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Economic and Production Effect of Tree Species Change as a Result of Adaptation to Climate Change

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Abstract: Climate change is increasingly affecting forest ecosystems. Modifying the species composition towards species mixtures with a higher potential to mitigate the negative effect of climate change is one of the basic silvicultural measures. Potential economic and production impacts of these actions need to be assessed. This study therefore aims to evaluate the economic and production effect of species composition change as a result of the adaptation of forest ecosystems to climate change. The differences between the value production of Norway spruce (*Picea abies* /L./Karst.), Douglas fir (*Pseudotsuga menziessi*/MIRBEL/FRANCO) and European beech (*Fagus sylvatica* L.) on fresh soils (represented mainly by mesotrophic cambisols), and soils affected by ground water (mainly pseudogley forms of cambisols and pseudogleys) were evaluated. The study was conducted on the area of the forest enterprise of the Czech University of Life Sciences (UFE) situated in the Central Bohemia region. For a model comparison of height and volume growth of Douglas fir and Norway spruce in this area, all stands (pure and mixed) with both species represented were analysed using the data from the current forest management plan and Korf's growth function. The course of current and mean height increments over time is very similar, yet with constantly higher annual increments for Douglas fir. In 100 years, the mean stand height of Douglas fir is 6 m larger than that of Norway spruce. Production and economic potential were also evaluated. At the rotation age, the volume and value production of Douglas fir was 30% to 50% higher than that of Norway spruce. A higher share of Douglas fir in the total forest area would lead to an important value increment of the forests in the study area. Different results were achieved by comparing the yield potential of Norway spruce with European beech, which most often substitutes spruce at middle altitudes. Beech potential yield is only 40–55% of the spruce yield level.

Keywords: climate change; introduced tree species; Norway spruce; Douglas fir; European beech; production capacity; value production

1. Introduction

Climate change has an increasing adverse effect on the adaptive capacity of forest ecosystems. In Central Europe, in recent years, it has led to a rise in temperatures and a deficit in rainfall [1], which has a very negative impact on the vitality and health of forest stands. Long-term drought can lead to economic and social losses. Forests play a crucial role in wood production but also offer many ecosystem services such as carbon storage, prevention of soil erosion and maintenance of biodiversity [2].

Recently, concepts of how to adapt forest management have been described [3–5]. One of the most important measures is to modify the species composition of forest stands by increasing the share of species with a high adaptation potential [3]. Previous introductions of non-native tree species to Central Europe have been motivated by their valuable timber and high-volume production or the maintenance of functionality and ecosystem services of forests [5], but nowadays, some of the species are also considered as resistant to the negative effects of climatic change.

Norway spruce (*Picea abies* /L./Karst.), still the main production species, is not considered ecologically sustainable at lower and middle elevations of the Czech Republic, especially in view of the negative phenomena of even-aged monoculture stands [6] and the ongoing climate change. A recent example of these increasing problems is the unprecedented bark beetle calamity in a significant part of the Czech Republic. Therefore, it is planned to gradually reduce its share in the total national forest area by as much as 15% [7]. It is, though, a highly productive tree species and the loss in production has to be made up for in the future. Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) is considered to be a tree species with higher resistance against drought and with higher production potential than Norway spruce. Therefore, it appears as a prospective tree species for many countries in context of climate change [8,9]. The aim, however, is to grow Douglas fir in a mixture with domestic trees, where its share will be about 20% to minimize the risk of invasive behaviour.

In forests of the Czech Republic, introduced species occur on 35,000 ha (approximately 1.5% of the total forest land area); this is similar to the share occupied by exotic species in northern European countries [10]. In the Czech Republic, the highest share is that of black locust (*Robinia pseudoacacia* L.) and exotic species of spruce, especially blue spruce (*Picea pungens* Engelm.). These trees were planted mostly on unfavourable sites and in areas affected by emission-ecological calamity caused by SO_2 emissions from brown coal power plants in the second half of the 20th century; their further cultivation is not considered prospective though, and they are being replaced by native species. At present, Douglas fir grows on 5800 ha in the Czech Republic, which is approximately 0.22% of the whole forest area of the state. This is similar to the proportion of Douglas fir in Austria and Bulgaria [11]. First three age classes prevail; there are only 50 ha of stands over 100 years old [12]. The broad experience shows that Douglas fir can be ranged amongst the most productive species. Its extraordinary production capacity is confirmed by many Czech authors [13–22]. It was validated also by authors from neighbouring European states [23–28]. The Douglas fir economic importance is indisputable in its native localities [29] as well as in areas, where the tree species is non-native [30].

In addition to its production capacity, attention also has to be paid to some ecological and environmental consequences of its cultivation [28], especially to the influence of the species on soil conditions [31–33]. There are numerous studies about natural regeneration of the species in the conditions of the Czech Republic [34–36] as well as about its impact on forest phytocenoses [37]. The proper management of seed material was studied [38] and the deciding importance of proper provenance was fully documented [39]. Nevertheless, the economic effects of large-scale Douglas fir cultivation have not been discussed properly yet.

This study aims to evaluate the economic and production effect of tree species composition change as a result of adaptation to climate change, the examples being taken from the forest enterprise of the Czech University of Life Sciences in Kostelec nad Černými lesy (UFE). This locality represents middle elevations (the third and fourth vegetation zone,) where Douglas fir is mostly expected to be grown and used as a commercial species. The study aims to comparing production and economic indicators between Norway spruce and Douglas fir. The comparison is supplemented by the expression of value production of European beech, which could become the main tree species in these sites as it was in natural forests. The current share of beech in forests in the Czech Republic is only about 9%, while in natural forests, its proportion is estimated at 40%. In recent years, the contribution of European beech in total artificial regeneration has exceeded 20% in the Czech Republic and it is the most frequently planted substitute of Norway spruce [7].

2. Materials and Methods

The relevant area of UFE lies at the elevation of 300–520 m above sea level, approximately 30–55 km southeast from Prague; average annual air temperature ranges between 7.5–8.5 °C and the long-term precipitation amounts to about 650 mm per year. Introduction of Douglas fir on this property has had a long tradition. On 6734 ha of forest land, Douglas fir is grown in 98 stands, its share ranging from 5% to 100%. The total area of Douglas fir is 14.56 ha, i.e., 0.22% of total forest area of UFE, which also approximately corresponds to the species representation in the whole Czech Republic.

For a model comparison of the growth capacity of Douglas fir and Norway spruce in this area, all stands with both species represented (pure as well as mixed) were analysed using the data from the forest inventory that was made during development of the forest management plan in 2010 (total number of stands: Douglas fir n = 72, Norway spruce n = 1035). According to the Czech typological system, stands were grouped in two site categories: fresh soils (edaphic category S, K, represented mainly by mesotrophic cambisols), and soils affected by ground water (edaphic category O, represented mainly by pseudogley forms of cambisols and pseudogleys). The production and value potential of the Douglas fir and Norway spruce in each category and between categories were compared and evaluated. Mean stand heights and standing volumes were used as input data to derive models for the development of height, volume stock, and value production over time. Korf's growth function [40] was used for this purpose:

$$y = A \cdot e^{\frac{k}{(1-n)t^{n-1}}} \cdot \frac{k}{t^n} = A \cdot e^{\varphi(t)} \tag{1}$$

The current increment was calculated as the first derivation of Korf's function:

$$f'(t) = A \cdot e^{\frac{k}{(1-n)t^{n-1}}} \cdot \frac{k}{t^n} \tag{2}$$

The mean annual increment (MI) was defined as the quotient of the Korf's function and time t:

$$MI = \frac{f_{(t)}}{t} \tag{3}$$

where

t—age (years)

A—asymptote

k, n—coefficients of the differential equation express the growth intensity in the form:

$$\alpha = \frac{f'(t)}{f(t)} = \frac{k}{t^n} \tag{4}$$

where α—growth intensity as the first derivative of a growth function to the growth function.

The wood production capacity was based on the derivation of the growing stock; individual tree volume was calculated by volume equations using height (h) and diameter at breast height (*dbh*). For Norway spruce, volume equation derived by Petráš and Pajtík [41] was used. For Douglas fir volume calculation a volume equation according to Bergel [42] was used. From expressions for stem form factor and smallwood (below 7 cm) form factor the stem (timber to the top of 7 cm) form factor was derived. Afterwards, a volume equation for Douglas fir was formed and used:

$$V = \pi \cdot \frac{d^2}{4} \cdot h \cdot \left(\left(0.10798 + \frac{0.71858}{\log(\mathrm{d})} + 0.04065 \frac{h}{d} \right) - \left(10^{5.947 - 2.174 \cdot \log(d) - \frac{5.228}{\log(h)} + \frac{11.867}{\log(d) \cdot \log(h)}} \right) \right) / 1000 \tag{5}$$

where h—height (m); d—diameter at breast height (cm).

Volume stock was recalculated on full stand density and 100% proportion of analysed species. For the calculations, Statistica software version 9 was used.

The accuracy of volume calculation according to the volume equation was tested on 20 felled samplers of Douglas fir. The volume of felled trees was precisely determined in sections using the Smalian formula:

$$V = \frac{l}{2}(g_0 + g_n) \tag{6}$$

where

l—section length

g_0—circular area at the beginning of the section

g_n—circular area at the end of the section

It was found that this volume equation underestimates the real volume by only 1%, while still recommended practices in the Czech Republic (volume equation for silver fir [19]) overestimate the volume of standing Douglas fir by more than 13% (Table 1).

Table 1. Comparison of methods of Douglas fir volume calculation on felled sample trees.

Sample Tree	dbh (cm)	h (m)	Stem Volume with Bark (m^3)			Difference from (%)	
			Real (by Sections)	Volume Equations		Petráš,Pajtík SF	Bergel DF
				Petráš, Pajtík SF	Bergel SF		
1	39.2	30.8	1.603	1.787	1.555	11.5	−3.0
2	23.0	13.3	0.289	0.271	0.239	−6.5	−17.3
3	30.8	26.4	0.892	0.977	0.849	9.5	−4.8
4	24.1	19.9	0.436	0.460	0.401	5.6	−8.1
5	25.0	19.2	0.435	0.473	0.413	8.7	−5.1
6	31.9	29.0	0.991	1.155	1.003	16.6	1.3
7	32.2	27.8	0.991	1.121	0.975	13.1	−1.7
8	49.8	35.7	2.814	3.241	2.820	15.2	0.2
9	62.0	36.7	4.329	4.969	4.338	14.8	0.2
10	41.2	34.8	1.911	2.240	1.944	17.2	1.7
11	28.2	27.9	0.750	0.888	0.770	18.3	2.6
12	26.6	29.1	0.702	0.837	0.725	19.2	3.2
13	32.2	30.5	1.042	1.243	1.078	19.3	3.5
14	33.4	26.9	1.022	1.154	1.005	12.9	−1.7
15	33.0	30.2	1.103	1.284	1.114	16.4	1.1
16	28.8	29.1	0.830	0.966	0.837	16.4	0.9
17	45.8	34.1	2.262	2.651	2.306	17.2	2.0
18	63.0	37.5	4.484	5.241	4.573	16.9	2.0
19	43.4	32.0	1.903	2.241	1.952	17.8	2.6
20	44.1	32.4	2.041	2.340	2.038	14.7	−0.1
Average						13.7	−1.0

Note: dbh—diameter at breast height, h—height, SF—silver fir, DF—Douglas fir.

To complement the comparison of possible substitution of tree species, economic calculations were also made for European beech, which is currently most often planted instead of spruce in this area (number of stands = 93). The mean annual value increment of the growing stock (MAVI) was selected as the main criterion for the evaluation of the economic yield. Costs were not included in these analyses, so they are calculations of potential financial income. The ascquired mensurational and production characteristics of the monitored stands were therefore supplemented by sorting of the growing stock by assortment yield tables [43] and the resulting value production was calculated on the basis of average domestic timber prices in 2016 (according to the Czech Statistical Office). Prices in Czech crowns were converted to Euro with the exchange rate 25:1. For the comparison of the potential value production, prices obtained in Germany, where Douglas fir is traded significantly more than in the Czech Republic, were used.

3. Results

3.1. Growth Characteristics

The course of height and volume stock growth of Norway spruce and Douglas fir over time in selected sites of the UFE model area is presented in Figures 1 and 2. Parameters of the model are shown in Table 2. The analyses show the growth predominance of Douglas fir over Norway spruce in both evaluated sites. The course of current and mean height increments over time is similar, though.

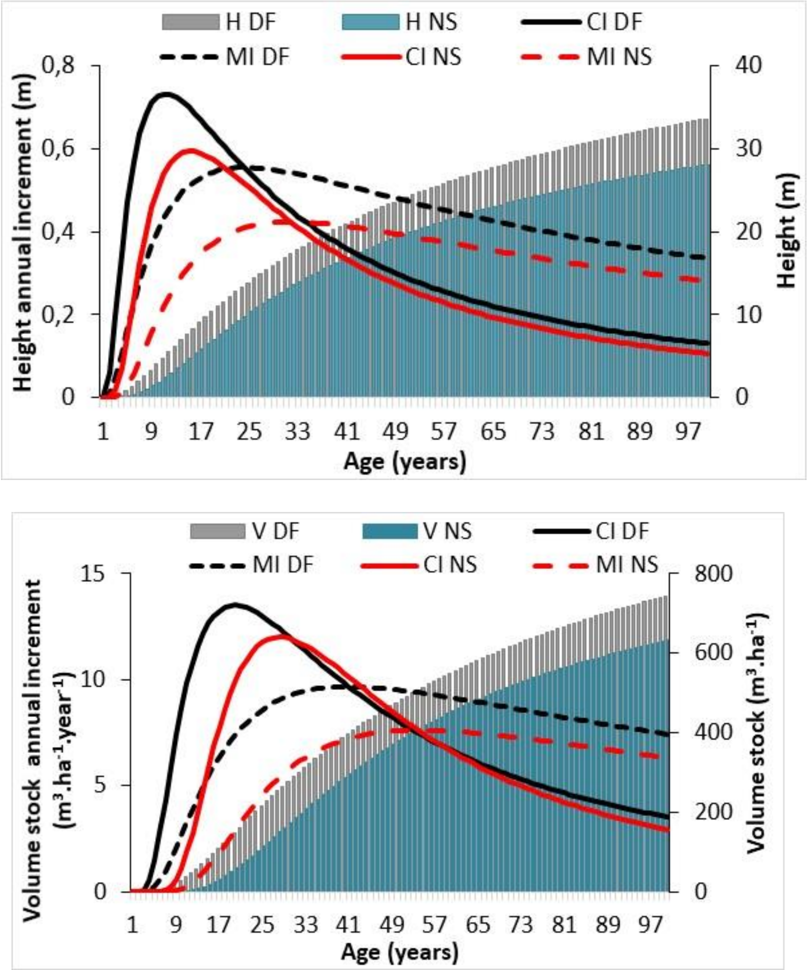

Figure 1. Courses of the current (CI) and mean increment (MI) of height (H) and volume stock (V) of Douglas fir (DF) and Norway spruce (NS) in fresh sites at UFE Kostelec nad Černými lesy, modelled by Korf's function.

It was found that the site conditions quite significantly affect the growth of Douglas fir. Superior growth being found in water-affected sites, where the model mean height was calculated at 100 years of age at 39.3 m and the growing stock (at full stocking and 100% proportion of Douglas fir) reached 906 $m^3 \cdot ha^{-1}$. Conversely, modelled production was documented in fresh sites (h = 33.6 m, V = 743 $m^3 \cdot ha^{-1}$). On the other hand, the differences in growth between the two site categories were considerably lower in the case of spruce compared to Douglas fir (h = 28.1 m and V = 632 $m^3 \cdot ha^{-1}$ in the fresh site, compared to h = 29 m, V = 654 $m^3 \cdot ha^{-1}$ on the water affected sites).

Table 2. Parameters of Korf's growth model for height (h) and volume stock.

Sites	Model Parameters	h (m)		V ($m^3 \cdot ha^{-1}$)	
		Norway Spruce	Douglas Fir	Norway Spruce	Douglas Fir
Fresh	A	44.08592	60.28914	920.8128	1310.693
	k	18.48889	8.31568	138.6074	22.336
	n	1.84360	1.66523	2.2369	1.836
	R^2	0.9661	0.9662	0.9582	0.9629
	R	0.9829	0.9829	0.9789	0.9813
Water-affected	A	53.83595	55.49930	985.8377	1485.663
	k	10.62707	32.10446	120.8209	37.705
	n	1.69586	1.98658	2.1954	1.952
	R^2	0.9634	0.9686	0.9590	0.9657
	R	0.9815	0.9842	0.9793	0.9827

Note: A—asymptote, k, n—coefficients of the differential equation expressing the growth intensity, R^2—coefficient of determination, R—coefficient of correlation, h—height, V—volume stock.

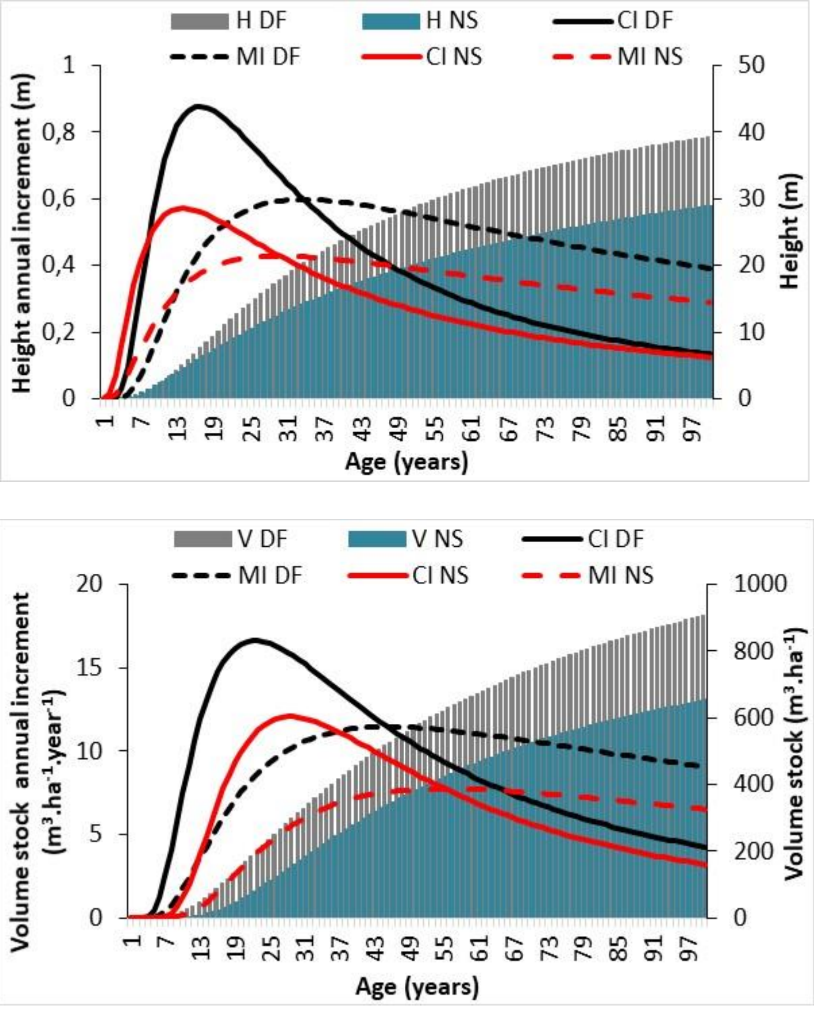

Figure 2. Courses of current (CI) and mean increment (MI) of height (H) and volume stock (V) of Douglas fir (DF) and Norway spruce (NS) at water-affected sites at UFE Kostelec nad Černými lesy, modelled by Korf's function.

In the water-affected sites the current height increment of Douglas fir culminates at 17 years of age (with 88 cm), Norway spruce culminates at 14 years with 57 cm. The mean height increment of Douglas fir culminates at 34 years of age (60 cm) while Norway spruce culminates at 30 years (43 cm). After culmination the increment of Douglas fir decreases rather quickly, nevertheless the difference is not striking in comparison to Norway spruce. The current volume stock increment of Douglas fir culminates at the age of 22 years with the annual maximum of 17 $m^3 \cdot ha^{-1}$; the mean volume increment culminates at the age of 45 years (11.5 $m^3 \cdot ha^{-1}$). The current volume stock increment of Norway spruce culminates at 29 years (12.1 $m^3 \cdot ha^{-1}$), while the mean volume stock increment culminates at 55, with the maximum of 7.7 $m^3 \cdot ha^{-1}$ (Figure 2).

3.2. Economic Evaluation

Figure 3 shows observed data together with the model for value production in fresh sites. The model accurately reflects the reality for all species, the proportion of variance explained by the models oscillates from 92% to 98%. The parameters of the model are shown in Table 3.

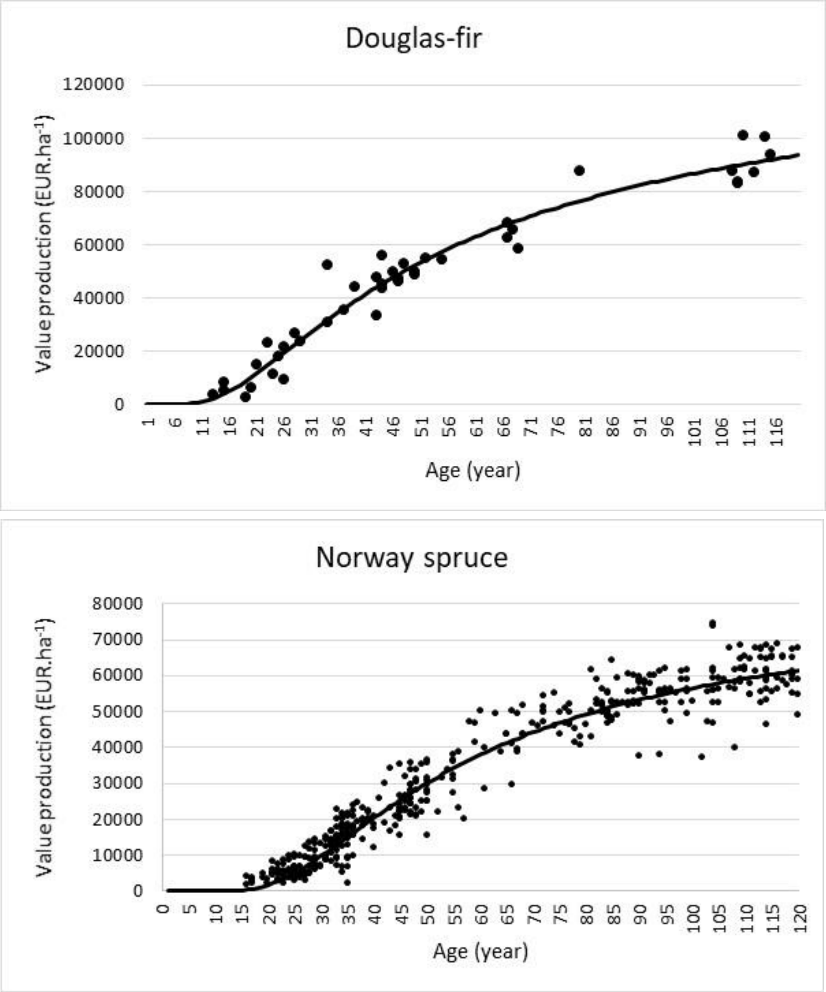

Figure 3. *Cont.*

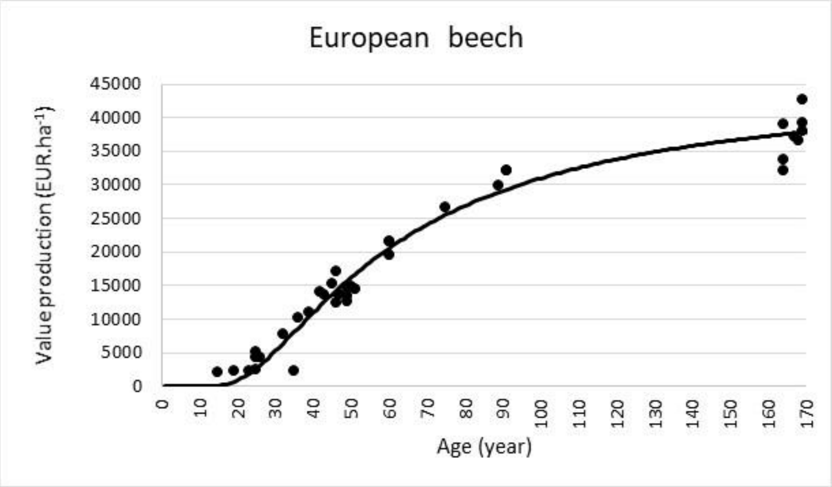

Figure 3. Model course of value production together with real values in fresh sites.

Table 3. Parameters of Korf's growth model for value production.

Sites	Model Parameters	Value Production (EUR·ha^{-1})		
		Norway Spruce	Douglas Fir	European Beech
Fresh	A	80,148.87	134,175.2	44,966.18
	k	487.57	76.3	444.54
	n	2.49	2.1	2.46
	R^2	0.9656	0.9731	0.9811
	R	0.9826	0.9864	0.9905
Water-affected	A	88,160.66	141,732.5	38,548.49
	k	422.87	300.7	153.39
	n	2.44	2.5	2.21
	R^2	0.9677	0.9769	0.9251
	R	0.9837	0.9884	0.9618

Note: A—asymptote, k, n—coefficients of the differential equation expressing the growth intensity, R^2—coefficient of determination, R—coefficient of correlation, h—height, V—volume stock.

Value productions of growing stock (standing volume and wood production from thinning) of Norway spruce and Douglas fir on fresh and water-affected sites in the UFE model area are presented in Figures 4 and 5. The parameters of the model are shown in Table 3.

The smallest relative difference (ca. 29,800 EUR·ha^{-1}) in value production at 100 years of age between Norway spruce and Douglas fir was found in fresh sites (DF: 86,424; NS: 56,580 EUR·ha^{-1}), which means only about 35% (Figure 4). Here, spruce reaches a comparable value of production as in the sites affected by water and Douglas fir has a much lower production. Therefore, a significantly higher difference in value production was documented in sites affected by water, where the model value of the Douglas fir at 100 years (EUR 115,987) exceeded the value of spruce production (EUR 59,862) by more than 56 thousand EUR, which corresponds to approx. 49%.

In Douglas fir (at age of 100 years), the average annual yield (MAVI) thus reached 864 EUR·ha^{-1}·year^{-1} and 1160 EUR·ha^{-1}·year^{-1}, respectively. It means that the annual yield of Douglas fir would be 299–561 EUR·ha^{-1}·year^{-1} higher than that of spruce (MAVI 565 and 599 EUR·ha^{-1}·year^{-1}). These data can already be considered as a real reflection of production and economic capacity of both tree species in the studied area as they encompass the whole rotation period. The culmination of the average value increment of Douglass fir was reached as early as at 45 years at fresh sites (1621 EUR·ha^{-1}·year^{-1}) and 52 years (1046 EUR·ha^{-1}·year^{-1}) in water-affected sites. In the case of spruce, the average annual value increment culminated at 64 years (637 EUR·ha^{-1}·year^{-1}) in fresh sites and at 67 years (661 EUR·ha^{-1}·year^{-1}) in water-affected sites.

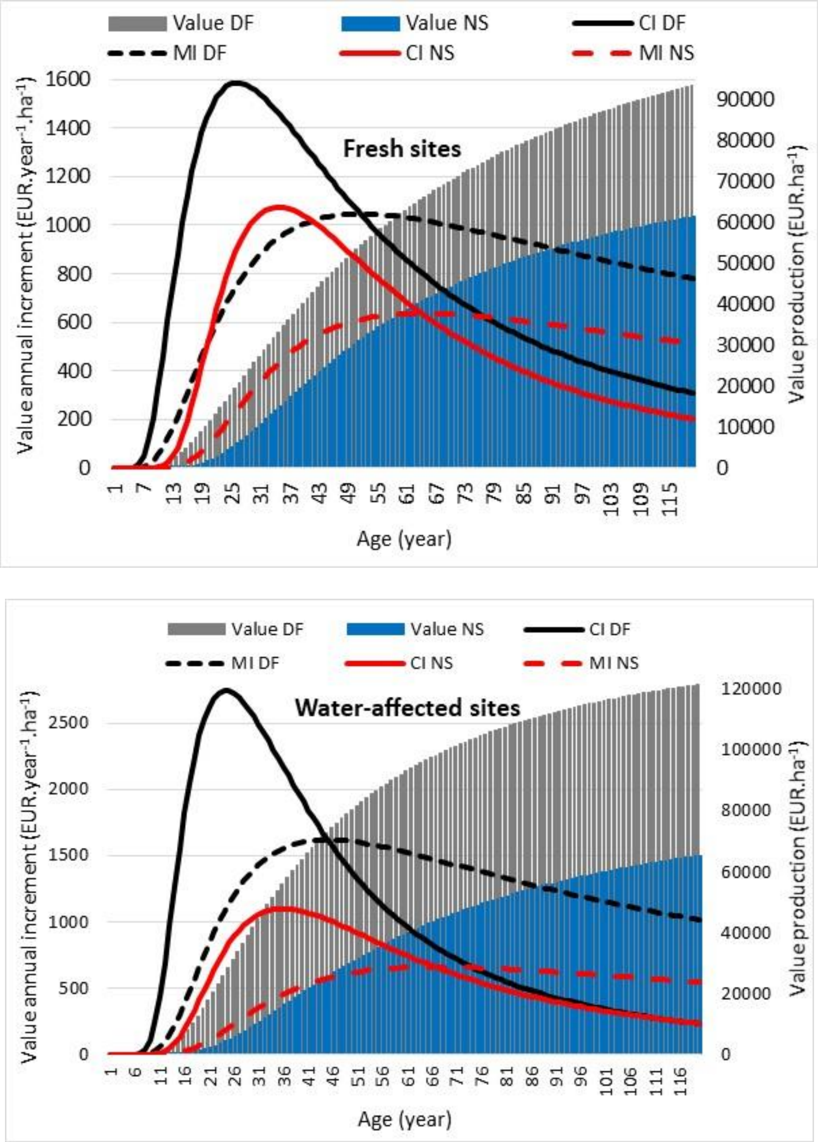

Figure 4. Courses of the current (CI) and mean (MI) value increment of growing stock for Douglas fir (DF) and Norway spruce (NS) in different sites conditions at UFE Kostelec nad Černými lesy, modelled by Korf's function.

Quite different results areachieved by comparing the yield potential of Norway spruce with European beech. The value production of the growing stock (standing volume and wood production from thinning) of Norway spruce and European beech in fresh and water-affected sites in the UFE model area are presented in Figure 5. Parameters of the model are shown in Table 3. The potential yield of beech stands at the age of 100 years, is significantly lower than that of spruce stands. There is less difference in fresh soils where beech reaches 31,003 EUR·ha^{-1}, compared to 56,580 EUR·ha^{-1}. Beech thus produces 55% of the spruce yield. Water-affected sites are not optimal for beech, which results in significantly lower yields (24,074 EUR·ha^{-1}) in comparison with spruce (59,862 EUR·ha^{-1}), which means only 40% of spruce yield.

A comparison of the value production of all three tree species at the age of 100 years in both sites is presented in Figure 6. The largest difference between tree species was documented in water-affected sites.

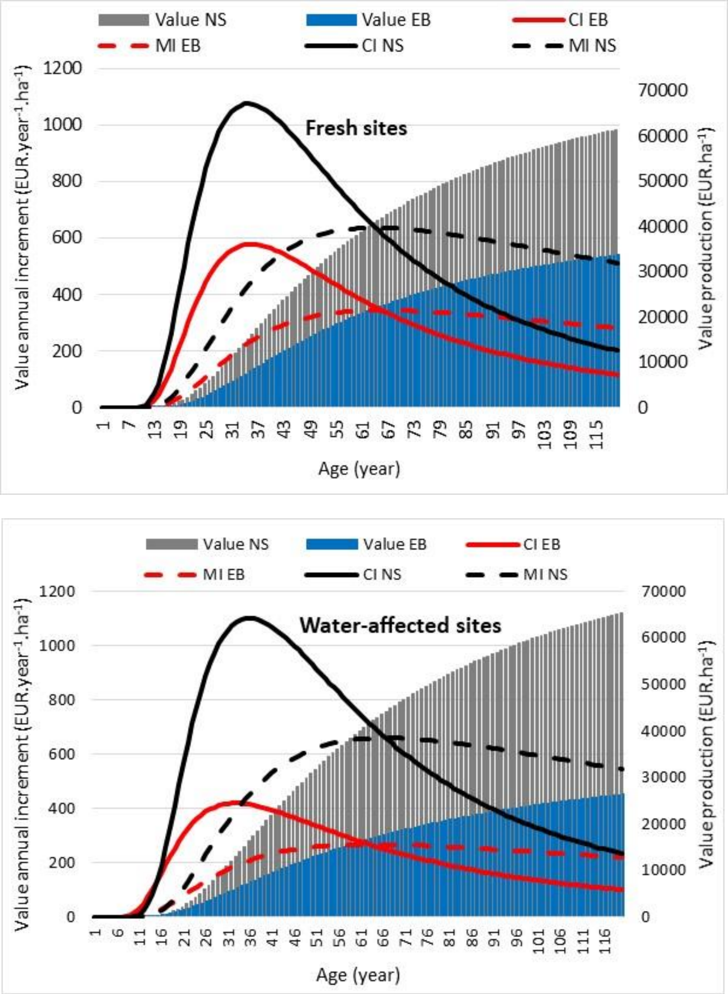

Figure 5. Courses of the current (CI) and mean (MI) value increment of growing stock for Norway spruce (NS) and European beech (EB) in different sites conditions at UFE Kostelec nad Černými lesy, modelled by Korf's function.

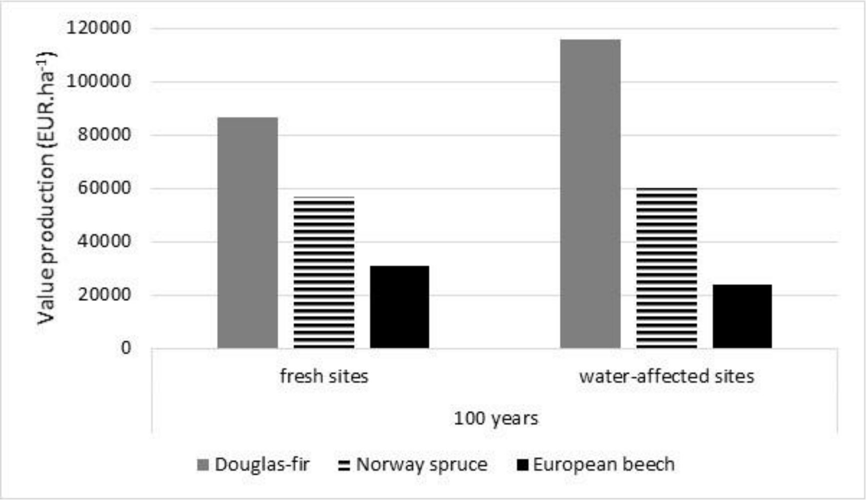

Figure 6. Value production at the age 100 years of Douglas fir, Norway spruce and European beech in fresh and water-affected sites.

4. Discussion

The production capacity and its superiority compared to autochthonous tree species is the main reason for the cultivation of Douglas fir outside its natural range [17,29]. In France, Douglas fir currently covers slightly under 400,000 hectares producing an annual increment of 14.8 $m^3 \cdot ha^{-1}$. In Germany, the species grows on more than 200,000 hectares and exhibits an average annual increment of 18.9 $m^3 \cdot ha^{-1}$. In both countries, Douglas fir increment exceeds the average annual increment of other conifers by 76% (France; 8.4 $m^3 \cdot ha^{-1}$) or 47% (Germany 12.8 $m^3 \cdot ha^{-1}$), respectively. Among the major conifers Douglas fir is the fastest grower, outdistancing even Norway spruce (average annual increment in France 13.2 $m^3 \cdot ha^{-1}$; in Germany 15.3 $m^3 \cdot ha^{-1}$) [11]. This was confirmed also in this study from the model area UFE. The parameters of height and yield growth of Douglas fir derived from the forest management summary data amounted to higher values than spruce that is the most productive domestic forest tree species in given sites. The site conditions also play a relatively important role (especially water content and nutrients). The highest growth rates were confirmed in water-affected sites, where the average stand height of Douglas fir derived from Korf's function in 50 and 100 years old stand corresponds to 28 and 39.3 m respectively. In the case of spruce, the average stand height amounted to 20 and 29 m respectively. These values correspond to the first site class [44–46] or are even superior to this site class according to the growth tables for the Czech Republic [47] and Netherlands [48]. A comparison of the height growth of the mid age average stand with the model values from Portugal [27] indicates the second site class (top height 26 m in 30 years) for this forest stand.

The average model parameters of Douglas fir on fresh sites then corresponded to a mean height of 24 m at 50 years of age, respectively 34 m in 100 years. These values correspond to the second to the third site classes derived from growth tables for Douglas fir in the Czech Republic [47] and 3rd site class derived from growth tables for northern Germany [44]. The results of Douglas fir production capacity evaluation in this study are similar to data from other parts of the Czech Republic and neighbouring countries. A substantial growing stock of 50-year old average Douglas fir stand in UFE was calculated to 571 $m^3 \cdot ha^{-1}$, which is less than values presented by Wolf [14,15]. He calculated 619 $m^3 \cdot ha^{-1}$ in an acidic site at middle elevation, the age of the stand being only 31 years. This implies a mean annual increment of almost 20 $m^3 \cdot ha^{-1}$, while the current annual increment at this age is 23 $m^3 \cdot ha^{-1}$. Similarly, Ponette et al. [26] demonstrate a standing volume of 747 $m^3 \cdot ha^{-1}$ at the age of 54 years. On the other hand, our results fully correspond to the results presented by Burbacher, Greve [24] who documented a growing stock of 52-year old Douglas fir stand amounting to 574 $m^3 \cdot ha^{-1}$.

Kantor's [17,18] observation confirmed that in comparison with Norway spruce, Douglas fir has significantly higher production. In stands aged 88 to 121 years, growing in acidic sites, he registered the volume of individual, dominant Douglas firs two or three times bigger than that of Norway spruce (when comparing ten largest trees of each species). The volumes of Douglas fir ranged between 3.6–5.2 m^3, the volumes of Norway spruce between 1.5–4.4 m^3 [18]. In fertile sites, in mixed stands aged 85–136 years, the values were even higher. The average volume of ten largest Douglas firs ranged between 3.9–10.6 m^3 and between 2.5–4.9 m^3 in the case of Norway spruce [17]. Using the same methodology our research team recorded an average volume of the largest Douglas firs 8.5–10.5 m^3, while that of Norway spruce was 3–3.5 m^3. Our results from water-affected sites are getting closer to production values in fertile sites documented by Kantor [17,18].

The total growing stock of the stand aged approximately 100 years on our sample plots of UFE (ca 800–1000 $m^3 \cdot ha^{-1}$) is similar to those calculated in other parts of the Czech Republic. Kinkor [19], for instance, gives 980 $m^3 \cdot ha^{-1}$ of growing stock for 126-year old Douglas fir stand at middle elevation (540 m a.s.l., ca 600 mm of annual precipitation) in a quite fertile site (with the average height 45 m, mean diameter 76 cm and mean volume 8.45 m^3). In the case of our sample plots, an analogous methodology showed 957 and 798 $m^3 \cdot ha^{-1}$ in stands aged 100 years. The production capacity of these stands is, though, significantly lower than stated by Kenk and Ehring [49] who recorded, in Schwarzwald (south-western Germany), a growing stock of 1387 $m^3 \cdot ha^{-1}$ in single stand aged 100 years (in 1991). The difference might be explained by substantially higher precipitation in

Schwarzvald (1300 mm). On the other hand, Pretzsch and Spellmann [50] in Harz (middle Germany) with average annual precipitation of 800 mm recorded 900 $m^3 \cdot ha^{-1}$ in stands aged 110 years with low thinning intensity. In other parts of the world where Douglas fir is also grown as an economically important tree species, even higher values of production capacity were recorded, e.g., in New Zealand, the growing stock of 50-year old stands is 1500–1900 $m^3 \cdot ha^{-1}$ [30]. Considerable differences in growth dynamics between Douglas fir and other tree species were also recorded on afforested agricultural land [51].

In rotation-age stands the differences in growing stock are not that apparent—caused, amongst other things, by large volumes of crowns and wide areas of crown projection of Douglas fir (on average, ca 60 m^2 of one Douglas fir crown projection to ca 20 m^2 of one Norway spruce crown projection). When we compare production of both tree species by full-stand density (calculated according to yield table) [47] per 1 ha Norway spruce will reach 73–87% of Douglas fir production.

When the value production is calculated, the gap between Douglas fir and Norway spruce widens again, as Douglas fir's sorting is related with higher values, (spruce has about 50–70% of the value production of Douglas fir). This is due to higher volume production of Douglas fir comparing to Norway spruce. This is related to economically more favourable sorting of harvested timber, our investigation confirmed that Douglas fir might provide almost 90% of round wood assortment at the age of 40 years already, while a 63-year old Norway spruce stand provides only 76%.

The difference grows again if we calculate with different prices of various timber assortments of both species. Some technical and mechanical properties of Douglas fir timber are better than those of Norway spruce [52–54] which reflect in higher prices especially of higher quality assortments.

At present, the Norway spruce's share in UFE is almost 50%, which is substantially more than it would be under natural, undisturbed forest development conditions. The health and vitality of spruce monocultures have deteriorated in recent years due to the drought and they are increasingly attacked by bark beetles. Therefore, the share of Norway spruce is gradually reduced—mostly by increasing the share of broad-leaved tree species and thus moving towards the natural tree species composition, which might not always bring on the desired economical effect which is important especially in commercially managed forests [37,55,56]. In particular, concerns about the loss of economic return are justified [57]. This was also confirmed by comparing the potential yield of beech and spruce in this study. Here, beech reached only 40–55% of the spruce yield, which means the average annual value increment (at 100 years of age) was lower by 350–400 $EUR \cdot ha^{-1}$. The very low value of beech production in water-affected sites proves the unsuitability of this site for beech. Conversely, Norway spruce and Douglas fir are exhibited higher production. Similarly, Möhring and Rüping [58] directly compared the potential annual yields of spruce and beech stands when considering artificial regeneration. The use of beech instead of spruce resulted in a financial loss of 109 $EUR \cdot ha^{-1} \cdot year^{-1}$ for the entire period of beech production (120 years). However, it has been proven that the economic yield of beech stands can be increased by proper tending. While the value production can increase by up to 20%, as evidenced by a study from Slovakia, where the value production in beech stands without tending (ca 40 thousands $EUR \cdot ha^{-1}$) was raised to 50 thousands $EUR \cdot ha^{-1}$ by thinning from above [59].

It is clear from the results that if the changes of the species composition within the adaptation measures were directed primarily to beech dominance, this would have significantly negative economic consequences. Especially if grown in a mixture with conifers, where beech has considerably lower stem quality [60]. However, if the spruce replacement is partially compensated by Douglas fir, the yield losses will be considerably lower going hand in hand with an increase in stability of the stands [61]. Although, there are also studies that consider Douglas fir a species with a high storm risk in Central Europe [62]. Douglas fir is still relatively free of biotic damage because its phylogenetic distance to native tree species is preventing rapid switches of most native pests [11]. The existing studies suggest that forest ecosystems in Central Europe are able to deal with the introduction of Douglas fir fairly well. To date, no severe ecological nor economic consequences have been detected, whereas large-scale attempts at eradicating Douglas fir from Europe would probably do more harm than good but negative consequences for single groups of organisms have been detected and are relevant for nature conservation [63].

The main means of adaptation to climate change in the model area should be the conversion of stands to mixed stands, always involving at least three main tree species. At least half should be made of autochthonous deciduous trees (especially beech and oak), conifers should be represented by silver fir, European larch and Douglas fir. The share of Douglas fir should not exceed 20% due to potentially slightly invasive behaviour of this species [64]. 20% of Douglas fir can replace 30–40% of Norway spruce in terms of economic yield. The higher proportion could be in water-affected habitats. Spruce can be grown at middle altitudes mainly at specific microhabitats (narrow deep valleys) where it naturally occurs. The conversion of spruce monocultures to mixed forests, with the participation of Douglas fir, should also be associated with more favorable dynamics of forest soils [11,65] and a positive effect on plant communities [11,37].

5. Conclusions

The presented study evaluates the production and economic capacity of Douglas fir in selected localities in central Bohemia, and at the same time, compares that with domestic tree species. Douglas fir is considered to be a tree species with higher resistance against drought. Therefore, it appears as a perspective tree species for many countries in context of climate change. The results of the analyses confirm the presumptions documented by other authors in the Czech Republic and abroad. Douglas fir guarantees high production capacity stands and high mean annual value increment. Significant production and economic superiority of Douglas fir was confirmed in comparison with the most important commercial tree species Norway spruce. The greatest differences were found in water-affected sites. Apart from its production efficiency, Douglas fir has a quite positive effect on forest soil (especially in comparison with Norway spruce) and can be grown in mixtures with domestic species in multi-storeyed stands and regenerate naturally; these are prerequisites of small-scale management of differentiated stands. It is justified therefore to consider Douglas fir a prospective tree species that can substitute Norway spruce in suitable sites, to a certain extent. It has been proven that under present timber price relations, it is not optimal from an economic point of view to convert spruce stands to stands dominated by European beech. The aim of the conversion at middle altitudes is to create mixed differentiated stands, where Douglas fir may occupy a share of about 20% of the forest area.

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