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**ORIGINAL PAPER**

# Growth-climate responses of *Picea sitchensis* (Bong.) Carr. versus *Picea abies* (L.) Karst. in the British Isles and Central Europe

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**Abstract**

Introduced tree species have become increasingly important in the context of the ongoing climate change. This paper focuses on the dendrochronology of the most widespread introduced tree species in the British Isles – Sitka spruce (*Picea sitchensis* [Bong.] Carr.) – in comparable soil conditions in England, Czechia, and Slovakia. The research aims to evaluate the growth dynamics and the influence of climatic factors on this tree species while comparing it with economically main tree species in Europe – Norway spruce (*Picea abies* [L.] Karst.). Based on the analysis of 150 increment cores, the radial growth of Sitka spruce was on average 24.2% higher than that of Norway spruce. The highest increments in 52 to 62-year-old stands were achieved in England by both Sitka spruce (8.7 mm) and Norway spruce (7.0 mm). In terms of negative pointer years (NPYs), there was no difference in the number of years with a significantly low increment between the two species at any site. The lowest effect of climatic factors on growth was found in Czechia, while the highest was in England. Higher resistance to climate was found for Sitka compared to Norway spruce. In general, the main limiting factor for the growth was the lack of precipitation in the previous year's vegetation season, or heavy frost in England. In Central Europe, due to low precipitation, Sitka spruce will not be a substantial introduced tree species in the future, but on suitable sites, it can achieve high production potential and play a significant role for increasing stand diversity in the face of climate change.

**Key words:** Sitka spruce; Norway spruce; ring-width index; temperature; precipitation

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## 1. Introduction

The introduction of new tree species in Europe dates back to the 17th century period of industrialization (Bolle 1887; Wein 1930; Kowarik & Säumel 2007). It was not until the 20th century that large-scale planting was implemented. Thus, forest plantations have gradually changed the distribution of tree species both within and outside their natural range (Spiecker 2004). Currently, 3.1%, i.e., 6.2 million ha, of Europe's forests are covered by non-native tree species, with the largest proportion in mid-western Europe, where they cover 8.9%, i.e., 2.2 million ha (Forest Europe 2020). In Czechia, introduced tree species occupy around 1.82% of the forest area, and introduced spruce species are, in aggregate, the most vital component of geographically non-native conifers (Podrázský & Prknová 2019).

Introduced spruce species occupy 9194 ha in Czechia, i.e., 0.49% of the forest area (Beran 2018). The most abundant species is blue spruce (*Picea pungens* Engelm.) which was used mainly in air-polluted mountain areas, especially in the Krušné hory Mts., Jizerské hory Mts., and Krkonoše Mts. (Vacek et al. 2003). In air-polluted areas, black spruce (*Picea mariana* [Mill.] Britton, Sterns & Poggenburg), Serbian spruce (*Picea omorika* [Pančić] Purk.), and, rarely, other spruce species such as Sitka spruce (*Picea sitchensis* [Bong.] Carr. – Funda et al. 2006 have been tested). The genus *Picea* spp., in particular Sitka spruce, and the most widespread in Europe – Norway spruce (*Picea abies* [L.] Karst.) – occur outside their natural range in Europe over an area of about 0.8 million ha (Forest Europe 2020). The proportion of introduced spruce species including Sitka spruce is gradually declining in Czechia due to the ongoing conversion of substi-

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tute species stands (Slodičák et al. 2005) and increasing political pressure for reduction of introduced tree species. The current proportion of Sitka spruce in Slovakia is negligible because this tree species is distributed especially in parks and is not managed like other commercial species. According to data from National Forest Center in Slovakia, introduced spruce species occupy less than 0.01% of the forest area (MARD 2021). On the other hand, Sitka spruce is widely distributed conifer species in England (Ludley et al. 2009). Current distribution exceeds 50% of coniferous woodland and therefore the Sitka spruce is the most important commercial tree species in England (Manso et al. 2022).

Sitka spruce is native to the west coast of North America, where it stretches along the Northern Pacific coast from Southern Alaska to Northern California (Harris 1990; Eckenwalder 2009; Praciak et al. 2013). It was introduced in Europe in the 1800s and is now cultivated in more than 16 countries worldwide (Peterken 2001; Halldórsson et al. 2003; Moore 2011; Lee et al. 2013; Deal al. 2014). It is a widely used tree species in Western Europe but under radically different climatic and soil conditions (Lines 1987; Bugała 2000; Moore 2011; Ogwu et al. 2012; Lee et al. 2013; Durrant et al. 2016). Under these conditions, Sitka spruce often markedly outperforms Norway spruce production (Rosvall et al. 2001; Bergh et al. 2005; Thompson & Harrington 2005). In particular, an oceanic climate with high precipitation of 1000–3000 mm and relatively mild winters (minima above −7 °C) at altitudes of up to 900 m a.s.l. is better suited for Sitka spruce (Lines 1987; Moore 2011) than for Norway spruce – which is a native montane species in the cool continental climate with an adequate soil water supply (Musil & Hamerník 2007; Farjon 2017).

In European forestry in the 19$^{th}$ and 20$^{th}$ centuries, there was an extensive introducing of fast-growing tree species (Poleno et al. 2007). Sitka spruce was also among the species planted in numerous experimental plantations in Europe, including Czechia and Slovakia. Presently, the most important non-native coniferous species in Europe for timber production include Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) and Sitka spruce (Podrázský et al. 2013a, 2016; Nygaard & Øyen 2017). While considerable attention has been paid to Douglas fir (Martiník & Kantor 2007; Kantor 2008; Kantor & Mareš 2009; Podrázský et al. 2013b, 2014; Mondek & Baláš 2019; Mondek et al. 2021; Zeidler et al. 2022), there are few studies dealing with Sitka, especially in Central Europe (Feliksik & Wilczynski 2008; Podrázský & Prknová eds. 2019). This is also true for other introduced tree species such as grand fir (*Abies grandis* [Douglas ex D. Don] Lindl. – Fulín et al. 2017, 2018), red oak (*Quercus rubra* L. – Miltner et al. 2017), Weymouth pine (*Pinus strobus* L. – Podrázský & Kupka 2011; Liao & Podrázský 2001), or black walnut (*Juglans nigra* L. – Hrib et al. 2017). More attention has focused on blue spruce, which has shown to have a rather negative effect on habitat conditions (Podrázský 2008; Podrázský et al. 2005, 2006) and is also threatened by the spruce bud blight (*Gemmamyces piceae* – Šefl et al. 2020). Regarding production and timber quality, we should look at the potential of black locust (*Robinia pseudoacacia* L. – Ábri et al. 2021a, 2021b; Honfy et al. 2021), European black pine (*Pinus nigra* J.F.A. – Ayan et al. 2021), and possibly also paulownia (Pástor et al. 2022).

For these reasons, the aim was to assess the effect of climate on the radial growth of Sitka spruce in comparable soil conditions in England, Czechia, and Slovakia. Dendroclimatological analysis of Sitka spruce stands was compared with that of Norway spruce, which is currently suffering from large-scale forest disintegration across Europe due to climate change and secondary pests (Šimůnek et al. 2020; Toth et al. 2020). The specific objectives of this study were to assess (i) basic growth characteristics of Sitka and Norway spruce, (ii) growth dynamics, including negative pointer years, and (iii) the influence of monthly air temperature and precipitation totals on the magnitude of radial growth of these species under the climatic conditions of non-continental Western Europe (England) and Central Europe (Czechia and Slovakia).

## 2. Material and Methods

### 2.1. Study area

The subject of the study was Sitka and Norway spruce stands in the Lake District in North West England, near the town of Ambleside. In Czechia, we analyzed stands in Central Bohemia near the town of Kostelec nad Černými lesy. In Slovakia, stands in Central Slovakia near the town of Zvolen were researched (Fig. 1). All permanent research plots (PRPs) are located in the lowlands at altitudes ranging from 230–440 m a.s.l. The average annual temperature is balanced (8.1–8.4 °C), with annual precipitation ranging from 663 to 2061 mm. In terms of Köppen's climatic classification (Köppen 1936), the area of interest belongs to two regions: Cfb – temperate oceanic climate (England and Czechia), and Dfb – warm-summer humid continental climate (Slovakia). The predominant soil type in all study areas is Cambisol. The studied PRPs 1–6 are pure spruce stands (Norway and Sitka spruce) of medium age with a relatively even horizontal structure and a significant horizontal canopy closure, which have been established by artificial regeneration. A detailed overview of the basic data on the PRPs is given in Table 1.

### 2.2. Data collection

For the analysis of radial growth, core samples were obtained from the Sitka and Norway spruce trees with a Pressler auger (Haglöf, Sweden) at a height of 1.3 m in the direction up/down the slope in spring 2016. From

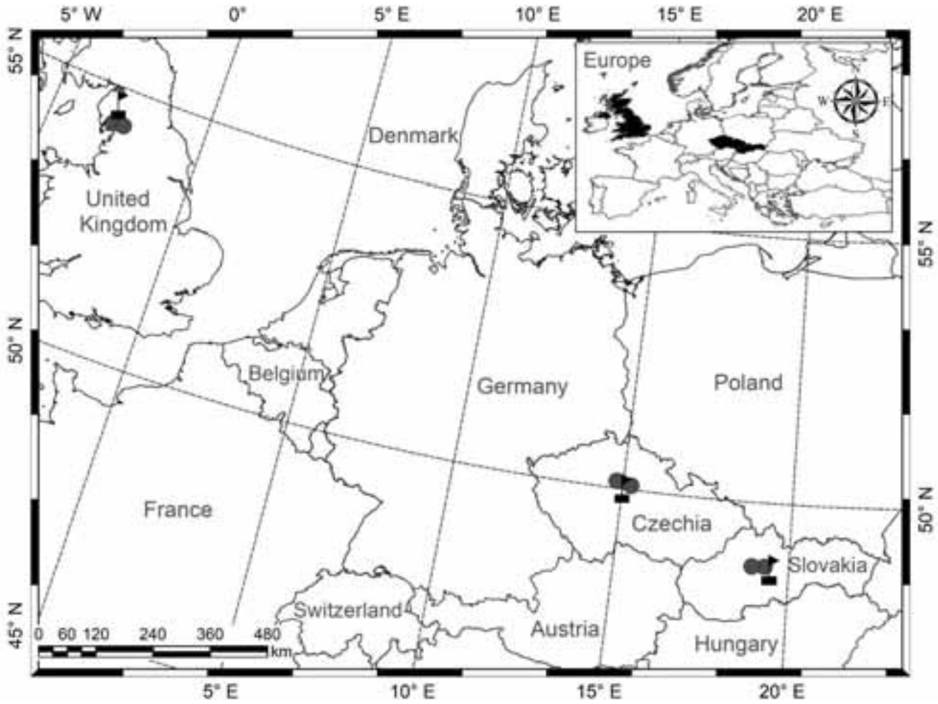


**Fig. 1.** Location of 6 research plots (•) with Sitka spruce and Norway spruce forest stands in England, Czechia and Slovakia, and three meteorological stations used for dendrochronology analyses.

**Table 1.** Basic characteristics of research forest stands with Sitka spruce and Norway spruce (according to the Forest Management Plan).

| Country | PRP | GPS | Altitude [m] | Expo. | Slope [°] | Veg. season [days] | Temper. [°C] | Precipitation [mm] | Forest site type[1] | Tree species | Age [year] | Stand volume $(m^3 ha^{-1})$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| England | 1 | 54°16'43"N 2°55'40"W | 230 | E | 4 | 247 | 8.4 | 2061 | *Quercetum acidophilum* | Norway spruce | 52 | 527 |
| | 2 | 54°16'42"N 2°55'39"W | 230 | E | 4 | 247 | 8.4 | 2061 | *Quercetum acidophilum* | Sitka spruce | 52 | 618 |
| Czechia | 3 | 50°00'25"N 14°51'13"E | 330 | NE | 3 | 158 | 8.1 | 663 | *Querceto-Fagetum acidophilum* | Norway spruce | 62 | 425 |
| | 4 | 50°00'22"N 14°51'09"E | 340 | NE | 3 | 158 | 8.1 | 663 | *Querceto-Fagetum acidophilum* | Sitka spruce | 62 | 456 |
| Slovakia | 5 | 48°38'11"N 19°05'01"E | 440 | S | 5 | 132 | 8.4 | 688 | *Abieto-Fagetum acidophilum* | Norway spruce | 59 | 468 |
| | 6 | 48°38'11"N 19°05'02"E | 440 | S | 5 | 132 | 8.4 | 688 | *Abieto-Fagetum acidophilum* | Sitka spruce | 59 | 506 |

Notes: [1]forest site type *Quercetum acidophilum* (Acidic Oak), *Querceto-Fagetum acidophilum* (Acidic Oak-Beech) and *Abieto-Fagetum acidophilum* (Acidic Fir-Beech) represent potential plant associations of *Luzulo albidae-Quercetum petraeae* Hilitzer 1932, *Luzulo luzuloidis-Fagetum sylvaticae* Meusel 1937, and *Luzulo luzuloidis–Abietetum* Oberdorfer 1957.

each research plot, 25 samples from the co-dominant and dominant live trees – according to the Kraft classification (Kraft 1884) – were randomly (RNG function, Excel) selected as the significant growth response (compared to subdominant and suppressed trees; Remeš et al. 2015). A total of 150 core samples from spruce trees (75 of Sitka spruce and 75 of Norway spruce) were collected (148 samples analyzed). The annual increments of tree rings were then measured with an accuracy of 0.01 mm using an Olympus binocular microscope on a LINTAB measuring table and recorded in the TsapWin software (Rinntech).

Measurements from meteorological stations were utilized to derive the effect of climate and stress factors on radial growth. Available data from the Ambleside station (100 m a.s.l.; WGS84 54°25'48"N, 2°57'36"W) for England, Sliač station (320 m a.s.l.; WGS84 48°38'8"N, 19°8'15"E) for Slovakia, and Ondřejov station (485 m a.s.l.; WGS84 49°54'24"N, 14°47'6"E) for Czechia were used for the analyses of the temperature and precipitation in the period of 1971–2015. The distance between the meteorological stations and research plots was in the range of 4–17 km. The development of temperature and precipitation was based on the data from temperature in individual months, the average annual temperature, the temperature in the vegetation season, annual total precipitation, total precipitation in the vegetation season, total monthly precipitation, and extreme climatic events like long-term droughts or historical temperature maxima and fluctuations.

## 2.3. Data analyses

Tree-ring increment series of Sitka and Norway spruce were individually cross-dated to remove errors caused by missing tree rings using statistical tests in the PAST application (Knibbe 2007). These series were subsequently subjected to a visual inspection, according to Yamaguchi (1991). If a missing tree ring was revealed, a tree ring of 0.01 mm in width was inserted in its place. Individual curves from research plots were detrended, and an average tree-ring series was created in the ARSTAN program (Tree Ring Laboratory, USA). Negative exponential spline, and subsequently, 0.67n spline was used for age detrending (Grissino-Mayer et al. 1992).

The first-order autocorrelation AR1 was calculated in package dplR in the R software (Bunn, 2008; R Core Team, 2019). The first-order autocorrelation assessed the relationship with the previous tree growth, or rather the connection between the radial increment in two consecutive years as a measure of the tree's physiological buffering capacity (Fritts 1976). The analysis of negative pointer years (NPYs) was performed by Schweingruber (1996) and Desplanque et al. (1999). For each tree, a pointer year was identified as an extremely narrow tree ring that did not reach 40% of the increment average from the preceding four years. The occurrence of the negative year was proved if a strong reduction in increment occurred in at least 20% of trees on the plot. To express the relationship between climate characteristics (monthly average air temperatures and sum of precipitation in particular years) and radial growth, the DendroClim software was used (Biondi & Waikul 2004).

# 3. Results

## 3.1. Radial growth of Sitka spruce and Norway spruce

The highest diameter increment was found in Sitka spruce in England (8.692 mm), whereas the lowest was in Norway spruce in Slovakia (2.800 mm; Table 2). Radial increment of Sitka spruce was 26.3% higher than that of Norway spruce in Czechia, 24.1% higher in England, and 22.3% higher in Slovakia. On average, this was 24.2% in favor of Sitka. The high first-order autocorrelation (AR1 0.695–831) suggests that radial growth was strongly influenced by previous year conditions for both species, particularly in Norway spruce. In terms of growth variability, higher fluctuations were found for Norway spruce in Czechia and Slovakia. In contrast, the opposite was true in England, where the largest difference was found between the two species studied.

## 3.2. Dynamics of radial growth

In terms of NPY, there was no difference in the number of years with significantly low radial increment between the two tree species at any site (Table 2). The highest number of NPY was found in both Central European countries. In England, no NPY was detected in Norway spruce. However, a large decrease in radial increment occurred in 1979, 1984, 1989–1990, 2006, and 2013–2015, when there was frequent ice damage to the spruce crowns and synergism of negative weather factors (Fig. 2). Consistently, no NPY was analyzed in Sitka spruce. Yet, a marked decrease in radial increment occurred in 1976, 1984, 1989–1990, 1995–1997, 2003, and 2006.

In Czechia, for Norway spruce, 1991 and 2001 were the NPY with minimal radial increment. The year 1991 was cold and also the driest between January–May (119 mm, average 234 mm) since 1971, preceded by the lowest annual precipitation in 1990. The year 2001 was characterized by extremely high temperatures outside the vegetation season (3.0 °C, average 1.7 °C). However, a marked decrease in radial increment occurred in 1977, 1992, 2000–2002, and 2010–2011, years with below-average precipitation in the vegetation season (Fig. 2). For Sitka, the identical NPY were analyzed – in 1991 and 2001. A marked decrease in radial increment also occurred in 1977, 1992, 2000–2002, and 2010–2011, similar to Norway spruce.

In Slovakia, NPY were demonstrated statistically in 1993 and 2000. The beginning of the vegetation season (March to May) in 1992 witnessed the lowest precipitation ever (54 mm, mean 161 mm). Precipitation in 2000 was also substantially below average, and in addition, it was the third warmest year historically (9.7 °C, average 8.5 °C). Furthermore, an insignificant decrease in increment occurred in 1994, 2003, and 2015, predominantly years with lower precipitation in the vegetation season (Fig. 2). For Sitka, it was 2012 and 2013, in regards to NPY. The year 2012 was marked by the warmest vegetation season on record (17.1 °C, average 15.2 °C)

**Table 2.** Characteristics of basic tree-ring chronologies of Sitka spruce and Norway spruce trees on permanent research plots differentiated according to country.

| Country | PRP | Tree species | Cores [n] | Age min–max [years] | RW mean | RWI SD | AR1 | Negative pointer years |
|---|---|---|---|---|---|---|---|---|
| England | 1 | Norway spruce | 24 | 42–49 | 3.501 | 0.143 | 0.775 | — |
| | 2 | Sitka spruce | 24 | 44–49 | 4.346 | 0.181 | 0.768 | — |
| Czechia | 3 | Norway spruce | 25 | 48–60 | 2.378 | 0.258 | 0.831 | 1991, 2001 |
| | 4 | Sitka spruce | 25 | 45–61 | 3.003 | 0.220 | 0.805 | 1991, 2001 |
| Slovakia | 5 | Norway spruce | 25 | 41–50 | 2.800 | 0.178 | 0.709 | 1993, 2000 |
| | 6 | Sitka spruce | 25 | 42–51 | 3.425 | 0.171 | 0.695 | 2012, 2013 |

Notes: Cores – number of analyzed core samples, Age – minimum and maximum age of cores, RW mean – mean tree-ring width, RWI SD – standard deviation of ring-width index, AR1 – first-order autocorrelation, negative pointer years – years with significantly extreme low radial growth

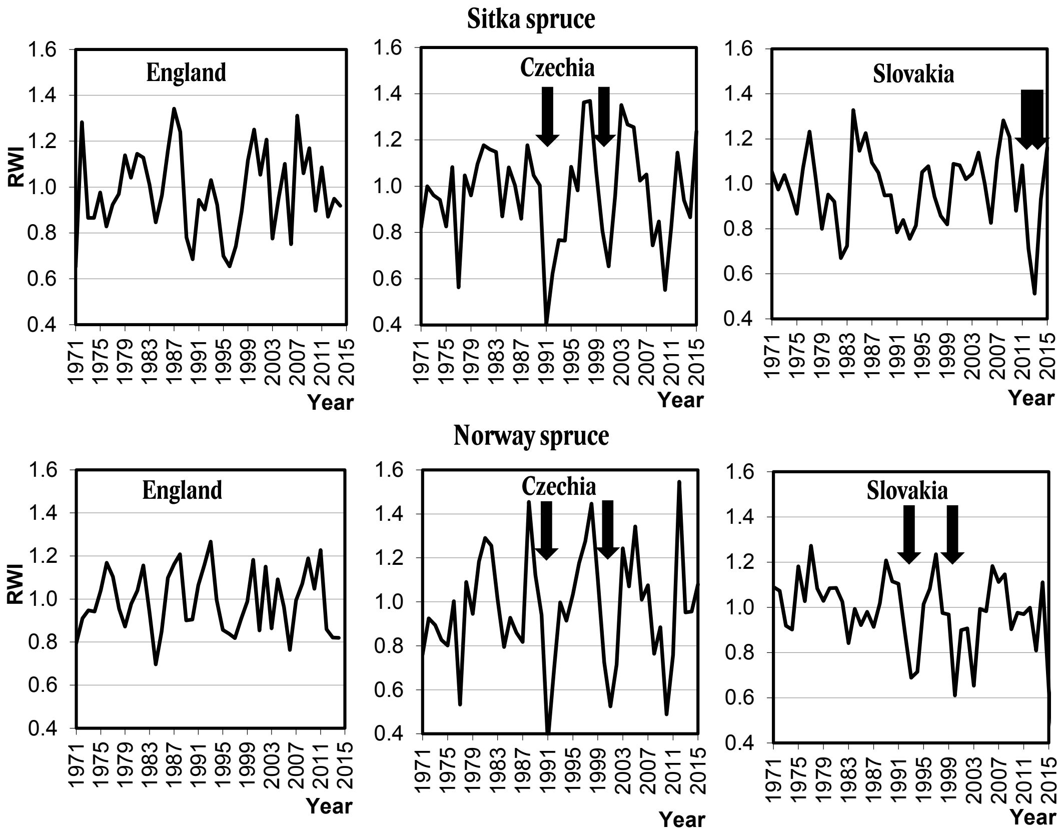


**Fig. 2.** Standardized mean chronology of Sitka spruce and Norway spruce in 1971–2015 after removing the age trend expressed by the tree-ring width index (RWI) and significant low radial growth expressed by negative pointer years (arrows).

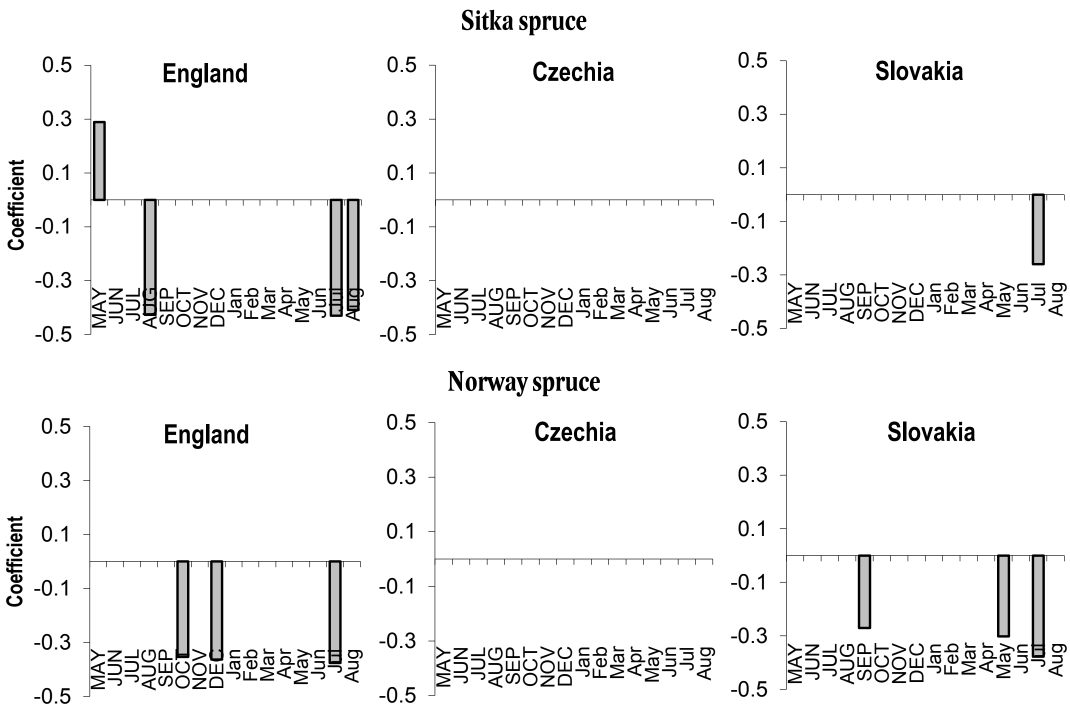


**Fig. 3.** Coefficients of correlation of the regional residual index tree-ring chronology of Sitka spruce and Norway spruce with monthly air temperatures from May of the previous year (capital letters) to August of the current year (lower-case letters) in the period 1971–2015; only statistically significant ($p < 0.05$) values are shown.

and below-average precipitation. Similarly, 2013 was extremely warm and variable in precipitation (historically the second-highest variability in monthly precipitation). However, the decrease in radial increment also occurred in 1982–1983, 1991–1994, 1999, and 2006.

## 3.3. Effect of climate on radial growth

In terms of the influence of climatic factors, precipitation had a more substantial effect (17 significant months) on radial spruce growth compared to temperature (11 months; Figs. 3 and 4). The lowest influence of climatic factors on diameter increment was found in the PRPs in Czechia, while the highest, in England. The greater resistance to climatic factors (precipitation and temperature) was found for Sitka compared to Norway spruce.

Respectively, monthly temperatures had a predominantly positive effect on the radial growth of both tree species, except in May of the previous year for Sitka PRP in England (Fig. 3). The influence of the previous current year was similar (5 versus 6 significant months). For precipitation, the crucial month (in terms of frequency of significant months) affecting growth is July of the current year. The highest correlation was found in this month for Sitka spruce in England ($r = -0.430$). In terms of precipitation, monthly precipitation had a significantly predominant positive effect on spruce growth, except for October and December of the previous year for Sitka spruce in PRP in Slovakia (Fig. 4). For precipitation, the previous year significantly (11 months) influenced the increment more than the current year (6 months). The most significant month that influenced tree growth was July of the current and previous year. Specifically, the highest correlation was found in June of the current year for Sitka in England ($r = 0.393$).

# 4. Discussion

## 4.1 Radial growth in Sitka spruce and Norway spruce

With increasing continentality and with similar soil (Cambisols), the conditions for the growth of Sitka spruce and Norway spruce are deteriorating. While in England, the average radial growth of Sitka spruce was 4.35 mm, it was 30.9% less in Czechia, and 21.2% less in Slovakia. For Norway spruce, it was 3.50 mm in England and 32.1% less in Czechia and 20.2% less in Slovakia. In England, Norway spruce reached only 80.6% of radial growth of Sitka spruce, while it attained 79.2% in Czechia and 81.8% in Slovakia. Similar results are documented, for example, by MacDonald (1979). The production potential of Sitka spruce over Norway spruce corresponds to its range of introduction. When it was introduced in Europe in the 19th century, it found relatively suitable growing conditions in the British Isles and around the Baltic Sea (Brazier & Mobbs 1993; Deans & Milne 1999; Green et al. 2008; Feliksik & Wilczynski 2008; Beauchamp et

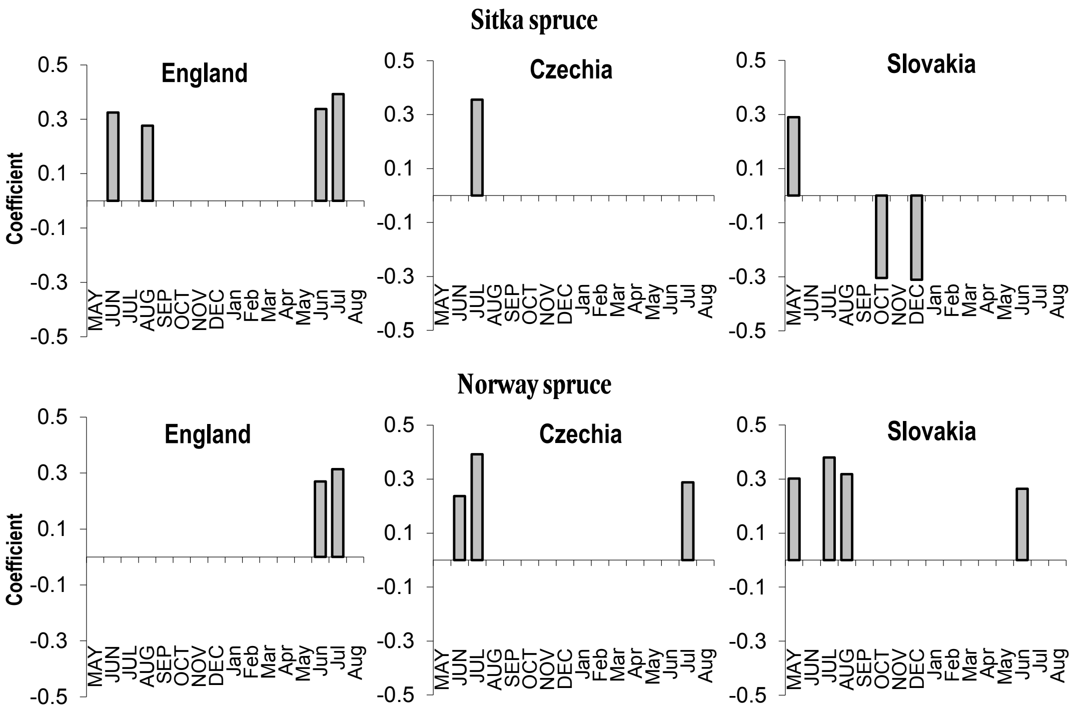


**Fig. 4.** Coefficients of correlation of the regional residual index tree-ring chronology of Sitka spruce and Norway spruce with a monthly sum of precipitation from May of the previous year (capital letters) to August of the current year (lower-case letters) in the period 1971–2015; only statistically significant ($p < 0.05$) values are shown.

al. 2013). In England, it is currently the most commonly planted commercial tree species (Forestry Commission 2014), grown in ca 40 to 50-year rotations (Fletcher & Faulkner 1972; McLean et al. 2016). Sitka spruce prefers temperate and humid oceanic climates with considerable precipitation during the vegetation season (Harlow et al. 1978; Thompson & Harrington 2005). In contrast, Norway spruce is one of the most common and economically important tree species in Northern and Central Europe (Musil & Hamerník 2007).

## 4.2. Effect of climate on radial growth

Interpreting correlations of radial increment of spruce with mean monthly temperatures and precipitation is relatively complicated, as the growth process is influenced by numerous factors such as windstorms, pathogens, drought, air pollution load, yellowing symptoms, damage by deer browsing and bark stripping (Giordano et al. 2013; Vacek et al. 2019a, 2020; Cukor et al. 2019a, 2019b; Gallo et al. 2021; Mikulenka et al. 2020). The positive effect of precipitation in July of the previous year and temperatures in July of the current year on radial increment can be explained by conditions during this period when a significant part of the radial increment is formed (Putalová et al. 2019). It is in line with the findings of Hlásny et al. (2017), who reported that spruce increment is influenced mainly by precipitation in June at lower altitudes and temperature at high altitudes. Our study of Norway spruce suggests that radial growth is significantly limited in lower-elevation PRPs in Czechia and Slovakia, particularly by the amount of precipitation in the vegetation season (particularly in July), in contrast to the PRPs in England, where precipitation totals even in the vegetation season were substantial. Temperatures, therefore, do not limit growth if there is sufficient water supply in the soil, which was rarely the case in the PRP in Czechia and Slovakia during the vegetation season. If water availability is reduced, stress, in the form of decreased increment will typically manifest itself one year later (Sander et al. 1995). Also, in our study, lack of precipitation in the previous year significantly affected tree growth increment compared to the current year. Similar results of the positive effect of temperature in June, July, and August on spruce growth have been found in foothill spruce forests in the Carpathian Mountains (Bednarz et al. 1999), in the Krkonoše Mts. (Král et al. 2015), Orlické hory Mts. (Rybníček et al. 2009; Vacek et al. 2015), Polish Tatra (Feliksik 1972), or in spruce stands in Norway (Andreassen et al. 2006). Conversely, the temperature during this period has a negative effect on spruce growth in the lowlands, as documented by studies from Central Bohemia (Vančura et al. 2020) or the Broumovsko Protected Landscape Area (Vacek et al. 2019b).

Our study of Sitka spruce suggests that the lack of precipitation during the vegetation season, combined with warm weather and winter frosts, are the main factors limiting its radial growth in Central Europe, in contrast to conditions in England. Moreover, in England, not a single NPY was discovered for both tree species, while in Czechia and Slovakia, two NPY were analyzed for each species. Vegetation season in Central Europe is considerably shorter than in England, which also significantly affects radial growth. In Western Europe, there is sufficient precipitation, but in places where the spruce canopy was damaged by frost, it was reflected in reduced radial growth in the years in question. Feliksik & Wilczynski (2008) also report that winter frosts and dry weather in summer are factors limiting radial increment of Sitka spruce in Poland along the Baltic coast. Bugała (2000) states that Sitka spruce is damaged by winter frosts and summer droughts in continental Europe. In general, spruce is more sensitive to high temperatures and intolerant of low relative humidity and air pollution loads than other tree species (Vacek & Lepš 1987; Král et al. 2015; Putalová et al. 2019).

## 4.3. Other aspects of Sitka spruce introduction

In recent years, there has been a great deal of debate about the impact of introduced tree species on ecosystem services and the landscape, both from the perspective of ecologists (Richardson & Rejmánek 2011; Van Wilgen et al. 2014; Pyšek et al. 2017) and foresters (Buriánek 2019; Podrázský et al. 2020). The context of the forest bioeconomy, including the entire consumption chain from forest production to the use of raw timber material in various ways, as well as the provision of ecosystem services, is also gaining importance (Di Franco et al. 2021; Endalew et al. 2021; Selivanov & Hlaváčková 2021). Sitka spruce is not an invasive tree species (Buriánek 2019). Its litterfall is comparable to that of Norway spruce (MacDonald 1979) and its more noticeable introduction in Europe is expected to occur mainly in coastal areas with sufficient precipitation (Worrell & Malcolm 1990a, 1990b; Moore et al. 2012). In Czechia, the introduction of Sitka spruce into forestry practice is not yet anticipated, from a legislative viewpoint (Beran & Šindelář 1996). However, concerning precipitation, on suitable sites, it can achieve high production potential and play a crucial role in increasing stand diversity in times of ongoing climate change. Moreover, the variability of increment, both in Czechia and Slovakia, was lower for Sitka spruce compared to Norway spruce, as was its resistance to climatic factors.

## 5. Conclusion

The evaluated spruce species (Norway spruce and Sitka spruce) at lower altitudes of Central Europe (Czechia and Slovakia) suffer from a precipitation deficit, especially in the summer months of the vegetation season – evidenced by its relatively low radial growth. Sitka spruce in particular suffers from winter drying damage. Contrastingly, in non-continental Western Europe (England), there is sufficient precipitation throughout the year for both spruce species to grow. Crown damage to both spruce species sometimes occurs during heavy frost. In particular, a mild winter without severe frosts suits Sitka spruce. Due to a favorable distribution of high precipitation and relatively mild and short winters, both spruce species show the best increment in England. So far, Sitka spruce has also grown better in Czechia and Slovakia than Norway spruce and is less responsive to adverse climatic conditions. This difference has been decreasing over the last 20 years and is likely to become even smaller as global climate change progresses. In conclusion, based on investigation of research plots in 3 European countries, the results indicates that Sitka spruce is tolerant to wet and poor habitats well, is more tolerant of wind and salty ocean air, and grows faster than Norway spruce, but it seems to be not recommended from an introduction point of view to grow it extensively in continental climates.

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## References

Ábri, T., Keseru, Z., Rásó, J., Rédei, K., 2021a: Stand structure and growth of *Robinia pseudoacacia* 'Jaszkiséri' – 'Jaszkiséri' black locust. Journal of Forest Science, 67:489–497.

Ábri, T., Keseru, Z., Szab´o, F., Rédei, K., 2021b: Structure of black walnut (*Juglans nigra* L.) stands on sandy soils in Hungary. Journal of Forest Science, 67:298–305.

Ayan, S., Yucedag, C., Simovski, B., 2021: A major tool for afforestation of semi-arid and anthopogenic steppe areas in Turkey: *Pinis nigra* J. F. Arnold subsp. *pallasiana* (Lamb.) Holmboe. Journal of Forest Science, 67:449–463.

Andreassen, K., Solberg, S., Tveito, O. E., Lystad S. L., 2006: Regional differences in climatic responses of Norway spruce (*Picea abies* L. Karst) growth in Norway. Forest Ecology and Management, 222:211–221.

Beauchamp, K., Mencuccini, M., Perks, M., Garnier, B., 2013: The regulation of sapwood area, water transport and heartwood formation in Sitka spruce. Plant Ecology & Diversity, 6:45–56.

Bednarz, Z., Jaroszewicz, B., Ptak, J., Szwagrzyk, J., 1999: Dendrochronology of Norway spruce (*Picea abies* [L.] Karst.) in the Babia Góra National Park, Poland. Dendrochronologia, 16–17:45–55.

Beran, F., Šindelář, J., 1996: Perspektivy vybraných cizokrajných dřevin v lesním hospodářství ČR. Lesnictví – Forestry, 42:337–355.

Beran, F., 2018: Introdukované dřeviny v lesním hospodářství ČR – Přehled. In: Vacek, Z., Podrázský, V. (eds.): Introdukované dřeviny jako součást českého lesnictví, ČLS, Kostelec nad Černými lesy, Praha 2018:7–16.

Bergh, J., Linder, S., Bergström, J., 2005: Potential production of Norway spruce in Sweden. Forest Ecology and Management, 204:1–10.

Biondi, F., Waikul, K., 2004: Dendroclim 2002: AC++ program for statistical calibration of climate signals in tree ring chronologie. Computers and Geosciences, 30:303–311.

Bolle, C., 1887: Andeutungen über die Freiwillige Baum- und Strauchvegetation der Provinz Brandenburg; Verlag des Märkisches Provinzial-Museum: Berlin, Germany.

Brazier, J. D., Mobbs, I. D., 1993: The influence of planting distance on structural wood yields of unthinned Sitka spruce. Forestry, 66:333–352.

Bugała, W., 2000: Drzewa i krzewy (Trees and shrubs). Warszawa, Państwowe Wydawnictwo Rolnicze i Leśne, 614 p.

Bunn, A. G., 2008: A dendrochronology program library in R (dplR). Dendrochronologia, 26:115–124.

Buriánek, V., 2019: Problematika invazních dřevin v Česku. – Přehled. In: Vacek, Z., Podrázský, V. (eds.): Introdukované dřeviny jako součást českého lesnictví, ČLS, Kostelec nad Černými lesy 2019. ČLS, Praha 2019:11–16.

Cukor, J., Vacek, Z., Linda, R., Sharma, R.P., Vacek, S., 2019a: Afforested farmland vs. forestland: Effects of bark stripping by *Cervus elaphus* and climate on production potential and structure of *Picea abies* forests. Plos One, PLoS ONE 14:e0221082.

Cukor, J., Vacek, Z., Linda, R., Vacek, S., Marada, P., Šimůnek, V., Havránek, F., 2019b: Effects of Bark Stripping on Timber Production and Structure of Norway Spruce Forests in Relation to Climatic Factors. Forests, 10:320.

Deal, R.L., Hennon, P., O'Hanlon, R., D'Amore, D., 2014: Lessons from native spruce forests in Alaska: managing Sitka spruce plantations worldwide to benefit biodiversity and ecosystem services. Forestry, 87:193–208.

Deans, J. D., Milne, R., 1999: Effects of respacing on young Sitka spruce crops. Forestry, 72:47–57.

Desplanque, C., Rolland, C., Schweingruber, F. H., 1999: Influence of species and abiotic factors on extreme tree ring modulation. Trees, 13:218–227.

Di Franco, C. P., Lima, G., Schimmenti, E., Asciuto A., 2021: Methodological approaches to the valuation of forest ecosystem Services: An overview of recent international research trends. Journal of Forest Science, 67:307–317.

Durrant, T. H., Mauri, A., de Rigo, D., Caudullo, G., 2016: *Picea sitchensis* in Europe: distribution, habitat, usage and threats. European Atlas of forest tree species. Luxembourg, Publ. Off. EU, e0137a1.

Eckenwalder, J. E., 2009: Conifers of the World: The Complete Reference. Timber Press, 744 p.

Endalew, B., Wondimagegnhu, B. A., Tassie, K., 2021: Willingness to pay for church forest conservation: a case study in northwestern Ethiopia. Journal of Forest Science, 67:105–116.

Farjon, A., 2017. *Picea abies*. The IUCN Red List of Threatened Species 2017: e.T42318A71233492.

Feliksik, E., 1972: Studia dendrochronologiczne nad świerkiem (*Picea excelsa* L.). Część I. Badania nad świerkiem z Lasu Gąsienicowego w Tatrach. Acta Agraria et Silvestria, 12:39–70.

Feliksik, E., Wilczynski, S., 2008: Tree-ring chronology as a source of information on susceptibility of Sitka spruce to climatic conditions of Pomerania (northern Poland). Geochronometria*,* 30:79–82.

Fletcher, A. M., Faulkner, R., 1972: A plan for the improvement of Sitka spruce by breeding and selection. Forestry Commission Research and Development Paper No. 85, HMSO, London, 567 p.

Forest Europe, 2020: State of Europe's Forests 2020. In: Ministerial Conference on the Protection of Forests in Europe - Forest Europe Liaison Unit Bratislava, 392 p.

Forestry Commission, 2008: Forestry statistics 2014. Forestry Commission, Edinburgh.

Fritts, H. C, 1976: Tree rings and climate. Academic Press, London.

Fulín, M., Novotný, P., Podrázský, V., Beran, F., Dostál, J., Jehlička, J., 2017: Evaluation of the provenance plot "Hrubá Skála" (Northern Bohemia) with grand fir at the age of 36 years. Journal of Forest Science, 63:75–87.

Fulín, M., Podrázský, V., Baláš, M., 2018: Vliv jedle obrovské na stav lesních půd: případová studie. Zprávy lesnického výzkumu, 63:129–135.

Funda, T., Kobliha, J., Vacek, S., 2006: Vývoj a současný stav provenienčních výzkumných ploch smrku černého v oblasti Krušných hor. [Development and current state of black spruce provenance trials in the Ore Mts.]. In: Slodičák, M., Novák, J. (eds.): Lesnický výzkum v Krušných horách. Recenzovaný sborník z celostátní vědecké konference. Teplice 20. 4. 2006, Opočno, VÚLHM VS, p. 215–231.

Gallo, J., Vacek, Z., Vacek, S., 2021: Quarter of a century of forest fertilization and liming research at the Department of Silviculture in Prague, Czech Republic. Central European Forestry Journal, 67:123–134.

Giordano, L., Garbelotto, M., Nicolotti, G., Gonthier P., 2013: Characterization of fungal communities associated with the bark beetle *Ips typographus* varies depending on detection method, location, and beetle population levels. Mycol Progress, 12:127–140.

Green, S., Hendry, S. J., Redfern, D. B., 2008: Drought damage to pole-stage Sitka spruce and other conifers in north-east Scotland. Scottish Forestry, 62:10–18.

Grissino-Mayer, H. D., Holmes, R. L., Fritts, H. C., 1992: International tree-ring data bank program library: user´s manual. Laboratory of Tree-Ring Research, University of Arizona, Tuscon, USA, Tuscon, p. 75–87.

Halldórsson, G., Benedikz, T., Eggertsson, O., Oddsdóttir, E.S., Óskarsson, H., 2003: The impact of the green spruce aphid *Elatobium abietinum* (Walker) on long-term growth of Sitka spruce in Iceland. Forest Ecology and Management, 181:281–287.

Harlow, W. M., Harrar, E. S., White, F. M., 1978: Texbook of Dendrology. Covering the Important Forest Trees of the United States and Canada. New York, McGraw-Hill Book Company, p. 134–136.

Harris, A.S., 1990: Sitka Spruce (*Picea sitchensis* (Bong.) Carr.), Agriculture Handbook 654, U.S. Department of Agriculture, Forest Service, Washington, D.C., p. 513–529.

Hlásny, T., Trombik, J., Bošeľa, M., Merganič, J., Marušák, R., Šebeň, V. et al., 2017: Climatic drivers of forest productivity in Central Europe. Agricultural and Forest Meteorology, 234:258–273.

Honfy, V., Ábri T., Juhász, L., Rásó, J., Keseru, Z., Rédei, K., 2021: A simple method for application of natural regeneration on black locust (*Robinia pseudoacacia* L.) stands in Hungary. Journal of Forest Science, 67:66–70.

Hrib, M., Podrázský V., Matějka, K., Viewegh, J., 2017: Effect of black walnut (*Juglans nigra*) on the understorey vegetation – a case study of South Moravian Forests (Czech Republic). Journal of Forest Science, 63:136–148.

Kantor, P., 2008: Production potential of Douglas fir at mesotrophic sites of Křtiny Training Forest Enterprise, Journal of Forest Science 54: 321–332.

Kantor, P., Mareš, R., 2009: Production potential of Douglas fir in acid sites of Hůrky Training Forest District, Secondary Forestry School in Písek. Journal of Forest Science, 55:312–322.

Knibbe, B., 2007: PAST4: personal analysis system for treering research, Version 4.2. SCIEM, Vienna, Austria, 161 p.

Kowarik, I., Säumel, I., 2007: Biological Flora of Central Europe: *Ailanthus altissima* (Mill.) Swingle. Perspectives in Plant Ecology, Evolution and Systematics, 8:207–237.

Kraft, G., 1884: Beiträge zur lehre von den durchforstungen, schlagstellungen und lichtungshieben. Klindworth, Germany, 147 p.

Král, J., Vacek, S., Vacek, Z., Putalová, T., Bulušek, D., Štefančík, I., 2015: Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014. Lesnícky časopis – Forestry Journal, 61:175–187.

Lee, S., Thompson, D., Hansen, J. K., 2013: Forest Tree Breeding in Europe. L. E. Pâques, ed., Springer Netherlands, vol. 25 of Managing Forest Ecosystems, p. 177–227.

Liao, C. Y., Podrázský, V., 2001: Growth dynamics of individual tree basal area of Eastern White Pine in Kostelec nad Černými lesy region. Journal of Forest Science, 47:124–129.

Lines, R., 1987: Choice of seed origins for the main forest species in Britain. Forestry Commission Bulletin 66. HMSO, London.

Ludley, K. E., Jickells, S. M., Chamberlain, P. M., Whitaker, J., Robinson, C. H., 2009: Distribution of monoterpenes between organic resources in upper soil horizons under monocultures of *Picea abies*, *Picea sitchensis* and *Pinus sylvestris*. Soil Biology and Biochemistry 41:1050–1059.

MacDonald, J. A. B., 1979: Norway or Sitka spruce? Forestry 40:129–138.

Manso, R., Davidson, R., McLean, J. P., 2022: Diameter, height and volume increment single tree models for improved Sitka spruce in Great Britain. Forestry 95:391–404.

MARD, 2021: Správa o lesnom hospodárstve v Slovenskej republike za rok 2020. Zelená správa. Ministry of Agriculture and Rural Development of the Slovak Republic, 71 p.

Martiník, A., Kantor, P., 2007: Branches and the assimilatory apparatus of full-grown trees of Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) of a different coenotic position. Ekológia (Bratislava), 26:223–239.

McLean, J. P., Moore, J. R., Gardiner, B. A., Lee, S. J., Mochan, S. J., Jarvis, M. C., 2016: Variation of radial wood properties from genetically improved Sitka spruce in the UK. Forestry, 89:109–116.

Mikulenka, P., Prokůpková, A., Vacek, Z., Vacek, S., Bulušek, D., Simon, J. et al., 2020: Effect of climate and air pollution on radial growth of mixed forests: *Abies alba* (Mill.) vs. *Picea abies* (L.) Karst. Central European Forestry Journal, 66:23–36.

Miltner, S., Podrázský, V., Baláš, M., Kupka, I., 2017: Vliv dubu červeného (*Quercus rubra* L.) na lesní stanoviště. Zprávy lesnického výzkumu, 62:109–115.

Mondek, J., Baláš M., 2019: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and its role in the Czech forests. Journal of Forest Science, 65:41–50.

Mondek J., Matějka, K., Gallo, J., Prokůpková, A., Hájek, V., 2021: *Picea abies* and *Pseudotsuga menziesii* radial growth in relation to climate: case study from South Bohemia. Austrian Journal of Forest Science, 138:209–244.

Moore, J., 2011: Wood properties and uses of Sitka spruce in Britain. Research Report – Forestry Commission, UK, 48 p.

Moore, J. R., Lyon, A. J., Lenhneke, S., 2012: Effects of rotation length on the grade recovery and wood properties of Sitka spruce structural timber grown in Great Britain. Annals of Forest Science, 69:353–362.

Musil, I., Hamerník, J., 2007: Jehličnaté dřeviny: přehled nahosemenných i výtrusných dřevin. Praha, Academia, 177 p.

Nygaard, P. H., Øyen, B. H., 2017: Spread of the Introduced Sitka Spruce (*Picea sitchensis*) in Coastal Norway. Forests, 8:24.

Ogwu, D.S., Nemesova, A., Lynch, T., Phillips, H., Hunter, A., Mac Siúrtáin, M., 2012: Site classification and growth models for Sitka spruce plantations in Ireland. Forest Ecology and Management, 283:56–65.

Pástor, M., Jankovič, J., Belko, M., Modranský, J., 2022: Evaluation of selected growth parameters of *Paulownia corevisa* plantation in the Danubian Lowland. Journal of Forest Science, 68:156–162.

Peterken, G. F., 2001: Ecological effects of introduced tree species in Britain. Forest Ecology and Management, 141:31–42.

Podrázský, V., Ulbrichová, I., Moser, W. K., 2005: Využití břízy a smrku pichlavého při obnově porostů na plochách s nenarušenou vrstvou nadložního humusu. Zprávy lesnického výzkumu, 50:75–77.

Podrázský, V., Remeš, J., Ulbrichová, I., 2006: Rychlost regenerace lesních půd v horských oblastech z hlediska kvantity nadložního humusu. Zprávy lesnického výzkumu, 51:230–234.

Podrázský, V., Kupka, I., 2011: Vliv borovice vejmutovky a metasekvoje čínské na stav nadložního humusu na stanovišti potočního luhu. Zprávy lesnického výzkumu, 56:14–19.

Podrázský, V., 2008: Tvorba povrchového humusu při zalesňování zemědělských ploch a po buldozerové přípravě v Krušných horách. Zprávy lesnického výzkumu, 53:258–263.

Podrázský, V., Čermák, R., Zahradník, D., Kouba, J., 2013a: Production of Douglas-fir in the Czech Republic based on national forest inventory data. Journal of Forest Science, 59:398–404.

Podrázský, V., Zahradník, D., Pulkrab, K, Kubeček, J., Peña, J. F. B., 2013b: Hodnotová produkce douglasky tisolisté (*Pseudotsuga menziesii* [Mirb.] Franco) na kyselých stanovištích Školního polesí Hůrky, Písecko. Zprávy lesnického výzkumu, 58:226–232.

Podrázský, V., Martiník, A., Matějka, K., Viewegh, J., 2014: Effects of Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) on understorey layer species diversity in managed forests. Journal of Forest Science, 60:263–271.

Podrázský, V., Remeš, J., Sloup, R., Pulkrab, K., Novotná, S., 2016: Douglas-fir – partial substitution for declining conifer timber supply–review of Czech data. Wood Research, 61:525–530.

Podrázský, V., Prknová, H. (eds.), 2019: Silvicultural, production and environmental potential of the main introduced tree species in the Czech Republic. Česká zemědělská univerzita v Praze, Kostelec nad Černými Lesy, Lesnická práce, 185 p.

Podrázský, V., Vacek, Z., Vacek, S., Vítámvás, J., Gallo, J., Prokůpková, A. et al., 2020: Production potential and structural variability of pine stands in the Czech Republic: Scots pine (*Pinus sylvestris* L.) vs. introduced pines – case study and problem review. Journal of Forest Science, 66:197–207.

Poleno, Z., Vacek, S., Podrázský, V., Remeš, J., Štefančík, I., Mikeska, M. et al., 2009: Pěstování lesů III. Praktické postupy pěstování lesů. [Silviculture III. Practical methods in silviculture]. Kostelec nad Černými lesy, Lesnická práce, 952 p.

Poleno, Z., Vacek, S., Podrázský, V., Remeš, J., Mikeska, M., Kobliha J. et al., 2007: Pěstování lesů II. Teoretická východiska pěstování lesů. [Silviculture II. Theoretical starting points of Silviculture]. Kostelec nad Černými lesy, Lesnická práce, 464 p.

Praciak, A. et al., 2013: The CABI Encyclopedia of Forest Trees. The CABI encyclopedia of forest trees. CABI Publishing, Oxfordshire, UK, 536 p.

Putalová, T., Vacek, Z., Vacek, S., Štefančík, I., Bulušek, D., Král, J., 2019: Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts. Central European Forestry Journal, 65:21–33.

Pyšek, P., Chytrý, M., Pergel, J., Sádlo, J. (eds.) 2017: Plant invasions in the Czech Republic. In: Flora and vegetation of the Czech Republic. Springer, Cham. Plant and vegetation 14:339–399.

R Core Team, 2019: R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Remeš, J., Bílek, L., Novák, J., Vacek, Z., Vacek, S., Putalová, T., Koubek, L., 2015: Diameter increment of beech in relation to social position of trees, climate characteristics and thinning intensity. Journal of Forest Science, 61:456–464.

Richardson, D. M., Rejmánek, M., 2011: Trees and shrubs as invasive alien species – a global review. Diversity and Distributions 17:788–809.

Rosvall, O., Jansson, G., Andersson, B., Ericsson, T., Karlsson, B., Sonesson, J. et al., 2001: Genetiska vinster i nuvarande och framtida fröplantager och klonblandningar. Redogörelse, 1. Skogforsk, Uppsala.

Rybníček, M., Čermák, P., Kolář, T., Přemyslovská, E., Žid, T., 2009: Influence of temperatures and precipitation on radial increment of Orlické hory Mts. spruce stands at altitudes over 800 m asl. Journal of Forest Science, 55:257–263.

Sander, C., Eckstein, D., Kyncl, J., Dobrý, J., 1995: The growth of spruce (*Picea abies* [L.] Karst.) in the Krkonoše Mountains as indicated by ring width and wood density. Annals of Forest Science, 52:401–410.

Schweingruber, F. H., 1996: Tree Rings and Environment Dendroecology. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, 609 p.

Selivanov, E., Hlaváčková, P., 2021: Methods for monetary valuation of ecosystem services: A scoping review. Journal of Forest Science, 67:499–511.

Slodičák, M. et al., 2005. Lesnické hospodaření v Jizerských horách. Hradec. Králové, Lesy České republiky; Jíloviště-Strnady, VÚLHM, 232 p.

Spiecker, H., 2004: Norway Spruce Conversion: Options and Consequences; European Forest Institute Research Report 18; Brill: Leiden, The Netherlands.

State of Europe's Forests 2007: The MCPFE report on sustainable forest management in Europe. Available online: http://foresteurope.org/wp-content/uploads/2016/08/FE-EN.pdf(accessed on 22 November 2015).

Šefl, J., Mottlová, V., Schořálková, I., 2020: Bud blight (*Gemmamyces piceae*) in the eastern part of the Krušné hory Mountains. Journal of Forest Science, 66:309–3017.

Šimůnek, V., Vacek, Z., Vacek, S., 2020: Solar cycles in salvage logging: National data from the Czech Republic confirm significant correlation. Forests, 119:973.

Thompson, D., Harrington, F., 2005: Sitka Spruce (*Picea sitchensis*). In: Jain, S. M., Gupta, P. K. (eds.): Protocol for Somatic Embryogenesis in woody Plants. Netherlands, Springer.

Toth, D., Maitah, M., Maitah, K., Jarolínová, V., 2020: The impacts of calamity logging on the development of spruce wood prices in Czech forestry. Forests, 11:283.

Vacek, S., Lepš, J., 1987: Changes in the horizontal structure in a spruce forest over a 9-year period of pollutant exposure in the Krkonoše Mountains, Czechoslovakia. Forest Ecology and Management, 22:291–295.

Vacek, S., Vacek, Z., Ulbrichová, I., Remeš, J., Podrázský, V., Vach, M. et al., 2019a: The Effects of Fertilization on the Health Status, Nutrition and Growth of Norway Spruce Forests with Yellowing Symptoms. Scandinavian Journal of Forest Research, 34:267–281.

Vacek, S., Zingari, P. C., Jeník, J., Simon, J., Smejkal, J. Vančura, K., 2003: Mountain forests of the Czech Republic. Prague: Ministry of Agriculture of the Czech Republic, 320 p.

Vacek, S., Prokůpková, A., Vacek, Z., Bulušek, D., Šimůnek, V., Králíček, I. et al., 2019b: Growth response of mixed beech forests to climate change, various management and game pressure in Central Europe. Journal of Forest Science, 65:331–345.

Vacek, Z., Vacek, S., Prokůpková, A., Bulušek, D., Podrázský, V., Hůnová I. et al., 2020: Long-term effect of climate and air pollution on health status and growth of Norway spruce peaty forests in the Black Triangle region. Dendrobiology, 83:1–19.

Vančura, K., Prokůpková, A., Balušek, D., Šimůnek, V., Hájem, V., Králíček, I., 2020: Dynamics of mixed lowland forests in Central Bohemia over a 20-year period. Journal of Forest Science, 66:49–62.

Wein, K., 1930: Die erste Einführung nordamerikanischer Gehölze in Europa. Mitteilungen Deutsche Dendrologische Gesellschaft, 42:137–163.

Worrell, R., Malcolm, D. C., 1990a: Productivity of Sitka spruce in northern Britain 1. The effects of elevation and climate. Forestry, 63:105–118.

Worrell, R., Malcolm, D. C., 1990b: Productivity of Sitka spruce in northern Britain 2. Prediction from site factors. Forestry, 63:119–128.

Yamaguchi, D. K., 1991: A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research, 21:414–416.

Zeidler, A., Borůvka, V., Černý, J., Baláš, M., 2022: Douglas-fir outperforms most commercial European softwoods. Industrial Crops and Products, 181:114828.