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The effect of harvesting on stump mortality and re-sprouting in aged oak coppice forests

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ABSTRACT

In Central Europe, traditional management of oak coppice forest was abandoned at the beginning of the last century, leaving large tracts of forest developing into aged coppice stands. Since the increasing importance and use of biomass as a renewable energy source, resumption of coppice management in these forests is being considered. However, there are uncertainties about the re-sprouting ability of large and old oak stumps. In this study we determined the re-sprouting ability of sessile oak (*Quercus petraea* (Mattuschka) Liebl.) stumps 80–100 years after the last coppice cut. Stump mortality and re-sprouting intensity were analyzed in relation to three different harvesting methods (harvester; conventional chainsaw cut; very low chainsaw cut), browsing intensity, vitality of parent trees and stump parameters. In addition, the extent to which stump mortality may be compensated by generative regeneration was quantified.

On average, 16% of all sessile oak stools died within two vegetation periods after coppicing. Stump mortality was higher in unfenced areas compared to areas protected against browsing. No clear relationships were observed between stump mortality and harvesting method or parent tree characteristics.

Two vegetation periods after coppicing, numerous new stump sprouts were recorded. In unfenced areas, average maximum sprout height was reduced by nearly 80%. Maximum sprout height (used as an indicator for re-sprouting intensity) was found to be unaffected by harvesting method and not related to stump height or parent tree characteristics. When stumps were cut close to the soil surface the majority of the most vigorous oak sprouts originated below ground.

Our results indicate that the re-sprouting ability of 80–100 year old oak trees originating from former coppice management is still high and little influenced by harvesting methods.

1. Introduction

Coppicing is an ancient form of woodland management whereby stands are clear felled at regular intervals of approximately 15–30 years (Ford and Newbould, 1970; Rackham, 1980). The fundamental feature of coppice forests is that they regenerate vegetatively as sprouts arise from the cut stumps of the previous tree generation (Evans, 1992; Rydberg, 2000).

For centuries, coppicing was practiced throughout Europe and for many people coppice forests supplied raw materials for various products (Evans, 1992; Papaioannou, 1938). However, in Central Europe their relevance vanished over time because of increasing use of fossil fuels and drastic changes in forest management since the beginning of the 20th century (Dohrenbusch, 1983; Pott, 1990). Where these forests were not converted or transformed into high forests, they have grown old and are now described as aged coppice forests (Logli and Joffre, 2001).

Recently renewed interest in coppicing has developed in many European countries (Rydberg, 2000) for two major reasons: (1) the increasing importance of renewable energy sources as a substitute for fossil fuels (BMU 2011, European Parliament 2009: directive 2009/28/EG) and (2) the preservation of coppice forests as a historical landscape element and habitat with high nature conservation value (Buckley, 1992; LANUV, 2007; Scherzinger, 1996). This economic and ecological interest may lead to a renaissance of coppice management in some areas of Central Europe.

However, the re-activation of coppicing, particularly of aged coppice forests has proceeded slowly for various reasons including the perceived environmental damage through clear felling. One major obstacle for the resumption of coppicing is the wide-spread belief amongst forest managers and practitioners that oaks in aged coppice forests are not able to re-sprout vigorously enough from the stump to ensure successful regeneration. Indeed, there is a

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large body of literature describing poor vegetative regeneration, particularly of oak stumps. Nevertheless, the explanations provided for this phenomenon often lack scientific underpinning.

Factors such as parent tree characteristics are often assumed to influence re-sprouting capacity of stumps (Randall et al., 2005), in particular parent tree size (Johnson, 1977, 1975; Roth and Hepting, 1943). However, no relationship between stump diameter and the number of sprouts were found for different tree species (Gardiner and Helmig, 1997; Guidici and Zingg, 2005; Tran et al., 2005; Wendel, 1975).

Further it has been described that re-sprouting decreases with increasing stool age (Becker, 2002), where the term "stool" refers to a cluster of at least two stumps with an aboveground connection (Röhrig et al., 2006). These have developed from repeated coppice cuts. It has also been assumed that re-sprouting ability declines with the number of cuts a stool has experienced (Gwinner, 1838; Hamm, 1896; Mulopulos, 1927). In contrast, coppicing is assumed by others to be infinitely repeatable and considered to be the key to an everlasting tree life (Rackham, 1980; Buckley, 1992). These observations are also in accordance with reports of Käpler (1805), who found no decline in the sprouting intensity of oak stumps coppiced for the fourth time.

Rather than stool age, a negative relationship between parent tree age and stump sprouting was observed for Central European and North American oak species (Groos, 1953) for *Quercus petraea*; Johnson, 1977, McGee, 1978 for *Quercus alba* L.; Dey and Jensen, 2002 for *Quercus velutina* Lam. and *Quercus coccinea* Muenchh.). However, information concerning the maximum parent tree age at which stumps are still able to re-sprout differs widely. For sessile oak, insufficient re-sprouting was observed, when parent trees were older than: 35 (Becker, 2002), 40 (Cotta, 1828; Mulopulos, 1927; Pott, 1990) or 50 years (Jentsch, 1899). In France, oak coppice forests lost their re-sprouting ability when the parent trees were between 60 and 70 years old (Hawes, 1908). In contrast, sufficient re-spouting was observed for some North American oak species after the parent trees were about 100 years old (Roth and Hepting, 1943).

In addition, it has been suggested, in particular in the older literature, that the method used to cut the parent trees, particularly the cutting height, is relevant for stump re-sprouting and low cuts of stumps have been advocated (Cotta, 1856; von Drais, 1807; Fürst, 1904; Gwinner, 1838; Jentsch, 1899). For example, oak stumps as old as 150 years re-sprouted vigorously, if the trees were cut below ground level and then covered with soil (Neubrand, 1869). In the 16th century, observations of the relationship between cutting height and re-sprouting intensity led to government regulations forbidding stumps to be cut above a height of 30 cm in areas of south-western Germany. Roughly 120 years later this threshold was reduced to 15 cm (Bauer, 1979). Also recent studies in aged *Castanea sativa* (Mill.) coppice forests in Switzerland confirm that stumps re-sprout more vigorously, if trees are cut low and cleanly (i.e. regular, plain and inclined; Guidici and Zingg, 2005).

The reason for cutting oak stumps as low as possible is that the probability increases that new shoots originate below ground or very close to it. Thus, the shoots themselves are able to develop a new root system and henceforth become independent individuals (Jentsch, 1899; Pfeil, 1860; Wagener, 1884). Additionally, independent sprouts are less likely to break or become infected by pathogens from the stump (Becker, 2002; Roth and Hepting, 1969; Wilson, 1968).

Wherever resumption of coppicing in aged oak coppice forests is being considered, certainty is needed about the re-sprouting ability of stumps. Therefore, the main objective of this study was to analyse whether the stumps in aged oak-dominated coppice forests survive and develop enough sprouts to guarantee a subsequent crop. In particular, we quantified stump mortality and potential sprout growth of sessile oak in response to three different harvesting methods (harvester; conventional chainsaw cut; very low chainsaw cut). Additionally, we analysed how mortality and re-sprouting were influenced by stump attributes, parent tree characteristics and browsing.

2. Materials and methods

2.1. Experimental sites

The study was carried out in four aged sessile oak coppice forest stands at two different sites. The first study site "Weisel" (henceforth called W, 1.44 ha in size), is situated on south-south-easterly facing slopes at 380 m above sea level and close to the municipalities of Weisel and Sauerthal (Lat. 50.075366 Long. 7.792135, 44 km south of Koblenz). Common soil types in this area are luvisols and brown earths of moderate base supply developed from argillaceous schist. Mean annual temperature is 8.3 °C and mean annual rainfall is 760 mm (Gauer, 2005).

The study site "Baumholder" (hereafter called B, 0.96 ha in size), ca. 10 km east of the town of Baumholder (Lat. 49.62289, Long. 7.439991, 60 km west of Kaiserslautern) is characterized by loamy, nutrient rich cambisol soils developed from melaphyre. Annual average temperature is 6.9 °C (1971–2000 period) and average annual precipitation is 850 mm. The study site is located at ca. 380 m above sea level on south-west facing slopes.

The selected study sites were representative of the conditions of most of the coppice forest of south-western Germany in terms of age, silvicultural treatments and species composition. An additional selection criterion was that sites had to be trafficable.

In all study stands, like in most forests of coppice origin in Germany, coppice management had ceased at the beginning of the 20th century and no other stand management had been applied since. At the time of installing the experiment, stands were approximately 90 years old. Owing to the very long tradition of coppicing in both regions, it is most likely that the majority of the stumps had been repeatedly cut.

2.2. Experimental design and measurement of the previous stand generation

At study site B, three blocks (two of 0.72 and one of 0.94 ha) were laid out in three different stands. At study site W two blocks, 0.72 ha each were established in one stand. Within each 0.72 ha block there were twelve rectangular (20 × 30 m) treatment plots. In the 0.94 ha block at study site B, 16 treatment plots of the same size were established.

For each tree (with a diameter at breast height of $\geqslant 7$ cm) in all plots the following attributes were recorded: species, diameter at breast height (dbh), crown class (in accordance to Kraft's classification) and stump status (single or grouped). Tree height was measured for a subset of trees distributed over the diameter range in each study stand (*sensu* Bachofen and Zingg, 2001). To analyse the relationships between parent tree characteristics and sprouting properties, each tree (total $N = 5468$) was permanently tagged by affixing numbered aluminium labels at the root collar.

All study stands were completely harvested (clear-cut without leaving standards) prior to budbreak between February and May 2009 using different harvesting methods. The treatments applied to the 0.06 ha plots were as follows: (1) motor manual/conventional chainsaw cut, where the cutting height was autonomously decided by a professional forest worker, (2) traditional deep cut (cutting height at ground level) and (3) fully mechanised harvest, where the cutting height was decided by the machine operator.

In the 0.72 ha blocks, treatments (2) and (3) were replicated three times, the remaining six plots were harvested by conventional cutting (treatment 1). In the 0.92 ha block, four plots were harvested by applying treatments (1) and (2) and eight plots were conventionally felled. All treatments were assigned randomly to each of the plots. At study site B, whole trees were harvested and processed into wood chips. At site W, only tree compartments with merchantable wood size (diameter ⩾7 cm) were removed and large parts of the tree crown were left on site.

At both sites, a fully mechanised harvester (HSM 405) was used in combination with a head particularly developed for broadleaf species (type CTL 40 HW, ForstInno (2007)). The timber was skidded using different types of rubber tired skidders.

After harvesting, two of the 0.72 ha blocks were completely fenced (one at study site B (unit 48) and one at site W) similarly half (eight plots) in the 0.92 ha block at study site B (unit 50). Thus the number of treatment plots was equal inside and outside the fence.

2.3. Measurement of the new coppice generation and sprouting related parameters

Stump mortality and sprouting vigor of oak and hornbeam stumps was quantified two vegetation periods after coppicing in October and November 2010. For that purpose, transects (5 × 30 m in size) were established in 48 of the 64 plots. Transect shape and size was defined by plot length and the intention that one fourth of the total plot area should be covered by the assessment. Transects were established in all plots, where trees were cut by the harvester (treatment 3) and close to the ground (treatment 2). From all conventionally cut plots ($N = 32$), 16 plots were chosen randomly (three in the 0.72 ha blocks and four in the 0.92 ha block at site B).

Mortality of stumps was visually assessed by determining the presence or absence of living sprouts. Stumps with only dead sprouts or without sprouts were classified as dead. If at least one living sprout was present, the stump was categorized as alive.

Sprouting vigor was quantified by recording the height of the tallest sprout per stump (maximum sprout height) and the tally of all sprouts with a diameter⩾1 cm (measured at a distance of 10 cm from the point of sprout emergence). Mean height of all sprouts per stump was estimated visually and recorded along with the horizontal extent of the whole stump sprout cluster (measured at the widest point and perpendicular to that). Within the fenced stands, we determined the point of origin (bark, callus tissue, below ground) of the three highest sprouts per stump. Mean height of each oak stump was calculated from two height measurements at the upslope and downslope side of stumps.

2.4. Statistical analysis

2.4.1. Selecting an indicator for re-sprouting intensity

To identify the best indicator for re-sprouting intensity, a correlation matrix (Spearman) was used to identify relationships between the recorded sprout parameters maximum sprout height, average sprout height, mean height of the three highest sprouts, mean diameter of the three highest sprouts, number of sprouts ⩾1 cm and volume of all sprouts (calculated from average sprout height and mean diameter of all sprouts). To exclude browsing influence, only measurements within fenced stands were considered for this calculation.

The variables describing re-sprouting intensity were highly correlated with each other (Table 1). In particular the maximum sprout height, i.e. the longest sprout per stump, was highly correlated with all other sprout parameters. Therefore we considered the maximum sprout height as a useful and easy to measure parameter to describe vitality of oak stumps and their re-sprouting intensity.

2.4.2. Analysis of differences between the treatments and sites

Since most of the stump and sprout parameters were not normally distributed (tested by Kolmogorov–Smirnov test, $N > 50$), equality of population medians among groups (defined by sites, treatments, living status (i.e. alive or dead)) were tested by applying the Kruskal–Wallis test to compare more than two groups followed by Mann–Whitney-*U* test post hoc test. Associations between harvesting method or fencing and stump mortality (dead or alive) were analyzed by χ^2-test (fourfold test).

All statistical tests were performed at $p < 0.05$ and carried out using the software package SPSS 18.0 (SPSS Inc., Chicago, IL, USA).

2.4.3. Model development and selection

We constructed a set of alternative models to estimate mortality and re-sprouting intensity as a function of multiple explanatory variables. Based on the hypothesis that stump height affects stump mortality, this factor was included in the models. Harvesting method was also considered an important model variable. However, since harvesting method directly determines stump height, both variables were never combined in the same models. We included dbh into the models based on the assumption that re-sprouting ability decreases with increasing parent tree dimensions. To test how browsing determines stump mortality, it was incorporated into the mortality models too. By including the factor "stump status" we tested whether re-sprouting ability was affected by the fact that stumps were growing individually (disregarding root anastomosis) or in the form of stools (at least two stumps with an aboveground connection).

The most parsimonious models only included one explanatory variable (fencing (fe), harvesting method (hm), stump status (ss), stump height (sh), dbh) and as a random effect the study area; the more complex models included a combination of these variables.

Mixed effect models (GLMM) were used to account for the lack of homogeneity of the variances between the study areas and the nested sampling design. To develop the models, we used the function 'lme' in the 'nlme' package, version 3.1-97 (Pinheiro et al., 2010) within R version 2.12.1 (R Development Core Team, 2010).

To evaluate the models, we used the information theoretic framework (Anderson, 2008; Burnham and Anderson, 2002). The evaluation of the models was performed using the R package "AICcmodavg" version 1.13 (Mazerolle, 2010). The second order Akaike´s Information criterion (AICc) for small samples was applied to evaluate the different models (Burnham and Anderson, 2002). Additionally we calculated two more measures to compare the models: the first one is delta AICc which measures the difference of each model relative to the best model. Another measure for the strength of evidence of each model is the Akaike weight, which indicates the probability that the model is the best from the whole set of candidate models (Burnham and Anderson, 2002). Akaike weights were calculated as the ratio of the delta AICc of a given model relative to the whole set of models.

The magnitude of the effect of each explanatory variable on the response variable was assessed with an estimated average across all models. To conduct the model averaging, the estimate (i.e. the regression coefficient) of each of the variables for each model was weighted by the Akaike weights (Mazerolle, 2010). The precision of the estimation (standard errors, SEs) of the model averaged estimate was calculated in the same way.

To explain re-sprouting intensity (i.e. growth of the new sprout generation, represented by the maximum sprout height per stump) models were developed following the methodology described above. However, the relationships between the response variable

Table 1

Spearman correlation coefficients for correlations between different vitality-describing variables for *Q. petraea* for each study-site. Only stumps in fenced areas have been considered. ASH = average height of all shoots, MSH = maximum shoot height, MH3 = average height of the 3 highest shoots per stump, MD3 = average diameter of the 3 highest shoots per stump, # >1 cm = number of shoots with a diameter >1 cm, vol. = sprout clump volume, *N* = number of stumps observed, *W* = Weisel, *B* = Baumholder.

Site	Variables	Correlation coefficients (Spearman) by variables						*N*
		ASH	MSH	MH3	MD3	# >1 cm	Vol.	
W	ASH		0.824**	0.862**	0.767**	0.718**	0.824**	130
	MSH	0.824**		0.965**	0.748**	0.706**	0.770**	
	MH3	0.862**	0.965**		0.799**	0.780**	0.834**	
	MD3	0.767**	0.748**	0.799**		0.742**	0.797**	
	# >1 cm	0.718**	0.706**	0.780**	0.742**		0.860**	
	Vol.	0.824^{a}	0.770^{a}	0.834^{a}	0.797^{a}	0.860^{a}		
B	ASH		0.815**	0.824**	0.719**	0.705**	0.732**	260–318
	MSH	0.815**		0.954**	0.776**	0.749**	0.763**	
	MH3	0.824**	0.954**		0.797**	0.804**	0.811**	
	MD3	0.719**	0.776**	0.797**		0.817**	0.758**	
	# >1 cm	0.705**	0.749**	0.804**	0.817**		0.826**	
	Vol.	0.732**	0.763**	0.811**	0.758**	0.826**		
W + B	ASH		0.787**	0.808**	0.705**	0.696**	0.736**	390–448
	MSH	0.787**		0.958**	0.779**	0.752**	0.782**	
	MH3	0.808**	0.958**		0.807**	0.811**	0.830**	
	MD3	0.705**	0.779**	0.807**		0.807**	0.776**	
	# >1 cm	0.696**	0.752**	0.811**	0.807**		0.843**	
	Vol.	0.736**	0.782**	0.830**	0.776**	0.843**		

** Correlation significant at $p \leqslant 0.01$.

(sprout growth) and the explanatory variables (harvesting method, stump and parent tree characteristics) were so weak that the applied mixed models did not provide any deeper insight. Therefore none of these models are presented or discussed here.

3. Results

3.1. Mortality

Two vegetation periods after harvesting 76% of all trees were found alive. However, in the whole experiment, only 16% of all stools died. Stump and stool mortality differ, since a stool consists of more than one stump. Only if all stumps of a stool were found dead, the stool was classified as dead. At study site B, stool mortality was 19% and therefore slightly higher compared to study site W, where it was only 14%. Within the inventory of the previous stand generation, 83 of the trees now re-measured as stumps were classified as apparently dead. Two vegetation periods after coppicing, 57% of these apparently dead trees had living sprouts.

3.1.1. Factors affecting mortality

After harvesting, only 8% of all stumps were not identifiable because the permanent labels were destroyed or removed from the root collar. At study site W, stump mortality was ca. 25% in and outside the fenced plots, whereas we found a significant association between fencing and stump mortality at study site B (χ^2-test, $p < 0.001$). At this particular site, mean stump mortality (regarding all sampled blocks) amounted to ca. 20% in blocks with browsing protection and ca. 32% in unprotected blocks. Therefore fencing increased the likelihood of stump survival.

In accordance with our experimental intentions, the height of the stumps was the most distinct difference between the applied harvesting techniques. At both study sites, the highest stumps resulted from harvester felling. Average stump heights of fully mechanized felled trees were 24 and 26 cm at study site W and site B respectively. Mean stump height was 20 cm, if trees were harvested motor-manually and between 11 and 12 cm, when trees were cut as close to the ground as possible (method T). Despite the different stump heights, no relationship was found between harvesting method and stump mortality at either study site (Fig. 1). Accordingly, stump mortality was also not influenced by stump height. At study site W, stump mortality was not related to stump status; it was the same for stumps growing in a stool or solitarily (Fig. 2). However, at study site B, significantly more stumps, which were sharing a rootstock with others, died.

Independent of study site, stump mortality increased slightly but continuously with increasing dbh up to a dbh of 25 cm. At study site W, mortality started to decline in parent trees with a dbh of 21 cm and higher. However, at study site B mortality was highest for trees with a diameter >25 cm.

3.1.2. Stump mortality models

The model comparison indicated that the full model with stump height + fencing + dbh + stump status (‘sh + fe + dbh + ss’) with an Akaike weight of 0.99 was the best of all 16 candidate models (Table 2). Only this model had a reasonable level of support (Delta $i < 10$; Table 2). As a general rule, a delta < 2 suggests substantial evidence for the model. The full model (‘sh + fe + dbh + ss’) was 229 times more likely to be the best model then the next best model 2 (‘sh + fe + dbh’) based on the evidence ratio (0.9944/0.0043).

When regarding also the individual variables (Table 3), we recognized that fencing (fe) and stump status (ss) had the highest impact on mortality. Mortality was reduced if the stumps grew within a fence (−0.43) and as single growing stump (0.58). Diameter at breast height and stump height were considered important within the model but as individual variables they did not explain much of the variation in stump survival. The models including harvesting treatment had such a low weight in the model averaging process that their effect could be ignored. The later mentioned factors (dbh, sh) interacted with fencing and stump status but they did not have a mentionable impact on stump survival.

3.2. The new sprout generation

To quantify the development of the new sprout generation, the number of re-sprouting points (i.e. point of origin of one sprout cluster and not to be confused with the number of single sprouts) was tallied on sampled stumps (sensu Roth and Hepting, 1943). Independent of study sites and fencing, we observed, on average,

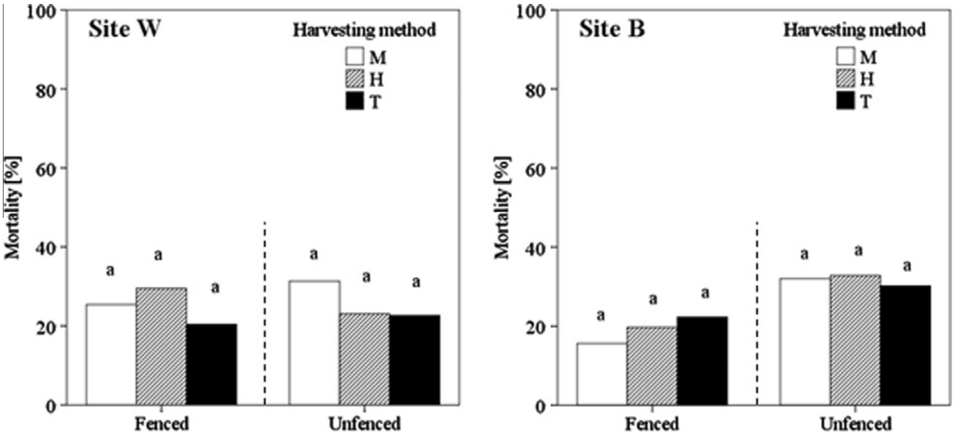

Fig. 1. Mortality [%] of stumps of *Q. petraea* in relation to the three harvesting methods (M=motor manual, H=fully mechanized, T=traditional low cut) and fencing at the study sites Weisel (W) and Baumholder (B). Within the figure compartments (separated by the dashed line) equal letters indicate no statistical significant association between mortality and harvesting method (Chi^2 -test, $p \leqslant 0.05$). N(site W)= 393, N(site B)= 753.

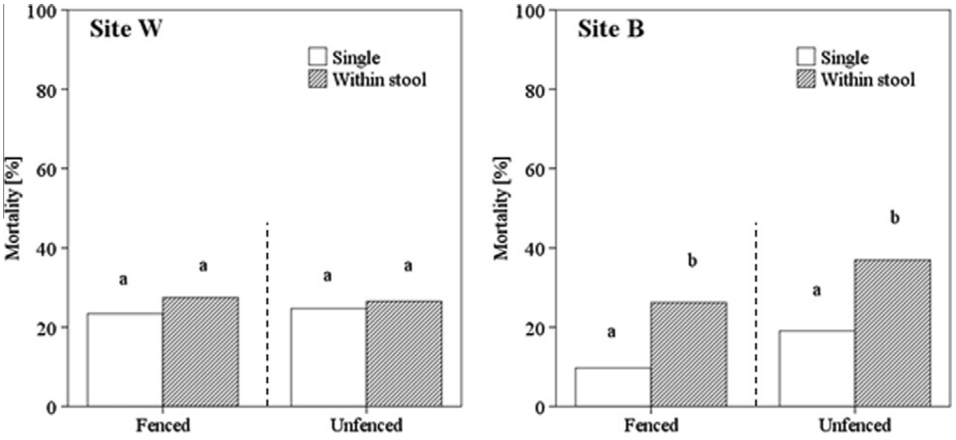

Fig. 2. Mortality [%] of *Q. petraea* stumps growing singly or within stools in fenced and unfenced areas at the study sites Weisel (W) and Baumholder (B). Within the compartments separated by the dashed line different letters indicate statistical significant associations between stump mortality and stump status (Chi^2-test, $p \leqslant 0.05$). N(site W)= 395, N(site B)= 756.

Table 2

Candidate models (Glmm) to estimate mortality, including the value of the maximized log-likelihood function (Max log), the number of estimated parameter (*K*; includes intercept and variance), Model selection criterion (AICc), the differences compared to the best model (Delta *i*), and the Akaike weights (weight *i*).

Model	Max log (LL)	*K*	AICc	Delta *i*	Weight
Harvesting methode (hm)	−6473.77	4	1302.79	1213.42	0.0000
Fencing (fe)	−6472.18	3	1300.46	1190.11	0.0000
hm + fe	−6417.07	5	1293.47	1120.26	0.0000
Stump status (ss)	−6399.46	3	1285.91	1044.65	0.0000
Mean stump height (sh)	−6385.09	3	1283.04	1015.92	0.0000
fe + ss	−6360.89	4	1280.21	987.67	0.0000
hm + ss	−6347.68	5	1279.59	981.42	0.0000
sh + fe	−6341.03	4	1276.24	947.95	0.0000
Diameter at breast Height (dbh)	−6105.82	3	1227.19	457.40	0.0000
hm + dbh	−6054.08	5	1220.87	394.27	0.0000
fe + dbh	−6033.76	4	1214.79	333.43	0.0000
hm + fe + dbh	−5980.89	6	1208.26	268.11	0.0000
sh + dbh	−5973.05	4	1202.65	212.02	0.0000
hm + fe + dbh + ss	−5903.33	7	1194.77	133.26	0.0013
sh + fe + dbh	−5911.29	5	1192.32	108.68	0.0043
sh + fe + dbh + ss	−5846.83	6	1181.45	0.00	0.9944

4–5 living re-sprouting points per stump. At both study sites stumps sharing one rootstock (i.e. stumps forming a stool) averaged 3 living re-sprouting points which was significantly fewer compared to single growing stumps (on average 5 living re-sprouting points; MWU-test study site W $p \leqslant 0.01$, study site B $p \leqslant 0.001$).

The number of sprouts (here not to be confused with sprout clusters) with a diameter of $\geqslant 1$ cm (measured at a distance of

Table 3
Parameter estimate (regression coefficients) and standard error (in parenthesis) by model and the multimodel averages based on AICc. For explanation of abbreviations see Table 2.

Model	Model ranking	dbh	Mean stump height (sh)	Fencing (fe) unfenced	Harvesting method (hm)		Stump status (ss) single
					Fully mechanized	Traditional low cut	
sh + fe + dbh + ss	1	0.00 (0.02)	−0.02 (0.01)	−0.43 (0.15)			0.58 (0.16)
sh + fe + dbh	2	0.01 (0.01)	−0.02 (0.01)	−0.50 (0.14)			
hm + fe + dbh + ss	3	−0.01 (0.01)		−0.45 (0.15)	−0.10 (0.17)	−0.5 (0.18)	0.62 (0.16)
sh + dbh	4	0.00 (0.01)	−0.03 0.01				
hm + fe + dbh	5	0.00 (0.01)		−0.53 (0.14)	−0.09 (0.17)	−0.06 (0.18)	
fe + dbh	6	0.00 (0.01)		−0.52 (0.14)			
hm + dbh	7	−0.01 (0.01)			−0.10 (0.17)	−0.08 (0.17)	
dbh	8	−0.1 (0.01)					
sh + fe	9		−0.02 0.01	−0.40 (0.14)			
hm + ss	10				−0.07 (0.16)	0.02 (0.17)	0.71 (0.15)
fe + ss	11			−0.37 (0.14)			0.67 (0.15)
sh	12		−0.03 0.01				
ss	13						0.71 (0.15)
hm + fe	14			−0.45 (0.14)	−0.04 (0.16)	0.04 (0.17)	
fe	15			−0.44 (0.14)			
hm	16				−0.05 (0.16)	0.02 (0.17)	
Model average (unconditional standard error)		0 0.02	0	−0.43 (0.15)	−0.1 (0.17)	−0.05 (0.18)	0.58 (0.16)

10 cm from the point of sprout emergence) at study site W and B was around 5700 per hectare. Each of the stumps at site W tended to develop around 7 sprouts $\geqslant 1$ cm within two vegetation periods after coppicing. At site B we observed on average 5 sprouts $\geqslant 1$ cm per stump. The harvesting method had no effect on the dimensions of the new sprouts (Fig. 3).

3.2.1. Factors influencing sprout growth

We found that maximum sprout height was a representative and easy-to-measure parameter describing re-sprouting intensity. Therefore, we used this response variable to quantify the impact of treatments and stump and parent tree characteristics on re-sprouting.

Average maximum sprout height differed significantly between study sites (in fenced areas: W = 152 cm, B = 130 cm; MWU-test: $p \leqslant 0.001$). In agreement with results for stump mortality, browsing had a strong effect as depicted by the difference in maximum sprout height between fenced and unfenced areas (Fig. 4). Outside the fence, average maximum sprout height was reduced by almost half at study site W, and by more than 70% at study site B, when compared to inside the fence.

At both study sites, maximum sprout height per stump was not affected by harvesting method (Fig. 5) or the average stump height. Moreover, no relationship was found between maximum sprout height and stump status (i.e. single or grouped growing stumps) or between maximum sprout height and parent tree dbh.

3.2.2. Sprout origin

Although height and diameter growth of the dominant sprouts were little affected by harvesting methods (Figs. 3 and 5), the point of sprout origin was influenced by stump height. In fenced areas, 63% of all stumps subjected to the traditional low cut harvesting method formed all of the three highest sprouts per stump below ground. This was significantly more than in the other harvesting methods (Kruskal–Wallis test $p \leqslant 0.001$). Only in ca. 40% of the stumps cut conventionally or fully mechanized, all of the dominant sprouts emerged below ground.

4. Discussion

4.1. Stump survival

In this study, 16% of oak stools (i.e. stumps within stools and single growing stumps) were apparently dead after two vegetation periods following harvest. A similar stool mortality was also observed in 30–80 year old (former) oak coppice forests growing in northern Luxemburg (canton Ösling; Krischel, 2006). In 60 year old *C. sativa* (Mill.) coppice stands, stool mortality was found to be slightly lower (10.6%; Guidici and Zingg, 2005). Moreover, the rate of stool mortality measured in this study was four times higher than observations made 4 years after coppicing a regularly managed *Quercus ilex* (L.) coppice forests in southern France (Ducery and Turrel, 1992). Conditions within these studies might not have been comparable, but they demonstrate that stool mortality occurs across various species, types of coppice forests and age classes. Hence, stump mortality is not a characteristic unique to aged oak coppice forests.

Surprisingly, a considerable proportion of apparently dead trees developed new sprouts after coppicing. These trees had either no living foliage and had almost no bark at the time of the pre-harvest inventory, however, some living buds must have remained. Root

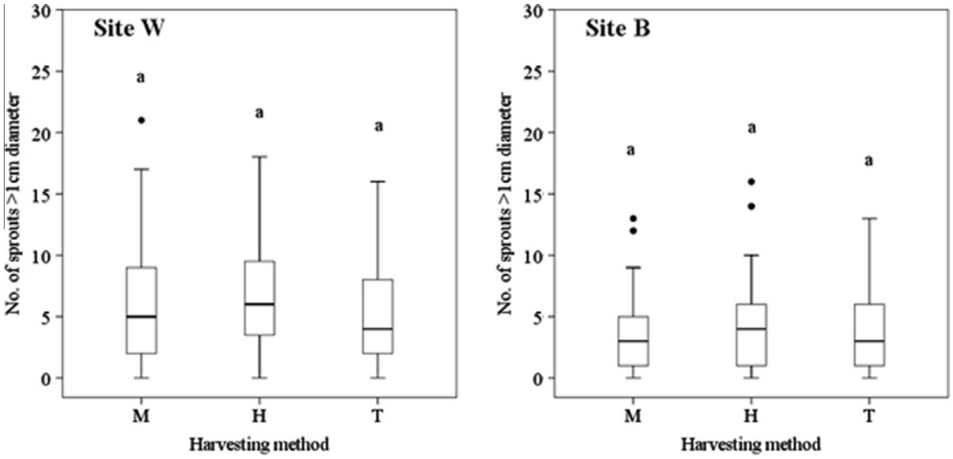

Fig. 3. Number of shoots with > 1cm diameter per stool for *Q. petraea* in relation to different harvesting methods (M=motor manual, H=fully mechanized, T=traditional low cut) in fenced areas of the study sites Weisel (W) and Baumholder (B). Different letters indicate statistical significant differences between harvesting treatments within one study-site (Kruskal,-Wallis-Test, p⩽0.05). N(site W)= 129, N(site B)= 262.

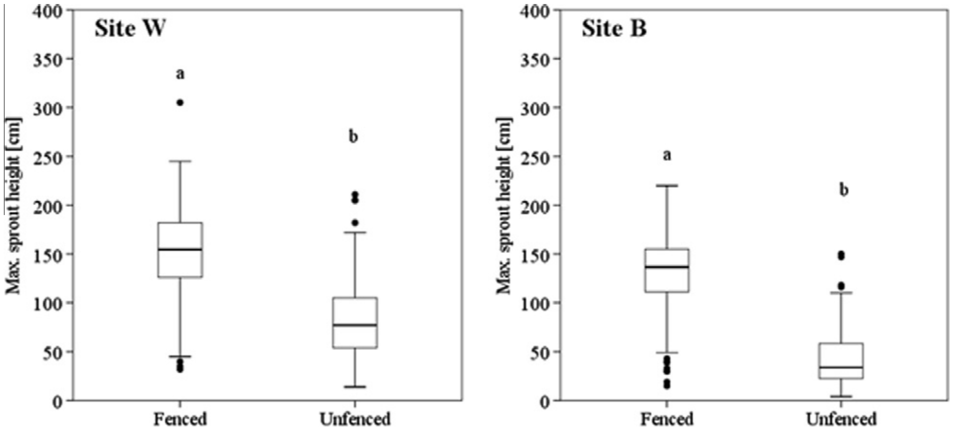

Fig. 4. Maximum sprout height [cm] of *Q. petraea* stumps in fenced and unfenced areas at the study sites Weisel (W) and Baumholder (B). Different letters indicate statistically significant differences within one study-site (MWU-test, p⩽0.001). N(site W)= 295, N(site B)= 566.

anastomosis, i.e. root grafting between individual trees (Schweingruber et al., 2008), might have ensured their survival and allowed stumps of apparently dead trees to re-sprout, as had been reported for *Castanea sativa* (Guidici and Zingg, 2005).

In accordance to Hamm (1896) 250–300 stools per hectare are acceptable to restock a site for the next coppice generation on high growth potential sites, while on less fertile sites 800 and more stools per hectare are needed. In this study the mean number of living stools per hectare found at the two study sites ranged between 654 (study site W) and 758 (study site B).

To estimate the optimal stocking density at the end of a coppice rotation, we chose the “crown width model” for 10–45 year old oaks developed by Nutto (1999). Based on this model calculation, stocking should be 1300 stems ha^{-1}, to achieve a minimum dbh of 15 cm (minimum stem diameter for commercially viable, fully mechanized harvesting) and a fully stocked site within a typical coppice rotation of 30 years. To reach this stocking density, every living stool at each study site has to develop at least two dominant sprouts or future crop stems, respectively. Before harvesting the 80–90 years old coppice stands, roughly 60% of all oaks were still growing in stools (i.e. growing together with at least one other stem). Therefore, it is very likely that, due to a shorter self thinning phase, the number of stools with at least two dominant sprouts would be higher in younger stands (see also Dohrenbusch, 1983). Hence the observed regeneration at both study sites can be regarded as acceptable.

We observed a higher mortality of stumps growing within stools than for solitary stumps at site B. Owing to the fact that this phenomenon occurred only at one of the sites, we have no plausible explanation for it. Our results also indicated that even in aged oak coppice forests, there is a sufficient number of re-sprouting stools to regenerate the forest vegetatively. In contrast to the widespread opinion of many forest practitioners and various authors (e.g. Becker, 2002; Jentsch, 1899; Mulopulos, 1927; Pott, 1990), we cannot confirm the assumption, that re-sprouting ability is low or absent in old parent trees. Differences between observations documented in the literature and the results of this study are difficult to explain but might be related to site quality and time of harvest. According to von Drais, 1807 the optimal time for coppicing is March and April. The majority of the study stands were harvested during this time and the high re-sprouting ability could be attributed to this factor.

4.2. Vitality of sprout growth

Stump mortality would be of no relevance if the new sprout generation grew poorly. However, sprout growth of sessile oak was vigorous. Only two vegetation periods after harvest, maximum

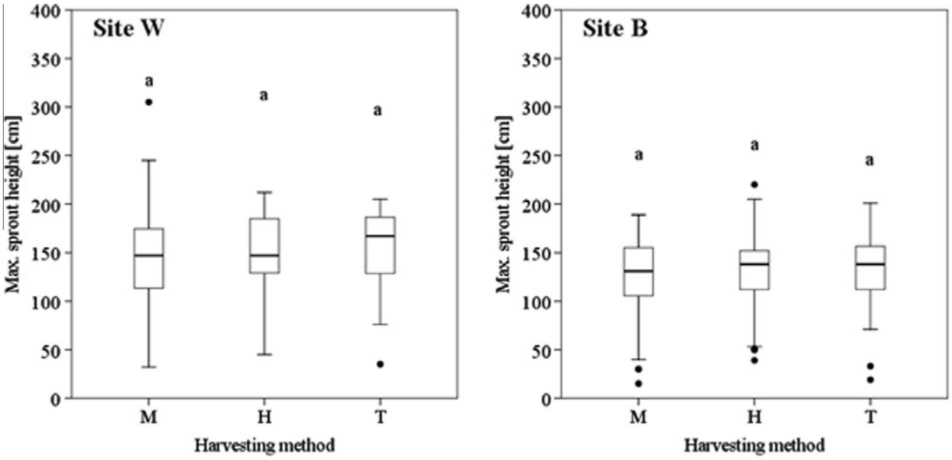

Fig. 5. Maximum sprout height [cm] of *Q. petraea* per stumps in relation to different harvesting methods (M=motor manual, H=fully mechanized, T=traditional low cut) in fenced areas of the study sites Weisel (W) and Baumholder (B). Different letters indicate statistically significant differences within one study site (MWU-test, $p \leqslant 0.05$). N(site W)= 129, N(site B)= 316.

sprout height per sessile oak stool was, on average, 152 cm at study site W, and 130 cm at study site B. These values were in agreement with old and recent records of initial annual height growth in regularly managed oak coppice stands (Hamm, 1896; Sorg, 1989). Also for various North American oak species (*Quercus prinus* L, *Q. coccinea* and *Q. velutina*) older than 66 years, a sprout height of 134 cm was observed 2 years after coppicing (Ross et al., 1986). The vigor of sprout height growth at both study sites suggests that coppicing can be resumed with old-parent trees.

4.3. Factors influencing re-sprouting ability and intensity

4.3.1. The impact of fencing

Browsing had the strongest influence on all coppice growth variables examined, even on stump mortality at site B. Differences between sites may be explained by higher abundances of ungulates (roe deer, fallow deer, European mouflon, red deer) at site B and the presence of crown slash at site W, which may have served as a protection against browsing for some stumps. Similar observations were made in previous studies (Sorg, 1989).

Clearly, the resumption of coppicing will only be successful when browsing intensity is reduced. Browsing was the only factor of all that were analyzed, which may discourage the resumption of coppicing.

4.3.2. The impact of harvesting method

In this study trees were cut using three different methods: (1) motor manual, (2) fully mechanized and (3) traditional deep cut. Since all methods involve the use of a chainsaw, no differences can be expected regarding the cut itself. However, for various technical (dimension of the stumps/stools) and ergonomic reasons (working safety and efficiency) the different methods resulted in different stump heights. Many authors regard a low cutting height as a crucial factor for re-sprouting (e.g. Coppini and Hermanin, 2007; Guidici and Zingg, 2005; Mudrich, 1961). In contrast to these authors, no relationship was found between harvesting method or stump height and stump mortality or coppice shoot vigor in our study. It is conceivable that differences in stump heights between the harvesting methods were not pronounced enough to cause differences. Additionally, the fact that in other coppice related studies no such relationship was found either (Ducery and Turrel, 1992; Roth and Hepting, 1943) indicates that this relationship is not a general rule. In addition, proventitious buds are most frequent near the root collar (Del Tredici, 2001) and that re-sprouting from this part of stumps is unaffected by stump height.

Similar to mortality, re-sprouting intensity (in this study expressed by the maximum sprout height per stump measured in fenced plots) was not related to harvesting method or stump height. These findings are in accordance with Ducery and Turrel (1992), who found that 4 years after harvesting there was no difference in terms of maximum sprout height and number of sprouts $\geqslant$1 cm, when *Q. ilex* trees were cut motor-manually either 0 or 15 cm above ground level. Likewise, there were only marginal differences in the number of new sprouts when different North American oak species were cut close to the ground or at a height of 30 cm (Roth and Hepting, 1943).

From a practical point of view, and in contrast to other suggestions (Jacke et al., 2010), our results show that aged oak coppice forests can be harvested by different methods and using conventional cutting heights without increasing stump mortality or decreasing re-sprouting intensity.

However, in agreement with previous studies (e.g. Jentsch, 1899), more dominant sprouts developed below ground, when trees were cut close to the soil surface. Therefore, a higher independence from the old root system, a lower breaking probability and therefore a higher sprout survival rate can be expected as advantages of lower stumps (Becker, 2002; Gould et al., 2007; Roth and Hepting, 1969; Wilson, 1968).

4.3.3. The impact of parent tree dimension

Many authors described a distinct relationship between stump mortality or re-sprouting intensity and parent tree dimensions (e.g. Johnson, 1975; Khan and Tripathi, 1986; MacDonald and Powell, 1983). However, in our study and in accordance to Gould et al., 2007 this relationship was only weak, which may be explained by a small dbh range and similarly aged parent trees (Gardiner and Helmig, 1997). In other studies, stump mortality only increased with increasing parent tree dbh when a diameter of more than 30 cm was reached (Johnson, 1975; Roth and Hepting, 1943). In our study mean dbh was less than 19 cm at both sites.

4.3.4. The combination of parameters

Although most of the factors considered had no direct impact on stump mortality the general linear and mixed models indicated that stump mortality might be dependent on a complex set of factors. The models indicate that re-sprouting ability of oak stumps was related to a combination of ontogenetic (parent tree dimension), anthropogenic (average stump height) and biotic factors (browsing), as was also suggested by Guidici and Zingg (2005). Their model (including the parameters: girth of the stool, distance to the closest neighboring stool, cutting height and cutting quality) explained 63% of the variation in re-sprouting of *Castanea sativa*.

5. Conclusions and silvicultural recommendations

The low stool mortality and vigorous sprout growth after two vegetation periods following coppicing of 80–90 year old oaks demonstrated that old stumps can still regenerate well.

In surprising contrast to a considerable number of previous studies, we found no clear relationship between the re-spouting behavior and harvesting methods. Hence, the necessity to cut trees as low as possible seems questionable. However, fully mechanized felling equipment must reach each stem separately and is forced to cut rather high above the ground. Under these conditions, motor manual-felling maybe a better alternative because it prevents wood waste (Suchomel et al., 2012).

Importantly, the number of dominant sprouts (i.e. the highest sprouts) originating from below ground parts of stump can be increased if stumps are re-cut close to the ground. This practice is likely to support the stability of the future stands.

At our study sites, browsing had a substantial influence on stump mortality and coppice shoot development. Hence, unless measures reducing browsing intensity to a tolerable level such as increased hunting or fencing cannot or shall not be implemented, regeneration of these types of forests should not be attempted. Owing to the rapid growth of new sprouts, these measures would have to be effective only for a few years.

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