway spruce [*Picea abies* (L.) H. Karst.], and silver birch (*Betula pendula* Roth). Nine study plots representing pure stands and 70:30 mixed-species stands were selected from forest inventory data on infertile light soils (Nbl), with stand ages ranging from 45 to 50 years. Within each plot, diameter at breast height, tree height, crown width, competition index, and stand volume were measured for a total of 809 trees. Statistical differences among stands were assessed using analysis of variance (ANOVA), followed by Duncan's multiple range test. Results indicate that mixed stands generally improved tree growth and stand volume compared with pure stands. Stand volume was consistently higher in mixed stands across all species combinations. The most pronounced effect was observed in pine–spruce mixtures, where stand volume exceeded that of pure pine stands by 85%. Admixtures of spruce or pine increased stand volume in birch-dominated stands by 28%–30%, while the admixture of pine in spruce stands increased stand volume by 29%. Although these differences may be influenced by site conditions, stand structure, and the limited number of plots. The highest mean diameter and height values were observed in pine–spruce mixtures, where Scots pine exhibited up to 36% greater diameter at breast height (DBH) and 16% greater tree height than in pure pine stands. Birch growth also benefited from species mixtures, particularly in pine–birch stands, where DBH increased by up to 32% compared with pure birch stands. The findings suggest

that species mixing may enhance stand volume under Lithuanian conditions, particularly in pine–spruce mixtures. However, management strategies should consider site conditions, stand structure, and production objectives. This study provides empirical evidence supporting the expansion of mixed-species forestry in Lithuania and highlights the need for further long-term research based on larger datasets.

KEYWORDS

allometry, forest productivity, mixed-species forests, Norway spruce, Scots pine, silver birch, species mixing, stand volume

1 Introduction

Silver birch (*Betula pendula* Roth), Norway spruce [*Picea abies* (L.) H. Karst.], and Scots pine (*Pinus sylvestris* L.) are the most common tree species in Lithuania and together account for approximately 76% of the total standing timber volume (LSFS, 2023). Pure stands of these species constitute 82% of pine, 74% of spruce, and 62% of birch stands (LSFS, 2023). Only in the past decade reforestation and afforestation policies in Lithuania begun to recommend the establishment of forest stands composed of two or more tree species. Numerous studies highlight the critical importance of species diversity for maintaining forest ecosystem functions and services (Bielak et al., 2014; Hilmers et al., 2020). Mixed-species stands are increasingly favored in forest management due to evidence suggesting that they have greater potential for productivity, multifunctionality, and ecological value compared with monocultures (Bielak et al., 2014; Riofrío et al., 2017). Tree–tree competition plays a key role in shaping growth dynamics in mixed stands, influencing tree structural attributes and allometric relationships that ultimately affect stand productivity (Cudjoe et al., 2025a). In Northern and Central Europe, Scots pine, Norway spruce, and birch are among the most dominant tree species, frequently forming natural or managed mixtures that cover extensive forest areas (Bielak et al., 2014; Frivold and Frank, 2002; del Río et al., 2016). For example, pine–spruce mixtures account for approximately 18% of Finland's forest area, while conifer mixtures represent about 20% of productive forest land in Sweden (Pukkala et al., 1994; Holmström et al., 2018).

Scots pine and silver birch are early-successional, light-demanding species, whereas Norway spruce is a shade-tolerant, late-successional species (Frivold and Frank, 2002; Valkonen and Valsta, 2001; Dosumu et al., 2024). Norway spruce can effectively utilize filtered light beneath the relatively transparent crowns of pine or birch, leading to vertical stratification within mixed stands (Bielak et al., 2014; Pretzsch, 2019; Pretzsch and Schütze, 2021). In addition, interspecific competition can modify height growth, crown development, and diameter increment, resulting in species-specific structural adaptations in mixed stands (Cudjoe et al., 2025a). Complementarity is also evident below ground: the root system of Scots pine is typically deeper than the shallow root system of Norway spruce, allowing mixed stands to utilize water and nutrient resources more efficiently across different soil horizons (Bielak et al., 2014; Pukkala et al., 1994; Sterba et al., 2002; Knoke et al., 2008). The admixture of broadleaved species

such as birch can further improve soil fertility by accelerating litter decomposition and nutrient cycling compared with pure coniferous stands (Sterba et al., 2002; Knoke et al., 2008). Species mixing can also influence biomass allocation and growth efficiency, as different species respond according to their ecological traits and competitive strategies (Cudjoe et al., 2024).

Recent research using advanced technologies such as LiDAR has demonstrated that species mixing significantly modifies individual tree allometry (Pretzsch, 2019; Pretzsch and Schütze, 2021). In mixed stands, trees often develop wider and longer crowns and exhibit greater crown plasticity than in monocultures (Pretzsch, 2019; Pretzsch and Schütze, 2021). This increased structural complexity leads to higher canopy packing density and leaf area index (LAI), which are key drivers of enhanced light interception and stand productivity (Riofrío et al., 2017; Pretzsch and Schütze, 2021). Furthermore, mixed stands often display more uneven size distributions, which can contribute to a more resilient canopy structure (Pretzsch and Schütze, 2016). Conifer mixtures may achieve volume increments that are 10%–15% higher than those of pure stands (Bielak et al., 2014; Pukkala et al., 1994). Long-term data from Poland indicate that some mixed stands can exceed the productivity of monocultures by an average of 41% (Bielak et al., 2014). Mixed stands are also generally more resistant to abiotic and biotic disturbances, including windthrow, snow damage, and pest outbreaks such as the bark beetle (*Ips typographus*) or fungal pathogens (Hilmers et al., 2020; Valkonen and Valsta, 2001; Knoke et al., 2008; Fahlvik et al., 2011; Bauhus et al., 2017). Although pure spruce stands are traditionally considered highly profitable, mixed stands can yield higher net present values (NPV) by reducing financial risk through species diversification (Valkonen and Valsta, 2001; Knoke et al., 2008). Retaining a birch overstory in spruce plantations has also proven economically beneficial due to its high value in the veneer industry and its role as a nurse crop that protects against frost (Valkonen and Valsta, 2001).

Previous studies in Lithuania have shown that optimizing stand structure in mixed forests should be based on light availability, ensuring that optimal light conditions are provided for the main tree species without reducing overall stand productivity (Kairiūkštis and Juodvalkis, 2005). Another study, based on Lithuanian National Forest Inventory data, concluded that diversifying native species and prioritizing ecological integrity can support the development of productive, self-sustaining forests in Lithuania (Petrokas et al., 2025).

This study is both relevant and novel within the Lithuanian and broader Baltic context. Previous research in Lithuania has

primarily focused on pure stands, with limited attention given to mixed stands. Although recent studies have analyzed mixed stands using National Forest Inventory data, empirical research under Lithuanian conditions addressing stand volume and allometric parameters in mixed stands at the site level remains scarce. This study provides new insights based on empirical data from both pure and mixed stands. Unlike previous research, it includes detailed measurements of all trees within the selected study sites. It therefore offers valuable insights and helps address existing knowledge gaps related to stand volume of key tree species in the region. As the proportion of mixed stands continues to increase across European forests, these findings provide important information on potential outcomes under typical site conditions. Furthermore, the study contributes to a better understanding of differences in key allometric parameters between pure and mixed stands under Lithuanian conditions. It highlights the potential to reconsider forestry practices and perceptions regarding the stand volume of mixed stands on infertile soils, particularly in pine–birch mixtures. The underlying hypothesis is that mixed stands may exhibit higher stand volume than pure stands. The dataset was developed by measuring selected parameters for all standing trees within the study sites. The aim of this study was to assess differences in allometric parameters and stand volume between pure and mixed stands of three dominant tree species in Lithuania.

2 Materials and methods

2.1 Study site

This investigation of stand allometric parameters and stand volume was conducted in Lithuania, a country located on the eastern shore of the Baltic Sea, between 53°54′–56°27′ N latitude and 20°56′–26°51′ E longitude. Lithuania covers a total area of 65,200 km² and lies within the temperate climatic zone. Its climate is transitional, influenced by both the maritime conditions of Western Europe and the continental climate of Eastern Europe (Galvonaitė et al., 2013). During the period 1981–2010, the mean annual air temperature was 6.9 °C, and the average annual precipitation was 695 mm. Lithuania is situated in the southern part of the hemiboreal forest region, forming a natural transition zone between boreal and nemoral forests. Forests cover approximately 2.2 million hectares, accounting for 33.9% of the country's land area (LSFS, 2023). Coniferous forests dominate, comprising 55.5% of the total forest area. Scots pine (*Pinus sylvestris* L.) is the most widespread species, covering 34.3% of forest land, followed by Norway spruce [*Picea abies* (L.) H. Karst.] at 21.2% and silver birch (*Betula pendula* Roth) at 21.8% (LSFS, 2023).

2.2 Study plots and field measurements

A total of nine study plots were selected from forest inventory data, with three plots representing each dominant tree species (Figure 1). Plot selection was based on specific criteria, including soil type, stand age, stocking level (forest site part occupied by trees), and species composition. All selected criteria (stocking level and tree age) were derived from forest inventory data. The selected

study sites were established through planting and had undergone at least two thinning operations. Tree mortality was not considered in this study. All plots were temporary and established specifically for the purposes of this research. For each dominant species—Norway spruce, Scots pine, and silver birch—one plot represented a pure stand (10S, 10P, and 10B, respectively). The remaining plots were mixed stands composed of 70% dominant species and 30% accompanying species, distributed as evenly as possible within each plot (7P3B, 7P3S, 7S3B, 7S3P, 7B3S, and 7B3P) (Table 1). Stand structure and species composition were verified by calculating the proportion in tree number of each tree species within the sample plots. The selected plots represent mixed stands with a random spatial distribution of individual trees, without distinct grouping of species within the sites.

Within each study plot, two rectangular sample plots measuring 20 × 30 m were established, resulting in a total sampled area of 0.12 ha per study plot. The following stand and tree attributes were assessed: diameter at breast height (DBH), tree height (H), height to the base of the live crown (HL), crown width (CW), and competition index (CI). In total, 809 trees were measured for analysis. All variables, except for the competition index, were calculated excluding second-layer Norway spruce trees. This second layer represents natural regeneration (next-generation trees) and was not included in the estimation of main stand parameters to ensure comparability with stands lacking a second layer. The second layer accounted for approximately 5% of stand volume in the selected sites. However, second-layer trees were included in the calculation of the competition index, as they contribute to competition for resources with first-layer trees. Diameter at breast height (measured at 1.3 m above ground) was determined using a caliper in two perpendicular directions (north–south and east–west). The average of these two measurements was used as the final DBH value.

Tree height and height to the crown base were measured using a Haglöf Vertex 3 ultrasonic hypsometer (Haglöf Sweden AB, Långsele, Sweden) in combination with a T3 transponder. This instrument is widely used in forestry for measuring tree height, distance, and angles.

Crown width was determined by measuring the horizontal extent of the crown in two perpendicular directions (north–south and east–west) using a measuring tape. The average of these two measurements was used as the crown width (CW) value.

The measured DBH data were subsequently used to calculate the competition index (CI) following Hegyi's method (Hegyi, 1974), a widely used approach for quantifying competitive interactions among trees within forest stands (Equation 1).

$$CI = \sum_{j=1}^N \frac{D_j}{D_i \times L_{ij}}, \quad (1)$$

where i denotes the target tree, j denotes a competing tree, D_i is the DBH of the target tree, D_j is the DBH of the competing tree, L_{ij} is the distance between the target tree (i) and the competing tree (j), and N is the number of competing trees.

All trees located within a distance of 1–2.8 m from the reference trees were included in the calculation of the Hegyi competition index (CI).

The volume of each tree was estimated using DBH, tree height, and a species-specific form factor. Form factors were obtained from Kuliešis (1993). A similar formula was applied to all tree species,

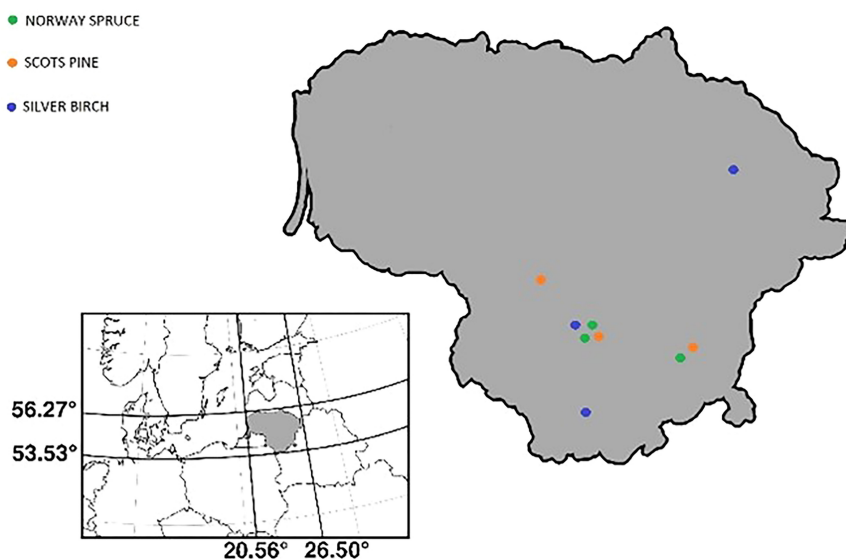


FIGURE 1

Location of the selected study sites in Lithuania. Different colors indicate sites according to the dominant tree species.

with parameter values varying depending on the species. Equation 2 presents the formula used for calculating the form factor of Scots pine.

$$f_s = 0.41097 + \frac{0.47997}{h} + \frac{1.02196}{DBH} + \frac{0.12880}{DBH \cdot h} - \frac{2.84120}{DBH^2} + \frac{6.3796}{DBH^2 \cdot h}, \quad (2)$$

where f_s is the form factor, h is tree height (m), and DBH is diameter at breast height (cm). Stand volume (V) per hectare was calculated by summing the volumes of all trees within the sample plot and dividing by the plot area.

2.3 Statistical analysis

Analysis of variance (ANOVA), followed by Duncan's multiple range test, was used to assess statistically significant differences in tree height, diameter, crown-base height, crown width, and the competition index. Prior to the analysis, the assumptions of normality and homogeneity of variances were evaluated using residual diagnostics, including histograms, Q-Q plots, and residual versus fitted value plots. These assumptions were satisfied for all variables except the competition index. Therefore, ANOVA was applied only to tree height, diameter, crown-base height, and crown width.

For the competition index, where the assumption of normality was not met, a non-parametric Kruskal-Wallis H test was applied, followed by Dunn's *post-hoc* test for pairwise comparisons. Bonferroni-adjusted p -values were used to account for multiple testing. All analyses were conducted at a 95% confidence level ($\alpha = 0.05$). ANOVA was performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, United States), while non-parametric analyses and assumption testing were conducted using SPSS version 25 (IBM Corp., Armonk, NY, United States).

3 Results

The mean values of diameter at breast height (DBH), tree height (H), height to the base of the live crown (HL), crown width (CW), and competition index (CI) for Scots pine, silver birch, and Norway spruce in pure and mixed stands are presented in Table 2. Mean DBH ranged from 17.80 cm in the pure silver birch stand to 24.31 cm in the mixed Scots pine–Norway spruce stand. The lowest mean tree height was observed in the pure Norway spruce stand, whereas the highest mean height occurred in the mixed pine–spruce stand. Mean crown width ranged from 3.09 to 4.10 m across the sites, while the competition index ranged from 0.76 to 1.29 (Table 2).

To assess tree responses in mixed stands compared with pure stands, ANOVA was performed. A comparison between pure silver birch stands (100%) and mixed stands with a 70:30 species composition revealed a 32% difference in mean DBH between the pure stand and the 7B3P stand. The second-highest mean DBH was observed in the 7P3B stand. The mixture of Scots pine and silver birch had a statistically significant effect on birch DBH.

The highest mean tree height was recorded in the 7B3P stand, representing a 6% increase compared with the pure stand. The height to the base of the live crown differed by 8%, with the highest mean value observed in the 7B3S stand relative to the pure stand. The smallest differences were observed for crown width. Only one stand (7S3B) showed a statistically significant difference in crown width for silver birch, with a 14% increase compared with the pure birch stand. The highest competition index was recorded in the 7P3B stand, where Norway spruce formed a second canopy layer. The results for silver birch are presented in Figure 2.

The differences between pure Norway spruce stands (100%) and mixed spruce stands with a 70:30 species composition are presented in Figure 3. The highest mean DBH was observed in the 7P3S stand, where it was 15% higher than in the pure spruce stand. Tree height was similar between the pure stand and the 7S3B and 7B3S stands. The highest mean height to the base of

TABLE 1 Main stand characteristics derived from forest inventory data for each study plot, including the proportion of measured trees in the selected sites.

Enterprise*	Forestry unit*	District*	Plot*	Area (ha)	Soil	Age	Species mixture	Stocking level	Second layer	Portion of trees in sites
Prienų	Meškapiėvio	87	18	0.7	Nbl	50	7B 3P	0.7	10S	67%–33%
Prienų	Dambraivos	137	34	2.5	Nbl	50	7S 3P	0.7	–	72%–28%
Prienų	Dambraivos	142	77	0.7	Nbl	50	7P 3B	0.7	10S	70%–30%
Trakų	Žėronių	147	10	0.7	Nbl	49	7S 3B	0.7	–	65%–35%
Ignalinos	Gražutės	250	15	1.3	Nbl	45	7B 3S	0.7	10S	65%–35%
Prienų	Dambraivos	124	13	0.8	Nbl	50	10S	0.7	–	100%
Prienų	Sudvajių	218	5	1.7	Nbl	45	10B	0.7	–	100%
Kazlų rūdos	Agurkiškės	2	11	1.2	Nbl	50	10P	0.7	–	100%
Trakų	Žėronių	70	1	1.8	Nbl	49	7P 3S	0.7	–	72%–28%

*The location of selected sites by Lithuanian forest cadastre data. All plots were established on Nbl soils (infertile light soils with a normal moisture regime), with stand age corresponding to the fifth age class (45–54 years) and a stocking level (forest site part occupied by trees) of 70% and measured sites proportion of trees by species.

the live crown was recorded in the pure Norway spruce stand, indicating more effective natural pruning compared with mixed stands. Mean crown width was lowest in the pure stand and did not differ significantly from the 7S3B and 7S3P stands (Figure 3).

For Scots pine, the highest mean DBH was observed in the 7S3P stand, where it was 36% higher than in the pure pine stand. The highest mean tree height was recorded in both the 7S3P and 7P3S stands. The difference in tree height between the pure pine stand and the 7S3P stand was 16%, indicating a positive effect of Norway spruce on pine height growth. Height to the base of the live crown was significantly higher in mixed pine–spruce and spruce–pine stands compared with the pure pine stand and mixed pine–birch and birch–pine stands. The highest mean crown width was also observed in the 7S3P stand, where it was 22% greater than in the pure stand. The 7S3P stand exhibited the lowest competition index, which may partly explain the higher values observed for the other growth parameters. Differences in Scots pine parameters between pure and mixed stands are presented in Figure 4.

The stand volume of the selected study sites indicates that, in all cases, mixed stands had higher stand volume than pure stands. A mixed birch stand with a 30% admixture of Norway spruce exhibited a 28% higher stand volume than the pure birch stand. In contrast, the admixture of birch into a spruce stand increased stand volume by only 7% compared with the pure spruce stand. Much larger differences were observed between the pure pine stand and the 7P3S mixed stand, where stand volume was 85% higher. A 30% admixture of Scots pine in a Norway spruce-dominated stand increased stand volume by 29% compared with the pure spruce stand. Similarly, a 30% admixture of birch or pine increased stand volume by 43% (7P3B) and 30% (7B3P), respectively, compared with pure pine and pure birch stands. Stand volume results for both mixed and pure stands are presented in Figure 5.

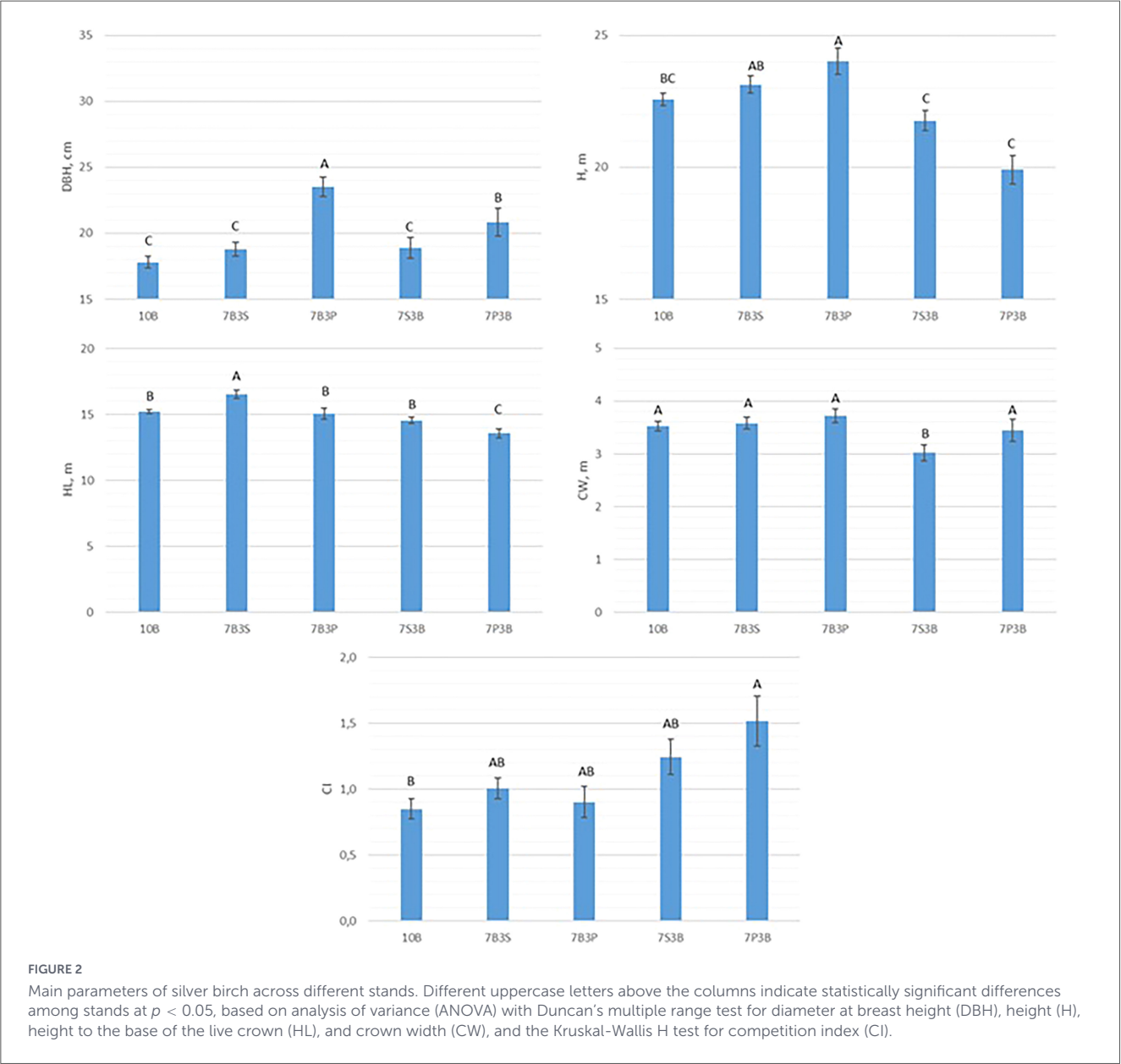
4 Discussion

The results of this study demonstrate the effect of species mixtures on key tree characteristics, including diameter at breast height (DBH), tree height, height to the base of the live crown, crown width, competition index, and stand volume. A comparative study based on national inventory data from Lithuania, Poland, Sweden, and Norway highlighted the importance of climatic conditions for tree mortality in mixed pine–birch and pine–spruce stands. In that study, the mean DBH of pine trees in pine–birch mixtures were 33% higher than that of birch, while in pine–spruce mixtures the mean DBH of pine was 24% higher than that of spruce (Condés et al., 2025). In comparison, the present study revealed a 43% difference in mean DBH between pine and birch in the 7B3P stand and a 4% difference in the 7P3B stand, with pine trees exhibiting larger diameters in both cases. In pine–spruce mixtures, pine DBH exceeded that of spruce by 41% in the 7S3P stand and by 17% in the 7P3S stand. These findings suggest that Scots pine may benefit from growing in mixed stands, particularly when it represents a smaller proportion of the stand (30%). One possible explanation for the increased pine DBH in spruce–pine mixtures is reduced intraspecific competition combined with complementary rooting patterns between pine and spruce.

TABLE 2 Mean values of the main parameters in pure and mixed stands.

Site	DBH (cm)	H (m)	HL (m)	CW (m)	CI
10B	17,80 (0,45) G	22,62 (0,24) A	15,24 (0,15) A	3,55 (0,10) CD	0,84 (0,08) BD
10S	18,54 (0,45) FG	19,41 (0,25) D	12,01 (0,14) CDE	3,09 (0,09) E	1,00 (0,05) ABCD
10P	22,53 (0,74) BC	21,22 (0,45) B	13,79 (0,43) B	3,92 (0,13) AB	1,03 (0,12) ABCD
7B3S	18,96 (0,37) EFG	20,77 (0,35) BC	11,48 (0,59) DE	3,79 (0,08) ABC	1,08 (0,06) ACD
7B3P	23,50 (0,56) AB	22,60 (0,44) A	13,98 (0,42) B	3,79 (0,11) ABC	0,88 (0,09) BC
7S3B	19,75 (0,47) DEF	20,75 (0,27) BC	10,84 (0,44) E	3,13 (0,09) E	1,29 (0,08) A
7S3P	21,27 (0,85) CD	20,08 (0,48) CD	12,17 (0,43) CD	3,75 (0,13) BC	0,95 (0,07) AC
7P3B	20,32 (0,50) DE	19,76 (0,29) CD	12,91 (0,28) BC	3,27 (0,10) DE	1,24 (0,08) B
7P3S	24,31 (0,61) A	23,00 (0,41) A	13,68 (0,62) B	4,10 (0,12) A	0,76 (0,06) ABCD

Standard errors are provided in brackets (italicized). Different uppercase letters (bold) indicate statistically significant differences among stands at $p < 0.05$, based on ANOVA with Duncan's multiple range test for diameter at breast height (DBH), height (H), height to the base of the live crown (HL), and crown width (CW), and the Kruskal-Wallis H test for competition index (CI).



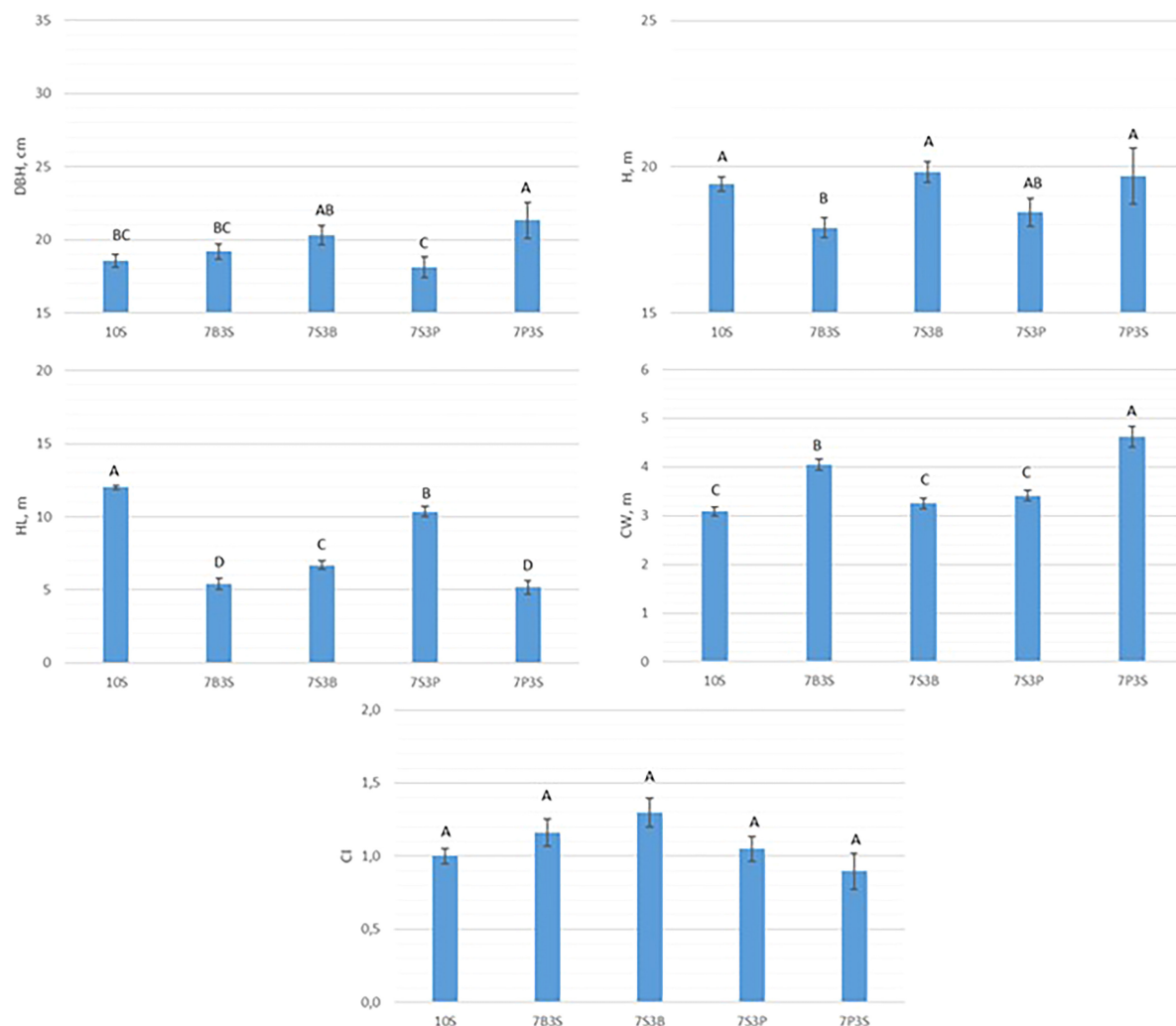


FIGURE 3

Main parameters of Norway spruce across different stands. Different uppercase letters above the columns indicate statistically significant differences among stands at $p < 0.05$, based on analysis of variance (ANOVA) with Duncan's multiple range test for diameter at breast height (DBH), height (H), height to the base of the live crown (HL), and crown width (CW), and the Kruskal-Wallis H test for competition index (CI).

A study conducted in France investigated crown allometric relationships in pure and mixed young pine–birch stands and found that species interactions increased crown size and stem diameter in pine, whereas the opposite effect was observed for birch (Martin-Blangy et al., 2023). In our study, mean crown width in mixed birch–pine stands was generally lower than in pure stands, except in the 7B3P stand, where birch crown width was 5% higher than in the pure birch stand. Differences between the French and Lithuanian results may be explained by variations in stand age and site conditions. In addition, responses to species mixing are often species-specific, with some species benefiting more than others depending on their ecological traits and competitive strategies (Cudjoe et al., 2024). A study conducted in Ukraine on mixed pine–birch stands aged 40 and 60 years (70% pine and 30% birch) reported a 5% difference in DBH between species in both age groups, with pine consistently exhibiting larger diameters. Pine height exceeded birch height by 2% at age 40 and by 4% at age 60. Stand volume reached 182 m³ ha^{−1} at age 40 and 305 m³ ha^{−1} at age 60 (Tkach et al., 2022). In comparison, our Lithuanian study suggests that at age 50, in the

7P3B mixture, differences in DBH and height between pine and birch were both approximately 4%, and stand volume reached 301 m³ ha^{−1}. Despite differences in geographic location, growth patterns were remarkably similar, while stand volume in Lithuania at age 50 approached the Ukrainian value reported for age 60. These similarities may reflect underlying biomass allocation patterns and structural adaptations influenced by species interactions in mixed stands (Cudjoe et al., 2024). Huuskonen et al. (2022) analyzed young mixed spruce–birch stands in Finland and found similar DBH values for both species, while birch height was 24% greater than that of spruce. In our study, spruce DBH in the 7S3B stand was 7% higher than birch DBH, whereas birch height exceeded spruce height by 9%, indicating broadly comparable trends.

Research conducted in southern Sweden has demonstrated that appropriate thinning strategies and the early establishment of mixed stands can produce productive and profitable spruce–birch stands over a full rotation (Dosumu et al., 2024). Several studies have concluded that mixed stands can generate higher stand volume than monocultures. For example, a Swedish study

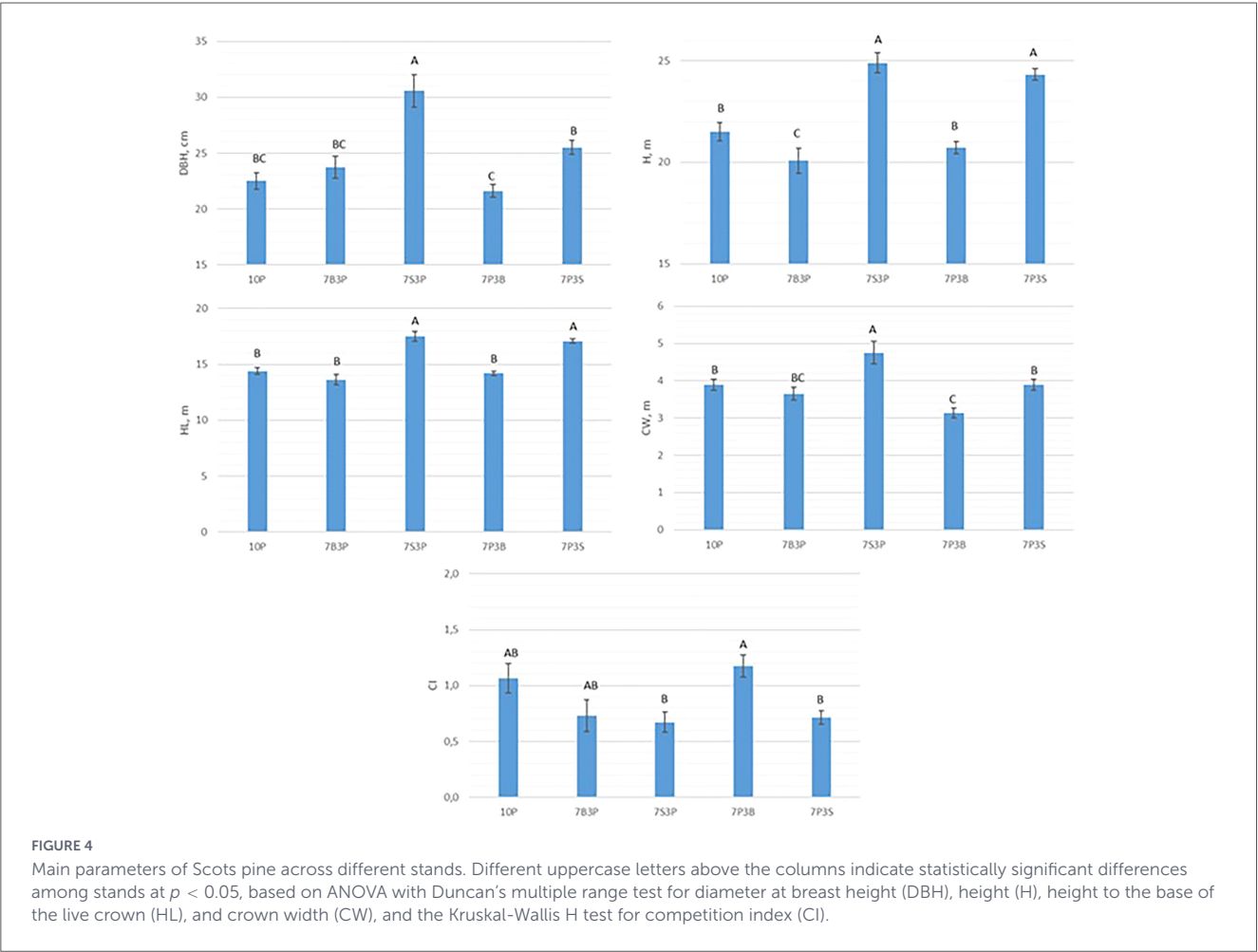


FIGURE 4
Main parameters of Scots pine across different stands. Different uppercase letters above the columns indicate statistically significant differences among stands at $p < 0.05$, based on ANOVA with Duncan's multiple range test for diameter at breast height (DBH), height (H), height to the base of the live crown (HL), and crown width (CW), and the Kruskal-Wallis H test for competition index (CI).

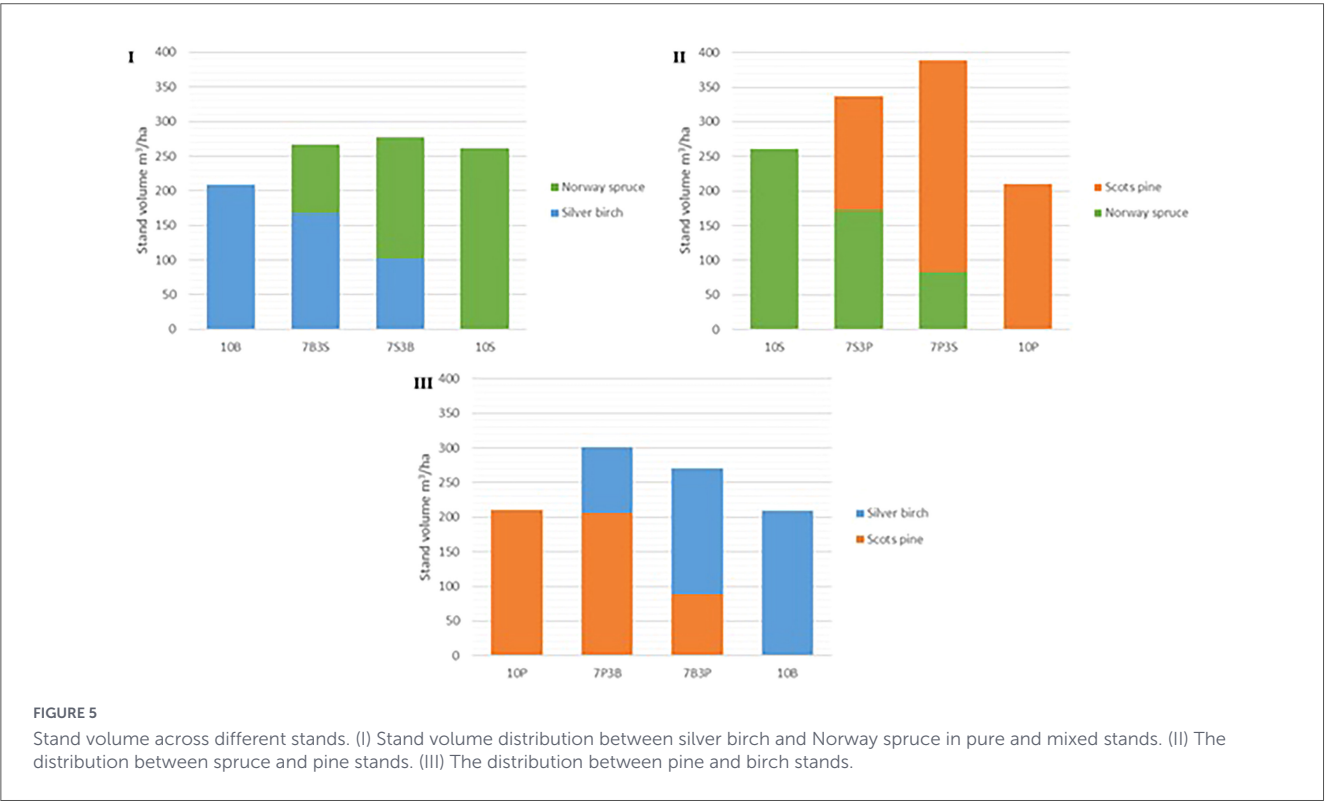


FIGURE 5
Stand volume across different stands. (I) Stand volume distribution between silver birch and Norway spruce in pure and mixed stands. (II) The distribution between spruce and pine stands. (III) The distribution between pine and birch stands.

found that a small admixture of Norway spruce in Scots pine stands increased pine volume increment (Lindén and Agestam, 2003). Similarly, our results showed higher stand volume in the 7P3S stand compared with the pure pine stand. However, a Finnish study reported that mixed pine–spruce stands produced lower volumes than pure pine stands but higher volumes than pure spruce stands (Holmström et al., 2018). In contrast, our results show that mixed stands consistently had higher stand volumes than both pure pine and pure spruce stands. These discrepancies should be interpreted with caution, as they may reflect not only the effects of species mixing but also site-specific conditions, stand structure, competition dynamics (Cudjoe et al., 2025b), and mixture proportions. Higher yields in mixed pine–spruce stands have also been reported in Poland (Bielak et al., 2014). In addition, pine–birch mixtures have been shown to enhance biodiversity and growth rates in the United Kingdom (Parry et al., 2025). Nevertheless, some studies from southern Finland suggest that pure pine stands may be more suitable when the primary objective is high-quality saw timber production (Hynynen et al., 2011). Analyses of mixed and monoculture stands in Central Europe have shown that mixed-species stands often exhibit higher tree densities, stocking levels, crown projection areas, and overall productivity, as well as greater canopy space utilization and structural diversity (Pretzsch and Schütze, 2016).

The competition index is an important parameter in mixed stands for assessing tree growing conditions. In this study, lower mean competition index values were associated with higher stand volume. Similar findings have been reported for mixed larch–birch stands (Zhang et al., 2022), while other studies indicate that increased competition in mixed stands, particularly for dominant tree species, may reduce productivity (Wang et al., 2024). Additionally, the competition index has been identified as a key factor influencing tree mortality (Pretzsch et al., 2023). Overall, mixed stands can provide higher stand volume throughout the rotation period; however, forest management strategies must be carefully tailored to specific stand conditions and management objectives. The results of this study are subject to several limitations. First, the availability of suitable mixed stands meeting the selection criteria was limited due to historical reforestation practices in Lithuania. Second, stand age selection was constrained by national forest management regulations, where commercial thinning is based on the age of the dominant tree species (e.g., 61 years for birch and 101 years for pine). In a changing policy and management context, an increasing number of mixed stands are being established in Lithuanian forests, and this study provides insights into potential future outcomes. The results suggest the potential to reduce the harvesting age to approximately 60 years in mixed stands such as birch–spruce, spruce–birch, pine–birch, birch–pine, spruce–pine, and pine–spruce. Mixed stands may achieve higher yields within the current fifth age class; however, more extensive sampling of both mixed and pure stands is required to confirm these findings. Therefore, the results should be interpreted with caution, as the study is based solely on comparisons within the fifth age class and a limited number of sample plots. The establishment of long-term experimental plots in mixed stands is necessary to obtain more robust and reliable results in future studies.

5 Conclusion

This study assessed stand volume and growth parameters in pure and mixed stands of Scots pine, Norway spruce, and silver birch in Lithuania. The results indicate that species mixtures may offer advantages over monocultures in terms of tree growth and stand volume under the studied conditions.

Mixed stands generally exhibited higher values of diameter at breast height, tree height, crown width, and stand volume than pure stands. The most pronounced positive effects were observed in pine–spruce mixtures, where Scots pine showed increases in diameter, height, and stand volume. Admixtures of spruce or pine also enhanced stand volume in birch-dominated stands, while the addition of pine to spruce stands resulted in moderate but consistent increases in stand volume.

The findings suggest that species complementarity, reduced intraspecific competition, and more efficient resource utilization contribute to enhanced stand volume in mixed stands. These results support the growing emphasis on mixed-species forest management in Lithuania and other hemiboreal regions.

However, this study is limited by the relatively small number of suitable mixed stands and the restricted age range determined by national forest management regulations. These limitations may constrain the generalizability of the results. Future research should include a larger number of study sites and long-term monitoring to better understand the development of mixed stands over a full rotation period.

Overall, the results indicate that increasing the proportion of mixed-species stands could improve stand volume, resilience, and sustainability in Lithuania, provided that silvicultural practices are adapted to site conditions and management objectives.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BŠ: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Writing – original draft. EL: Conceptualization, Formal analysis, Writing – original draft. LB: Investigation, Methodology, Writing – review & editing. MA: Conceptualization, Writing – review & editing. JK: Investigation, Writing – review & editing. RV: Investigation, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was funded through the Research Council of Lithuania Postdoctoral project ID: S-PD-24-167, Productivity and wood quality of pure and mixed stands.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. The Generative AI was used for the English language corrections.

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