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ORIGINAL PAPER

Cedrus libani: A promising tree species for Central European forestry facing climate change?

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Abstract Considering climate change, the discussion intensifies whether and to what extent exotic tree species should be taken into account for forest cultivation, especially when indigenous species are no longer able to fulfill essential forest functions. In this study, for the first time growth potential of *Cedrus libani* was evaluated under climatic conditions in Central Europe (Bayreuth, Germany). The sampled trees exhibited extraordinary growth with tree ring widths averaging 4.9 mm year^{-1} during the past 23 years. A continuously available soil water supply enhanced radial stem growth. Thus, growth declined during the dry year of 2003, but recovered to average values the following year. Our results confirm that *C. libani* is a light-demanding species which is sensitive to competition and which shows a typical age trend. In a second study, we compared cambial growth in Bayreuth with a natural stand in Elmali (Turkey) in 2009. Cambial growing season in Bayreuth was 45 days longer, and radial growth rates in Bayreuth were four times higher than in Elmali. Interestingly, *C. libani* maintained a slow but continuous radial growth at Elmali even during the dry summer period, confirming its exceptional drought tolerance. Our results indicate a high adaption of *C. libani* to current and future climate conditions in Central Europe. It tolerates extreme cold in winter and prolonged droughts during summer. Thus, its promising potential for establishing stable and productive forest stands in Central Europe under a changing climate should be confirmed in further studies.

Keywords *Cedrus libani* · Exotic · Assisted migration · Global warming · Silviculture · Tree ring analysis

Abbreviations

EBG	Ecological-Botanical Gardens
DCI	Hegyi's diameter-distance competition index
DOY	Day of year

Introduction

Facing climate change, the forestry sector with its long production cycles will have to deal with enormous challenges (Spittlehouse and Stewart 2003; Brang et al. 2008; Hemery 2008; Lindner et al. 2010). The magnitude of climate change on a regional scale is difficult to predict (Millar et al. 2007; Lindner et al. 2010). One thing is certain: The forests of Central Europe will be affected by climate change (Hemery 2008). For forestry, one strategy to minimize the risks of losing future forest stability and function is to establish mixed stands of tree species which are adapted to warmer climatic conditions (Kölling and Ammer 2006; Hemery 2008; Milad et al. 2013). However, it cannot be excluded that autochthonous tree species are

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not sufficiently capable of adapting to future climate conditions (Millar et al. 2007) and thus will become obsolete as forest species.

It is widely accepted that *Picea abies*, the most common tree species in Germany (25.4 % of all forested areas; BWI3 2012), will substantially loose importance for timber production due to its susceptibility to summer drought (e.g., Kölling and Ammer 2006; Kölling et al. 2009; Milad et al. 2013). Given this scenario, the discussion on the introduction and cultivation of exotic tree species, mainly conifers, faces a revival (e.g., Millar et al. 2007; Rigling et al. 2008; Schölch et al. 2010; Gray et al. 2011; Reif et al. 2011). Exotic tree species, supposedly better adapted to future climate conditions than indigenous species, could amplify the spectrum of forest species in Central Europe (Kölling 2013). A promising species is *Cedrus libani* A. Rich (Lebanon cedar). This species currently grows in its natural habitat under climatic conditions which are expected in the future for large areas of Central Europe (Schmiedinger et al. 2009).

Among the Mediterranean cedar species, *C. libani* (Pinaceae) exhibits the largest geographic range and occurs naturally in the Taurus Mountains of Southern Turkey, in Western Syria and in the Lebanon Mountains (Senitza 1989; Boydak 2003). Century-long overexploitation resulted in devastation or degradation of most forests, but small populations survived in a well-preserved state in disjunct areas, particularly with impassable topography (e.g., Sevim 1955; Boydak 2003; Debreczy and Rácz 2011). This disjunct distribution together with site conditions (i.e., elevation, exposure, microclimate, absence or rareness of associating tree species) leads to morphological, phenotypical and/or molecular differences between different populations (i.e., provenances, Scaltsoyiannes 1999; Kurt et al. 2008; Senitza 1989). Many attempts were done to describe the taxonomic position of the morphologically differentiated provenances of *C. libani* in the Taurus Mountains of Southern Turkey in contrast to those in Western Syria and in the Lebanon Mountains. In the recent literature, *C. libani* is in most cases divided into subsp. *libani* for Western Syria and the Lebanon mountain ranges and subsp. *stenocoma* for Southern Turkey (Scaltsoyiannes 1999: based on isoenzymes; Qiao et al. 2007: based on cpDNA; Dagher-Kharrat et al. 2007: based on AFLP markers; Fady et al. 2008: based on chloroplast microsatellite and isozyme; Jasińska et al. 2013: based on needle characteristics).

Cedrus libani typically grows between 800 and 2100 m a.s.l. Smaller stands may occur in lower (500–600 m a.s.l.) or higher (up to 2400 m a.s.l.) elevations (Evcimen 1963; Senitza 1989). The lower elevation sites near the coast are exposed to a montane Mediterranean climate with winter rain (supra-Mediterranean). High elevations have an upper montane Mediterranean climate with a transition to the dry and winter cold continental climate of the Central Anatolian steppe (oro-Mediterranean). These sites are characterized by a peak of monthly precipitation from November until February and a dry season between July and September (Senitza 1989; Atalay 2002). Annual mean temperature ranges from 7.5 to 15 °C, and extremes of −35 °C in winter and +30 °C in summer may occur (Aussenac 1984 cited by Ducrey et al. 2008). *C. libani* prefers carbonate soils with pH between 6.6 and 8.2 (Kantarci 1985; Ayasligil 1997) but also grows on soils with parent materials consisting of sandstones, mica schist, serpentine and olivine basalt (Sevim 1952, 1955). Preferred soils are either Calcaric–Chromic Cambisols (terra rossa, terra fusca) or Luvo-Chromic Cambisol and Albic Luvisols (transitions to and modifications of brown luvic soils, Kantarci 1985) at higher elevations. *C. libani* occurs in monospecific stands or mixed with *Abies cilicica* and *Quercus cerris*. On dry sites, it associates with *Juniperus excelsa* and *Juniperus foetidissima*, at lower elevations with *Pinus nigra* subsp. *pallasiana* and *Pinus brutia* (Öner and Uysal 2009; Farjon 2010). *C. libani* may reach a mean tree height of 26 m and a DBH of 42 cm after 150 years (Evcimen 1963, growth tables for non-managed stands with very good site quality). The valuable wood is very durable and versatile in application and use (Ayasligil 1997). Besides *P. brutia* and *A. cilicica*, *C. libani* belongs to the major commercial tree species in Turkey (Brooks et al. 2008).

Growth performance, wood properties and the consequences of introducing Lebanon cedar into Central European ecosystems must be studied in order to evaluate the potential and the risks involved (cf. Schmiedinger et al. 2009; Richardson et al. 2014). No studies are known to us dealing with the performance of *C. libani* in Central Europe as a forest tree. The Ecological-Botanical Gardens (EBG) of the University of Bayreuth in Northern Bavaria, Germany, host four small stands of approx. 32-year-old Lebanon cedars with a total of 66 individuals. We used these well-established stands to evaluate the growth potential of *C. libani* in Central Europe (Germany). In this study, we tested the assumptions that *C. libani* (1) represents an exotic species with good growth under current climate conditions in Central Europe and (2) that this species is well adapted to future climate scenarios in Central Europe with elevated temperatures and a higher frequency of summer droughts (cf. Ciais et al. 2005; IPCC 2007; Lindner et al. 2010).

Materials and methods

Study sites and stand properties

Study site at Bayreuth, Germany

Growth of four 32-year-old stands of *C. libani* situated at 360 m a.s.l. on level terrain (Table 1) was studied at the

EBG in Bayreuth (Northern Bavaria, Germany). The local climate is a transition from oceanic to continental climate with a mean annual temperature of 7.9 °C (minimum −25 °C, maximum 36.1 °C) and a mean annual precipitation of 724 mm (Foken et al. 2004, Fig. 1). According to current scientific knowledge (Scaltsoyiannes 1999; Qiao et al. 2007; Dagher-Kharrat et al. 2007; Fady et al. 2008; Jasińska et al. 2013) the seed material of the *C. libani* individuals in Bayreuth belonged to the subsp. *stenocoma* (Schwarz) Davis as it originated from the province of Antalya in the Western Taurus Mountains (stands of the so called Elmali type; Senitza 1989) near the town of Elmali in an elevation of 1600–2000 m a.s.l. In 1978, seeds from Elmali were germinated and cultivated in a tree nursery in Germany. The 2-year-old seedlings were brought to Bayreuth and cultivated until their final planting in the EBG. Three of the four stands are monospecific (Table 1). Stands 1 and 3 were established as pure cedar stands, whereas stand 2 was planted in mixture with *A. cilicica* (wide spacing, approx. 3 × 3 m). All stands were cleared of competing vegetation during the first years. Several tree-thinning operations were performed in stand 2, and all *A. cilicica* and other tree species were completely removed. Stand 4 consists of two 27- and 21-m-long tree rows parallel along an unpaved road at 3 m distance from the road. Stands 1, 2 and 4 stock on mixed soil material of clay and sandy loam with a shallow top layer of humus (mull-like Moder). The pH (H_2O) of the soils in the cation exchange and silicate buffer ranges varies from 4.4 to 5.3. Stand 3 grows on a Luvisol-gley which is influenced by stagnant groundwater below 60 cm depth (pH between 4.4 and 5.0).

Study site at Elmali, Turkey

In natural *C. libani* subsp. *stenocoma* stands near Elmali in SW Turkey, annual radial stem growth was measured in 2009 (the seeds used for cultivation in Bayreuth came from this very same site). The study area is located within the Elmali Cedar Research Forest in the Southwestern Taurus Mountains (1655 m a.s.l.) which is situated 130 km southwest of Antalya in Southwest Turkey. It is situated on a northwestern slope with an approx. inclination of 38° and exhibits a homogenous natural stand of *C. libani*. The site has an oro-Mediterranean climate with cold winters and a drought period during summer (June–September, Fig. 1). Mean annual values for precipitation and temperature are 645 mm and 7.3 °C, respectively (Fig. 1). Absolute air temperature extremes (1970–2003) were −31 and +32 °C (Fig. 1). The stand stocks on skeletal soil with a stone proportion of 50–75 %. Soil characteristics are between clayey to clay loam, and the pH (H_2O) varies from 7.6 to 7.73 (Basaran et al. 2008).

Growth analysis at the Bayreuth site

Stem analysis and growth ring analysis of single trees

For stem analysis of single cedars, three dominant and co-dominant individuals (according to the tree classes 1–2, after Kraft 1884) of stands 1 and 4, respectively, were measured in DBH and height using a laser range finder (Forestry 550, Nikon, Germany) and afterward felled in May 2010. In order to determine the age-dependent development of radial and terminal growth as well as the stem form factor ($f_{1,3}$), tree disks were sampled at 0, 0.5, 1, 1.3 m (DBH), 2 m height above ground and following on every meter up to a stem diameter of 1 cm. For each log section, exact volume was calculated and real total stem volume per tree computed from the sum of all individual volumes. Afterward the stem form factor ($f_{1,3}$) could be calculated for all sampled trees with breast height (1.3 m above tree's base, DBH) as reference point.

Furthermore, annual radial stem growth of overall 20 trees was measured for the time period from 1988 until 2010. Therefore, tree cores (using a Suunto 300/400-mm increment borer, Finland) from eleven trees (stands 3 and 4, November 29, 2010) and nine tree disks (stands 1 and 4, April and May 2010) were sampled at 1.3 m height. The width of each fully developed tree ring was measured with the LINTAB linear measurement table (Rinntech, Heidelberg, Germany) at a 10-µm radial resolution. For each tree disk, two radii were measured in a North–South orientation and values were averaged. Growth curves were plotted using indicator years for synchronization. Increment areas for each annual growth ring were calculated using the program Time Series Analysis and Presentation (TSAP,

Table 1 The four *Cedrus libani* stands studied at the Bayreuth site in Germany

Stand	Description	Year of planting	Area Length	Individuals (ha^{-1})
1	Monospecific stand	1994	188 m^2	1220
2	Monospecific stand	1985	184 m^2	597
3	Monospecific stand	1982	83 m^2	1080
4	Two planted rows	1988	27/21 m	–

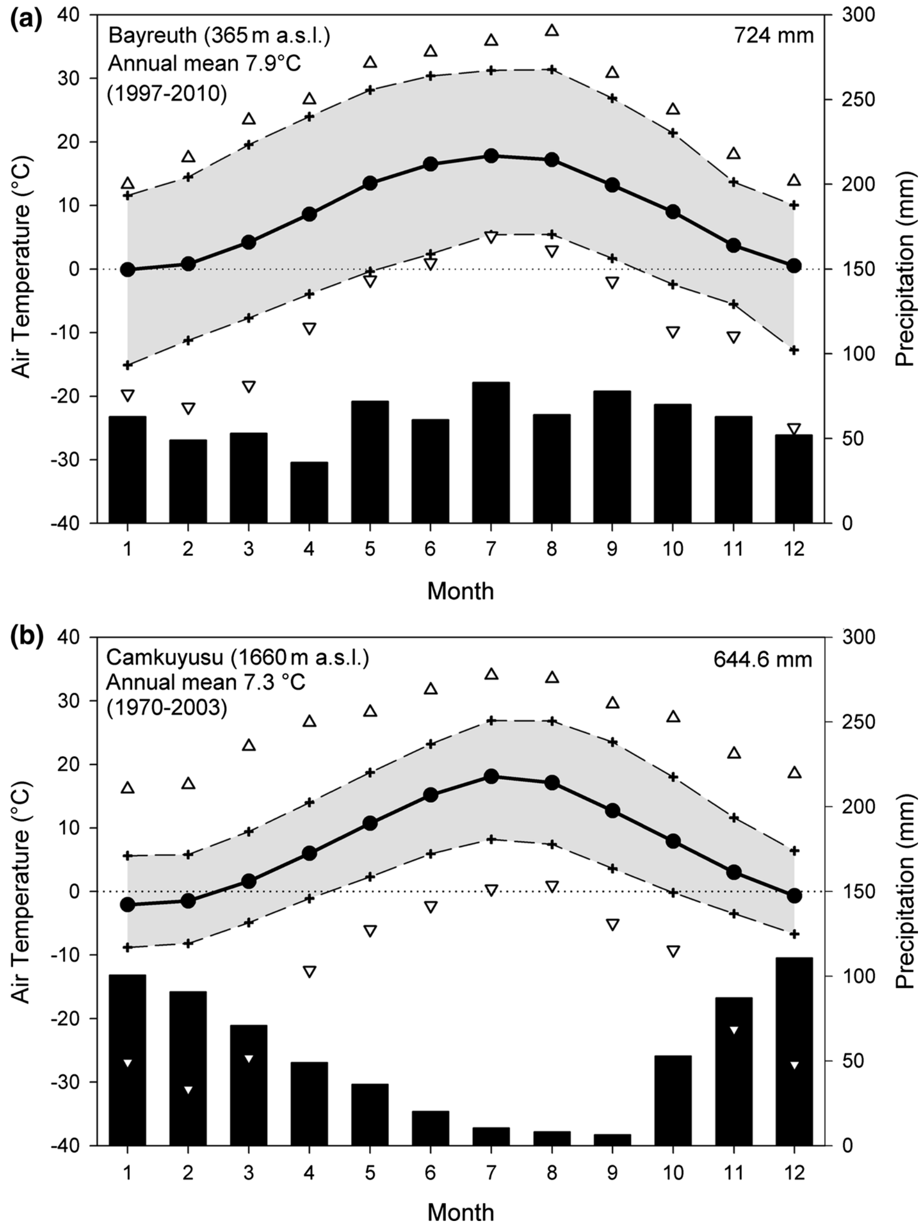

Fig. 1 Climate diagram of Bayreuth, Germany (**a**), and Camkuyusu near Elmali, Turkey (**b**). The climate diagram of Bayreuth was generated from data of the meteorological station of the Ecological-Botanical Gardens Bayreuth (Foken et al. 2004). Data of the climate diagram of the Camkuyusu meteorological station are from the Elmali Cedar Research Forest in SW Turkey (Southwest Anatolian Forest Research Institute). Temperature is given as monthly mean (*dots*), monthly minimum and maximum mean, respectively (*crosses*), monthly absolute maximum and minimum values, respectively (*triangles*). Monthly sum of precipitation is indicated by *bars*

Rinntech, Germany) and growth curves plotted using SigmaPlot 11.0 (Systat Software Inc., 2001, Build 11.1.0.102).

Climate parameters

Climatic data used for our analysis came from two sources: Data until the year 2000 are from the station Bayreuth of the German Weather Service (Deutscher Wetterdienst, station number 4070), and from 2001 on, data are from the climate station at the EBG in Bayreuth (360 m a.s.l., BayCEER). For all growing seasons (April–September) between 1997 and 2010, sum of monthly average air temperature at 2 m height, sum of monthly precipitation (Soldner 2010) and total number of days with rainfall ($\geq$1.2 mm day^{-1}) were calculated.

Effect of competition on tree growth

The effect of competition by neighboring trees on tree growth (DBH, annual growth ring) was analyzed for nine trees in stand 3 which mostly met silvicultural aspects. Competing trees for each individual tree were first determined in the field using the relascope method after Bitterlich, thus taking into account the influence of distance and DBH of each competing tree (Pretzsch 2002). In detail, trees were selected with a mirror-type relascope using factor 4. Competing trees (j) which were then closer in distance ($Dist_{ij}$ in m) to the central tree (i) than the DBH (D in cm) multiplied by 0.25 were finally chosen (Eq. 1; Pretzsch 2002). The competition index DCI [according to Hegyi (1974)] was calculated for each central tree considering all previous selected competitors (Eq. 2). Additionally, five trees distributed over a diameter range (DBH) of 20 and 35 cm were then cored and the mean width of annual growth rings for the last 3 years (2008–2010) was determined.

$$\mathrm{Dist}_{ij} < D_j \times 0.25 \quad (1)$$

$$\mathrm{DCI} = \sum_{j=1}^{n} \frac{D_j}{D_i \times (\mathrm{Dist}_{ij} + 1)} \quad (2)$$

Stand analysis

In all four stands, diameter at breast height (DBH) was measured of all individuals. Tree height was averaged from three measurements taken with a laser range finder (Forestry 550, Nikon, Germany). Stem basal area and stem volume were calculated per stand and per area (ha^{-1}). For standing trees, the mean stem form factor ($f_{1,3}$) of the six felled trees (see "Stem analysis and growth ring analysis of single trees" section) was used to calculate stem volume.

Radial stem growth in 2009 at the Bayreuth and Elmali sites

Electronic dendrometers with a resolution of 10 µm (Megatron® resistor MM1011, Resistance 1 kΩ, Linearity 1 %, Megatron, Munich, Germany) were used to continuously monitor the radial stem growth dynamics of *C. libani* at DBH from March until December 2009. At the Elmali site, dendrometers were installed at nine individuals of *C. libani*, which were evenly situated within a circular plot (20 m radius) representing this natural site. Absolute tree age ranged between 75 and 173 years, DBH between 24 and 52 cm, and tree height from 16.4 to 24.1 m. In Bayreuth, dendrometers were installed on five cedars of stand 4. The entire period of net radial growth was recorded and daily radial growth as well as total annual growth averaged for the Bayreuth and Elmali stand, respectively. Maximum growth period was determined for each site using as the starting day the steep and continuous increase of the daily radial stem increment and following this point for the next 40 days. During this defined maximum growth period, daily radial growth was averaged per site and given as the mean maximum daily growth rate. Additionally, daily precipitation sum and hourly air temperature were measured during entire observation time.

Statistics

Statistical analysis was performed using R version 2.10.0 (R Development Core Team 2009) and RStudio version 0.97.551 (RStudio Inc., 2009–2012). Plots were done in R and SigmaPlot version 11.0 (Systat Software Inc., 2001, Build 11.1.0.102). The effect ($p < 0.05$) of tree age on individual tree growth at the Bayreuth site was analyzed by the linear mixed model function "lme" (package "nlme" in R, Pinheiro et al. 2009) with stand as factor and tree as random factor. For evaluating potential climatic effects, the age trend on the annual tree growth was removed (cf. Pretzsch 2002). A growth curve ($y = -0.02x^2 + 0.58x + 1.95$) with r^2 as an indicator for "goodness-of-fit" was derived from all studied trees ($n = 20$). Using this curve, the average individual tree growth of each stand (stands 1, 3 and 4) was modeled and compared to actual growth. Age-trend-removed growth values per year were then correlated with air temperature, number of days with rainfall and sum of precipitation per growing season from 1997 to 2010, respectively. We checked whether or not the correlations were stand specific (climate parameter × stand) by using a linear model (LM). We found no effect of stand ($p > 0.05$) on correlations between annual growth and each climate parameter (temperature, numbers of days with rainfall and precipitation, respectively), meaning that correlation did not differ between the three stands. Therefore, regression analysis (LM) as well as a fitted curve was calculated for values of all stands. We calculated different models (linear and quadratic equation) and compared them for significant differences by using the function "anova." The effect of competition by neighboring trees (indicated as DCI) on diameter growth (DBH) of the nine trees analyzed was tested by using a linear regression model.

Results

Growth at the Bayreuth site

Individual tree growth

The six trees felled for stem analysis averaged a height of 10.6 m, DBH of 20.3 cm and form factor of 0.46 (Table 2). The mean annual height growth was 0.5 m $year^{-1}$ (Fig. 2). Conspicuously, *C. libani* showed a high annual diameter growth. During the past 10 years, average annual growth was 1 cm $year^{-1}$ for DBH and reached a maximum of 1.4 cm $year^{-1}$. The 20 trees cored for tree ring analysis grew between 1988 and 2010 at an average rate of 4.9 mm radially, but annual growth was highly affected by tree age ($F = 18.90$; $p < 0.001$***). Obviously, the 32-year-old cedars showed a typical age trend as tree ring width increased to a maximum between 1999 and 2002 and slowly dropped afterward (Fig. 3). Trees behaved differently in ring width, especially during the first years. However, in all stands tree growth was clearly reduced by −23 % during the dry year of 2003 relative to the mean

(Fig. 3). The cedars in stands 3 and 4 recovered in 2004, while growth in stand 1 was below average until 2006.

Influence of climate on tree ring width

Tree ring width of *C. libani* correlated significantly with the number of days with rainfall ($F = 11.32$; $r^2 = 0.22$; $p = 0.0018$**) and precipitation sum ($F = 7.67$; $r^2 = 0.25$; $p = 0.0016$**) during the growing season at Bayreuth (Fig. 4). While growth increased linearly with number of days with rainfall, a nonlinear correlation (optimal curve) was observed for precipitation sum. In that case, annual growth increased with precipitation sum until reaching an optimum at about 425 mm and then decreased slightly afterward (Fig. 4). Accordingly, an even distribution of rainfall (expressed by high numbers of days with rainfall) was more favorable for tree ring growth of *C. libani* than absolute amount of precipitation during growing season. Air temperature was highly and negatively correlated with annual growth of *C. libani* ($F = 8.33$; $r^2 = 0.15$; $p = 0.0063$**; Fig. 4).

Effect of competition on individual tree growth

The nine cedars studied were exposed to five to eight neighboring trees at a distance between 3.3 and 4.3 m. We found a strong negative linear relationship between competition (expressed by DCI) and growth ($n = 9$; $r^2 = 0.77$; $p < 0.01$**; Fig. 5). The more a tree was exposed to competition, the smaller was its DBH (Fig. 5). Regarding mean radial growth of the last 3 years, a similar trend of tree ring width was revealed for the five sampled trees supporting a strong impact of competition on individual tree growth of *C. libani*.

Stand growth

The four stands studied showed quite different growth (Table 3). Stand 2 reached highest and stand 1 lowest values for DBH, basal area, tree height and stem volume. Stand basal area and stem volume were quite different for stands 1, 2 and 3: Tree density of stand 2 was 600 n ha^{-1} and stem volume 336 m^3 ha^{-1}, while tree density in stand 1 was double and stem volume was only 178 m^3 ha^{-1} (Table 4).

Radial stem growth in 2009 at the Elmali and Bayreuth sites

Radial stem growth varied throughout the observation period in 2009. Daily stem radius variation was up to ± 0.2 mm due to stem water storage and water potential changes. Net radial (i.e., cambial) growth was observed at Elmali during 110 days from about April 30 (day of year, DOY 120) to August 18, 2009 (DOY 230), and at Bayreuth during 155 days from April 5 (DOY 95) to September 7, 2009 (DOY 250). Thus, growth period in 2009 was 45 days longer in Bayreuth than in Elmali (Fig. 6). Obviously, precipitation sum was higher in Bayreuth (353 mm) than in Elmali (217 mm) for the observation period (DOY 86 until DOY 245). Different to Bayreuth where precipitation was well balanced throughout the growing season (April 70 mm, May 60 mm, June 65 mm, July 129 mm, August 34 mm), a drought period occurred at Elmali in June and July 2009 (April 45 mm, May 102 mm, June 6 mm, July 10 mm, August 47 mm). But nevertheless net radial growth was still measured for cedars at the Elmali site during whole growth period. Choosing the 40-day period of maximum radial growth as reference, maximum growth started 20 days earlier in Bayreuth (DOY 130–170) compared with Elmali (DOY 150–190) and mean maximum radial growth rate per day was 0.013 ± 0.004 mm for Elmali and 0.044 ± 0.008 mm for Bayreuth (Fig. 6). Total annual growth for 2009 was 4.76 ± 1.01 mm in Bayreuth and therefore 5–6 times higher than in Elmali (0.85 ± 0.44 mm).

Discussion

High growth potential when tree spacing is sufficient

The *C. libani* trees at the Bayreuth site in Germany showed excellent growth. The average annual terminal growth of 0.5 m $year^{-1}$ is comparable with that of *Picea abies*, *Pinus sylvestris* and *Larix decidua* on similar sites, and annual

Table 2 Tree height, DBH, stem form factor ($f_{1,3}$) and stem volume of six *Cedrus libani* trees (age 32 years) harvested at the Bayreuth site

Tree label	Stand	Tree height (m)	DBH (cm)	Stem form factor	Stem volume (m^3)
1	1	11.6	19	0.44	0.14
2	1	8.6	16	0.50	0.08
3	1	11.1	19	0.49	0.15
4	4	12.5	24	0.42	0.25
5	4	8.7	18	0.52	0.12
6	4	11.0	26	0.39	0.23

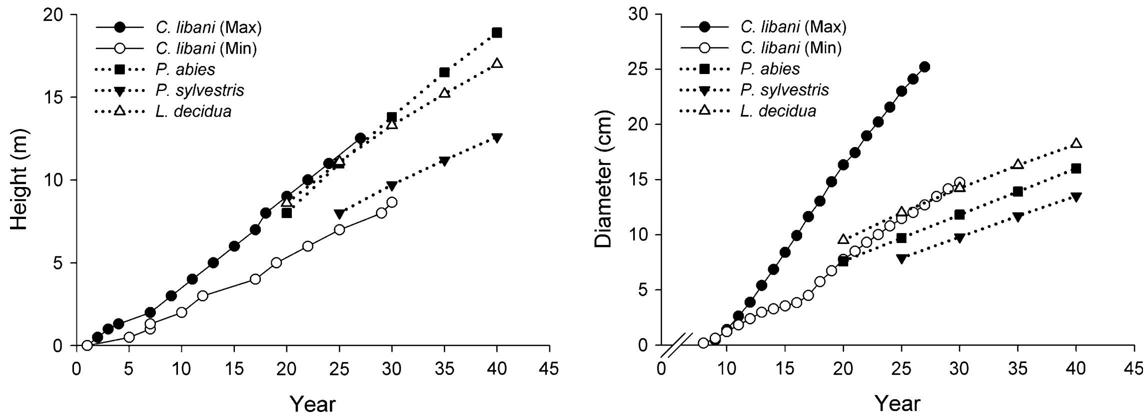

Fig. 2 Annual height growth (*left*) and annual stem diameter growth at DBH (*right*) for six 32-year-old *Cedrus libani* trees sampled at the Bayreuth site. Values are given of two trees with maximum and minimum growth. For comparison, tree growth according to yield tables is given for three European conifers: *Picea abies* (medium yield level, productivity index 36, Assmann-Franz, 1963), *Pinus sylvestris* (moderate thinning, yield class 2, Wiedemann, 1943), *Larix decidua* (moderate yield class 2, Schober, 1946) (Hilfstafeln für die Forsteinrichtung, STMELF 1979)

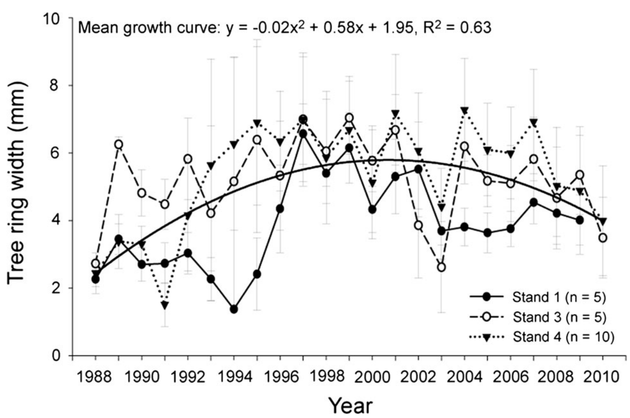

Fig. 3 Tree ring width of *Cedrus libani* in Bayreuth from 1988 to 2010: mean of trees from stands 1, 3 and 4 with standard deviation. Tree ring width measurements between 1988 and 1993 were not possible for all trees because the stem center was missed by coring (1988: $n = 10$, 1989: $n = 12$, 1990: $n = 16$, 1991: $n = 17$, 1992: $n = 18$, 1993: $n = 19$, 1994–2010: $n = 20$). The mean growth curve (*solid line*) was calculated from all trees in the three stands

stem diameter growth at DBH during the past 10 years was even much higher (1 cm year^{-1}, STMELF 1979). Tree ring width declined slightly in the last years, most likely due to the early culmination of growth of the 32-year-old stands, since *C. libani* is a light-demanding species (Senitza 1989). Competition for light could also explain the observed decline in tree ring width since intraspecific competition impacted diameter growth negatively. Carus and Catal (2010) demonstrated for 25-year-old *Cedrus* stands near Isparta, W Turkey, that forced thinning leads to increases in diameter, basal area and stem volume. Because of its low competitiveness for light, *C. libani* is frequently restricted to stony and basic soils (Huber and Storz 2014). Hence, *C. libani* requires sufficient spacing to develop its full growth potential. This is further confirmed by the fact that stand 1 in Bayreuth with the highest tree density (1220 n ha^{-1}) had the lowest mean DBH of 20.9 cm, while stand 2 with the lowest tree density (597 n ha^{-1}) showed the highest mean DBH of 33.5 cm.

Tolerance to drought

Cedrus libani is well adapted to summer drought. Plant-physiological studies (xylem sap flux density, xylem conductivity) of *C. libani* water use in Elmali revealed a uniform water use pattern, indicating that water supply for adult *C. libani* is not critical throughout summer. The extrapolated water use during growing season from individual level to the forest stand of *C. libani* correspond to 1 mm (Sökücü 2010) which is within the lower range of temperate coniferous forests (Larcher 2001, p. 246). In compliance with these findings, we also observed a good performance of *C. libani* in Bayreuth to limited water supply. For instance, compared with other exotic tree species growing in the EBG of Bayreuth, *C. libani* showed the smallest reduction in ring width during the dry summer of 2003 and returned to normal or even higher tree ring growth the years after the drought (Zahn 2008). Dry summers, which are expected in increasing frequency as a consequence of higher climatic variability and climate change in Central Europe (Schär et al. 2004), appear to cause moderate growth reduction only during the drought stress period without affecting growth in the following years. The exceptional drought tolerance of *C. libani* was confirmed by our comparative measurements of tree ring growth in natural stands at Elmali, SW Turkey. In spite of very low rainfalls (sum of precipitation 68 mm) and high temperatures (mean air temperature 18 °C) at Elmali

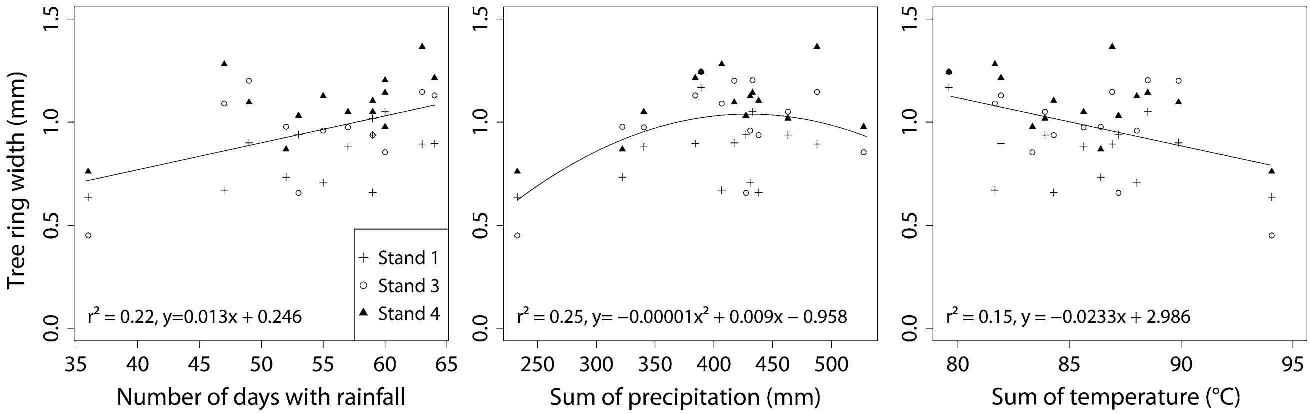

Fig. 4 Correlation between climate parameters during growing season (*left* number of days with ≥1.2 mm precipitation per day, *right* sum of monthly average temperature, *center* sum of precipitation per growing season) and age-trend-removed variations in annual growth ring widths of *C. libani* from 1997 to 2010. Values of individual tree ring growth was averaged for each stand (stand 1: $n = 5$, stand 3: $n = 5$, stand 4: $n = 10$) and given as growth variation from the modeled growth curve (*symbols*). Since correlations were not stand specific ($p > 0.05$), we calculated regressions (LM) and fitted curves (*lines*) for values of all stands

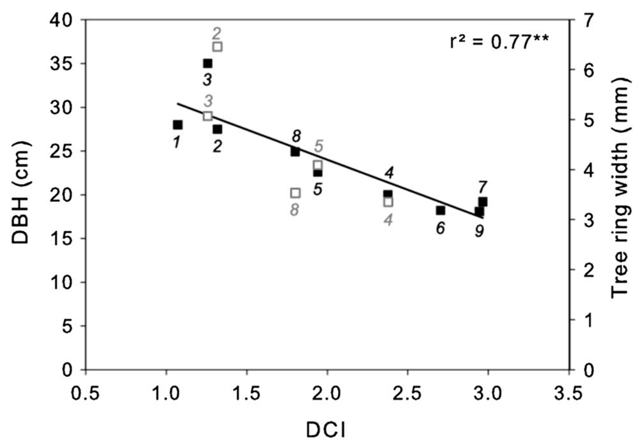

Fig. 5 Linear regression ($n = 9$; $p < 0.01$**) for the competition index DCI (Hegyi 1974) and DBH (*black squares*). For five trees, the mean annual tree ring width for 2008–2010 is given (*gray squares*). *Numbers* indicate the label number of each tree

during summer (DOY 150 until DOY 250) and compared with 245 mm and 16.6 °C, respectively in Bayreuth, radial growth was observed at Elmali during the entire observation period. This is also in accordance with the observations of Ladjal et al. (2007) on Cedrus height growth. In addition to its drought tolerance, the required minimum water supply for *C. libani* in Elmali during the drought summer may be further provided by fine soils in deep and creviced limestone formations which feature a high water-holding capacity (Boydak and Calikoglu 2008).

However, absolute growth in Bayreuth was superior to the natural site at Elmali in Turkey. Annual radial stem growth was 5–6 times higher, and maximum daily growth rates were triple. The trees at Elmali may have a lower growth rate because they are in average 100 years old, while the trees measured at Bayreuth are much younger. Different soil and relief conditions may also have a positive

Table 3 DBH, tree height, stem basal area and stem volume (mean and ±min/max) of four *Cedrus libani* stands (age 32 years) at the Bayreuth site

Stand	Number of trees	DBH (cm)	Tree height (m)	Stem basal area $g_{1,3}$ (m^2)	Stem volume (m^3)
1	20	20.9 (±9.6/6.0)	9.5 (±2.3/2.3)	0.035 (±0.010/0.057)	0.155 (±0.041/0.278)
2	11	33.5 (±6.4/6.3)	13.8 (±2.0/2.7)	0.089 (±0.058/0.124)	0.564 (±0.313/0.763)
3	9	23.7 (±5.6/11.3)	12.2 (±1.7/3.5)	0.047 (±0.026/0.096)	0.274 (±0.126/0.693)
4	26	28.3 (±9.9/10.4)	11.0 (±1.8/3.1)	0.065 (±0.027/0.118)	0.336 (±0.126/0.700)

Table 4 Tree density, basal area and stem volume (Vfm) of three *Cedrus libani* stands (age 32 years) at the Bayreuth site

Stand	Area (ha)	Tree density (ha^{-1})	Basal area (m^2 ha^{-1})	Stem volume (m^3 ha^{-1})
1	0.0188	1220	37	178
2	0.0184	597	53	336
3	0.0083	1080	50	296

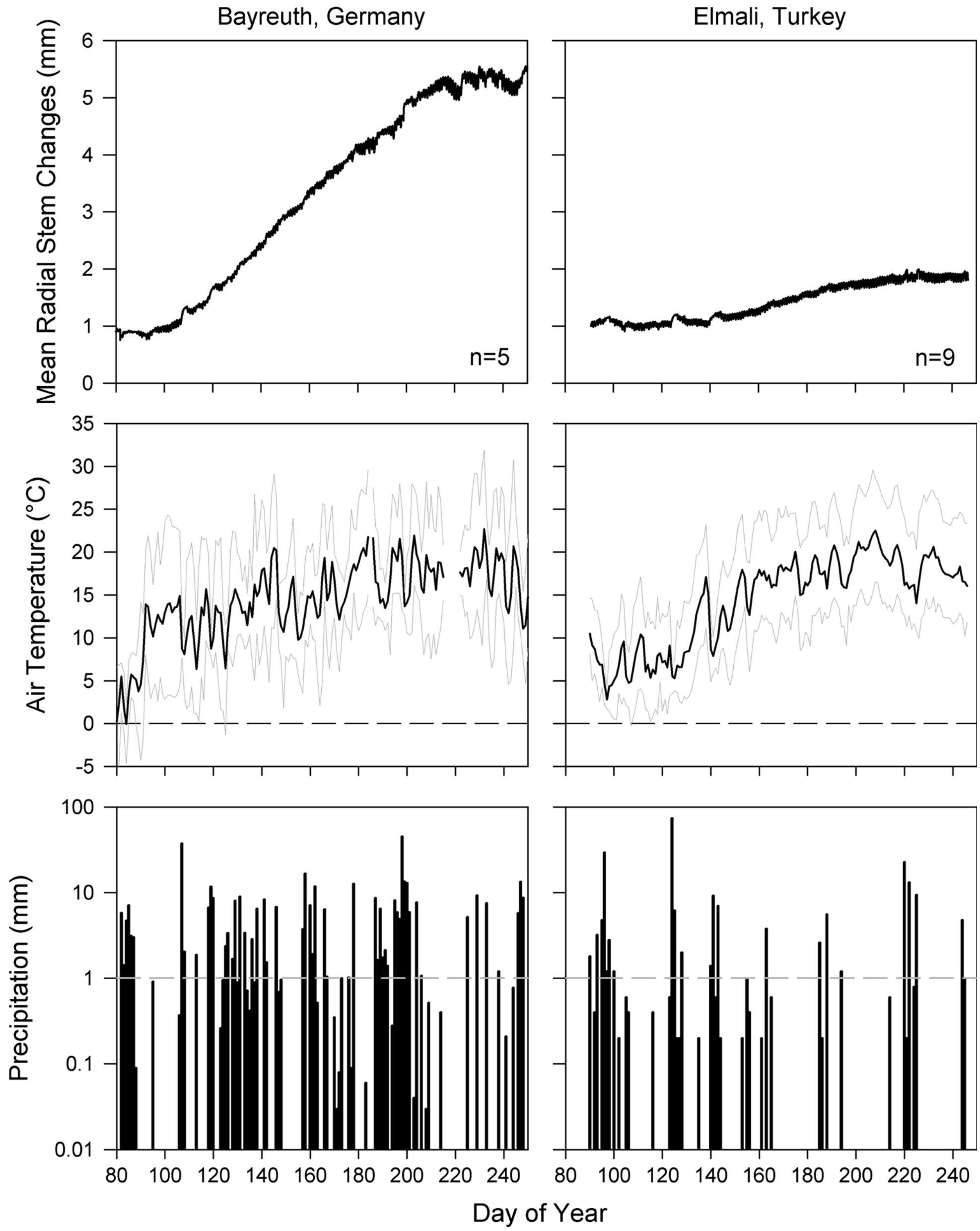

Fig. 6 Comparison of daily variation of stem radius (*top*) for *Cedrus libani* in 2009 (Day of year 80–250) at the Bayreuth site (*left* $n = 5$, tree age 32 years) and the Elmali site (*right* $n = 9$, tree age in average 100 years, ranging from 75 to 173 years), as well as daily mean (*black line*), maximum and minimum (*gray lines*) air temperature (*center*) and the daily sum of precipitation as log (*bottom*)

effect on growth dynamics and productivity for the cedar individuals at Bayreuth. The Bayreuth site was characterized by a deep soil and level relief, both leading to a higher water storage capacity and hence presumably to more favorable conditions for plant growth compared to Elmali. More important for growth performance differences between Bayreuth and Elmali appears to be the fact that as a result of a constant and ample water supply by rain, stem growth at the Bayreuth site lasted overall 45 days longer. Our analysis further showed that tree ring width was positively correlated with the number of days with rainfall during the growing season and that regular rainfalls enhanced growth performance. The reduced growth of *C. libani* during the extreme dry summer of 2003 in Bayreuth confirmed that optimal growth performance is limited by lack of water during the growing season (cf. Akkemik 2003; Touchan et al. 2005; Ducrey et al. 2008). It appears that the relatively humid and temperate climate during the growing season in Central Europe is favorable to the growth performance of *C. libani*.

Tolerance to frost

The challenge in identifying tree species adapted to future Central European climate scenarios is to find trees which are not only tolerant to increased summer drought stress but also tolerant to present and future very low air temperatures in winter (Vavrus et al. 2006; Kodra et al. 2011). In the upper montane regions at Elmali, Turkey, *C. libani* is well adapted to long winters with snowfall (Ayasligil 1997; Boydak 2003). Absolute minimum air temperature documented at Elmali was −31 °C. Measurements of frost tolerance of 27 tree species at Bayreuth showed that *C. libani* tolerates at least −24 °C during February (Kreyling et al. 2015). It is remarkable that *C. libani*, reached maximum frost tolerance already in November and maintains this approximate tolerance until March (Kreyling et al. 2015). This finding is confirmed by 20 years of observation at the EBG of Bayreuth: *C. libani* tolerated evenly well extremely low temperatures (minimum on January 6, 2002, was −25 °C; Foken et al. 2004) and the frequent early- and late-frost events. It is not adequately known whether mild winters negatively affect *C. libani* tolerance and make it more susceptible to frost events. The natural stands in Turkey are occasionally exposed to mild winters. However, no records exist to our knowledge which indicates obvious damage due to frost events in early spring.

Potential for forestry: limitations, chances and risks

Provenances

The results clearly showed that the stands studied at Bayreuth (Northern Bavaria, Germany) are vital, exhibit good growth and so far have been insensitive to biotic and abiotic damages. We like to stress that our statements are valid only for observations on *C. libani* at the Bayreuth site and thus its growth potential should be certainly tested on other sites. However, the study presented strongly indicates for the first time that *C. libani* (montane provenances of subsp. *stenocoma* in the Western Taurus Mountains from SW Turkey) is a tree species with high potential for forestry in Central Europe. Indeed, it can be assumed that differences in growth, tolerance to drought as well as to extreme frost events exist for *C. libani*, a tree species with a large and very disjunct natural distribution (see also Ladjal et al. 2007; Ducrey et al. 2008; Bariteau and Vauthier 2007; Huber and Storz 2014). As early as 1939, Schenck advocated test with provenances from the Taurus Mountains and recommended against provenances from Lebanon. Indeed, recent studies revealed that provenances of Turkey showed a higher drought tolerance, a 20-day-later sprout and thus lower susceptibility to late-frost events than those provenances of Lebanon (Huber and Storz 2014; Ducrey et al. 2008). Tests with *C. libani* seeds from the Lebanon Mountains confirmed their limited frost tolerance (Aas, personal observation). Further experimental plantations should be established to test the performance of various provenances of Lebanon cedar under different and changing climatic and edaphic conditions.

Silvicultural behavior and suitability in forestry

According to information from their natural range (Senitza 1989) and from findings in our study, Lebanon cedar is a light (to semi-light)-demanding species. It has a juvenile phase of early and fast growth comparable to *Larix decidua*. The high demand for light might be a limitation for its successful establishment in mixed forests in Central Europe since it possesses a low competitive power compared with shade-tolerant species such as *Abies alba* and *Fagus sylvatica*. With regard to the current trend in Central Europe to establish sustainable and robust forests mainly by converting conifer forests into mixed broad-leaved woodlands (Zerbe 2002), *C. libani* presumably plays an inferior role. Thus, valuable natural, and protected woodlands, e.g., Natura 2000 sites or national parks, should be excluded from any plantations with *C. libani*, in order to reduce the risks of negative effects on the native flora and fauna (see, e.g., Richardson 1998; Engelmark et al. 2001; Peterken 2001; Mueller and Hellmann 2008; Reif et al. 2011; Felton et al. 2013; Richardson et al. 2014).

But the outstanding properties of *C. libani* to tolerate drought as well as frost events could make this exotic tree species very promising for facing current and future climate conditions in Central Europe. Even under matching climate and soil properties, the current cultivation of the exotic conifer species such as *C. libani* should be focusing on afforestations and on converting man-made conifer plantations, expected to be vulnerable to global warming (e.g., dominated by *Picea abies*: see, e.g., Kölling and Ammer 2006; Kölling et al. 2009; Milad et al. 2013). Furthermore, *C. libani* might be an attractive component of semi-natural mixed coniferous–deciduous forests with *Pinus nigra*, *Quercus petraea*, *Sorbus torminalis*, *Ulmus glabra* and *Acer platanoides* on moderate dry, base-rich soils in colline-submontane zones (e.g., in the South German Scarp lands). Such mixed stands with species of graduated drought tolerance closely resemble the tree species compositions of mesophilous subtypes of natural *C. libani* forests of the Taurus Mts. (Ayasligil 1987; Ayasligil and Duhme 1993) and possibly ensure risk spreading and resilience under climate change.

Moreover, tests at the Institute for Wood Research (Technical University, Munich) showed that the wood from the Lebanon cedars felled at Bayreuth is of a prime technological quality, in spite of the relatively wide tree rings (Risse 2013). The wood shows high technical strength and offers an alternative to the current commercially used conifers. Impressive is its durability class 1 (=very durable according to DIN EN 350-2:1994-10) which is comparable to Teak (*Tectona* sp.) and *Robinia pseudoacacia.* It clearly exceeds the durability of *Quercus* spec., *L. decidua* and *Pseudotsuga menziesii* (Risse 2013).

Biotic threats

Since the previous ice ages, *C. libani* is a neophyte (exotic species) in Central Europe (Senitza 1989). Consequently, its introduction into local forestry requires a critical check of all potential and collateral risks (see, e.g., Richardson 1998; Engelmark et al. 2001; Peterken 2001; Mueller and Hellmann 2008; Reif et al. 2011; Felton et al. 2013; Richardson et al. 2014). This pertains to all negative consequences for the local flora and fauna and the susceptibility of Lebanon cedar to biotic pests. Several primary and secondary pest agents have been reported from its natural distribution in the Western Taurus Mountains (Senitza 1989; Avci and Carus 2005; Carus and Avci 2005; Ayasligil 2008). The most important biotic threat to *C. libani* in natural stands are moths, e.g., the cedar leaf moth (*Acleris undulana*) whose larvae can infest young shoots causing significant growth depressions up to 3 years (Senitza 1989), the cedar processionary moth (*Traumatocampa ispartaensis*) which also causes defoliation (Avci and Carus 2005) and the pine processionary moth (*Thaumetopoea pitocampa*, Senitza 1989). In contrast, bark beetle species play a minor role in the natural range of *C. libani* mainly because of the hot and dry climate and the fact that trees are immediately debarked after logging (Senitza 1989). Furthermore, some fungal species may be important to consider. Experiments of Lehtijärvi et al. (2011) on 5-year-old seedlings demonstrated that *C. libani* is highly susceptible to Turkish *Heterobasidion* isolates. Their investigation also include the species *Heterobasidion annosum* which is a very common fungus in Central Europe (Lehtijärvi et al. 2011) and might therefore infest *C. libani* when cultivated in Central Europe.

It is still unresolved whether these pests might pose a danger to *C. libani* in Central Europe and whether such pests might change its host from cedar to other tree species, e.g., *Larix decidua*. Recently, the first biotic non-lethal damage noticed on single *C. libani* individuals at the Bayreuth site was infested by *Lophodermium cedrinum*, a fungus which leads to premature loss of needles, similar to the infestation on pine by *L. seditiosum* (Brand and Butin 2015).

Invasion potential

The potential for ecosystem invasion, especially for conifers, is a hot topic in the current discussion about the introduction of exotic species into European forest systems (see also Richardson 1998; Richardson and Rejmánek 2004; Essl et al. 2010). No information is available about the natural regeneration and spreading in Central Europe. In Bayreuth, the trees began seed production at age 25. Since then, well-germinating seeds are produced almost every year. Occasional natural regeneration from seeds was observed after 2012, mainly next to adult trees. Further studies are needed to clarify whether and over which distances seeds of *C. libani* may travel by anemochorous or zoochorous vectors and what conditions are required for successful germination. Exotic trees may set seeds and regenerate naturally, but they do not always threat native woodland types, e.g., the widely planted *L. decidua* in Britain (Peterken 2001). *C. libani* appears to be an almost non-competitive tree species in Central European forests with a neglectable invasive potential in closed forests.

We consequently consider the Lebanon cedar as a tree species which should be further intensively tested for forestry to fully explore its potential (e.g., "KLIP 18" project where a network of experimental forest plantations in Germany, Austria and Switzerland was initiated, Bayerische Landesanstalt für Wald und Forstwirtschaft, Bavaria, Germany, Schmiedinger et al. 2009), especially if local tree species will no longer be able to form stable and productive forest stands in Central Europe under a changing climate.

Conclusions

The exotic species *C. libani* shows good growth in Bayreuth, Germany, if sufficient canopy space is provided during tree development. The Central European humid climate during summertime apparently favors growth. Beyond, *C. libani* tolerates drought as well as extremely low temperatures during winter. Hence, it appears to be a forest species which is well adapted to current and future climate conditions in Central Europe. With respect to climate change, this exotic species has a high economic and ecologic potential in forestry, and its cultivation and economic potential should be further explored and tested in silvicultural plantations.

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