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GROWTH, QUALITY AND REGENERATION OF SESSILE OAK (*QUERCUS PETRAEA* (MATT.) LIEBL.) IN COPPICE WITH STANDARDS IN FRANCONIA, GERMANY

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Abstract

Coppice with standards (CWS) has recently regained importance in forestry. This is due to increased demand for firewood, the high ecological value of CWS, its potential to produce highly valuable timber from oak and Noble Hardwoods and its potential to adapt forests to climate change. In silvicultural investigations of CWS in Franconia/Bavaria which began in 2007, three treatments were carried out in oak-dominated (*Quercus petraea* (Matt.) Liebl.) forests on two different sites. Local coppicing systems varied as to the amount of basal area maintained, canopy cover and volume hectare. Investigations of the maidens showed that pruning to a height of 6 m in 2007 failed to improve stem quality. Due to epicormic shoots, the pruned maidens had significantly shorter branch-free bole lengths five years after pruning. The level of regeneration was high (up to 220.000 plants·ha^{-1}), with a large oak component (up to 95 %). Generative regeneration dominated, with coppice shoots comprising a small share of the total of young plants (<23 %). Although oak dominated in numbers, shade-tolerant species like beech (*Fagus sylvatica* L.) gained more height. Thus, oak is expected to play a minor role in the next stand generation and mixture regulation is needed if oak is favored. The mean height of regeneration decreased with increasing canopy cover. Furthermore, the larger the diameter of the coppiced oak stump, the more coppice shoots were produced. These results can be used to modernize and adapt management options for CWS in times of climate change, and also can give some hints for the heavy crown thinnings that have become common today in the management of broadleaf, and particularly, of oak stands with elite trees.

Key words: climate change, maidens, pruning, sprouting, timber quality.

Introduction

Coppicing – with or without standards – used to be a common silvicultural technique practiced throughout Europe (Ellenberg 1978, Hausrath 1982, Bärnthol 2003) and dates back to 13th – 14th century (Burschel and Huss 2003, Hausrath 1982). Decreasing demand for firewood virtually ended this silvicultural system in Germany up to 200 years ago, and most former coppices have been converted into high forests for the production of larger amounts of stem wood (Cotta 1828, Hartig 1861, Hausrath 1982, Vollmuth 2021). Hence, the importance and share of total forest area has decreased dramatically for this management system not only in Germany. Today, this silvicultural technique is very rare, and only of local importance in small areas of Germany – most notably in Bavaria and Rhineland-Palatine (BMVEL 2004, Albrecht and Müller 2008, Vollmuth 2021). In contrast, other European countries such as France, still have a lot of coppiced area (Fischer 2003, Ruch 2017). The substitution of coal and petroleum for firewood (Bärnthol 2003, Burschel and Huss 2003, Geb at al. 2004) and the often unsatisfying yield and quality of logs from coppices (Mayer 1977, Freist 1985, Hochbichler 2008, Beinhofer and Knoke 2009) are the main reasons this silvicultural technique has been abandoned across large areas. Currently, however, coppice with standards (CWS hereafter) is again becoming of interest to forest practitioners. CWS provides firewood, for which demand has again increased (Grütz 1986, Bally 1999, Hochbichler 2008, Short and Hawe 2012). Due to the high ecological habitat quality that is provided by CWS (Brand 1997; Bolz 1999; Coch and Müller-Bauerfeind 2002; Treiber 2002, 2003; Müller-Kroehling 2007; Albrecht and Müller 2008; Short and Hawe 2012, Vollmuth 2021) nature protection programs focus on this type of forest, and state subsidies are available to support reactivation of CWS (Freist and Klüssendorf 1991, Schulte et al. 2004, Mosandl et al. 2010). The chance to input new climate-adapted tree species by every coppicing-cycle – thus much more often than in a common forest rotation period – is a further advantage of CWS in times of climate change.

Coppice with standards

A CWS is a mixture of a coppice and a high forest on the same area (Hartig 1861), where a combination of vegetative and generative regeneration form a two layer forest (Krissl and Müller 1989). The vegetative component of regeneration takes place in the regularly coppiced understory that re-sprouts from stumps, and the generative regeneration component forms the overstory, mostly dominated by oak (Groß and Konold 2010) and admixed Noble Hardwoods. The best-formed trunks resulting from this generative regeneration are chosen before coppicing is carried out on the remaining stand and are maintained as so-called maidens. Timbal and Aussenac (1996) reported that *Quercus robur* L. is favored over *Q. petraea* (Matt.) Liebl. for CWS. However, Vlad (1940) pointed out that the choice of appropriate species in CWS is dependent on site conditions, with *Q. robur* being better suited to floodplain sites, and *Q. petraea* to dryer regions. Due to the existence of hybrids of the two species, the right provenance may be of more importance, however, than the species (Aas 1991, Steinhoff 1993, Neophytou et al. 2010). A CWS stand has no homogeneous age like a high forest because of its perpetuating nature, and thus is more similar to an uneven-aged forest

(Duchiron 2000, Schütz 2001, Kerr 2002). Each tree falls into an age class characterized by the number of coppice-cuttings it has undergone. Normally, six coppicing cycles are thought to be optimal, with a single rotation lasting about 30 years (Cotta 1828, Hartig 1861, Heyer 1893, Hamm 1896). Therefore, 6×30 years corresponds to a rotation time that is quite common for oak silviculture in Germany (Krahl-Urban 1959, Fleder 1981, Mosandl and Paulus 2002). The number of trees per ha in each age class is quite strictly regulated in theory – according to the old references, which date back prior to 1900 (Cotta 1828, Hartig 1861, Heyer 1893, Hamm 1896) – and approximates the distribution similar to an uneven aged forest (Mayer 1977, Schütz 2001; Hochbichler 2008). With reference to volume per ha or canopy cover percentage, CWS are typically classified as rich, normal or poor in yield (Hamm 1896, 1900; Vanselow 1941; Schaeffer and Schaeffer 1951; Köstler 1955; Mayer 1977; Grütz 1986, Hochbichler 2008). It is important to note that CWS is a form of land-use that influences and changes natural vegetation cover intensely (Pott 1981). Oaks and admixed species of Noble Hardwoods were fostered for centuries at the expense of naturally dominating beech due to their timber value and masting quality for livestock (Fischer 2003, Küster 2008). Hence, CWS is a very artificial vegetation cover while at the same time, it is considered very valuable for biodiversity, firewood production and maintenance of rare species.

Although a lot of traditional and descriptive information is available, however, current and data-based information and knowledge on CWS is limited (e.g. Utinek 2004, Hochbichler 2008, Pyttel 2012). Therefore, this study aimed to investigate whether the CWS stands studied were similar to theoretical considerations in terms of structure and species composition. So these parameters as well as the increment were assessed.

Furthermore, pruned oaks were investigated to find out whether the quality of timber could be improved by this treatment. Additionally, the regeneration was studied to clarify whether oak dominance can be maintained for the future by practicing current management techniques.

Material and Methods

Study area and experimental design

The investigation took place in one of the last remaining Bavarian CWS, situated in the Steigerwald area – a hilly region in the middle of Germany located between Nuremberg and Wuerzburg in Franconia. Two forests were chosen near the localities of Weigenheim (hereafter referred to as W, 49°34´29" N, 10°15´47" E) and Iphofen (hereafter referred to as I, 49°40´16" N, 10°19´19" E). The elevation of the forests ranges between 270 and 493 m in altitude. The climatic conditions can be described as viticultural; with an average temperature of about 8.5 °C, about 700 mm precipitation per year with a maximum in summer, and a growing period of 170 days. The woodland near W is located on a moderately dry site with a flat exposition and brown soil formed by clay and loam, which is quite poor in nutrients. The mixed hardwood forest on this site is dominated by sessile oak (*Quercus petraea*) and other associated species, such as pedunculate oak (*Quercus robur*), European beech (*Fagus sylvatica*), hornbeam (*Carpinus betulus* L.), wild service tree (*Sorbus torminalis* (L.) Crantz), birch (*Betula* sp. L.), aspen (*Populus tremula*

L.), European wild pear (*Pyrus pyraster* (L.) Burgsd.) and small-leaved lime (*Tilia cordata* Mill.). The second forest focused on in this study is located on a south-facing slope near I. It is also dominated by sessile oak, in association with pedunculate oak, hornbeam, beech, lime and true service tree (*Sorbus domestica* L.). The soil on this site is also classified as a brown soil on quite dry sand beds, but the soil fertility is slightly higher than in the previously described site. The tree species that occurred in the regeneration of the forests on both sites were next to the mentioned ones out of the overstory European ash (*Fraxinus excelsior* L.), field maple (*Acer campestre* L.), sycamore maple (*Acer pseudoplatanus* L.), wild cherry (*Prunus avium* L.), mountain ash (*Sorbus aucuparia* L.), crab apple (*Malus sylvestris* (L.) Mill.), blackthorn (*Prunus spinosa* L.), hawthorn (*Crataegus laevigata* L.), goat willow (*Salix caprea* L.), hazel (*Coryllus avellana* L.), elder (*Sambucus nigra* L.), privet (*Ligustrum vulgare* L.) and rose (*Rosa canina* L.).

The experiment was established in 2007. Three different treatments were carried out in the CWS:

a) Treatment ‘control’ (C): In these plots, no coppicing was to be carried out in the future and the stands were to be transformed passively into high forest since the 1960s.

b) Treatment ‘traditional’ (T): In these plots, coppicing is carried out by locally common practice.

c) Treatment ‘modified’ (M): These plots were coppiced in 2007 following the recommendations given by Cotta (1828), Hartig (1861), Heyer (1893) and Hamm (1896) to realize a true CWS structure. To improve timber quality, all oak maidens (trees up to 20 cm DBH in the second coppicing cycle) were pruned of all branches below a height of 6 m in 2007, and again of all braches below 5 m in 2013.

For easier data collection and analysis, a coding system has been used, where the letter codes for each of the two sites – W and I – are combined with the first letter of each of the treatments (e.g. IM means Iphofen treatment ‘modified’, WC means Weigenheim treatment ‘control’) – thus distinguishing among the 6 variants forming the experiment. There were two replications of each treatment per site. Therefore, on each site, 6 randomly arranged experimental stands were used (3 treatments × 2 replications) and thus, in total, 12 stands formed the experiment (6 stands per site × 2 sites). Each of the experimental stands had an area of 0.25 ha, for a total of 3 ha in the entire area investigated. In each plot, a 24 m × 24 m raster was applied to identify 49 inventory points at a distance of 3 m from one another. Each point served as the center of a 1 m^2 circle where the data was collected for regeneration assessment. In the managed stands in W, the last coppicing took place in 2006/07, while in the control stands on this site conversion to high forest (abandonment of the use of coppicing) had begun in the 1960s. In the managed stands in I, the last coppicing took place in 2003/04 while the transformation into high forest had also begun in the 1960s. Due to very intense coppice cutting in W, additional maidens had to be chosen outside of the plots in the WT stands in order to gather adequate sample size. Further information about the experimental design can be found in Summa and Mosandl (2009) and Mosandl et al. (2010).

Data collection

Data was collected in the summer of 2011 and the spring of 2013. In 2011, a complete inventory of each stand (including but not limited to the area within the 1 m^2 circles described above) was carried out. For every tree in each stand with a DBH larger than 7 cm, the species and DBH were recorded. The height of each of these trees was measured using a Vertex IV by Haglöf®. Also in each stand, 8 crown radii – one in each of the main cardinal directions – were estimated for each of 15 oaks ranging in size across the spectrum of DBH, which were randomly chosen. Hence, 12 stands × 15 oaks = 180 oak crowns were measured by visual estimation (Preuhsler 1979). For every maiden present, the number of epicormic branches was recorded using a 3-point scale, where 1 = less than 5 branches, 2 = from 6 to 20 and 3 = more than 20. Next, an inventory of regeneration was carried out in the 1 m^2 circles, where each tree species found was recorded, and the number of individuals and their origin (seedling or coppice shoot) was noted. The height of the tallest individual of each tree species was also recorded. The diameter of any stumps of which more than 50 % was located inside the circles were assessed and recorded. Furthermore, the data reported by Summa and Mosandl (2009) and Mosandl et al. (2010) was used to determine the amount of development and change in the stands since the beginning of the experiment. In the spring of 2013, the maidens in the 'modified' treatment were re-pruned up to a height of 5m on both the W and I sites. Due to maidens which had been lost in WT in 2011 because of worn markings, new ones were chosen outside the experimental stands and newly measured in 2013. Bias of the results was not expected from this measure, because the entire forest was coppiced in the same way throughout the experiment. The newly chosen trees were included in the analysis of branch-free bole length in maidens, but not in any other analysis. Data analysis was done using the Statistic Package for Social Science 19 (IBM SPSS Statistics 2011) for all analysis consisting of linear regression models, independent one-way ANOVA and non-parametric tests when the assumption of normality or homogeneity of variance was not met. The normality of residuals was checked visually (Field 2009, Backhaus et al. 2011).

Calculation of further parameters

Using the raw data from 2011 and 2013, the following specific parameters were derived to be used in the analysis. Basal area (*BA*) was computed for each tree and then summed to the stand level ($BA = \frac{DBH^2}{4\pi}$). Afterwards, this *BA* value was extrapolated to ha-unit. For each stand, a height curve was estimated using a linear regression model (height [m] = b_0 + b_1 · ln DBH [cm]). All trees were included in this regression, regardless of species. To reach linearity, DBH was log-transformed (ln). To describe the stands, d_g and h_g were derived ($d_g = \sqrt{\frac{\sum n_i \cdot d_i^2}{N}}$). The stand height curves were used to estimate h_g by using d_g. The volume of the stands was determined using form-height-curves ($V = HF = \frac{DBH^2 \cdot \pi}{40000}$) reported by Kennel (1973). In doing so, the measured DBHs and the heights derived from the linear regression model were used. The coefficients for *HF* used were those reported by Kennel (1973). A linear regression model was calculated to link DBH and crown projection area (*CPA*). *CPA* for each single tree was computed following the suggestions of Kramer and Dong (1985) ($CPA = \sum_{n=1}^{8} \frac{1}{8} \cdot \pi \cdot \text{crown radius}_n^2$). Afterwards, the single values of CPA were summed and then extrapolated to ha unit. Slenderness (*SL*) was also derived for each individual tree ($SL = \frac{h}{DBH}$) in order to check for a possible relationship between *SL* and the number of epicormic branches. For the parameters of the regression models see Appendix 1 to 4.

Results

Main stand

The number of trees that formed the main stand (those with a DBH > 7 cm) ranged between 80 and 419 ha^{-1} among the variants (Table 1). The number of trees per ha was largest in variants WC (419) and IT (258), followed by IC (210). This can be attributed to the number of stems maintained in a forest where the traditional coppice concept used in I is practiced. Similarly, the basal area showed differences between treatments (Fig. 1). Coppiced stands in W had a basal area of 6.7 to 7.2 m^2·ha^{-1}, while the real correspondent stand IM showed a basal area of 10.1 m^2·ha^{-1} in 2011. In the stand IT, *BA* of 18.1 m^2·ha^{-1} was detected. A similar amount – 19.3 m^2·ha^{-1} was found in both IC and WC h in 2011. Thus, the traditionally coppiced variant in I showed rather the same basal area as the control stands in I and also resulted in a larger total basal area than in W. The absolute increment in basal area from 2007 to 2011 was different between control and coppiced stands. In WC the *BA* increment was as high as 4 m^2·ha^{-1} as compared to 3 m^2·ha^{-1} in IC, whereas the *BA* in the coppiced stands increased in this time only between 0.5 m^2·ha^{-1} in WT and 2.5 m^2·ha^{-1} in IM. Table 2 lists the d_g and h_g of the experimental stands. It was observed that the d_g

Table 1. Number of trees per ha by species and variant in 2011.

Tree species	WC	WT	WM	IC	IT	IM
Oak (*Quercus* sp.)	321	60	102	140	190	140
European beech (*Fagus sylvatica*)	0	2	2	44	22	0
Birch (*Betula* sp.)	0	4	0	4	8	2
Aspen (*Populus tremula*)	4	2	0	0	0	0
Small-leaved lime (*Tilia cordata*)	23	0	0	12	28	28
Wild service tee (*Sorbus torminalis*)	21	8	0	8	8	6
True service tree (*Sorbus domestica*)	0	0	0	2	2	4
Ash (*Fraxinus excelsior*)	2	0	0	0	0	0
Field maple (*Acer campestre*)	2	2	2	0	0	4
Hornbeam (*Carpinus betulus*)	44	0	0	0	0	2
European wild pear (*Pyrus pyraster*)	2	2	2	0	0	0
Σ	419	80	108	210	258	186

Note: the abbreviations in the tables 1–7, figures 1, 2 and 6, and Appendixes 1 and 2 have the following meanings: WC – Weigenheim treatment ‘control’, WT – Weigenheim treatment ‘traditional’ WM – Weigenheim treatment ‘modified’, IC – Iphofen treatment ‘control’, IT – Iphofen treatment ‘traditional’, IM – Iphofen treatment ‘modified’.

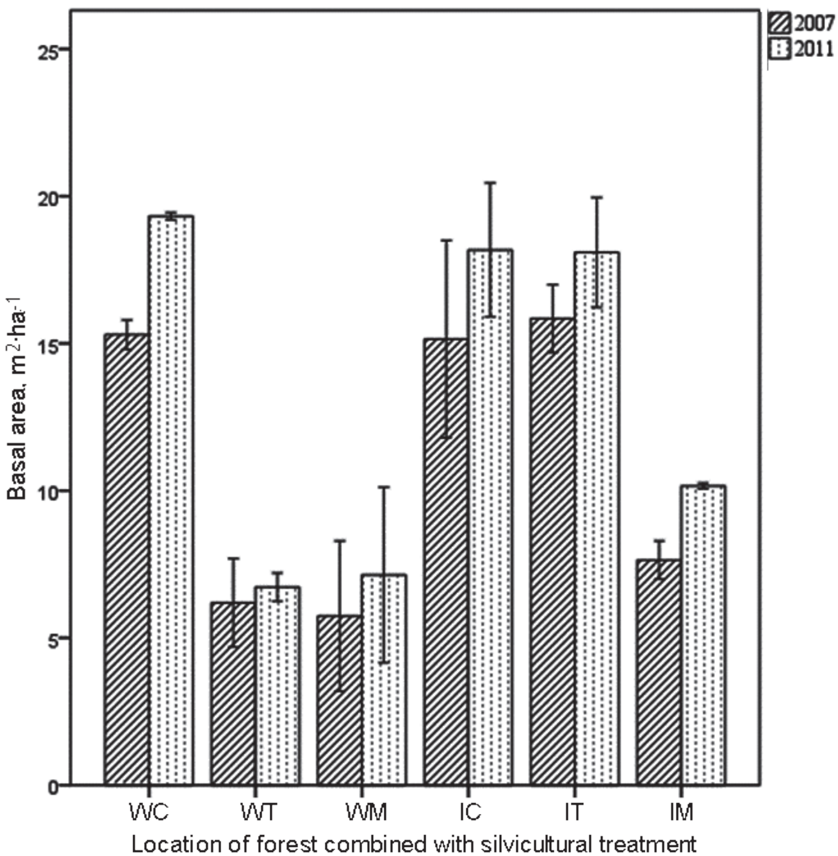

Fig. 1. Basal area of experimental CWS stands in 2007 and 2011.
Note: Error bars shown are standard errors.

Table 2. Basal center trunk diameter (d_g) and height (h_g) in stands and treatments in 2007 and 2011 and increment (Δ) relative to the year 2007.

Indicators and years		WC	WT	WM	IC	IT	IM
	2007	21.6	31.5	23,9	31.1	28.7	28.3
d_g, cm	2011	24.5	32.6	28.1	33.7	29.5	27.8
	Δ, %	13.4	3.5	17.5	8.3	2.8	-1.8
	2007	16.6	16.5	15.2	19.1	18,3	18.6
h_g, m	2011	17.9	17.3	15.8	20.2	18.5	17.9
	Δ, %	7.8	4.8	3.9	5.7	1.1	-3.8

values did not differ significantly between treatments (Kruskal-Wallis $H(2) = 1.4$; $p > 0.05$) just as h_g did (Kruskal-Wallis $H(2) = 2.1$; $p > 0.05$). Therefore, height-growth was not shown to be affected by the silvicultural management carried out. Height curves were determined for each treatment on every site. So, six height curves were computed using linear regression models. The results of these regressions are reported in Appendix 1. Differences in the volumes detected in the stands were evident between I and W. In I, the volumes were generally higher than in W – both in control stands and in coppiced stands (Table 3). However, the increment

Table 3. Volume in stands and treatments in 2007 and 2011 and increment (Δ) relative to the year 2007.

Indicators and years		WC	WT	WM	IC	IT	IM
Volume, $m^3 \cdot ha^{-1}$	2007	133.7	58.3	49.5	170.9	164.7	80.1
	2011	185.1	66.6	66.5	214.9	197.2	106.9
	Δ, %	38.4	14.2	34.3	25.7	19.7	33.5
Ø increment, m^3 per year		10.3	1.7	3.4	8.8	6.5	5.4

in trees bigger than DBH 7 cm in WC was 10.3 m^3 per year, and therefore, even higher than that found in IC – 8.8 m^3 per year in the control stands. However, merely 16 % (1.7 $m^3 \cdot ha^{-1} \cdot yr^{-1}$) of the increment compared to WC as a potential maximum was detected for the overstory in WT. In the IM stands the share was 61 % (5.4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$) of the potential showed by IC. Burschel and Huss (2003) and Hochbichler (2008) described that the increment of a CWS is not different to a high forest. Therefore, the missing proportion of the increment that was detected in the CWS plots (up to 84 %) is supposed to be accumulated in the regeneration fraction – anyway, it was not assessed in this study.

The canopy cover of the stands was derived using linear regression models. Six models were computed to link DBH to the corresponding crown projection area. They are reported in Appendix 2. Coppiced stands showed distinctly lower canopy cover percentages than those that had already been converted to high forests (Fig. 2). Again, IT with a canopy cover of about 70 % showed more similarity to a high forest than to a CWS. In W, the coppiced stands showed the lowest canopy cover percentage – about 30 %.

In general, the allometric relationship between the DBH and the crown projection area that is generally known in forest science was shown to fit also for CWS by the study at hand.

Maidens

The DBH of oak maidens in the different stands in 2011 and 2013 is listed in Table 4. In total, 244 maidens (all of them oaks) were measured. The DBH of the maidens ranged between a maximum of 24.8 cm and a minimum of 5.7 cm. The smallest tree was recorded in W although its DBH was less than 7 cm because it was the fastest growing individual in the surrounding area, and there was a lack of maidens in W. The mean DBH of all maidens was 17.3 cm. Figure 3 shows the DBH increment of the maidens since 2007. In WT only 2 trees formed the mean and therefore results should be interpreted with caution. Nevertheless, maidens generally showed the potential to form year-rings of more than 5 mm. No treatment showed less growth than 2.5 mm between measurements. In I the increment was generally lower than in W, with the exception of variant IM. Pruned trees showed no difference in DBH growth performance between 2007 to 2011 than unpruned ones in W (Kruskal-Wallis $H(2) = 2.5$; $p > 0.05$). However, in I there was a

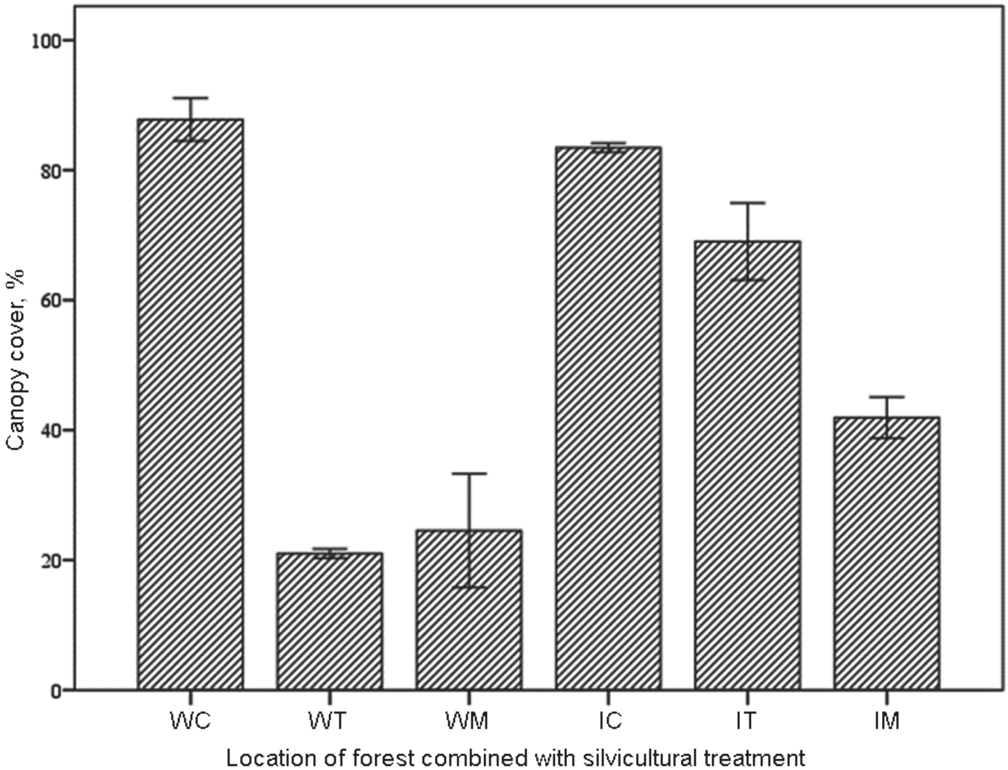

Fig. 2. Canopy cover of the experimental CWS stands in 2011.
Note: Error bars shown are standard errors.

Table 4. DBH of maidens in 2011 respectively 2013.

Stands in silvicultural technique	*N*	Ø DBH, cm	min DBH, cm	max DBH, cm	SD
WC	94	19.5	7.0	24.3	3.66
WT	20	16.6	5.7	24.0	4.21
WM	23	14.4	8.8	19.5	3.18
IC	24	15.3	8.0	23.5	4.82
IT	45	15.9	7.3	24.8	4.91
IM	38	15.7	7.3	24.8	5.36
Over all	244	17.3	5.7	24.8	4.80

Note: Abbreviations code *N* in quantity, Ø as average, and SD as standard deviation of data analyzed.

significant difference in DBH increment between treatments (Kruskal-Wallis $H(2) = 21.8$; $p < 0.000$), with the pruned trees which were promoted by the additional coppicing in 2007 showing better growth than the un-pruned ones. Table 5 lists the

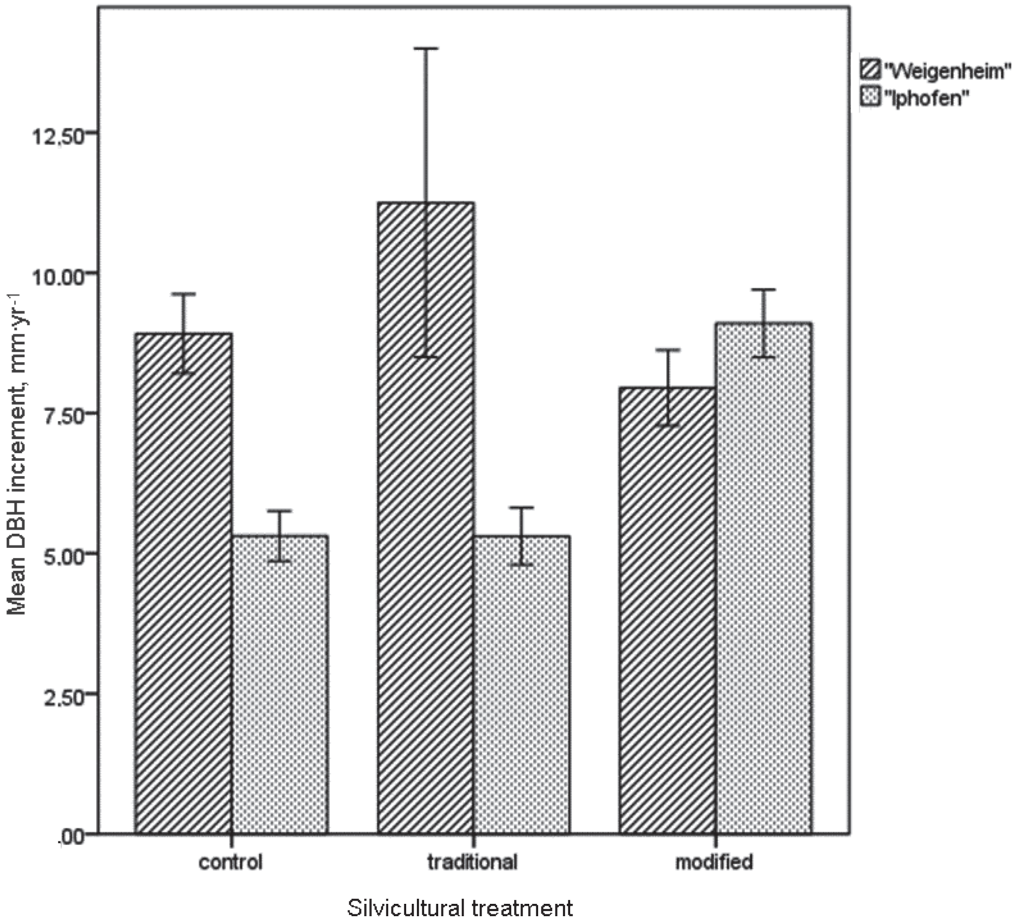

Fig. 3. Mean increment of maidens in DBH per annum and treatment on the two sites.
Note: Error bars shown are standard errors.

branch-free bole length of the trunks – one of the most important quality criteria in timber assessment. The data displayed was gathered during the inventories conducted in 2011 and 2013. The mean branch-free bole length over all maidens was 3.1 m. While some trees reached more than 12 m of branch-free bole length, others had epicormic branches beginning right at the butt end. The branch-free bole length was not always greatest in the control stands. Figure 4 shows the branch-free bole length of the maidens in the treatment 'modified' on the two sites before and after pruning in 2007 and 2013. Again, during the pruning in 2007, all branches were removed up to a height of 6 m: However, when the branch-free bole length was re-measured prior to pruning in 2013, it had decreased significantly in W (Mann-Whitney U = 72.5; p < 0.000; r = -0.57) as well as in I (Mann-Whitney U = 42; p < 0.000; r = -0.73). Therefore, the maidens were re-pruned in 2013. To reduce re-growth of epicormic branches pruning was done only up to 5 m. In total,

Table 5. Branch-free bole length of maidens in 2011 and before second pruning in 2013.

Stands in silvicultural technique	*N*	Ø, m	min, m	max, m	SD
WC	94	3.7	1.0	10.9	1.93
WT	20	1.7	0.9	7.4	1.34
WM	23	3.2	0.8	7.6	2.31
IC	24	1.9	0.5	4.4	.98
IT	45	3.1	0.5	12.0	2.53
IM	38	2.4	0.1	7.2	1.84
Over all	244	3.1	0.1	12.0	2.7

Note: Abbreviations code *N* in quantity, Ø as average, and SD as standard deviation of data analyzed.

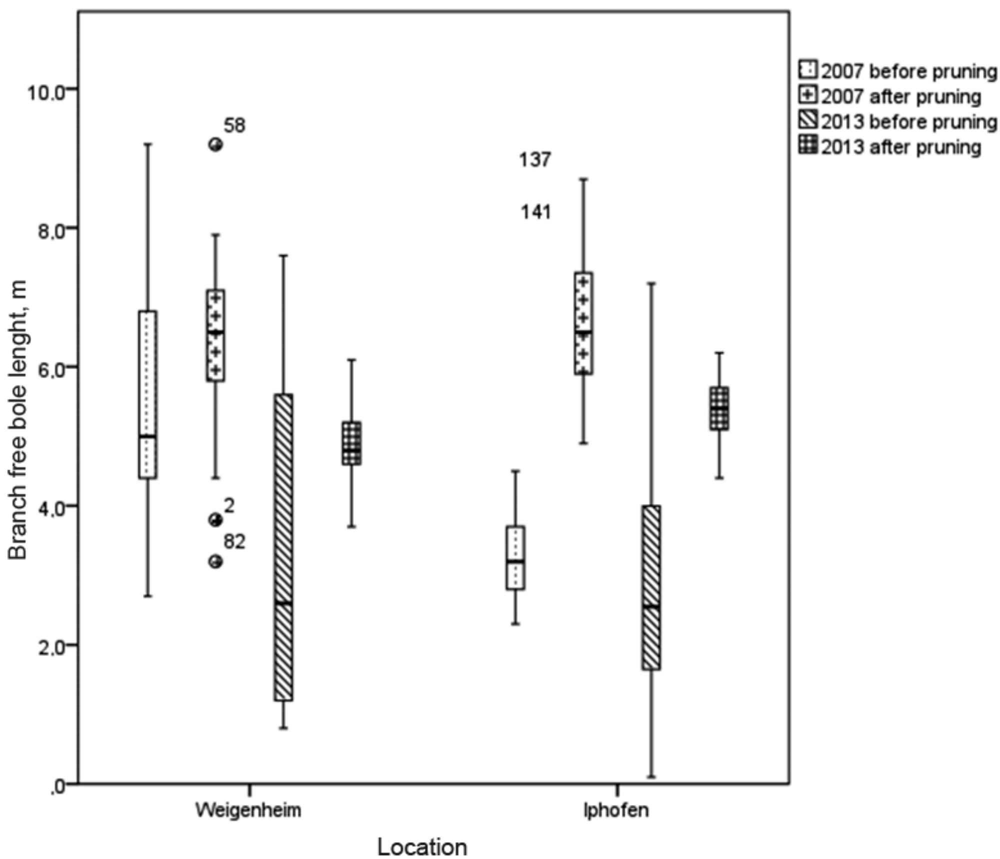

Fig. 4. Branch-free bole length of maidens before and after pruning in 2007 and 2013 in treatment 'modified'.

Note: Error bars shown are standard errors.

61 maidens were re-pruned in 2013, 1570 epicormic branches were cut for with an average per tree of 26.6 branches (as min 1 and as max 74) with a maximum basis diameter of 52 mm. Slenderness values are given in Table 6. Slenderness had no influence on the number of epicormic branches, as proven by an independent one-way ANOVA with F (2.250) = 0.23; $p > 0.05$.

Table 6. Slenderness *h*/*d* of maidens in 2011 and before second pruning in 2013.

Stands in silvicultural technique	*N*	Ø *h*/*d*	min *h*/*d*	max *h*/*d*	SD
WC	94	154	103	278	27.51
WT	20	218	162	284	36.55
WM	23	164	134	210	21.09
IC	24	153	111	251	29.64
IT	45	161	94	231	32.33
IM	38	177	114	351	48.20
Over all	244	164	94	351	36.97

Note: Abbreviations code *N* in quantity, Ø as average, and SD as standard deviation of data analyzed.

The need of pruning to receive branch-free bole lengths shows the need to manage maidens in CWS as natural processes do not lead to these desired stem qualities. Without silvicultural actions focusing on maidens the production of high-quality timber seems to be impossible or at least very uncertain.

Regeneration

Table 7 shows the number of all regeneration (DBH < 7 cm) next to separately shown oak regeneration in both 2007 and 2011. Regeneration was vigorous, with up to 220.000 plants per ha in WT in 2007. In total, 23 native tree and shrub species were detected among the new individuals identified in 2011. The number of young plants generally decreased after 2007 up to 35.6 %, except to the variant IC. Here, the regeneration was stable or even slightly higher between 2007 and 2011. Oak formed a large fraction of the number of new individuals ranging from 42 % in variant WM up to 95 % in variant IT. However, the number of new oak individuals decreased more than that of other species between 2007 and 2011. Furthermore, Figure 5 shows that the

Table 7. Number of regenerated plants per ha in stands and treatments in 2007 and 2011 and increment (Δ) relative to the year 2007.

Indicators and years		WC	WT	WM	IC	IT	IM
All plants, N·ha^{-1}	2007	127.143	220.205	123.673	112.040	163.469	90.204
	2011	81.837	158.163	122.551	116.836	133.572	75.408
	Δ, %	-35.6	-28.2	-0.9	4.3	-18.3	-16.4
Oak, N·ha^{-1}	2007	117.767	196.955	95.655	100.620	160.855	88.340
	2011	72.143	104.490	52.449	101.326	127.245	66.633
	Δ, %	-38.7	-46.9	-45.2	0.7	-20.9	-24.6

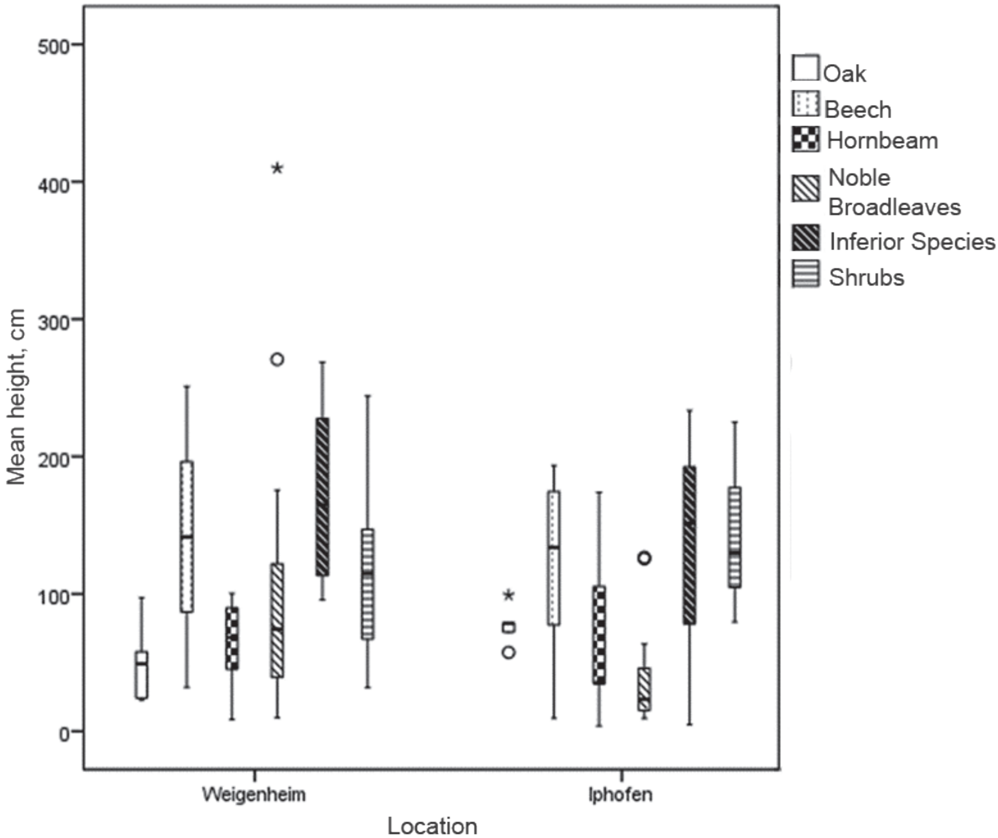

Fig. 5. Mean heights of different groups of regeneration in 2011.
Note: Error bars shown are standard errors.

mean height of the young oaks was less than that of the other species. Particularly individuals of shade-tolerant species such as beech and hornbeam gained more in height during this period, but also inferior species such as goat willow or aspen performed better than oak. Figure 6 shows the relationship between the mean height of all new individuals and the percent canopy cover. A linear regression model was computed to describe the relationship of decreasing mean with increasing canopy cover. The model is reported in Appendix 3. The largest amount of regeneration detected was of generative origin, with less than 23 % of the new stems found being coppice shoots. Hence, the vegetative regeneration was of minor importance to the total amount of regeneration. A positive relationship between stump diameter and the number of coppice shoots was detected in the experimental stands – the higher the mean diameter of the stump, the higher was the number of shoots. A linear regression model was computed using a ln transformation for the number of shoots. The model is reported in Appendix 4 and illustrated in Figure 7.

Thus, the cutting of older and bigger trees indicates a more intense sprouting

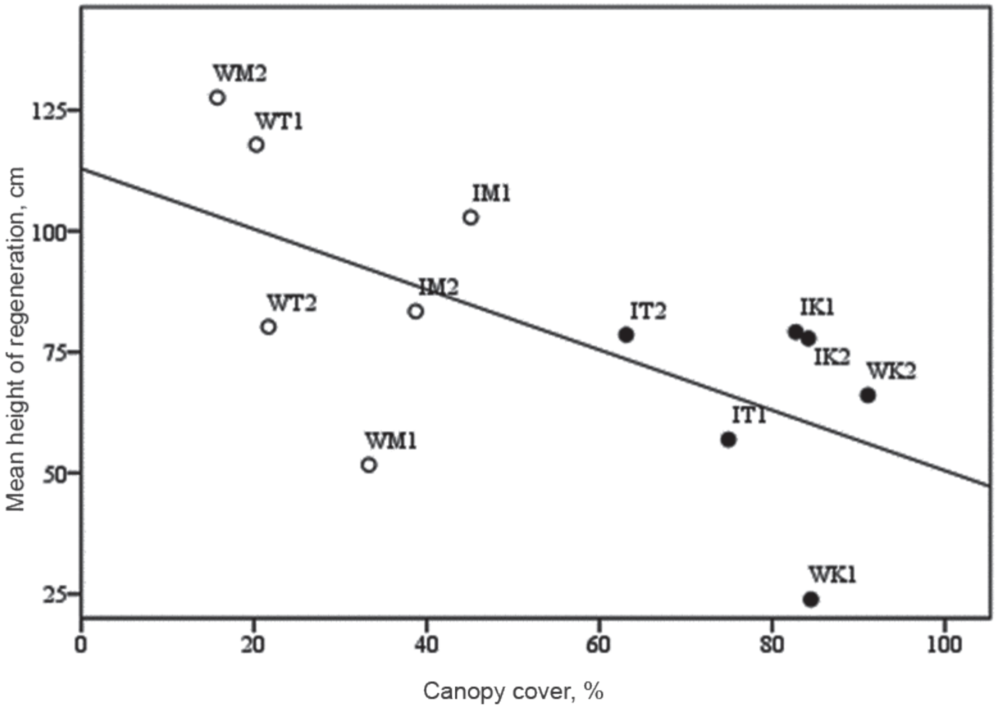

Fig. 6. Mean height of regeneration and canopy cover in 2011.

Note: Open circles represent CWS stands, filled circles symbolize high-forest-like stands with canopy cover higher than that of typical CWS.

effect than in younger trees. Combined with the finding that regeneration in CWS is depending on canopy cover hints are given to land managers how to control regeneration. The more generative regeneration is claimed, the more open the canopy layer and the less dimensioned harvested logs should be.

Discussion

Characteristics of the main stand in the CWS

CWS is a type of forest that incorporates a large number of both tree and shrub species (Grütz 1986, Decocq et al. 2004, Hochbichler 2008, Collet et al. 2008, Dodet et al. 2011). In this study, 23 species occurred in either the overstory or regeneration layer. Some of them (for example wild sevice tree and true service tree) are considered vulnerable in Germany (BLE 2013). This finding fits very well the nature of a classical CWS – where normally a lot of associated Noble Hardwoods occur more often than in high forest. On the W site, the CWS had a structure accordingly to theory (Cotta 1828; Hartig 1861; Heyer 1893; Hamm 1896, 1900) and also Czech, Austrian and German studies reported that such stands are still detectable today (Utinek 2004, Hochbichler 2008, Beinhofer et al. 2009). But in single stands in I the number of trees and the canopy cover was higher than is generally the case in a classical CWS. Refer-

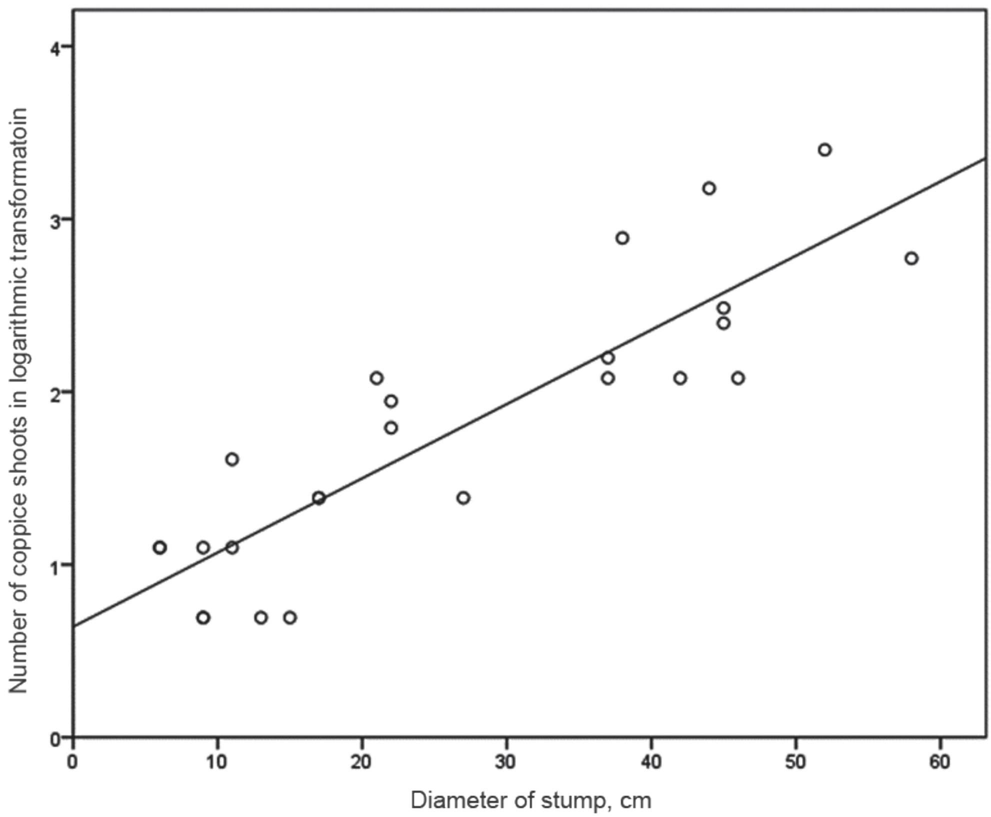

Fig. 7. Number of coppice shoots (transformed using ln-function) and stump diameter.

ring to the thresholds in literature (Hamm 1896, 1900; Vanselow 1941; Schaeffer and Schaeffer 1951; Köstler 1955; Mayer 1977; Grütz 1986) the coppiced stands in W can be defined as poor in terms of volume, whereas in I, the traditionally coppiced stands were normal or even rich in volume. A high volume can lead to a loss of CWS structure. This seems to be the general problem nowadays in CWS and not only in the stands in the current study (Hochbichler 2008, Beinhofer et al. 2009). Additionally, a large percentage of beech was found on the I site in the overstory – in the CWS up to 22 trees·ha^{-1}. Normally, beech is not considered to be a suitable or desired tree species in a classical CWS, and was therefore selected against through management techniques in the past (Fischer 2003, Küster 2008). The findings of different beech shares correspond to the management system that is carried out in the study area.

The control stands produced a volume increment of up to 10.3 m^3 per year. This is more than reported by Jüttner (1955) for first yield class for oak high forests. In coppiced stands, the increment of the main overstory stand was lower, of course, due to a smaller overstory component, although the total increment including all trees also being smaller than DBH 7 cm, is thought to be the same as in control plots (Burschel and Huss 2003, Hochbichler 2008). The reduced increment for the overstory found in this study was similar to the findings of Crockford and Savill (1991), Hochbichler (2008) and Beinhofer et al. (2009).

The correlation between increment and basal area per hectare showed also that the coppiced stands on site I were more similar to a high forest than to a classical CWS (Borchert and Reitenspieß 2009, Beinhofer et al. 2009, this study). Due to the high number of beech trees in the control stands, the process of transformation into a high forest and one that could be referred to as a 'close to nature forest' in terms of species can be said to have begun.

Characteristics of the maidens in the CWS

The DBH increment of maidens in this study was observed to be up to 1 cm per year. This is a quite high value compared to that generally found for oaks in high forests that have been thinned heavily to promote DBH growth. The literature reports results for oaks in the pole stage ranging from 2 mm to 4.5 mm under heavy thinning regimes (Mosandl et al. 1991, Spiecker 1991, Hochbichler 1993, Kerr 1996, El Kateb et al. 2006, Nagel 2007, Dong et al. 2007, Abt 2018). Results from the CWS showed comparable increments in DBH on the upper threshold of high forest oaks, ranging 2.5 mm to 3.5 mm (Krissl and Müller 1989, Beinhofer et al. 2009). Hein (2009) as well as Wilhelm and Rieger (2013) however, stated that oaks are able to grow even faster than in the study at hand, and to achieve up to 8 mm year-rings. Next to the diameter and the volume, the branch-free bole length is the main criteria in assessing the quality of oak logs (Schulz 1961, Lüpke 1998). One of the research questions addressed by this study was whether it is possible to improve the timber quality of maidens in a CWS stand by pruning. Pruning of oaks is common practice in many European countries in both CWS (Hamm 1900, Vlad 1940, Köstler 1955, Vollmuth 2021) and in high forests (Zieren 1970, Holten 1986, Hochbichler et al. 1990, Hochbichler 1993, Jensen and Skovsgaard 2009, Kerr 1996, Lemaire 2010, Attocchi 2013, Wilhelm and Rieger 2013). However, in this study pruning failed to produce better timber quality, due to the intense occurrence of epicormic branches afterwards. Every single tree formed epicormic shoots after pruning in 2007, and the branch-free bole length was actually reduced notably by the time the trees were re-measured in 2013 compared to the status right after pruning. Attocchi (2013) reports similar results for pedunculate oak in high forests – pruning led to an increase in the total production of epicormic shoots. Hubert and Courrad (2002) reported critical values for slenderness that were thought to foster the growth of epicormics – for *Q. petraea*, these were thought to be higher than 50, and for *Q. robur* higher than 45. This relationship was not found in this study, with epicormic branch occurrence showing no relationship with slenderness value. Attocchi (2013) and Zieren (1970) observed increased production of epicormic shoots after pruning in pedunculate oak. In contrast, Hochbichler et al. (1990) recommended pruning of oak up to 6 m, and reported only minor problems in the occurrence of epicormics. Kerr and Harmer (2001) reported that a pruning regime for oaks had no statistically significant effect on the production of new epicormic shoots. The production of epicormic shoots is thought to occur for several reasons, and as yet has not been completely assessed. Genetic aspects (Harmer 1990, Spiecker 1991, Savill and Kanowski 1993, Jensen 2000, Colin et al. 2010), site index (Muchin 2005), social status (Fabricius 1932, Rohmeder 1935), inadequate light conditions (Fabricius 1932, Harmer 1990), high slenderness values (Hubert and Courrad 2002) stand density (Ward 1966, Dale and Sonderman 1984, Miller 1996, Fontaine et al. 2001, Colin et al. 2008, Morisset et al. 2012), species (Jensen 2000) or temperature on the bole (Wignal and Browning 1988) are all reasons that have been given for the occurrence of epicormic branches. It is probable that a combination of these factors with certain anatomical aspects (Fontaine et al. 1998, Morisset et al. 2012) control the occurrence of epicormics. Nevertheless, in 2013 re-pruning was carried out up to 5 m, both in order to reduce the number of epicormic shoots for better timber quality and to assess the impacts of such re-pruning. Losses in DBH increment were not detected for pruned trees compared to ones that were not pruned. Thus, the loss of epicormic branches did not seem to affect the metabolism of the pruned oaks. In summary it can be stated that high quality timber, at least in terms of dimension can be produced in a CWS in a short time if the high increment in DBH can be maintained. Today, the veneer industry accepts oak with up to 4 mm year-rings (Lüpke 1998). This is in contrast to former times when the limit was from 1 mm to 2 mm (Fleder 1981, Polge 1984, Lüpke 1998). The oaks in this study showed larger year-rings as those reported by Lüpke (1998), but in the end it can be expected that the dimension of the logs will be the most important factor influencing price (Schulz 1955, 1961; Göttlein 1994; Diwold 2008), and that the width of year rings might be less important, as long as it is consistent throughout the log. If in the future, epicormic branching can be prevented by re-pruning, then production of large-dimension branch-free timber in a short time frame seems to be a realistic and achievable target, as described by Beinhofer (2010).

Characteristics of the regeneration in the CWS

The amount of regeneration observed in this study was quite large. Johnson (1977) pointed on the high silvicultural importance of generative advance regeneration in CWS generally – thus in times of climate change a most important factor to maintain forests. Hamm (1900) reported 100,000 young plants per ha as a maximum to be expected for a CWS. Pyttel (2012) refer to 56,000 young plants per ha after coppicing in a coppice of oaks in Rhineland-Palatine, Dworschak (1996) reported 15.000 plants·ha^{-1} 7 years after cutting, whereas the most commonly occurring trees were of inferior species (*Sorbus aucuparia, Betula* sp., *Populus* sp.) with low timber value. Tiefenbacher (1996) pointed out the importance of regeneration of Noble Hardwoods in CWS in times of oak decline. Such a decline has already been detected in recent times in the region where the experiment is located (Wolf and Petercord 2012). Brand (1997) reported that planted hornbeam was suppressed by Noble Hardwoods following coppicing in a CWS in Lower Saxony; he found about 20.000 young plants per ha after coppicing. In our study, more than 220.000 young plants per ha were found. Most of these young trees were of generative origin, and thus, the fraction of coppice shoots was never more than 23 %. Brand (1997) found a fraction of 40 % of coppice shoots in his investigation in Lower Saxony. Hochbichler (2008) reported a share of coppice shoots ranging from 8 % to more than 40 % in a CWS in Austria. Hence, the portion of coppice shoots in the study at hand (0.8–22.8 %) was quite low compared to that reported in the literature. For the further growth dynamic of the coppice shoots the distinction between adventitious and dormant (preventive) buds is of importance, but was not analyzed so far in the study at hand. A regression analysis showed that the number of coppice shoots was higher for oak stumps as the stump diameter increased (Albrecht and Abt 2014). This finding was opposite to findings from other studies on *Quercus alba* L. (Johnson 1977, Weigel and Peng 2002, Gould et al. 2007, Sands and Abrams 2009). Due to the fact that *Quercus alba*, *Q. petraea* and *Q. robur* are all closely related in the subgenus *Leucobalanus* (Nixon 1993, Schütt et al. 2002), a comparison in this subgenus seemed to be more valid than a comparison with other oak subgenera, sections and species, such as *Quercus rubra* L. Hartig (1861), Grütz (1986) and Müller (1986) all concluded that the older a European oak stump is, the lower the probability that it will re-sprout after coppicing. Indirectly, this could be linked to the diameter of the stump. In contrast, Pyttel (2012) reported for a CWS in Rhineland-Palatine that there was no correlation between the rate of sprouting of an oak stump and the corresponding DBH. The reasons for these divergent findings could be an objective of further investigations.

The fraction of oak was never less than 42 % and in some cases was up to 95 % of the regeneration. The combination of a high percentage of generative regeneration and a high share of oak can be seen as a very good start to the rejuvenation of the stands, as well as the maintenance of oak-dominated forests in the future. However, as oak was found here to have a mean height lower than the other species present, especially the shade-tolerant ones like beech and hornbeam, tending seems to be necessary in order to promote oak and avoid beech dominance in these stands in the future (Fleder 1981, 1988; Mosandl et al. 1991; Küster 2000; Collet et al. 2008). Pott (1981) and Fischer (2003) both pointed to the fact that a reduction in or abandonment of coppicing leads to the re-establishment of the naturally occurring beech-forest structures and a rising faction of beech in European forests. The height increment of regeneration was dependent on canopy cover of the stands, as proven by a regression analysis presented above. The greater the percentage of canopy cover was detected the lower the height increment of regeneration was observed. This phenomenon is well-known and caused by shading or less resource availability (Bolte and Roloff 1993; Ammer 1996, 2000, 2003; Gemmel et al. 1996; Collet et al. 1997, 2001; Finzi and Canham 2000; Löf 2000; Hees and Clerkx 2003), but was not reported for CWS before.

To conclude, it can be stated that if the fraction of oak should be maintained, in some cases the canopy should be opened more and in some cases tending will be unavoidable. This way mixed stands that consist of a lot of generatively regenerated individuals of a wide variety of species could be formed.

These mixed stands consisting of Noble Hardwoods and oak could clearly be an advantage in a future forest which is expected to be greatly affected by climate change.

Conclusions and Recommendations

CWS is a silvicultural system that has a high potential for fulfilling a broad spectrum of societal needs from forest in the future. In addition to meeting the public´s demands for both biodiversity protection and recreation, fuel wood as well highly valuable timber could be produced – and forests can be maintained despite challenges caused by climate change. In the end, one prerequisite for the production of high quality timber from CWS is the suppression of epicormic sprouts in maidens. It could be reasonable to change the classical coppicing system by maintaining secondary species (especially shrubs like blackthorn or hawthorn) in a small radius around maidens and other overstory trees to improve their quality by shading the trunks. Hence, the need for pruning could be reduced and the production of epicormic shoots could be hindered, or at least reduced following heavy crown thinnings. To do pruning merely is risky due to the tendency to result in an increase in epicormic shoots and cannot be recommended based on the results of this study. Heavy crown thinnings are common today in broadleaf forest management. This practice is thought to have been derived from and inspired by CWS practices (Wilhelm et al. 1999, Wilhelm and Rieger 2013), as these kinds of thinnings lead to structures in high forests that are very like those present in CWS. Therefore, the results found in this study can serve as a silvicultural feedback both, high forest and CWS.

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References

Aas G. 1991. Kreuzungsversuche mit Stiel- und Traubeneichen (*Quercus robu*r L. und *Q. petraea* (Matt.) Liebl.). Allgemeine Forst und Jagdzeitung 162(8): 141–145.

Abt A. 2018. Die Bewirtschaftung junger Traubeneichenbestände (Quercus petraea (Matt.) Liebl.) in Unterfranken unter Berücksichtigung von waldbaulichen, forstökonomischen und naturschutzfachlichen Gesichtspunkten. PhD thesis. Technische Universität München. 268 p.

Albrecht L., Müller J. 2008. Ökologische Leistung aktiver Mittelwälder. LWF aktuell 62: 36–38.

Albrecht L., Abt A. 2014. Die Bedeutung der Eiche im bäuerlichen Mittelwald. LWF Wissen 75: 41–47.

Ammer C. 1996. Konkurrenz um Licht. Zur Entwicklung der Naturverjüngung im Bergmischwald. Forstliche Forschungsberichte München 158. 198 p.

Ammer C. 2000. Untersuchungen zum Einfluss von Fichtenaltbeständen auf die Entwicklung junger Buchen. Shaker, 1st edition. 185 p.

Ammer C. 2003. Growth and biomass partitioning of *Fagus sylvatica* L. and *Quercus robur* L. seedlings in response to shading and small changes in the R/FR-ratio of radiation. Annals of Forest Science 60: 163–171. DOI: 10.1051/forest:2003009

Attocchi G. 2013. Effects of pruning and stand density on the production of new epicormic shoots in young stands of pedunculate oak (*Quercus robur* L.). Annals of Forest Science 70(7): 663–673. DOI: 10.1007/

s13595-013-0309-5

Backhaus K., Erichson B., Plinke W., Weiber R. 2011. Multivariate Analysemethoden. Springer, 13th edition. 583 p.

Bally B. 1999. Energieholzproduktion in Mittel- und Niederwäldern der Schweiz. Schweizerische Zeitschrift für Forstwesen 150(4): 142–147.

Bärnthol R. 2003. Nieder- und Mittelwald in Franken. Fränkisches Freilandmuseum. 152 p.

Beinhofer B., Hahn A., Englert J., Knoke T. 2009. Wie wachsen Mittelwaldeichen? AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 6: 299–301.

Beinhofer B., Knoke T. 2009. Zur Astung von Mittelwaldeichen. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 6: 302–303.

Beinhofer B. 2010. Comparing the financial performance of traditionally managed beech and oak stands with roomy established and pruned stands. European Journal of Forest Research 129: 175–187. DOI: 10.1007/s10342-009-0311-5

BLE (Bundesanstalt für Ernährung und Landwirtschaft) 2013. Erfassung und Dokumentation genetischer Ressourcen der Flaum-Eiche (*Quercus pubescens*), der Elsbeere (*Sorbus torminalis*) und des Speierlings (*Sorbus domestica*) in Deutschland. Untersuchungen zur Elsbeere. 109 p.

BMVEL (Bundesministerium für Verbraucherschutz, Ernährung und Landwirtschaft) 2004. Die zweite Bundeswaldinventur – BWI 2. Das wichtigste in Kürze. Jentzsch. 87 p.

Bolte A., Roloff A. 1993. Einfluß von Buchenüberhältern auf Bodenvegetation und Naturverjüngung. Allgemeine Forst und Jagdzeitung 164(6): 97–102.

Bolz R. 1999. Mittel- und Hudewälder als ein Leitbild für eine ‘natürliche‘ Waldform in Mitteleuropa. In: Gerken B., Görner M. (Eds) Natur- und Kulturlandschaft, 3rd volume: 198–207.

Borchert H., Reitenspiess B. 2009. Organisation der Mittelwaldbewirtschaftung. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge6: 304–306.

Brand W. 1997. Mittelwaldwirtschaft im niedersächsischen Forstamt Liebenburg. Forst und Holz 52(6): 144–148.

Burschel P., Huss J. 2003. Grundriss des Waldbaus. 3rd edition, Ulmer. 487 p.

Coch T., Müller-Bauerfeind M. 2002. Wiederaufnahme des Mittelwaldbetriebes im Opfinger Mooswald. Naturschutz und Landschaftsplanung 34(6): 165–170.

Colin F., Robert N., Druelle J., Fontaine F. 2008. Initial spacing has little influence on transient epicormic shoots in a 20-year-old sessile oak plantation. Annals of Forest Science 65: 508–517. DOI: 10.1051/forest:2008032

Colin F., Ducousso A., Fontaine F. 2010. Epicormics in 13-year-old *Quercus peraea*: small effect of provenance and large influence of branches and growth unit limits. Annals of Forest Science 67: 312–322. DOI: 10.1051/forest/2009118

Collet C., Colib F., Bernier F. 1997. Height growth, shoot elongation and branch development of young *Quercus petraea* grown under different levels of resource availability. Annals of Forest Science 54: 65–81.

Collet C., Lanter O., Pardos M. 2001. Effects of canopy opening on height and diameter growth in naturally regenerated beech seedlings. Annals of Forest Science 58: 127–134.

Collet C., Piboule A., Leroy O., Frochot H. 2008. Advance *Fagus sylvatica* and *Acer pseudoplatanus* seedlings dominate tree regeneration in a mixed broadleaved former coppice-with-standards forest. Forestry 81(2): 135–150. DOI: 10.1093/forestry/cpn004

Cotta H. 1828. Anweisung zum Waldbau. 4th edition, Arnoldische Buchhandlung. 413 p.

Crockford K., Savill P. 1991. Preliminary yield tables for oak coppice. Forestry 64(1): 29–49.

Dale M., Sonderman D. 1984. Effect of thinning on growth and potential quality of young white oak crop trees. USDA Forest Service research paper NE-539. 12 p.

Decocq G., Aubert M., Dupont F., Alard D., Sa-

GUEZ R., WATTEZ-FRANGER A., DE FOUCAULT B., DELELIS-DUSOLLIER A., BARDAT J. 2004. Plant diversity in a mangaged temperate deciduous forest: understory response to two silvicultural systems. Journal of Applied Ecology 41: 1065–1079.

DIWOLD G. 2008. Waldbauliche Untersuchungen zur Qualitäts- und Preisstruktur von wertvollem Eichenholz. Master Thesis Vienna. 132 p.

DODET M., COLLET C., FROCHOT H., WEHRLEN L. 2011. Tree regeneration and plant species diversity responses to vegetation control following a major windthrow in mixed broadleaved stands. European Journal of Forest Research 130: 41–53. DOI: 10.1007/s10342-010-0406-z

DONG P., BLOCK J., EDER W., LÜPKE V B., MUTH M., SCHUCK J., SEIFERT T., SPIECKER H. 2007. Eiche im Pfälzerwald. Mitteilungen aus der Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz 63. 150 p.

DUCHIRON M. 2000. Strukturierte Mischwälder. 1st edition, Parey. 256 p.

DWORSCHAK U. 1996. Vegetationsentwicklung in ehemaligen Mittelwäldern der Niederrheinischen Bucht. Forst und Holz 51(12): 392–395.

EL KATEB H., FELBERMEIER B., HÖLLERL S., MOSANDL R. 2006. Growth and quality of young sessile oak stands (*Quercus petraea* Liebl.) under different tending concepts. Silvicultural Experiments 1, Karl Gayer Institut. 8 p.

ELLENBERG H. 1978. Vegetation Mitteleuropas mit den Alpen. 2nd edition, Eugen Ulmer. 981 p.

FABRICIUS L. 1932. Ursachen der Wasserreiserbildung an Eichen. Forstwissenschaftliches Centralblatt 54(22): 753–766.

FIELD A. 2009. Discovering statistics using SPSS. 3rd edition, Sage. 822 p.

FINZI A., CANHAM C. 2000. Sapling growth in response to light and nitrogen availability in a southern New England forest. Forest Ecology and Management 131: 153–165.

FISCHER A. 2003. Forstliche Vegetationskunde. 3rd edition, Ulmer. 421 p.

FLEDER W. 1981. Furniereichenwirtschaft heute. Holz-Zentralblatt 107(98): 1509–1511.

FLEDER W. 1988. Zur Eichenwirtschaft im Spessart. Allgemeine Forstzeitschrift 43(26): 735–737.

FONTAINE F., DRUELLE J., CLÉMENT C., BURRUS M., AUDRAN J. 1998. Ontogeny of proventitious epicormic buds in *Quercus petraea*. I. In the 5 years following initiation. Trees 13: 54–62.

FONTAINE F., COLIN F., JARRET P., DRUELLE J. 2001. Evolution of the epicormic potential on 17-year-old *Quercus petraea* trees: first results. Annals of Forest Science 58: 583–592.

FREIST H. 1985. Erfahrungen auf dem Wege vom Mittelwald zum Hochwald im Forstamt Bramwald. Allgemeine Forstzeitschrift 49: 1331–1338.

FREIST H., KLÜSSENDORF J. 1991. Vertragsnaturschutz zum Erhalten historischer Waldformen an einem Beispielsfall in Niedersachsen. Forst und Holz 46(4): 86–88.

GEB M., SCHMIDT W., MEYER P. 2004. Das Mittelwaldprojekt Liebenburg – Entwicklung der Bestandesstruktur. Forst und Holz 59(12): 567–573.

GEMMEL P., NILSSON U., WELANDER T. 1996. Development of oak and beech seedlings planted under varying shelterwood densities and with different site preparation methods in southern Sweden. New Forests 12: 141–161.

GÖTTLEIN A. 1994. Der Einfluß von Baumdimension, Standort und Holzqualität auf den Versteigerungserlös von Furniereichen. Forstwissenschaftliches Centralblatt 113: 354–366.

GOULD P., FEI S., STEINER K. 2007. Modeling sprout-origin oak regeneration in the central Appalachians. Canadian Journal of Forest Research 37: 170–177. DOI: 10.1139/X06-206

GROSS P., KONOLD W. 2010. Mittelwald als Agroforstsystem zwischen geordneter Nachhaltigkeit und Gestaltungsvielfalt – Eine historische Studie. Allgemeine Forst und Jagdzeitung 181(3/4): 64–71.

GRÜTZ A. 1986. Mittelwald als forstwirtschaftliche Betriebsart. Allgemeine Forstzeitschrift 47: 166–1168.

HAMM J. 1896. Der Ausschlagwald. 1st edition, Parey. 267 p.

HAMM J. 1900. Leitsätze für den Mittelwaldbetrieb. Forstwissenschaftliches Centralblatt 8: 392–404.

Harmer R. 1990. The timing of canopy and epicormic shoot growth in *Quercus robur* L. Forestry 63(3): 279–283.

Hartig G. 1861. Lehrbuch für Förster und für die, welche es werden wollen. 2ter Band. 10th edition, Cotta´scher Verlag. 345 p.

Hausrath H. 1982. Geschichte des deutschen Waldbaus von seinen Anfängen bis 1850. 1st edition, Hochschulverlag. 416 p.

Hees A., Clerkx A. 2003. Shading and root-shoot relations in saplings of silver birch, pedunculate oak and beech. Forest Ecology and Management 176: 439–448.

Hein S. 2009. Wertholzproduktion mit Buche, Eiche, Esche und Ahorn. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 5: 240–242.

Heyer C. 1893. Der Waldbau oder die Forstproduktenzucht. 4th edition, Teubner. 634 p.

Hochbichler E., Krapfenbauer A., Mayrhofer F. 1990. Ein Pflegemodell für Eichenjungbestände – Grünastung, eine wirtschaftliche Problemlösung der Wertholzerziehung. Centralblatt für das gesamte Forstwesen 107: 1–12.

Hochbichler E. 1993. Methods of oak silviculture in Austria. Annals of Forest Science 50: 583–591.

Hochbichler E. 2008. Fallstudien zur Struktur, Produktion und Bewirtschaftung von Mittelwäldern im Osten Österreichs (Weinviertel). Forstliche Schriftenreihe Universität für Bodenkultur, Wien. 246 p.

Holten N. 1986. Eichenwirtschaft – dargestellt an Beispielen aus dem dänischen Forstamt Bregentved. Forstarchiv 57(6): 221–227.

Hubert M., Courrad R. 2002. Élagage et taille de formation des arbres forestiers. 3rd edition, Forêt privée francaise. 282 p.

IBM SPSS Statistics 2011. SPSS v19.

Jensen J. 2000. Provenance variation in phenotypic traits in *Quercus robur* and *Quercus petraea* in Danish provenance trials. Scandinavian Journal of Forest Research 15: 297–308.

Jensen F., Skovsgaard J. 2009. Precommercial thinning of pedunculate oak: Recreational preferences of the population of Denmark for different thinning practices in young stands. Scandinavian Journal of Forest Research 24: 28–36. DOI: 10.1080/02827580802592475

Johnson P. 1977. Predicting oak stump sprouting and sprout development in the Missouri Ozarks. USDA Forest Service research paper NC-149. 11 p.

Jüttner O. 1955. Ertragstafeln für Eichen. In: Schober R. 1975. Ertragstafeln wichtiger Baumarten bei verschiedener Durchforstung. 2nd edition, Sauerländer´s. 154 p.

Kennel E. 1973. Bayerische Waldinventur 1970/71. Inventurabschnitt I: Großrauminventur Aufnahme- und Auswertungsverfahren. Forschungsberichte Forstliche Forschungsanstalt München 11. 143 p.

Kerr G. 1996. The effect of heavy or ‘free growth’ thinning on oak (*Quercus petraea* and *Q. robur*). Forestry 69(4): 303–317.

Kerr G., Harmer R. 2001. Production of epicormic shoots on oak (*Quercus robur*): effects of frequency and time of pruning, Forestry 74(5): 467–477.

Kerr G. 2002. The potential of sustainable management of semi-natural woodlands in southern England using uneven-aged silviculture. Forestry 75(3): 227–243.

Köstler N. 1955. Waldbau. 2nd edition, Parey. 418 p.

Krahl-Urban J. 1959. Die Eichen. 1st edition, Parey. 288 p.

Kramer H., Dong P. 1985. Kronenanalyse für Zuwachsuntersuchungen in immissionsgeschädigten Nadelholzbeständen. Der Forst- und Holzwirt 40(5): 115–118.

Krissl W., Müller F. 1989. Waldbauliche Bewirtschaftungsrichtlinien für das Eichenmittelwaldgebiet Österreichs. Schriftenreihe der Forstlichen Bundesversuchanstalt, Wien. 134 p.

Küster B. 2000. Die Auswirkungen unterschiedlicher waldbaulicher Behandlungen auf das Wachstum und die Qualitätsentwicklung junger Traubeneichen (*Quercus petraea* (Matt.) Liebl.). Forstliche Forschungsberichte München 179. 223 p.

Küster H. 2008. Geschichte des Waldes. 2nd edition, Beck. 267 p.

Lemaire J. 2010. Le chêne autrement. 1st edition, Forét Privée Francoise. 176 p.

Löf M. 2000. Establishment and growth in seedlings of *Fagus sylvatica* and *Quercus robur*: influence of interference from herbaceous vegetation. Canadian Journal of Forest Research 30: 855–864.

Lüpke v B. 1998. Silvicultural methods of oak regeneration with special respect to shade tolerant mixed species. Forest Ecology and Management 106: 19–26.

Mayer H. 1977. Waldbau auf soziologisch-ökologischer Grundlage. 1st edition, Gustav Fischer. 483 p.

Miller G. 1996. Epicormic branching on Central Appalachian hardwoods 10 years after deferment cutting. USDA Forest Service research paper NE-702. 9 p.

Morisset J., Mothe F., Bock J., Bréda N., Colin F. 2012. Epicormic ontogeny in *Quercus petraea* constrains the highly plausible control of epicormic sprouting by water and carbohydrates. Annals of Botany 109: 365–377. DOI: 10.1093/aob/mcr292

Mosandl R., El Kateb H., Ecker J. 1991. Untersuchungen zur Behandlung von jungen Eichenbeständen. Forstwissenschaftliches Centralblatt 110: 358–370.

Mosandl R., Paulus F. 2002. Rationelle Pflege junger Eichenbestände. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 11: 581–584.

Mosandl R., Summa J., Stimm B. 2010. Coppice-With-Standards: Management options for an ancient forest system. Forestry Ideas 16(1): 65–74.

Muchin A. 2005. Analytische Untersuchungen zum Einfluss des Standorts auf das Wachstum non Stiel- und Traubeneiche im nordostdeutschen Tiefland. Forstwissenschaftliche Beiträge Tharandt 24. 264 p.

Müller F. 1986. Praktizierte Mittelwaldbewirtschaftung aus der Sicht des Wirtschafters und Waldbesitzers. Allgemeine Forstzeitschrift 47, 1177.

Müller-Kroehling S. 2007. Laufkäfer unterschiedlich bewirtschafteter fränkischer Eichenwälder, unter besonderer Berücksichtigung der Bedeutung von Mittelwäldern für die Biodiversität. Angewandte Carabidologie 8: 51–68.

Nagel R. 2007. Bestandesentwicklung, Einzelbaumwachstum und Qualitätsentwicklung von Stiel- und Traubeneichenbeständen in Nordwestdeutschland unter dem Einfluss unterschiedlicher Durchforstungsstärken. DVFFA – Sektion Ertragskunde. 19 p.

Neophytou C., Aravanopoulos F., Fink S., Dounavi A. 2010. Detecting interspecific and geographic differentiation patterns in two interfertile oak specis (*Quercus petraea* (Matt.) Liebl. and *Q. robur* L.) using small sets of microsatellite markers. Forest Ecology and Management 259: 2026–2035. DOI: 10.1016/j.foreco.2010.02.013

Nixon K. 1993. Infrageneric classification of *Quercus* (Fagaceae) and typification of sectional names. Annals of Forest Science 50(1): 25–34.

Polge H. 1984. Werteichenproduktion in Frankreich. Allgemeine Forstzeitschrift 39: 430–434.

Pott R. 1981. Der Einfluss der Niederholzwirtschaft auf die Physiognomie und die floristisch-soziologische Struktur von Kalkbuchenwäldern. Tuexenia 1: 233–242.

Preuhsler T. 1979. Ertragskundliche Merkmale oberbayerischer Bergmischwald-Verjüngungsbestände auf kalkalpinen Standorten im Forstamt Kreuth. Forschungsberichte der Forstlichen Forschungsanstalt München. 45 p.

Pyttel P. 2012. Aspekte einer nachhaltigen Bewirtschaftung durchgewachsener Niederwälder. Schriftenreihe Freiburger Forstlicher Forschung 52. 166 p.

Rohmeder E. 1935. Zusammenhänge zwischen Baumklasseneinteilung und Wasserreiserbefall jüngerer Eichenbestände. Forstwissenschaftliches Centralblatt 57(7): 205–210.

Ruch P. 2017. France. In: Lazdina D., Celma S. (Eds), National Factsheets on Coppice Forests. COST Action FP1301 Reports. Freiburg, Germany: Albert Ludwig University of Freiburg, 64 p.

Sands B., Abrams M. 2009. Effects of stump diameter on sprout number and size for three oak species in a Pennsylvania clearcut. Northern Journal of Applied Forestry 26(3): 122–125.

Savill P., Kanowski P. 1993. Tree improvement programs for European oaks: goals and strategies. Annals of Forest Science 50(Suppl. 1): 368–383.

Schaeffer L., Schaeffer A. 1951. Amélioration des tailles sous futaie. Revue forestière française 9: 538–551.

Schulte M., Rohe W., Freis H. 2004. 15 Jahre Naturschutzvertrag im genossenschaftsforstlichen Mittelwald. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 24: 1339–1342.

Schulz H. 1955. Untersuchungen über die Bewertung von Eichenstammholz. Forstarchiv 26: 182–184.

Schulz H. 1961. Die Beurteilung der Qualitätsentwicklung junger Bäume. Forstarchiv 32(5): 89–99.

Schütt P., Schuck H., Stimm B. 2002. Lexikon der Baum- und Straucharten. 1st edition, Nikol. 581 p.

Schütz J. 2001. Der Plenterwald. 1st edition, Ulmer. 207 p.

Short I., Hawe J. 2012. Possible silvicultural systems for use in the rehabilitation of poorly performing pole-stage broadleaf stands – Coppice-with-standards. Irish Forestry 69(1–2): 148–166.

Spiecker H. 1991. Zur Steuerung des Dickenwachstums und der Astreinigung von Trauben- und Stieleichen (*Quercus petraea* (Matt.) Liebl und *Quercus robur* L.). Schriftenreihe der Landesforstverwaltung Baden-Württemberg 72. 151 p.

Steinhoff S. 1993. Results of species hybridization with *Quercus robur* L and *Quercus petraea* (Matt) Liebl. Annals of Forest Science 50(Suppl. 1): 137–143.

Summa J., Mosandl R. 2009. Waldbauliche Untersuchungen zur Qualität von Mittelwald-Lassreiteln. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 6: 296–299.

Tiefenbacher H. 1996. Silvicultural planning under conditions of environmental change: Evaluation of options in a dieback in Austrian oak forests. Forest Ecology and Management 83: 133–136.

Timbal J., Aussenac G. 1996. An overview of ecology and silviculture of indigenous oaks in France. Annals of Forest Science 53: 649–661.

Treiber R. 2002. Mittelwaldnutzung – Grundlage der Vegetationsdynamik und Artenvielfalt in Wäldern der südelsässischen Hardt. Naturschutz und Landschaftsplanung 34(11): 334–345.

Treiber R. 2003. Genutzte Mittelwälder – Zentren der Artenvielfalt für Tagfalter und Widderchen im Südelsass. Naturschutz und Landschaftsplanung 35(1): 50–62.

Utinek D. 2004. Conversions of coppices to coppice-with-standards in Urban Forests of Moravský Krumlov. Journal of Forest Science 50(1): 38–46. DOI:10.17221/4599-JFS

Vanselow K. 1941. Einführung in die Forstliche Zuwachs- und Ertragslehre. 1st edition, J.D. Sauerländers. 155 p.

Vlad J. 1940. Zuwachsverhältnisse im Mittelwald. Doctoral Thesis Munich. 134 p.

Vollmuth D. 2021. Die Nachhaltigkeit und der Mittelwald. Göttinger Forstwissenschaften Band 10. 581 p.

Ward W.W. 1966. Epicormic Branching of Black and White Oaks. Forest Scence 12(3): 290–296. DOI: 10.1093/forestscience/12.3.290

Weigel D., Peng C. 2002. Predicting stump sprouting and competitve success of five oak species in southern Indiana. Canadian Journal of Forest Research 32: 703–712. DOI: 10.1 139/X02-042

Wignal T., Browning G. 1988. The effects of stand thinning and artificial shading on epicormic bud emergence in pedunculate oak (*Quercus robur* L.). Forestry 61(1): 45–59.

Wilhelm G., Letter H., Eder W. 1999. Konzeption einer naturnahen Erzeugung von starkem Wertholz. AFZ, der Wald: allgemeine Forst-Zeitschrift für Waldwirtschaft und Umweltvorsorge 5: 232–240.

Wilhelm G., Rieger H. 2013. Naturnahe Waldwirtschaft mit der QD-Strategie. Ulmer. 207 p.

Wolf M., Petercord R. 2012 Eichenschäden in Nordbayern. LWF aktuell 88: 4–8.

Zieren A. 1970. Zur Ästung von Esche und Eiche. Allgemeine Forstzeitschrift 25(36): 771–772.

Appendix 1

Regression model for stand height curves:
Height [m] = b_0 + b_1 · ln DBH [cm]

Group	*N*	R^2	b_0	SD	b_1	SD	ß	*p*-value for b_1
WC	201	0.60	-3,84	1.20	6.80	0.39	0.77	<0.000
WT	39	0.82	-10.32	1.97	7.93	0,54	0.90	<0.000
WM	52	0.84	-4.73	1.18	6.24	0.37	0.92	<0.000
IC	105	0.81	-10.27	1.32	8.66	0.40	0.90	<0.000
IT	129	0.81	-8.23	1.03	7.89	0.33	0.90	<0.000
IM	92	0.79	-11.91	1.43	8.96	0.47	0.89	<0.000

Note: Abbreviations in all 4 appendixes: Group codes the experimental stands, *N* indicates the quantity, R^2 is the coefficient of determination in the regression model, SD is standard deviation, and *ß* is the coefficient of the regression model.

Appendix 2

Regression model for crown projection area of Oaks:
Crown projection area [m²] = b_0 + b_1 · DBH [cm]

Group	*N*	R^2	b_0	SD	b_1	SD	ß	*p*-value for b_1
WC	30	0.57	-10.58	7.05	1.40	0.22	0.75	<0.000
WT	29	0.61	-33.12	9.76	1.75	0.27	0.78	<0.000
WM	30	0.78	-8.26	3.50	1.17	0.11	0.88	<0.000
IC	30	0.56	-1.32	7.24	1.33	0.22	0.75	<0.000
IT	30	0.68	-6.36	4.55	1.27	0.16	0.82	<0.000
IM	29	0.55	-11.18	7.33	1.45	0.25	0.74	<0.000

Appendix 3

Regression model for canopy cover and height of regeneration:
Mean height of regeneration [cm] = b_0 + b_1 · canopy cover [%]

N	R^2	b_0	SD	b_1	SD	ß	*p*-value for b_1
12	0.39	112.92	15.03	-0.62	0.24	-0.62	<0.05

Appendix 4

Regression model for stump diameter and number of coppice shoots:
ln number of coppice shoots [ln N] = b_0 + b_1 · stump diameter [cm]

N	R^2	b_0	SD	b_1	SD	ß	*p*-value for b_1
25	0.77	0.64	0.15	0.04	0.00	0.87	<0.000