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The Possibility of Using Non-Native Spruces for Norway Spruce Wood Replacement—A Case Study from the Czech Republic

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Abstract: European forests are facing ongoing climate change, and certain tree species are being critically impacted. The Norway spruce (*Picea abies* (L.) Karst.) is one of the most sensitive species to climate fluctuations, a fact manifesting itself through massive dieback resulting in a lack of high-quality timber and timber market destabilization. Therefore, the possibility of wood substitution with non-native spruce species, namely, black spruce (*Picea mariana* (Mill.) Britt., Sterns, et Poggenburg), Serbian spruce (*Picea omorika* (Pančić) Purk.), and blue spruce (*Picea pungens* Engelm.), under the specific conditions of forest reclamations with great potential for future afforestation was tested. Wood density, modulus of rupture, and modulus of elasticity were used to evaluate wood quality in comparison with native Norway spruce. The results confirmed that only the Serbian spruce reached the quality of Norway spruce and even exceeded it in terms of wood density (*P. omorika* 525 kg·m^{-3} vs. *P. abies* 517 kg·m^{-3}) and exhibited comparable parameters with regard to other properties. The density of the other species was significantly lower for blue spruce (476 kg·m^{-3}) and black spruce (468 kg·m^{-3}). A similar trend was found for other wood parameters, which confirmed that Norway spruce quality was nearly comparable with that of Serbian spruce. On the other hand, black spruce and blue spruce did not match the quality of Norway spruce. The within-stem variability of the properties tested was low for all the spruce species examined. In conclusion, the Serbian spruce showed great potential for future usage in forest management and is one of the possible methods of Norway spruce replacement in times of unprecedented forest disturbances under the effects of global climate change.

Keywords: *Picea abies*; *Picea mariana*; *Picea pungens*; *Picea omorika*; wood quality; climate change

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1. Introduction

Climate change poses a significant threat to global ecosystems. Forests are extremely sensitive to such risks [1–3]. However, the long-term stability of forest stands is essential for sustainable wood production [4] as well as for ensuring non-productive functions, including biodiversity conservation, and especially climate change mitigation through carbon sequestration, wherein forest ecosystems play a crucial role [5–7]. After all, current forests serve as a vital carbon sink. Wood biomass sequesters approximately 26% of global fossil fuel emissions through the photosynthesis process of trees [4].

The cumulative effect of climate change consists not only of direct impacts, including escalating temperatures or lack of precipitation [8,9], but also increasing the risk of pests, diseases, and wildfires destabilizing forest ecosystems [3,10]. Most notably, the emergence and spread of pests among forest species have been exacerbated by changing climatic conditions [1]. This fluctuating dynamic represents a significant challenge for maintaining the resilience of these ecosystems, especially in the case of the large-scale dieback of Norway spruce (*Picea abies* (L.) Karst.) in Central Europe [11,12]. Therefore, the stabilization of forest ecosystems goes hand in hand with a sustainable and stable timber market and is one of the most important aims for forest management practices in future decades. Introduced tree species sourced from regions with analogous climatic conditions offer a promising solution [13]. By strategically incorporating resilient species with adequate production potential, the adaptive capacity of forests in the face of climate-induced stressors can be enhanced [14]. Among the potential replacements for the economically significant Norway spruce are non-native spruce species [3,15]—non-native in terms of other continents but also from southern parts of Europe, providing species more resistant to drought events.

One of the reasons for the current dieback of Norway spruce is that this species was planted outside its natural distribution range [16]. Still, the Norway spruce is one of the most important tree species in Europe, both ecologically and economically, representing around 25% of the European wood growing stock [17–19]. One of the main reasons for such a high proportion of Norway spruce in forest stands is its wood quality. Softwood timber, particularly from spruce, is widely used as constructional timber, unlike hardwoods, due to an exceptional quality coefficient (the ratio of strength to density). For timber to be used for wood construction, it must meet specific requirements. The available studies concerning timber grading show that spruce is an excellent raw material for construction. First, it has good resistance to load in terms of bending and sufficient stiffness [20–22]. Also, wood density ranks among the most important wood properties, as most mechanical properties are closely related to density. Density is a reliable quality indicator that provides significant information in terms of future wood processing [23]. Not only Norway spruce but also other spruce species, which are not naturally spread over Europe, provide satisfactory properties [24]. Although it is possible to find plantations or experimental plots with non-native spruces in Europe, the corresponding data on wood quality, compared to that for Norway spruce, are limited, especially for Serbian spruce (*Picea omorika* (Pančić) Purk.), black spruce (*Picea mariana* (Mill.) Britton, Sterns et Poggenb.), and blue spruce (*Picea pungens* Engelm.).

The Serbian spruce originated in Serbia and Bosnia and Herzegovina. It is taxonomically close to European spruce species. Despite Serbian spruce having been successfully introduced into Central and Northern Europe, it was unable to migrate on its own [25]. Serbian spruce wood is used mainly as a construction material. Serbian spruce trees are also planted as ornamental trees in cities thanks to their high resistance to air pollution [26]. Although it is a European native species, it has received little attention for its wood. There are limited studies of its wood properties from the areas of its native distribution. Petrović et al. [27] tested the wood density, modulus of rupture, and modulus of elasticity of Serbian spruce from native sites. Studies that have compared the wood quality of Serbian spruce to that of other softwoods are rare. Kommert [28] evaluated some of the physical and mechanical properties of Serbian spruce in Germany, i.e., outside the area of its natural distribution.

The black spruce is another introduced tree species that originates in northern parts of North America, ranging from the Northern USA to the tree line in Northern Canada. The black spruce adapts to low temperatures; however, it can survive in much higher temperatures in the summer months. These trees are also widely used to provide high-quality pulp and as Christmas trees [29]. In particular, in Canada, it ranks among the most important commercial softwoods, providing timber with high stiffness and strength [24]. This species is well researched in its native area in terms of its physical and mechanical properties [24,30–33], but studies from Europe comparing black spruce to native species are insufficient.

The blue spruce is a slow-growing spruce introduced to Europe from the Southwestern USA. Because of its brittle wood, it is not often used in construction. The blue spruce is also often used as a Christmas tree like the previously mentioned black spruce [29]. Although it was introduced to parks in Central Europe as early as the 19th century, nowadays, there are almost 9000 hectares of forests covered with blue spruce in the Czech Republic [34] offering wood that can be used for industrial purposes. However, the information on wood properties under European conditions is limited. Gryc et al. [35] tested the wood properties of blue spruce from an ornamental garden in Central Europe, but their data could not be objectively compared to trees from forest stands; therefore, the corresponding information is not helpful for industry.

The dominant Norway spruce mass will have to be replaced by other sources shortly due to massive diebacks caused by bark beetle outbreaks, drought events, and other climatic extremes connected with climate change [3,16]. Introduced spruce species that are more resilient to expected climate change are the primary choice to ensure a comparable quality of raw material for industry. However, there is a lack of comparative studies assessing wood quality in European conditions. Moreover, it is crucial to evaluate the aforementioned non-native species as an alternative wood source before extending into standard forest stands. Therefore, this paper aims to compare the high-quality wood of native Norway spruce to the non-native Serbian spruce, black spruce, and blue spruce from the perspective of physical and mechanical wood properties and thereby evaluate the usability of the material potential for industrial purposes. The primary objectives are the evaluation of crucial wood properties such as the (i) wood density, (ii) modulus of rupture, and (iii) modulus of elasticity of introduced spruce species compared to those of the native spruce.

2. Materials and Methods

2.1. Study Site

Research was performed on a permanent experimental plot used to test the growth and production potential of non-native tree species. The Antonín Forest Plantation in the northeastern part of Czechia (GPS: 50°10′20′′ N, 12°37′45′′ E), characterized by a post-coal-mining landscape, spans 165 ha with a maximum altitude of 444 m a.s.l. [36]. The soil-forming substrates determining the initial stages of pedogenesis are cypress clays and volcanic detrital series, including porcelanites (erdbrants), which determine the physical features of the soil and fundamental factors of soil chemistry. Presently, there is a differentiation of the soil profile that corresponds to the development of the soils into Cambisol [37,38]. Climate-wise, it falls under the "Cfb" Köppen-Geiger climate classification, with warm, dry summers and cold, dry winters [39]. The average annual temperature is 7.3 °C, with an average precipitation level of 607 mm from 1975 to 2021. Maximum precipitation occurs in July (105 mm), and the minimum occurs in October (55 mm). The vegetation period spans 220–227 days. The Antonín-Sokolov coal mine operated from 1881 to 1965, extracting 22.5 million metric tons of coal and 10.8 million cubic meters of overburden. Reclamation efforts led to the establishment of the Antonín Forest Plantation between 1969 and 1974. Over 220 tree and shrub species (including over 30 introduced species) were systematically planted. Forest management practices have involved targeted tree thinning and sanitary treatments, contributing to the ecological balance and health of the ecosystem [36].

To limit factors affecting tree growth and wood development, all studied spruce species were located at the same site, with identical growth conditions in terms of soil parameters and climate factors. Four spruce species were used to assess wood quality (Table 1): native Norway spruce (*Picea abies*), non-native (but European) Serbian spruce (*P. omorika*), and two North American spruces, black spruce (*P. mariana*) and blue spruce (*P. pungens*). The age of the tested trees was about 50 years.

Table 1. Overview of basic site and production parameters of spruce stands differentiated by spruce species in 2022.

Species	Altitude	Exposure	Slope	DBH (cm)	Height (m)	Stem Volume (m^3)	Tree Density ($trees \cdot ha^{-1}$)	Basal Area ($m^2 \cdot ha^{-1}$)	Stand Volume ($m^3 \cdot ha^{-1}$)	Carbon Stock ($t \cdot ha^{-1}$)
P. abies	432	-	0	14.3	13.8	0.122	1733	28.5	189	76.7
P. mariana	428	S	4	11.2	11.1	0.048	1733	17.0	83	40.3
P. omorika	433	-	0	19.9	14.0	0.186	1080	32.5	195	79.6
P. pungens	441	SE	6	14.8	10.9	0.089	1267	22.9	116	50.6

Notes: DBH—mean quadratic diameter at breast height (measured at 1.3 m above the ground); carbon stock—the content of carbon in spruce trees was calculated following the method in [40] using the unit content of elements in 10 $mg \cdot kg^{-1}$ of dry matter of tree biomass that was derived from the above-ground biomass (stem, branches, and needles) and below-ground biomass (roots and snags) from the models developed in [41].

2.2. Data Collection and Determination of Properties

Four sample trees from each species were cut on long-term research plots, and 2 m long sections from a basal part of the stem were collected to prepare test samples (specimens were obtained from a stem height of 0.2 to 2.2 m above the ground). To obtain the samples for individual tests, the procedure applied by Zeidler et al. [42], especially for evaluating the distribution of properties around the stem radius, was used. Samples with dimensions of 20 × 20 × 300 mm (tangential × radial × axial) were prepared to test basic physical and mechanical properties (Figure 1). In total, 290 samples were tested with respect to selected wood quality properties.

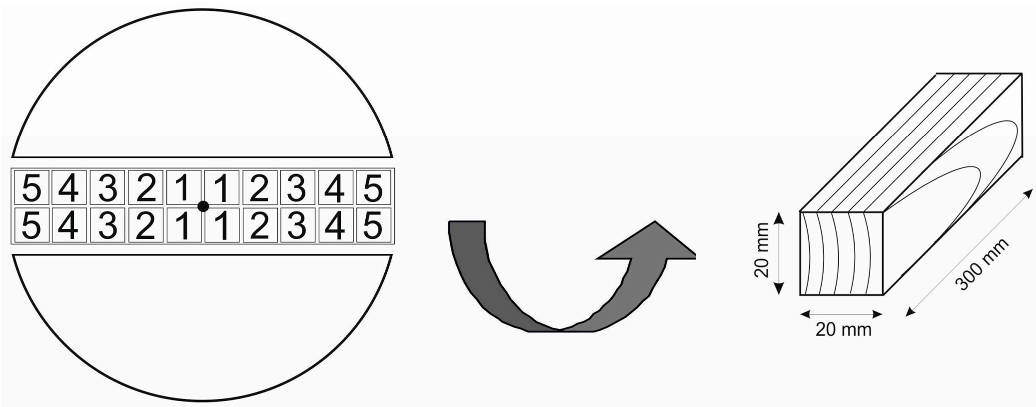

Figure 1. Schematic diagram of the log sampling of spruce trees [43] (numbers 1–5 denote the position of the samples in relation to the pith).

The test samples were exposed for a certain amount of time to an air temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% in an air-conditioned environment to attain standardized equilibrium moisture content [44]. Once the equilibrium moisture content was reached, tests on the individual physical and mechanical properties were performed. For the physical properties, wood density was tested for 12% moisture content [45]. The mechanical properties were represented by the modulus of rupture [46] and the modulus of elasticity [47]. TIRAtest 2850 (Tira GmbH, Schalkau, Germany) universal testing machine was utilized to test both the modulus of rupture (MOR) and modulus of elasticity (MOE).

2.3. Statistical Analysis

Statistical analyses were performed using STATISTICA software (version 13.4.0.14, TIBCO Software, Palo Alto, CA, USA). The wood density, modulus of rupture, and modulus of elasticity were statistically compared between spruce species. Data were first tested using the Shapiro–Wilk normality test and then via the Bartlett variance test. When both requirements were met, the differences between the examined parameters were tested using an analysis of variance (ANOVA), followed by the Tukey HSD test (in all cases). This Tukey multiple range test was employed to reveal individual species differences and assess the property distribution around the radius. Significantly different variants are marked with dissimilar characters (significance level $\alpha = 0.05$ was used). Relationships between tested properties were also evaluated using a linear regression model.

3. Results

3.1. Wood Density

The Serbian spruce was the type of spruce that attained the highest value for wood density from among all the tested species (525 $kg \cdot m^{-3}$), followed by Norway spruce, with a density of 517 $kg \cdot m^{-3}$ (Table 2). The spruces originating from the North American region, namely, black and blue spruce, lagged in terms of density, with considerably lower values. Blue spruce achieved a value of 476 $kg \cdot m^{-3}$, and black spruce showed the lowest value (468 $kg \cdot m^{-3}$). From a statistical point of view, however, it is impossible to distinguish between the values achieved by Serbian and Norway spruce, so the species can thus be seen as equivalent in this regard. The same is true in the case of blue and black spruce, as these spruce species are very similar in terms of wood density and statistically indistinguishable. The variability in the properties was low for all the species, with coefficients of variation ranging from 5.3 to 9.7%.

Table 2. Spruce comparison regarding wood density assessed using basic statistical indicators ($kg \cdot m^{-3}$); the significantly ($p < 0.05$) highest values are in bold; significantly different variants are marked with different letters.

	Mean	**Min.**	**Max.**	**SD**	**CV**	
Black spruce	468 [a]	406	533	28	5.9	*Test*
Norway spruce	**517** [b]	457	583	31	6.0	ANOVA
Serbian spruce	**525** [b]	427	646	51	9.7	*p-value*
Blue spruce	476 [a]	425	543	25	5.3	$p < 0.001$

Notes: SD—standard deviation; CV—coefficient of variation (%).

An attempt was made to find differences between species regarding trends, i.e., the changes in properties relating to increasing age. Figure 2 shows the trend for wood density in the stem for each spruce species in the direction from its center to the periphery. Apart from the differences in density values mentioned above, there is no significant difference in the density trends between species. Most likely due to the small diameter of the sample trees and the small number of positions in the radial profile, we could not confirm any pronounced trend in the distribution of properties. Although the wood density appears to decrease gradually with an increasing distance from the center of the stem, this trend is not statistically significant, except near the bark position (featuring a low number of test specimens).

3.2. Modulus of Rupture

Norway spruce dominates in terms of its bending strength compared to the non-native spruce species. With a value of 84.6 MPa, it considerably surpassed the other species in this regard (Table 3). The Serbian spruce had a value 15 MPa lower, with a bending strength of 69.2 MPa. The lowest value for bending strength was exhibited by the blue spruce (54.8 MPa). However, it was not statistically different from the black spruce, which achieved an only slightly higher value (57.2 MPa). Norway spruce is statistically significantly ($p < 0.001$) different from the Serbian spruce and the North American spruce species. The Serbian spruce is also significantly different ($p < 0.001$) from the black and blue spruce. Moreover, the Norway spruce is characterized by a low variability of properties compared to the remaining species.

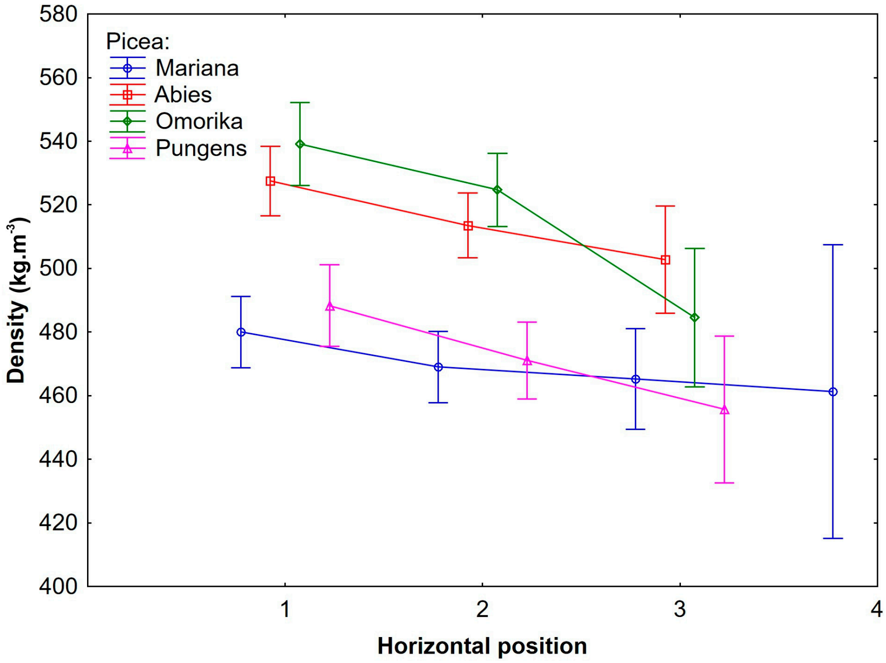

Figure 2. Wood density within-stem distribution. (x-axis: Figures denote the relative position of the test specimen with respect to the pith, i.e., 1 indicates a position near the pith, while 4 is a position close to the bark. The intervals represent standard deviations).

Table 3. Spruce comparison regarding modulus of rupture evaluated in reference to basic statistical indicators (MPa); the significantly ($p < 0.05$) highest values are in bold; significantly different variants are marked with different letters.

	Mean	Min.	Max.	SD	CV	
Black spruce	57.2 [a]	17.9	83.4	12.1	21.2	*Test*
Norway spruce	**84.6** [c]	56.4	106.6	8.8	10.4	ANOVA
Serbian spruce	69.2 [b]	33.6	114.1	16.4	23.8	*p-value*
Blue spruce	54.8 [a]	22.7	74.9	10.1	18.4	$p < 0.001$

SD—standard deviation; CV—coefficient of variation (%).

The distribution of the modulus of rupture in the trunk in the radial direction from the pith to the cambium is shown in Figure 3. There is no apparent trend difference between the evaluated spruce species. Although what is shown may appear to be an increasing trend, it is predominantly statistically insignificant. Thus, the effect of the position on the characteristic under consideration is not entirely clear.

3.3. Modulus of Elasticity

The modulus-of-elasticity results largely correspond to the results for the modulus of rupture, as these mechanical properties are closely correlated. Again, the superiority of Norway spruce (8764 MPa) for this characteristic was confirmed (Table 4). The second-highest value was attained by Serbian spruce (6670 MPa). The lowest value was reached by blue spruce (4863 MPa), which differed slightly from black spruce (5107 MPa). Norway spruce and Serbian spruce were both statistically significantly different ($p < 0.001$) from each other and the other species; the North American spruces could not be statistically distinguished from each other. Analogous to the bending strength results, the Norway spruce is notable for its low modulus-of-elasticity variability, which would be more consistent with the values for density variability than for bending.

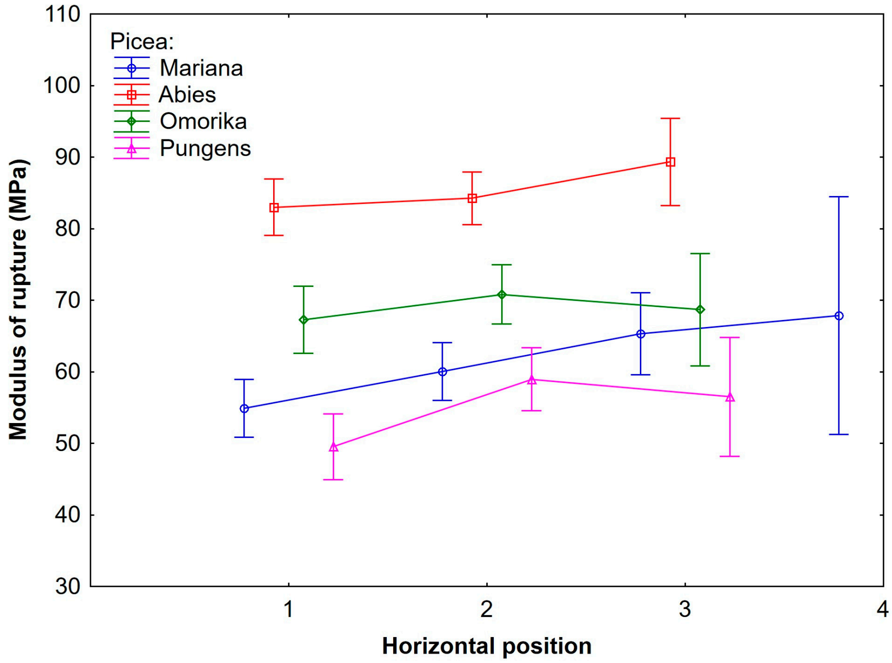

Figure 3. Modulus of rupture within-stem distribution. (x-axis: Figures denote a relative position of the test specimen with respect to the pith, i.e., 1 indicates a position near the pith, while 4 is a position close to the bark. The intervals represent standard deviations).

Table 4. Spruce comparison for modulus of elasticity in reference to basic statistical indicators (MPa); the significantly ($p < 0.05$) highest values are in bold; significantly different variants are marked with different letters.

	Mean	Min.	Max.	SD	CV	
Black spruce	5107 [a]	2667	8681	1548	30.3	*Test*
Norway spruce	**8764** [c]	5364	11053	1122	12.8	ANOVA
Serbian spruce	6670 [b]	3257	11090	1663	24.9	*p-value*
Blue spruce	4863 [a]	2718	7565	1193	24.5	$p < 0.001$

SD—standard deviation; CV—coefficient of variation (%).

The modulus of elasticity also does not differ significantly depending on the position in the trunk and wood quality and is therefore the same in all parts (Figure 4). This is true for all the species tested. The apparent increasing trend towards the bark is not statistically significant for all the tree species and all positions.

3.4. Relationships among Tested Properties

A certain degree of dependence was assumed between physical and mechanical properties. It is also largely valid for bending strength and modulus of elasticity. Knowing these relationships makes it much easier to predict the behavior of a material in applications. For the evaluated spruce species, the dependence of the modulus of rupture on density, the dependence of the modulus of elasticity on density, and the dependence of the modulus of rupture on the modulus of elasticity were tested. The correlation between the modulus of rupture and the modulus of elasticity was found to be the closest, with a coefficient of correlation r = 0.77 (Figure 5). The ability of density to explain the variability in the modulus of rupture was thus lower (r = 0.52). The lowest dependence on wood density was confirmed in the case of the modulus of elasticity (r = 0.45). When it comes to individual spruce species, Serbian spruce showed the highest degree of dependence for all the evaluated parameters.

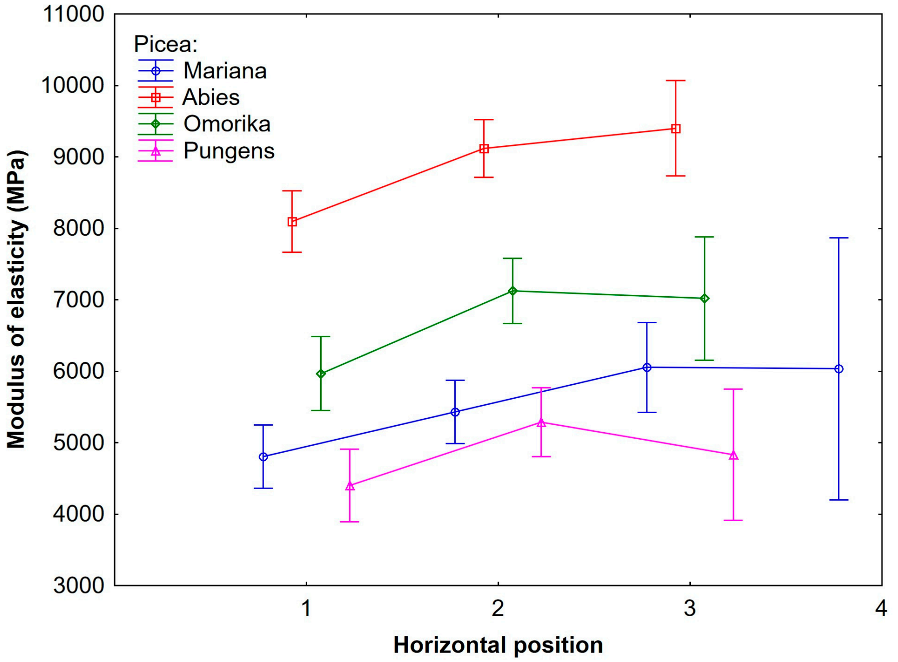

Figure 4. Modulus of elasticity within-stem distribution. (x-axis: Figures denote a relative position of the test specimen with respect to the pith, i.e., 1 indicates a position near the pith, while 4 is a position close to the bark. The intervals represent standard deviations).

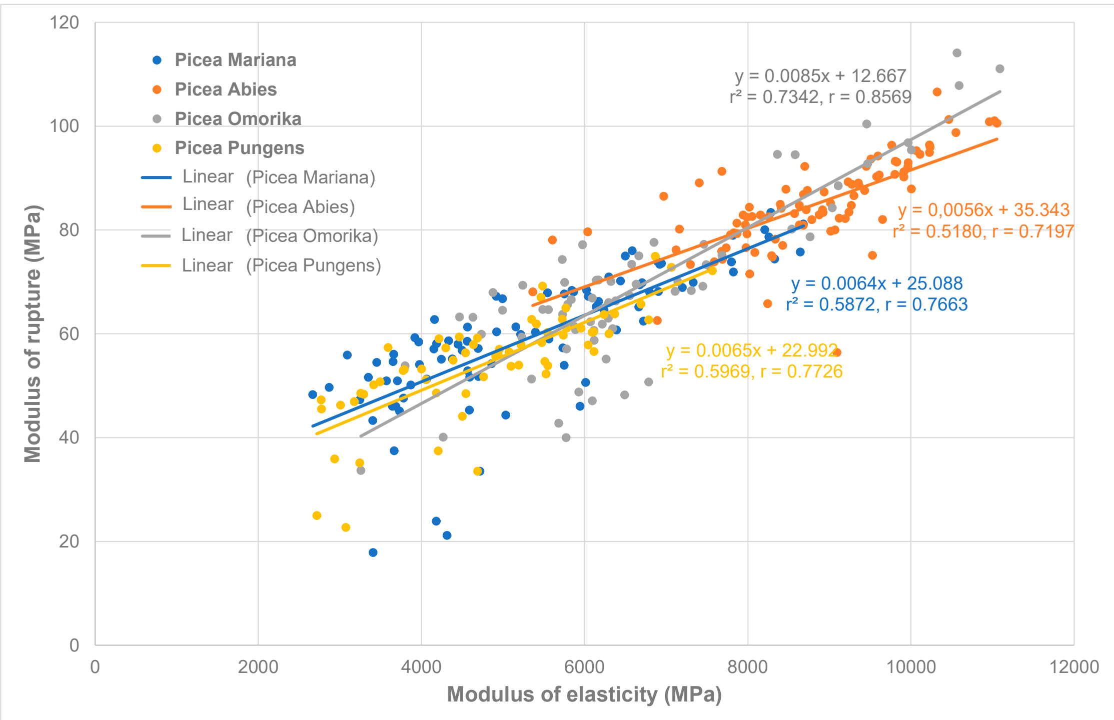

Figure 5. Linear regression model for the tested spruces (r—coefficient of correlation, r^2—coefficient of determination).

4. Discussion

The Norway spruce is a widely used coniferous tree species in Europe, especially in the construction industry, in which it is used for structural purposes. However, its large-scale dieback places a question mark on the future use of its wood [11,48]. The main aim of this study was to answer the following research question: "Can the wood of any of the introduced spruces in the Czech Republic replace the wood of native Norway spruce?" The wood properties of Norway spruce and their variability have been well studied and described [22,49].

Wood density is the most important property of wood: it not only influences the mechanical properties of wood but is also a crucial factor in determining its use and processing [23]. According to Wagenführ [50], the average wood density of Norway spruce is 470 kg·m^{-3}, while its MOR is 78 MPa, and its modulus of elasticity is 11,000 MPa. The results obtained in this study for Norway spruce are much higher. However, the wood of coniferous species is subject to considerable variability, depending on site, provenance, forest management, and other factors [20,51,52]. Although Bartoš et al. [53] studied the density of Norway spruce from former agricultural land at an age similar to that analyzed in this study, the presented results were also lower than those in our study. Moreover, disregarding the effect of several variables on wood density, most scientific works have reported lower wood density [51,54,55]. Similar values for the wood density of Norway spruce were not found in a literature review. A similar phenomenon was observed concerning the modulus of rupture value, where the trees evaluated in this study exhibited higher values compared to those reported in most of the literature. This difference, in most comparisons with the literature data, is not noticeable [49,55,56], but in some cases, the obtained results are two times greater [20]. Only Jelonek et al. [57], who compared the MOR values of healthy and decayed 95-year-old spruce wood from trees in North-Eastern Poland, obtained MOR values of healthy wood similar to those found in this study. On the other hand, in contrast to the previous two properties, values of MOE were lower than the assumptions. A low value of the modulus of elasticity was also reported by Šilinskas et al. [20] in spruce stands characterized by low tree density per hectare. In comparison, Jelonek et al. [57] reported a value of 10,679 MPA for healthy 95-year-old spruce wood in Poland, while Verkasalo and Leban [49] reported similar and even higher results in France—12,872 MPa. Here, the influence of the age of the sample trees, especially the presence of the juvenile wood zone, and the fact that this characteristic is not so closely correlated to density in contrast to most of the remaining mechanical properties [23,24], is likely to have had an effect.

In contrast to Norway spruce, the wood properties of Serbian spruce have not been widely studied. Besides being a native European species, it is not commonly used in the wood industry, mainly because of its limited distribution. Petrović et al. [27] carried out a complex study in the Balkan Peninsula involving Serbian spruce wood properties. The average wood density was 517 kg·m^{-3}, but depending on the original location, it varied between 508 and 534 kg·m^{-3}. The modulus of rupture varied between 84.00 and 95.82 MPa depending on the site and the height of the sample location in the log, while the modulus of elasticity ranged from 10,674 to 12,626 MPa. In comparison with the data provided by Petrović et al. [27], in this study, comparable results were obtained only in the case of wood density, in which all values of the tested mechanical properties were lower. On the other hand, the wood properties of Serbian spruce outside its natural range were studied by Kommert [28]. Their study was conducted in Saxony (Germany) and evaluated the effect of age and habitat on the wood properties of Serbian spruce. Depending on the location and age of the specimens, the wood density ranged from 420 to 510 kg·m^{-3}, which are lower results compared to the wood density values obtained in this study. However, in the case of the values of MOR, the results obtained by Kommert [28] are comparable with the results from this study.

The black spruce is a commercial tree species used by the wood industry in North America—its native range. Torquato et al. [24] reported a 430 kg·m^{-3} wood density of black spruce. Regarding mechanical properties, Alden [58] reported a value of 11,000 MPa for the modulus of elasticity and 74.5 MPa for the modulus of rupture. However, Tong et al. [31] obtained lower results, ranging between 8710 and 11,830 MPa for MOE and 38.11 and 52.48 MPa for MOR, depending on the tree diameter and forest management intensity. A similar observation regarding MOE values was made by Vincent et al. [32], who noticed results ranging between 10,530 and 9630 MPa. In comparison to the results obtained in the native range of black spruce, the results found in this study, which was conducted in the Czech Republic (Central Europe), are comparable in regard to wood density and modulus of rupture, while the modulus of elasticity exhibited considerably lower values compared to the data from the literature review.

Compared to all the examined spruces in this study, blue spruce is one of the least important for the wood industry sector, even in its native range. In Europe, it occurs primarily in cities and gardens. Accordingly, there are no complex studies on blue spruce wood properties available in the literature. The only reported data on wood density—401.6 kg·m^{-3}—were acquired by Gryc et al. [35], who gathered wood samples from ornamental gardens. In this study, the data were collected from blue spruce stands and showed a higher wood density value than in the case of Gryc et al. [35]. The results obtained for blue spruce in this study are comparable with those obtained for black spruce.

Due to its nature and long-term formation, wood is considerably variable in terms of its structure and consequently its properties [59,60]. From the viewpoint of the wood-processing industry and applications, a different distribution of properties within a stem is the most consequential manifestation of variability. This is the reason why it has been the focus of research studies. The distribution of wood density, modulus of rupture, and modulus of elasticity in the radial direction for black spruce was evaluated by Rossi et al. [61], while modulus of rupture and modulus of elasticity were evaluated for the same spruce species by Torquato et al. [24]. Both authors noted an increasing trend from the stem center to the cambium up to a certain age. This must be attributed—to a great extent—to structural changes, especially the negative influence of juvenile wood in the central stem part [31,52].

The influence of wood density on mechanical properties is generally assumed and has been confirmed by many authors [23,62–64]. The degree of dependence varies for different types of strength. Compressive strength exhibits the highest value of density dependence for wood, while it is lower for bending strength. The effect of wood density on the modulus of elasticity is lower because of the effect of cell wall structure [65]. For black spruce, Tong et al. [31] reported a dependence of modulus of elasticity on density corresponding to $r = 0.41$ and a dependence of modulus of rupture on density corresponding to $r = 0.54$. These are similar values to those obtained in the course of this research. An even smaller effect of density for spruce was mentioned by Alteyrac et al. [33], who noted that the correlation between density and the modulus of rupture was weak ($r = 0.29$), and on the matter of the modulus of elasticity, the effect of density could not be statistically demonstrated. Torquato et al. [24] reached a similar conclusion regarding the weak influence of density on the mechanical properties tested, with the more fundamental factor being the structural arrangement of the cell wall.

Wood has been used by humans for thousands of years. Unfortunately, the increasing occurrence of bark beetle outbreaks and forest fires has shown that it is easy to destabilize wood production on a large scale [66,67], especially via outbreaks in monocultural pine or spruce stands. On the other hand, according to available models, the demand for wood material will still increase [68,69] and could be exceeded when the world population surpasses ten billion. Therefore, it seems necessary to find a proper solution for the regeneration of died-back areas, utilizing more resistant tree species, with at least similar wood properties; this can be accomplished by introducing non-native species [13], which may be more suitable for future climate conditions in Central Europe [70,71].

Before providing the conclusions, it is important to mention the possible study limitations. The primary one is the limited study area, with similar tree age, soil fertility, and growth conditions for all the species, a fact that is highlighted in the article's title. This paucity could not be remedied due to the non-existence of forest stands with evaluated introduced tree species in Central Europe. Moreover, the study area where the samples were collected is a poor forest reclamation stand [36] with low soil fertility. Therefore, higher potential of all the compared species can be expected in standard forest soils. Generally, all of the examined species have similar properties to native spruce. The most promising seems to be Serbian spruce, whose density was slightly higher than that of Norway spruce, which mechanical properties were lower but still the best among all the examined non-native tree species.

5. Conclusions

This case study provides data concerning the wood properties of three introduced spruces and native Norway spruce in western Czechia. The results prove that non-native spruce species of a similar age and with the same climate and growth conditions do not provide similar wood quality to Norway spruce. Generally, all the examined introduced spruces produced lower results in terms of modulus of rupture and modulus of elasticity. Comparable wood density was observed in Norway spruce and Serbian spruce, which reached the highest densities among all the examined species. Serbian spruce was also evaluated as the best alternative for native spruce since it yielded the best results from the evaluated properties among non-native spruces. The differences obtained between its properties and those of North American spruces were statistically significant. Future studies on Serbian spruce wood quality in Central European growth conditions should be considered. Research on this species' resistance to ongoing climate change and secondary pests must also be a priority.

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