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GROWTH AND PERFORMANCE OF MACEDONIAN PINE (*PINUS PEUCE* GRISEB.) IN BAVARIA AGAINST THE BACKDROP OF CLIMATE CHANGE

Martin Bachmann[1], Daniela Rommel[2], and Bernd Stimm[3*]

[1]Department for Food, Agriculture and Forestry, Ebersberg, Bahnhofstrasse 23, D-85560 Ebersberg, Germany. E-mail: martin.bachmann@aelf-eb.bayern.de
[2]Bern University of Applied Sciences, School of Agricultural, Forest and Food Sciences HAFL, Länggasse 85, CH-3052 Zollikofen, Switzerland. E-mail: daniela.rommel@bfh.ch
[3]Institute of Silviculture, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany. [*]E-mail: stimm@mytum.de

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Abstract

One strategy for mitigating the effects of climate change on forests in an uncertain future is the allocation of risk across a portfolio of different tree species. Since the beginning of 2009, a project of the Bavarian State Institute of Forestry (LWF) has sought to identify warm- and drought-tolerant exotic tree species suited to conditions expected in Bavaria under climate change. As an outcome of this process, six potential non-native tree species were selected for the establishment of species trials in Germany (Bavaria and Thuringia), Austria and southern Switzerland. Parallel to the creation of young trial plantations, one species – *Pinus peuce* – was analyzed in detail in 67- to 105-year-old planted stands in Bavaria to obtain complementary information. This effort sought to quantify growth and performance of this species and compare these results with those of other tree species already grown successfully in Central European forests, e.g. Norway spruce, Scots pine, Eastern white pine, and Douglas fir. Measurements in four small planted stands in the Grafrath Experimental Forest showed mean DBHs from 26.8 to 43.8 cm and average heights from 24.1 to 28.4 m, with single tree volumes ranging from 0.7 to 1.8 m³. Due to drought conditions, particularly during a period of increased temperatures, the radial growth rate of *P. peuce* was considerably reduced in 1976 and 2003 and beyond, after which the species recovered only moderately. As a consequence of decreasing precipitation and more frequent late spring frosts, *P. peuce* exhibited strong negative reactions in annual ring growth. In general, these trees reacted positively to increasing mean annual temperature. Despite high volume production, the results revealed several uncertainties about the suitability of *P. peuce* for southern Bavaria under conditions of climate change. Based on the assumption of further decreases in precipitation in the near future, *P. peuce* can be expected to suffer increasingly from drought stress and to demonstrate decreased annual increment. Nevertheless, the species seems to be appropriate for afforestation in montane areas because of its proven resistance to wind throw and snow break.

Key words: *Pinus peuce***,** climate change, forest transformation, tree species selection, growth trials, Bavaria

Introduction

Foresters worldwide are confronted with the question of how to react properly to the implicit dynamics of climate change. Decision making should be based on critical scientific analyses.

One of the first and most important steps in silviculture is species selection for afforestation and reforestation purposes.

This has far-reaching implications for silvicultural practice against the background of the rapidly changing conditions for forestry.

Growth and performance of forests is influenced not only by the specific site requirements of tree species, but also by current and future climatic conditions. According to the Intergovernmental Panel on Climate Change (IPCC) report of 2007 (IPCC 2007), forests worldwide will be endangered because of water shortages, heavy precipitation events and increased temperatures. In Europe, even well-established native tree species like Norway spruce, Scots pine and European larch will be threatened by increases in temperature and lack of precipitation, which in turn can lead to enhanced susceptibility to forest pests (Kölling and Zimmermann 2007).

One strategy for mitigating the effects of climate change on forests in an uncertain future is the allocation of risk across a portfolio of different tree species. Since the beginning of 2009, a project of the Bavarian State Institute of Forestry (LWF) has sought to identify warm- and drought-tolerant exotic tree species suited to conditions expected in Bavaria under climate change. The selection of these species was done by applying three filters. The first filter was created by obtaining a geographic information system (GIS) layer containing climate data worldwide with focus on areas where the climatic conditions are similar to those currently existing in Bavaria or those expected under climate change. This layer was then overlaid with information on natural distributions of tree species occurring in these areas which resulted in a set of potential tree species. Two additional filters were then applied – a utility value filter created through a utility value analysis in which ecological and socio-economic parameters were evaluated; and finally, a growth filter containing existing knowledge on tree growth of each selected species. Based on the outcome of this process, six potential non-native tree species were chosen for the establishment of species trials in Bavaria (Schmiedinger et al. 2009) and later in Austria, southern Switzerland and Thuringia. These species include Bornmüller fir (*Abies bornmülleriana* Mattf.), Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Lebanon cedar (*Cedrus libani* A.Rich.), Oriental beech (*Fagus orientalis* Lipsky), Silver linden (*Tilia tomentosa* Moench) and Macedonian pine (*Pinus peuce* Griseb.).

For quite a long time, Eastern white pine (*Pinus strobus* L.) was favored by the wood industry because of its potential for rapid growth on nutrient-limited forest sites in Central Europe. Unfortunately, the species' susceptibility to white pine blister rust (*Cronartium ribicola* J.C.Fisch.) resulted in the dieback of vast areas of white pine stands. As an alternative, Macedonian pine was planted in several locations in Germany (Alexandrov 1998).

During the planning period of the above described project, some older plantings of *Pinus peuce* (67- to 105-year-old planted stands) were identified in Upper Bavaria and Upper Palatinate and analyzed in detail to obtain complementary information. This effort sought to quantify previous growth and performance of *P. peuce* in Germany and compare these results with those of other tree species, e.g. Norway spruce, Scots pine, Eastern white pine, and Douglas fir. The focus of this analysis was the quantification of individual tree and stand growth of *P. peuce* under recent climatic conditions on several Bavarian sites.

Material and Methods

Study site locations

Experimental Forest Area Grafrath

The Grafrath Experimental Forest comprises 34 ha and is located 40 km west of Munich, Germany (latitude 48°11'67"N, longitude 11°16'67"E) at an elevation of approximately 580 m a.s.l. The average temperature recorded at the site between 1961 and 2010 was 8.1° C·year^{-1}, and the average precipitation between 1963 and 1980 was 977 mm·year^{-1}. Soils range from calcareous sandy-loamy gravel to gravelly-sandy loams.

There are four stands containing *Pinus peuce* at the site, some of which are growing in mixture with other species. Details regarding the age and size of these four *P. peuce* stands (from hereon referred to as G1, G2, G3 and G4) are shown in Table 1 (along with information about one additional stand – stand BW – at another location which is described below).

The Grafrath Experimental Forest was established in 1881 by Prof. Dr. Robert Hartig for the purpose of conducting experiments with exotic species which remain active today (LWF Bayern 2015). In 1970, Rohmeder (1970) published the first reports regarding two of the *Pinus peuce* stands described above. However, even in this publication, no information is provided about the origin and provenance of the seeds used to establish these stands. According to him, these two stands were allowed to remain very dense, and thinning activities were marginal and occurred relatively late. This accounts for the dense stocking which persists to this day. Rohmeder provided no detailed information about any pre-commercial and commercial thinning from these stands. In the period subsequent to Rhomeder's investigation – 1970 to 2011 – damages and self-thinning events in these stands were also very limited.

Bodenwöhr

A fifth mixed forest stand consisting of 58 % *Pinus peuce*, 39 % *Pinus sylvestris* L. and 3 % *Picea abies* (L.) Karst. is located near Bodenwöhr (BW), Germany which lies about 160 km north of Munich (latitude 49°17'46"N, longitude 12°20'138"E). The elevation at this site is 378 m a.s.l., the average temperature is 8.5° C·year^{-1} and the average precipitation is 677 mm·year^{-1}. The area is 0.13 ha in size, and the soils are secondary podsols.

The most recent thinning measures – applied in 1997 – were focused mainly on *Pinus strobus,* and thus, only single specimens of *P. peuce* were harvested. The vitality of *P. peuce* at this site is good, and here too, damages are very rare.

Methods

Initially, key parameters of forest growth (e.g. DBH and height growth as well as calculated growth indicators like basal area, volume, and stocking of the stands) were collected. Tree and crown heights were measured with a Vertex IV instrument and DBH was determined using a circumference tape. Height-diameter relations and a stand height curve were derived on the basis of measurements from at least 30 individual trees in each stand. Crown length was calculated from tree and crown height to be used as an indicator of vitality. Form factor was determined with a Criterion RD 100 instrument which was applied to ten trees per stand.

Derived data for each of the five stands was compared with yield tables for Norway spruce and Scots pine, and with data gathered from other non-native conifers, i.e. *Pinus strobus* and *Pseudotsuga menziesii* (Mirb.) Franco grown in Grafrath and Bodenwöhr. To this end, increment cores were sampled, and the deviation of annual radial growth increment from average radial increment for several periods between 1950 and 2008 was analyzed.

To conduct growth ring analyses, samples were taken in Bodenwöhr at 1.1 m above surface. Two samples per tree were taken from a total of 20 trees from the dominant collective. In Grafrath, five increment cores per stand were sampled. All cores at both locations were gathered with a Pressler's borer (Ø: 5 mm). Subsequent analyses took place in the lab of the Chair of Forest Growth and Yield Science with the help of a Digital Positiometer (after Johann 1977).

These data were initially analyzed using the software Lignometer.exe, and further analyses were conducted with the help of the statistic functions in both Microsoft Office Excel 2007 and R. Measured data series were synchronized with the help of climatic pointer years. Two dry years – 1976 and 2003 – were particularly important in this procedure.

Statistical procedures

The different aged stands were chosen to allow for an evaluation of growth series and were thus, ranked according to their stand age (in 2011). The age of the stand in Bodenwöhr (BW) was 67 years, Grafrath stand G2 – 74, G4 – 77, G1 – 97 and G3 – 105 years.

To calculate the diameter-height curve, the statistic program R (Version 2.10.0, R Development Core Team 2009) with the function $h = 1.3 + [d/(a + b \cdot d)]^3$ after Petterson (1955) was used, where: a and b are regression coefficients, d is the DBH and h represents the height.

Form factor was calculated using the formula $f_{1.3} = V/W_{1.3} => V/(g_{1.3} \cdot h)$, where: V is the volume and W is the reference cylinder with d as DBH and h as height (see Kramer and Akça 2008 for details).

Growing stock is the cumulative volume of the stand from the point of establishment until 2011, including both intermediate felling volumes and volume stock in 2011. The unit used is m³/ha standing gross volume over bark. Again, it should be noted that, because of the lack of information about the amount of intermediate fellings from Grafrath, the cumulative volume of the stands at this site is likely to be underestimated.

For the growth ring analysis, age trends were first eliminated using a second-degree polynomial, and the ratio of the expected value from this smoothed curve and the actual measured radial increment was then calculated. The resulting index curve makes it possible to show the percentage and normalized deviation of the growth increment (Pretzsch 2003). The correlation between the trend-adjusted annual growth ring increments and climatic variables like precipitation, temperature and other variables was done with the help of the statistics program R (Version 2.10.0, R Development Core Team 2009) and Microsoft Office Excel 2007 was used for the graphical presentation.

Results

In the following section, the basic results of the studies on growth and yield in stands of Macedonian pine in Bavaria are summarized (Table 1).

Table 1. Characteristics of existing Macedonian pine stands in Grafrath and Bodenwöhr, Germany.

Indicator \ Location	Bodenwöhr BW	Grafrath G2	Grafrath G4	Grafrath G1	Grafrath G3
Age, years	67	74	77	97	105
Mixture, %	MPi 58, SPi 39, NSp 3	MPi 83, Be 12	MPi 95, others 5	MPi 99	MPi 77, Be 15, others 8
Area, ha	0.113	0.063	0.061	0.036	0.058
Density (N), trees/ha	932	741	659	632	310
Mean DBH, cm	21.1	28.6	38.5	41.5	43.8
$DBH_{Top100,}$ cm	41.2	53.1	47.9	47.8	55.4
Mean Ht, m	22.8	18.9	28.5	27.4	21.9
Ht_{Top100}, m	28.9	31.0	29.5	29.5	31.3
Crown length, m	14.4	11.0	9.4	7.4	14.8
Basal area, m²/ha	32.50	61.51	77.43	85.16	46.47
Growing stock, m³/ha	326	721	906	1,015	534
MAI, m³/ha/a	4.9	9.7	11.8	10.5	5.1
$SDI_{Reineke}$	710	919	1,319	1,423	763
H_{100}/d_{100}-ratio	70	58	62	62	57

Abbreviations: MPi – Macedonian pine, SPi – Scots pine, NSp – Norway spruce, Be – European beech, DBH – diameter at breast height, Ht – height, MAI – mean annual increment, SDI – stand density index.

Height growth

Figure 1 shows the stand height curves for Macedonian pine in Grafrath and Bodenwöhr. The dots and curves represent the analysis of the current state of the existing and fitted diameter/height relations of the surveyed stands in 2011.

The height data measured in the four stands in Grafrath (G1-G4) were combined to construct one diameter/height curve which is defined by the regression parameters a = 2.45294 and b = 0.278907. The data from the Bodenwöhr stand were used to form a curve defined by the parameters a = 1.802837 and b = 0.287547. The coefficient of determination for the Grafrath curve is R^2 = 0.9473 and that for the Bodenwöhr curve R^2 = 0.8991. Thus, both show a quite strong diameter/height relationship. Figure 1 demonstrates that the Bodenwöhr curve (red) initially goes steeper than the Grafrath curve (blue). Both curves show a slow but steady increase and end at a height of 30–31 m. Over the entire range of diameters, the Bodenwöhr curve shows growth superior to that demonstrated by the Grafrath curve.

The mean tree height in Bodenwöhr is 22.8 m, and in the Grafrath stands G2,

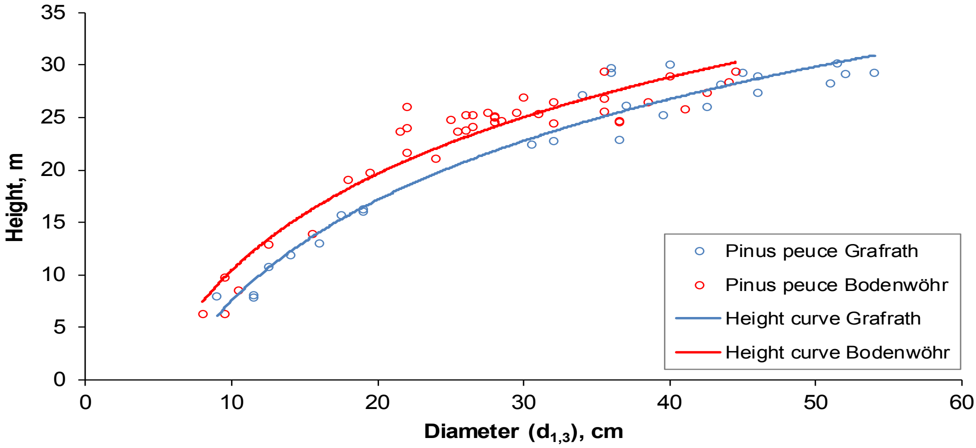


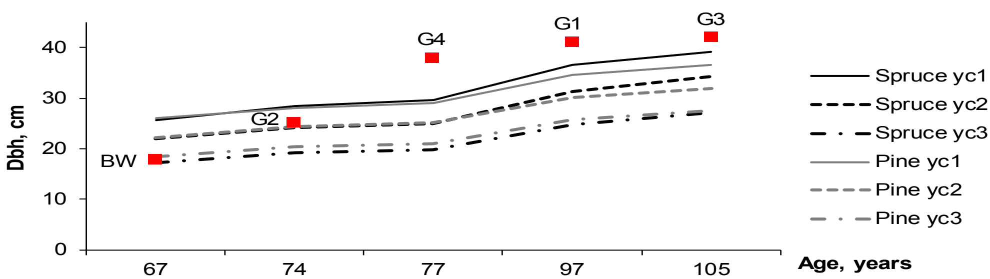
Fig. 1. Diameter/height relations and stand height curves (after Petterson) for Macedonian pine in Grafrath and Bodenwöhr, Germany.

G4, G1, G3 is 18.9 m, 28.5 m, 27.4 m and 21.9 m respectively. The mean height of the top100 trees in Bodenwöhr is 28.9 m, and in the Grafrath stands is as follows: G2 – 31.0 m, G4 – 29.5 m, G1 – 29.5 m, and G3 – 31.3 m (Table 1).

The height where tree crowns commence in the four stands in Grafrath is on average 11.5 m and in Bodenwöhr 8.5 m. Crown length is a valuable indicator for vitality and stability of individual trees as well as of stands. In addition, this parameter gives an indication of stand density and competition. Table 1 shows that the trees in Bodenwöhr have very long crowns with an average crown length of 14.4 m. In Grafrath, the trees in stand G3 have the longest crowns with an average of 14.8 m, followed by those in stand G2 with a mean crown length of 11 m.

Diameter growth

Figure 2 shows a comparison of the diameters of the mean basal area trees of the measured stands of Macedonian



Note: yc – yield class.

Fig. 2. Age-based comparison of mean DBH values of Macedonian pine (red boxes) in each of the measured stands in Grafrath and Bodenwöhr, Germany with values from Norway spruce and Scots pine taken from Wiedemann-yield tables.

pine with yield tables for *Picea abies* and *Pinus sylvestris* (after Wiedemann 1936/42 and 1943). The data displayed from the Wiedemann tables are for yield classes 1 to 3. Interpretations of this kind must be done with care in this case, because yield tables are usually based on the assumption of a consequent thinning regime and schedule and, as previously mentioned, the Macedonian pine stands in this study (with the exception of the Bodenwöhr (BW) stand) never underwent thinnings. The mean diameter of the BW stand (age 67, poor site) is very similar to that found in the growth curve for a stand of spruce/pine in yield class 3. With increased stand age (Grafrath stands), the mean diameters for G4, G1, and G3 exceed spruce/pine in yield class 1.

Stand density

The largest number of *Pinus peuce* trees in Grafrath are found in the nearly pure stand, G1. Other stands dominated by *P. peuce* are G4 and G2. Using the data gathered to calculate Reineke's Stand Density Index (SDI) yielded a value of 1,423 trees per ha for G1, 1,319 for G4, 919 for G2, 763 for G3, and 710 for BW. Sterba (1991) referred to reference values between 600 and 750 trees per ha for *P. sylvestris*. Thus, the calculated SDI values for the Grafrath stands clearly exceed this benchmark, while the SDI for BW meets it nicely. Normally indications of self-thinning are found in very dense stands. In Grafrath, however, this is true only in G2, while the others are still very densely stocked.

Stand basal area

Stand G1 has the highest basal area with 85.16 m²/ha for *Pinus peuce* and 1.23 m²/ha for all other species. G4 has a basal area of 77.43 m²/ha for *P. peuce*, while the other remaining species combined have a basal area of 3.71 m²/ha. In G2, *P. peuce* basal area is 61.51 m²/ha, 8.85 m²/ha for all other species combined and 3.59 m²/ha for standing *P. peuce* deadwood. In the oldest stand (G3), *P. peuce* has a basal area of only 46.47 m²/ha and 13.93 m²/ha of basal area are formed from other species. In the Bodenwöhr stand (BW), *P. peuce* has a basal area of 32.50 m²/ha, while *P. sylvestris* and *Picea abies* together have a combined basal area of 23.40 m²/ha (Fig. 3).

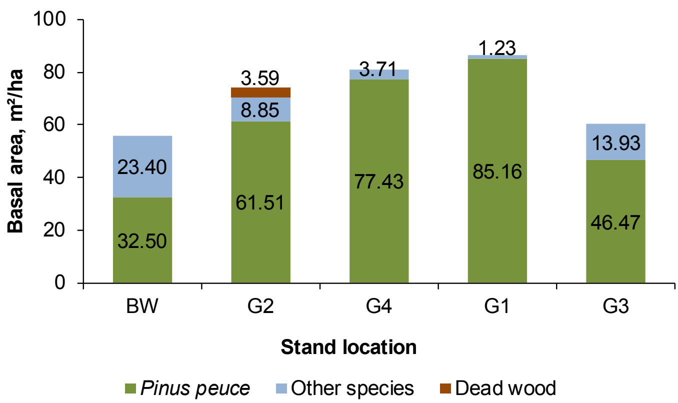
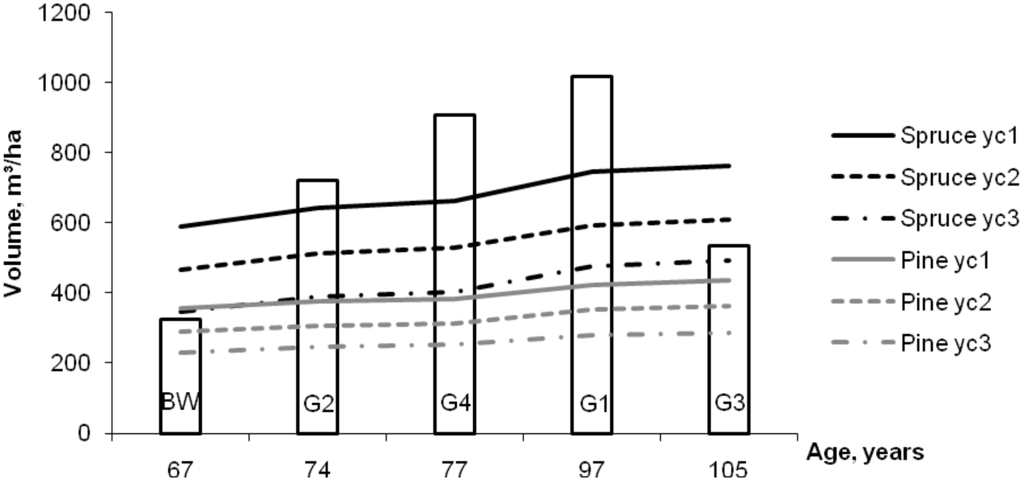


Fig. 3. Basal area of Macedonian pine stands in Grafrath and Bodenwöhr, Germany.



Note: yc – yield class.

Fig. 4. Comparison of growing stock of Macedonian pine in Grafrath and Bodenwöhr, Germany with yield table values (Wiedemann) for Norway spruce and Scots pine.

Growing stock and yield

The highest total standing growing stock can be found in stand G1 with a calculated amount of 1.015 m³/ha (Table 1). Stand G4 carries the second highest stock with 906 m³/ha, G2 has 721 m³/ha, and G3 has the lowest stock of the Grafrath stands with 534 m³/ha. Growing stock in Bodenwöhr (BW) was calculated to be 326 m³/ha.

In comparing the total volume of growing stock of Macedonian pine with the yield table values for Norway spruce (after Wiedemann 1936/42, Fig. 4, black lines) and Scots pine (after Wiedemann 1943, Fig. 4, gray lines), it becomes obvious that the volume of *Pinus peuce* (age 67) is very similar to that of *P. sylvestris,* yield class 1. Volume growth of Macedonian pines in the stands of age 74, 77 and 97 greatly exceeds that from the yield tables for *Picea abies*, yield class 1. However, in the oldest stand (105 years) *Pinus peuce* falls behind *Picea abies*, yield class 2, but is still superior to *Pinus sylvestris,* yield class 1.

Mean annual increment

The largest mean annual increment (MAI) was produced in stand G4 with 11.8 m³/ha/year (Table 1), followed by G1 with 10.5 m³/ha/year and G2 with 9.7 m³/ha/year. In the oldest stand, G3, the MAI was only 5.1 m³/ha/year. This is very close to the result from Bodenwöhr (BW) of 4.9 m³/ha/year.

Slenderness-ratio

The height100/DBH 100-ratios of *Pinus peuce* for the four stands in Grafrath and the single stand in Bodenwöhr were calculated, as these ratios are an indicator of the support matrix of a forest stand and thus, of resistance against storm damage. All the values calculated range between 70 and 57, which shows a high level of stability against wind and storms.

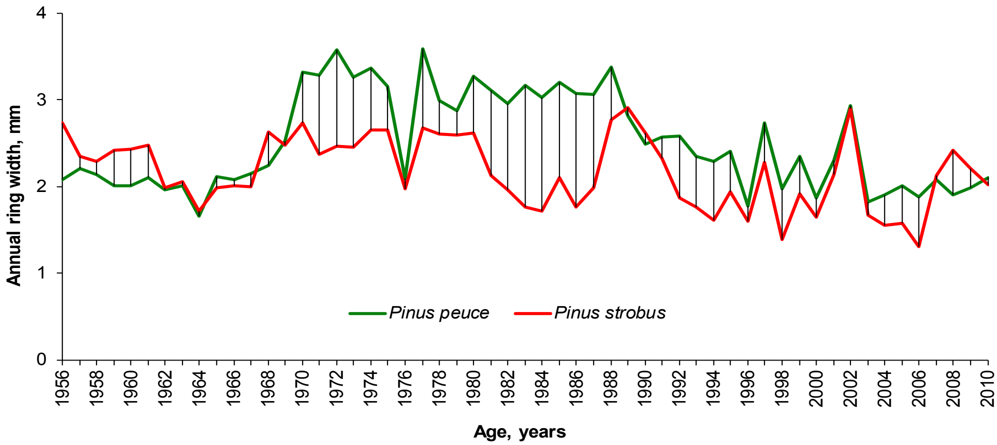


Fig. 5. Comparison of annual ring width between Macedonian pine and white pine in Bodenwöhr, Germany between 1956 and 2010.

Dendrochronological investigations

With only a few exceptions (1968, 1990, 2008, 2009) dendrochronological studies of the annual ring width in Bodenwöhr demonstrate that *Pinus peuce* exceeds the average radial increment of *P. strobus* (Fig. 5).

Factors influencing the annual ring width of *Pinus peuce*

Figure 6 gives an overview of the annual ring width chronology of *Pinus peuce* derived from wood cores taken from all four stands in Grafrath and the one stand in Bodenwöhr.

In the two dry pointer years, 1976 and 2003, *Pinus peuce* demonstrated a possible drought response with a decrease in annual ring width; while in the two wet pointer years, 1965 and 2002, this tree species showed an increase in growth ring width.

The deviations (in %) from the average radial increment are shown in Figure 7. The

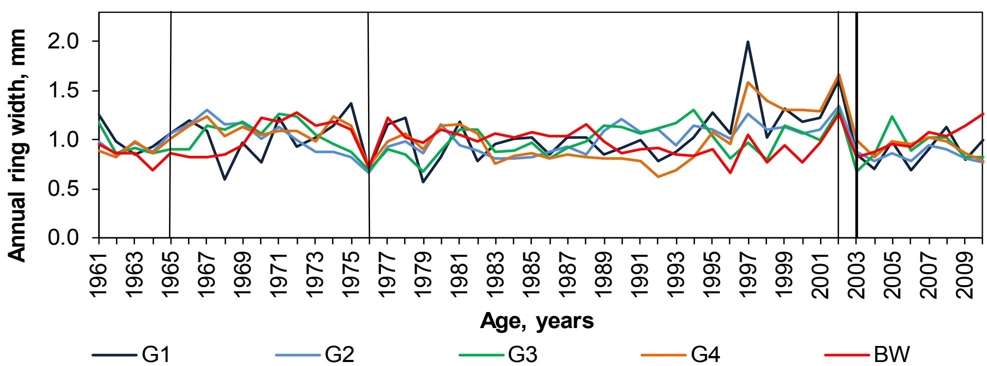


Fig. 6. Dendrochronology (annual growth ring width data) of Macedonian pine in Grafrath and Bodenwöhr, Germany over a time span of 50 years.

Note: Climatic pointer years – 1965 (wet year), 1976 (dry year), 2002 (wet year), and 2003 (dry year) – are marked by vertical lines).

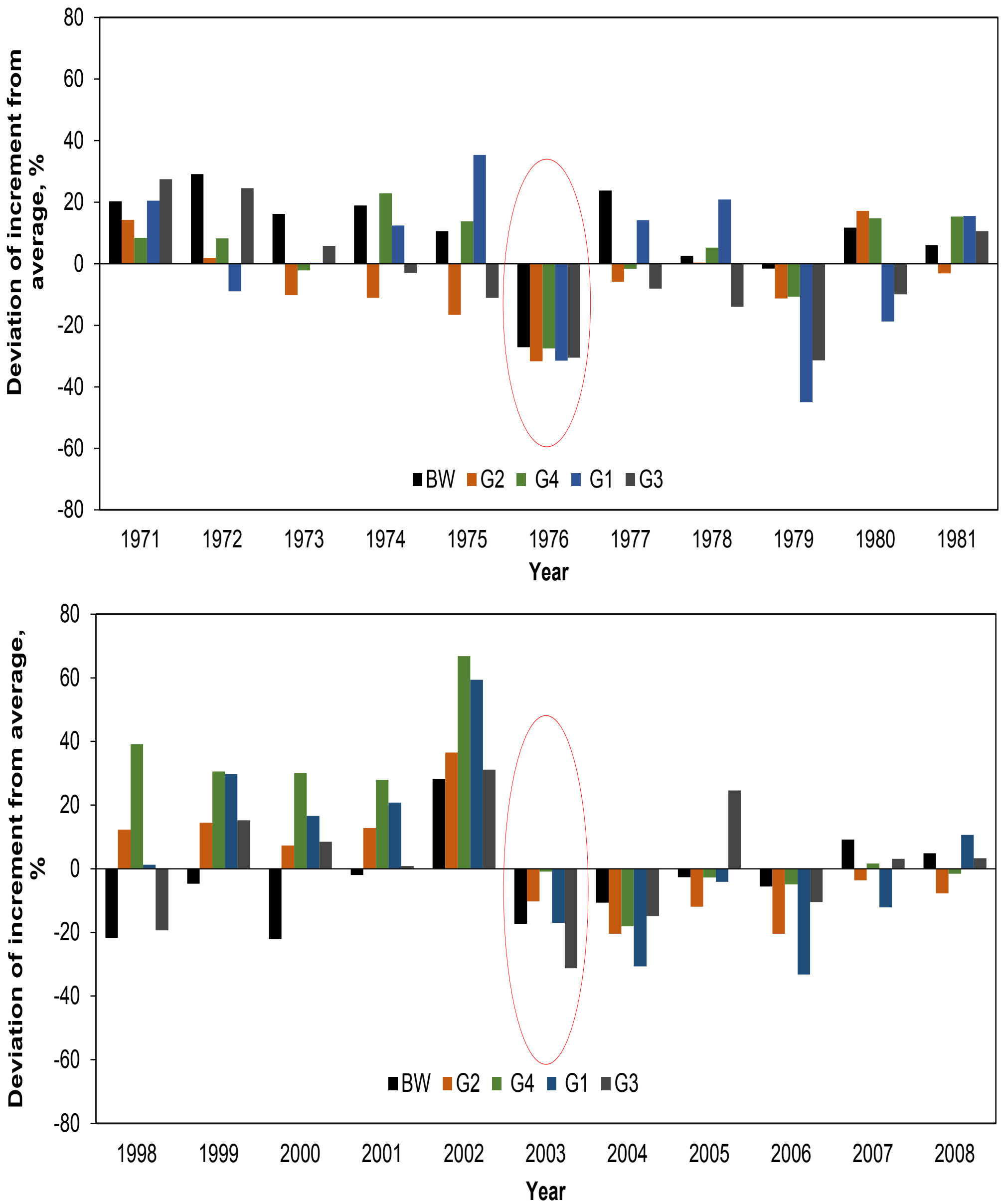


Fig. 7. Deviation of annual radial growth increment (in %) from average radial increment in Grafrath and Bodenwöhr, Germany for the period from 1971–1981 (above) – pointer year 1976 (red oval), and for the period from 1998–2008 (below) – pointer year 2003 (red oval).

dry spells of 1976 and 2003 were marked by a decrease of up to 40 % in radial increment. These losses are very similar to those seen in *Pinus strobus* and *Pseudotsuga menziesii* during the same period (data not shown).

Discussion

When Rohmeder (1970) provided early results for the growth of Macedonian pine in Bavaria, he could not have been aware of the upcoming problem of climate change. His brief publication was hardly noticed by forest scientists and forestry professionals. Four decades later, a new Bavarian initiative (project KLIP 18) has searched worldwide for species that are presumably well adapted to drought conditions and the dynamics of climate change. *Pinus peuce* was found to be a promising candidate. This was one starting point for this study aimed at obtaining additional information and data from planting trials with this species in Bavaria. Existing plantations of *P. peuce* were located in one stand in Bodenwöhr and four stands in Grafrath, where a survey and measuring campaign of growth, yield and performance was begun. A comprehensive study was carried out and issued by Rommel (2012).

In this paper, some of the key results of the study are presented and compared with yield table data for Norway spruce and Scots pine. It should be noted that a comparison of this kind may be of limited value, because model stands for yield tables of Norway spruce and Scots pine have undergone well-defined thinning schedules, while the *Pinus peuce* stands investigated here did not. Thus, although the calculated growing stock and basal area figures, as well as the stand density indices presented here demonstrate remarkably high productivity and yield reliability, these results should be treated with caution.

In the initial years in the life history of the *Pinus peuce* stands investigated, growth was very slow. The expected culmination of the diameter increment in this species has been estimated to be between ages 30 and 80 (Lines 1985, Alexandrov 1998). On the other hand, it is well known that *P. peuce* can continue producing high diameter increments for a relatively long time period (Holzer 1972). In comprehensive studies on the structure and productivity of natural *P. peuce* forests in the North Pirin Mt., Tsakov (2001) was able to demonstrate the good condition, very good growth and productivity of the stands.

A closer look at the five particular Bavarian samples presented here shows a slow growth pattern during the early juvenile growth phase with increasing increments in subsequent growth stages. With increasing stand age, diameter increment slows down and eventually, decreases. According to Holzer (1972), the slow growth of *P. peuce* during the early juvenile phase is genetically determined and cannot be improved by transplanting of the species to more temperate conditions.

Factors determining growth and yield of forest species are, inter alia, site factors like soil, exposition, topography, and altitude; but also, factors intrinsic to the stand itself, like stand density, vitality, and crown length. A very important and complex group of factors are climatic factors.

The dendrochronological data shown here seem to exhibit visible signs of drought and support the assumption that *Pinus peuce* may suffer from dry spells and periods of high temperature – phenomena which are very similar to that which have been found true for Norway spruce and Scots pine. This situation suggests that *P. peuce* may not be much better adapted to drought than conifer species that are native to the study area or other, previously introduced species like Douglas fir. The dry pointer years – 1976 and 2003 – seemed to act in a very negative way on the growth of *P. peuce*, while in the wet pointer years – 1965 and 2002 – a distinct increase in growth increment was detected. It is assumed that *P. peuce* suffers from dry spells as well as other tree species. High temperatures during the growing season in 2003 could have made the situation even worse. On the basis of the Bavarian data and the climate data, the documented losses in increment can nicely be explained. These results indicate that precipitation has an important and significant influence on annual growth ring width. This is in accordance with the findings of Panayotov and Yurukov (2007) and Panayotov et al. (2010) in the Pirin Mountain in Bulgaria where *P. peuce* had small annual rings in years with low annual or seasonal (summer) precipitation levels. The data are also supported by the recently presented results of Ivanova et al. (2015) who found that the capacity for stomatal control of photosynthesis in saplings of Macedonian pine decreased with drought in summer. This can be interpreted as a signal of imbalance in physiological processes.

Interestingly, an increase in growing season temperature in Grafrath had a positive effect on annual growth ring increment, while the opposite reaction was found in Bodenwöhr.

Seen against the backdrop of climate change, the results of this study suggest that *Pinus peuce* may suffer from declining precipitation during the vegetation period and possibly also from increased temperatures.

Pinus peuce is a very cold-tolerant species and dehardened more slowly - in comparison to other temperate tree species – in the period from mid-winter to early spring (Kreyling et al. 2015). The data do not allow for conclusions to be drawn as to whether this characteristic may allow *P. peuce* to escape from late spring frost damage on new needles after bud break.

Overall, the Macedonian pine in the studied stands appears to be in good condition and has successfully withstood the heavy windstorms that occurred in Bavaria 1990 and 1999 without any damage.

Alexandrov and Andonovski (2011) give a short overview of pests and diseases of *Pinus peuce*. One of the most serious pathogens of five-needle pines is white pine blister rust (*Cronartium ribicola*). A few signs of this pathogen (i.e. resin flow, yellow spots on needles and single dead branches) were found in the stands in Grafrath and Bodenwöhr. Nevertheless, there were no typical signs like aecia or pycnia. Rohmeder (1970) mentioned sporadic outbreaks of blister rust disease in Grafrath, but those were concentrated on *P. strobus*, which grew in close vicinity to *P. peuce*, and the latter did not suffer from this significantly. Damages from wood-rotting found in natural stands of *P. peuce* in Bulgaria were mostly caused by the fungi *Phaeolus schweinitzii* (Fr.) Pat., while wood-rotting in plantations of *Pinus peuce* mainly resulted from infection with *Heterobasidion annosum* (Fr.) Bref. (Rossnev 1985). Wood-rotting caused by infections with the above mentioned pathogens in *Pinus peuce* stands in Bavaria was never highlighted as a problem.

Conclusions

Despite high volume production, the results of this investigation reveal several uncertainties about the suitability of *Pinus peuce* for Bavaria under future climatic conditions. Based on the assumption of further decreases in precipitation in the near future in Bavaria, the species will most likely suffer increasingly from drought stress and show decreases in annual increment.

Nevertheless, it seems appropriate for afforestation in montane areas because of its demonstrated resistance to windthrow and snowbreak.

Unfortunately, there is still little information from provenance studies beyond its natural range in other parts of Europe. Genetic characterization of *Pinus peuce* was carried out through analyses of the composition of needle oils by Hagman (1989), Dobrev (1992), and Nikolić et al. (2008, 2014), and of allozyme markers by Zhelev et al. (2002) and Zhelev and Tzarska (2009). The information obtained from these studies may offer an instrument for studying population genetics. An overview of genetic research in five-needle pines (*Pinus* subgenus *Strobus*) in Europe was given by Blada and Popescu (2004a). Genetic research with a focus on conservation efforts of *P. peuce* in Bulgaria was presented by Alexandrov et al. (2004), Dobrev (2007) and Alexandrov and Dobrev (2012, 2015). Hence, up to now no molecular genetic markers for the identification of unknown provenances like the ones in the Bavarian study have been developed.

Another interesting aspect already suggested by researchers in the 1970s deals with the idea of breeding hybrids of *Pinus peuce* × *P. strobus.* The products of such crosses are expected to combine the high productivity of *P. strobus* with the low susceptibility of *P. peuce* to blister rust and snowbreak (Rohmeder 1970, Grossmann 1974, Lattke et al. 1987, Popnikola et al. 1978, Alexandrov 1998). Subsequent experiments have already shown the feasibility of creating such hybrids (Blada 1989, Blada and Popescu 2004b).

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