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Development of Sessile Oak and European Hornbeam Sprouts after Thinning

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Abstract: We observed the growth of juvenile sprouts at stool level in an oak-hornbeam selective coppice after selective thinning. We tested the relations of sprouting probability, number and height of new sprouts, and stool biometric characteristics with thinning intensity and light conditions. We compared the results between the two species. The sprouting probability, number of new sprouts, and height of new sprouts were modelled using different types of regression (logistic, generalized linear, and multiple linear regression) evaluated from 84 sessile oak (*Quercus petraea* Matt. Liebl.) and 139 European hornbeam (*Carpinus betulus* L.) stools with the same site conditions. There were no significant relations between sprouting probability and the tested parameters because nearly all stools re-sprouted. The growth (number and height) of new sprouts depended on the stool basal area before thinning and on thinning intensity. Light conditions (indirect site factor) only influenced the number of new European hornbeam sprouts in 2016 and the height of new sessile oak sprouts. The number of new sprouts in European hornbeam was higher than in sessile oak.

Keywords: light conditions; re-sprouting; stool basal area; stump sprouting probability; thinning intensity

1. Introduction

Coppicing has recently become more popular, as it provides a renewable source of energy (biomass and firewood), promotes higher biodiversity, and provides an adaptation of forest management to climate change [1–3].

Several coppice management systems may be distinguished, such as (a) traditional coppice forests; (b) coppice-with-standards forests; (c) short-rotation coppice forests; (d) 'high coppice' forests; (e) coppice forests for transformation and reconstruction; (f) pollarding/grazing forests; (g) selective coppice forests; and (h) shelterbelts [4,5]. In this study, we focus on selective coppice forests.

Selective coppicing has been used in several European countries and was established in Sweden for *Betula pendula* Roth, *Betula pubescens* Ehrh., and *Populus tremula* L. [6]; in Italy for beech [7]; in Spain for *Arbutus unedo* L. [8] and for *Quercus ilex* L. and *Quercus cerris* Wilk. & Costa [9]; and in France for *Quercus ilex* [10,11]. Our pilot project tested whether a selective approach applied to coppicing in the Czech Republic could be used under the current conditions for *Quercus petraea* Matt. Liebl. (sessile oak) and *Carpinus betulus* L. (European hornbeam). There are no recent results for selective coppicing in Central Europe. In the selective coppice system, sprouts of different ages are present on the same stool, for which the individual approach is considered as the most appropriate measure. During the rotation period—between eight and 12 years—the largest and the oldest sprouts are cut, and smaller sprouts are lightly thinned [7]. Another definition describes selective coppicing as a strategy in which trees are cut when they reach a certain height, resulting in an uneven aged structure, which favours shade tolerant species [4]. Sprouts that remain after thinning are called retained sprouts, and the new generation that emerges after thinning is called the new sprouts. In comparison with this management system, traditional coppice means that sprouts on one stool are of the same age. At the end of the rotation period, all sprouts in the stool are harvested. Low thinning or thinning from below consists of the removal of suppressed and sub-dominant trees of a small diameter cut primarily from the lower part of the canopy. The goals of such low thinning are to remove competing smaller trees and to establish better conditions (more light, water, and nutrients) for the growth of larger trees [12]. The removal of mature stools (stools that consist of individual sprouts) and the consequent formation of secondary cutting surfaces encourage re-sprouting [13] and result in a more uneven-aged stand structure [14]. Early selective thinning can improve future sprout value and quality without compromising the stand stability or long-term financial viability [15]. Selective thinning may therefore be more attractive in urban forests [6].

Sessile oak, as a light-demanding tree species during early development, is considered moderately shade tolerant [16]. Sessile oak represents the main tree species in the uplands of the Czech Republic. European hornbeam is more shade tolerant and is more competitive with light-demanding species [17].

Our aim in the present study was to describe the growth of new sprouts in oak-hornbeam coppices during the first two years after selective low thinning. Together with light measurements, the results may be considered unique in the Czech Republic. We tested whether the sprouting probability and number and height of new sprouts were related to stool biometric parameters: basal area of the stool before and after thinning, leaf area index, etc. (1); thinning intensity (2); and light conditions (3). We also compared the results between the two species (4).

2. Materials and Methods

2.1. Study Area

The pilot project for selective coppicing (or uneven-aged coppicing) was established in Drahanská vrchovina in the southeast region of the Czech Republic, in the Training Forest Enterprise Masaryk Forest Křtiny, 323 m a.s.l. Predominant soil types are cambisols on a granodiorite bedrock. The dominant tree species are sessile oak and European hornbeam.

The pilot project was established at the beginning of the growing season in 2008, where the clear-cut was applied in the winter of 2008/2009. The sample plot was rectangular (125 m × 40 m), covering 5000 m^2 in total.

During the 2014/2015 winter, at a stand age of seven years, thinning from below was applied to 50 % of the sample plot (2500 m^2). The thinning intensity ranged between 6% and 83%. The weakest sprouts were cut, and one to four dominant sprouts per stool were left.

The positions of all stools were recorded, along with the stool basal area before (BA_{bt}) and after (BA_{at}) thinning, and the basal area of harvested sprouts (BA_t) was measured at the height of stump level. The thinning intensity (I_t), defined as the removed proportion of the total stool basal area, was computed from measured variables. The probability of stump sprouting, the number of live and dead new sprouts, and the height of the tallest new sprouts were recorded for both tree species after selective thinning. The sprouting probability was determined by logistic regression due to its suitability for modelling binary data (e.g., "occurrence" and "absence") [18]. In our data, "occurrence" was defined as at least one live new sprout, and "absence" was defined as the absence of any new live sprouts. In total, we analysed 84 sessile oak and 139 European hornbeam stools at this site.

The potential solar radiation below the canopy was evaluated by the analysis of hemispherical photographs taken in the centre of each stool 1 m above the ground using a Canon EOS 60D camera (Canon Inc., Tokyo, Japan) with a Sigma (4.5 mm) fisheye lens (Sigma corporation, Kanagawa, Japan) during the middle of the growing season after the thinning. The camera was levelled horizontally and oriented towards magnetic north using a compass. Photos were taken under standard overcast conditions early in the day. All images were analysed with WinScanopy software (version Pro 2012, Regent Instruments Inc., Québec, QC, Canada). The following data were used: gap fraction (GF), openness (OP), leaf area index (LAI) from the Licor LAI2000 using the generalized linear method, direct site factor (DSF), indirect site factor (ISF), and total site factor (TSF). Basic information concerning the measured data is listed in Tables 1 and 2.

Table 1. Basic characteristics of selected variables measured at stool level.

Variable	Species	Mean Value	Standard Deviation	Minimum Value	Maximum Value
BA_{bt} (m^2)	O	0.0050	0.0055	0.0005	0.0404
	H	0.0050	0.0030	0.0008	0.0152
BA_t (m^2)	O	0.0024	0.0033	0.0002	0.0243
	H	0.0025	0.0018	0.0002	0.0082
BA_{at} (m^2)	O	0.0025	0.0025	0.0003	0.0161
	H	0.0025	0.0015	0.0002	0.0092
I_t (%)	O	46.9289	15.7934	6.1305	80.3030
	H	48.8586	14.1870	15.0495	82.9964
GF (%)	O	11.3858	3.4163	3.3400	20.8100
	H	8.5797	2.8654	4.3900	18.0800
OP (%)	O	12.2251	3.6223	3.6200	22.3400
	H	9.3228	3.1226	4.8500	19.3700
LAI (m^2/m^2)	O	2.2394	0.3539	1.3500	3.2100
	H	2.5045	0.2652	1.7500	3.0300
DSF	O	0.2003	0.1239	0.0345	0.5898
	H	0.1550	0.0993	0.0494	0.6307
ISF	O	0.1622	0.0503	0.0516	0.3014
	H	0.1313	0.0468	0.0641	0.3192
TSF	O	0.1953	0.1124	0.0367	0.5492
	H	0.1519	0.0906	0.0561	0.5857

BA_{bt}—stool basal area before thinning, BA_t—basal area of thinning, BA_{at}—stool basal area after thinning, I_t—intensity of thinning, GF—gap fraction, OP—openness, LAI—leaf area index, DSF—direct site factor, ISF—indirect site factor, TSF—total site factor, O—sessile oak, H—European hornbeam.

Table 2. Basic parameters of new sprouts.

Variable	Year	Species	Mean Value	Standard Deviation	Minimum Value	Maximum Value
height of new sprouts (cm)	2016	O	47.44	25.40	7.00	140.00
		H	57.44	21.33	20.00	138.00
number of live new sprouts (pcs/stool)	2015	O	7.17	8.47	0	49
		H	17.26	16.70	1	108
	2016	O	7.21	8.89	1	50
		H	13.36	11.30	0	82
number of dead new sprouts (pcs/stool)	2015	O	0.36	0.72	0	4
		H	0.93	2.35	0	15
	2016	O	1.66	1.94	0	9
		H	3.76	4.65	0	30

O—sessile oak, H—European hornbeam.

2.2. Data Analysis

Three types of models were built for an evaluation of the relationships between analysed variables:

- the sprouting probability model constructed using logistic regression (LR);

- the number of new sprouts model, which used a generalized linear model (GLM) with a Poisson distribution (live new sprouts) or with a zero inflated Poisson distribution (ZIP) (dead new sprouts);
- and the height model of new sprouts assembled by using multiple linear regression (MLR).

The logistic regression model of stump sprouting probability uses a binomial distribution with a logit-link function of the response variable. The significance of the model parameters was verified by the Wald statistic, and model significance was provided by the χ^2 test of maximum log-likelihood. The sprouting probability model is expressed by the equation:

$$p_{it} = \frac{e^{\beta_0+\beta_1 X_{1it}+\beta_2 X_{2it}+\ldots\beta_j X_{jit}}}{1+e^{\beta_0+\beta_1 X_{1it}+\beta_2 X_{2it}+\ldots\beta_j X_{jit}}} \tag{1}$$

p_{it}—modelled probability of stump sprouting; β_0, β_1, β_2, … β_j—estimated parameters of the model; and X_{1it}, X_{2it}, … X_{jit}—explanatory variables j of subject stool i in year t.

As the number of live new sprouts is a discrete variable, the dependent variable of the model follows a Poisson distribution with a log-link function. The model of live new sprouts could be expressed by the following equations:

$$E(Y_{it}) = \mu_{it} \tag{2}$$

where

$$\mu_{it} = e^{\beta_0+\beta_1 X_{1it}+\beta_2 X_{2it}+\ldots\beta_j X_{jit}} \tag{3}$$

$E(Y_{it})$—mean value of the distribution (fitted count) of the number of live new sprouts of the subject stool i in year t; μ_{it}—modelled mean for the Poisson count data; β_0, β_1, β_2, … β_j—estimated parameters of the model; and X_{1it}, X_{2it}, … X_{jit}—explanatory variables j of subject stool i in year t.

In the case of dead new sprouts, there were two sets of data. Count data (with true zeros—at stool level, there were only live sprouts (number of dead new sprouts was 0 = true zero) throughout the duration of the experiment), which are distributed as a Poisson with a log-link function, and false zero data (for example, a mistake by an observer who did not see any dead sprouts even though they were present or a dead sprout that broke off before counting), which have a binomial distribution with a logit-link function. For more information about true and false zero data, see [19]. The model for dead new sprouts thus has the equations [19]:

$$E(Y_{it}) = \mu_{it} \times (1-\pi_{it}) \tag{4}$$

where

$$\mu_{it} = e^{\beta_0+\beta_1 X_{1it}+\beta_2 X_{2it}+\ldots\beta_j X_{jit}} \tag{5}$$

and

$$\pi_{it} = \frac{e^{\gamma_0+\gamma_1 X_{1it}+\gamma_2 X_{2it}+\ldots\gamma_j X_{jit}}}{1+e^{\gamma_0+\gamma_1 X_{1it}+\gamma_2 X_{2it}+\ldots\gamma_j X_{jit}}} \tag{6}$$

$E(Y_{it})$—mean value of distribution (fitted count) of the number of dead new sprouts of the subject stool i in year t; μ_{it}—modelled mean for the Poisson count data; π_{it}—modelled probability of false zeros for the binomial distribution; β_0, β_1, β_2, … β_j, γ_0, γ_1, γ_2 … γ_j—estimated parameters of the model; and X_{1it}, X_{2it}, … X_{jit}—explanatory variables j of subject stool i in year t.

The significance of the model parameters of the number of new sprouts was tested by a z-test and the overall model significance by the likelihood ratio χ^2 test.

The model for the heights of new sprouts assumed a normal distribution (with an identity link function) of the dependent variable. The significance of the model parameters was tested by a t-test and the overall model significance by the F-test. The model can be expressed by the equation:

$$E(Y_{it}) = \beta_0+\beta_1 X_{1it}+\beta_2 X_{2it}+\ldots\beta_j X_{jit} \tag{7}$$

$E(Y_{it})$—mean value of distribution (fitted height) of the height of the new sprouts of the subject stool i in year t; $\beta_0, \beta_1, \beta_2, \ldots \beta_j$—estimated parameters of the model; and $X_{1it}, X_{2it}, X_{jit}$—explanatory variables j of subject stool i in year t.

All models were constructed for both species and years separately. Models were developed for each biometric variable concerning the state of the stools before and after thinning and for each variable characterizing the light conditions of the stools (Table 1). Forward stepwise regression was used for the selection of the best model based on the combination of tested variables. Goodness of fit characteristics of models based on each variable and the best combinations of variables according to stepwise regression for each model are shown in Tables S1–S4. Akaike's Information Criterion (AIC) [20], coefficient of determination (R^2) for the MLR model, and pseudo R^2 [21] for LR and GLM models were used as goodness of fit criteria. A statistically better model was chosen such that the value of AIC was seven to 10 units less than the comparison model [22] and according to the likelihood ratio test in the comparison of GLM models. All statistical analyses were performed using the software package *R* [23] and tested at a significance level $\alpha = 0.05$.

3. Results

3.1. Probability of Stump Sprouting

The fitted models of stump sprouting probability for sessile oak and European hornbeam were not statistically significant for the tested biometric variables and their combinations for either studied year (all tested models had p values > 0.05). This was because in 2015, 96.4% of sessile oak stumps re-sprouted, and only three stumps had no sprouts. The re-sprouting of European hornbeam stumps was 100% in the same year. In 2016, 100% of stumps of both studied species re-sprouted. We may thus conclude that the stump sprouting probabilities of sessile oak and European hornbeam did not depend on the tested variables, and the probability of stump sprouting was essentially 100% (96.4% for sessile oak in year 2015) for both studied species under the given conditions.

3.2. Live New Sprouts

The number of live new sprouts of sessile oak was significantly influenced by all tested variables in 2015 (Table S1). In 2016, only DSF and TSF were not significant (Table S1). The best model in both years was based on $\mathrm{BA}_{\mathrm{bt}}$ and I_{t}. The goodness of fit characteristics of the best models are presented in Table 3. The model parameters are listed in Table 4. Very similar results were obtained for European hornbeam. In both studied years, all tested variables were statistically significant (Table S2). The best selected models again contained a combination of independent variables. For European hornbeam in both years, $\mathrm{BA}_{\mathrm{bt}}$ and I_{t} were statistically significant, and in comparison to sessile oak, the model was improved by including LAI in the year 2015 (pseudo R^2 higher by 0.0014) and LAI and ISF in the year 2016 (pseudo R^2 higher by 0.0351). The goodness of fit characteristics of selected models are shown in Table 3. The estimates of the best model parameters are listed in Table 4. From the modelled curves in Figures 1 and 2, it is evident that with increasing $\mathrm{BA}_{\mathrm{bt}}$ and I_{t}, the fitted number of live new sprouts increased for both studied species. LAI and ISF had a negative influence on the number of live new European hornbeam sprouts, while $\mathrm{BA}_{\mathrm{bt}}$ and I_{t} positively affected the number of live new European hornbeam sprouts (Table 4, Figure 2). When we compare the fitted values of both studied species from Figure 3, we notice that the number of sessile oak sprouts was similar in both studied years, but the number of European hornbeam sprouts was different between the years 2015 and 2016 due to the higher mortality of European hornbeam sprouts. The number of live new European hornbeam sprouts was significantly higher than the number of sessile oak sprouts (with the same $\mathrm{BA}_{\mathrm{bt}}$ and I_{t}) (Figure 3).

Table 3. The goodness of fit characteristics of the number of live new sprouts model for both species.

Species	Year	Predictor	χ^2 (DF)	p	ps. R^2	AIC
O	2015	$BA_{bt} + I_t$	219.20 (3)	<0.0001	0.9265	626.5
	2016	$BA_{bt} + I_t$	223.21 (3)	<0.0001	0.9299	657.0
H	2015	$BA_{bt} + I_t$ + LAI	781.71 (4)	<0.0001	0.9964	1488.6
	2016	BA_{bt} + It + LAI + ISF	528.52 (5)	<0.0001	0.9768	1129.3

χ^2—likelihood ratio χ^2 test value, DF—degree of freedom, ps. R^2—pseudo R^2, AIC—Akaike information criterion, BA_{bt}—stool basal area before thinning, I_t—intensity of thinning, LAI—leaf area index, ISF—indirect site factor, O—sessile oak, H—European hornbeam.

Table 4. The estimation of parameters for the number of best live new sprouts models.

Species (year)	Predictor	Parameter	Estimation	SE	z	p
sessile oak (2015)	$BA_{bt} + I_t$	β_0	0.5819	0.1583	3.676	0.0002
		β_1	52.2106	3.8415	13.591	<0.0001
		b_2	0.0211	0.0029	7.114	<0.0001
sessile oak (2016)	$BA_{bt} + I_t$	β_0	0.6266	0.1569	3.993	<0.0001
		β_1	53.2652	3.7962	14.031	<0.0001
		β_2	0.0202	0.0029	6.848	<0.0001
European hornbeam (2015)	$BA_{bt} + I_t$ + LAI	β_0	2.7737	0.2463	11.261	<0.0001
		β_1	147.5858	5.8988	25.020	<0.0001
		β_2	0.0116	0.0017	6.739	<0.0001
		β_3	−0.5539	0.0834	−6.644	<0.0001
European hornbeam (2016)	$BA_{bt} + I_t$ + LAI + ISF	β_0	5.2030	0.5453	9.542	<0.0001
		β_1	120.4584	7.0269	17.142	<0.0001
		β_2	0.0106	0.0020	5.378	<0.0001
		β_3	−1.4214	0.1748	−8.131	<0.0001
		β_4	−2.3678	0.9455	−2.504	0.0123

z—z-test value; SE—standard error; β_0, β_1, β_2, β_3, β_4—model parameters; BA_{bt}—stool basal area before thinning; I_t—intensity of thinning; LAI—leaf area index; ISF—indirect site factor.

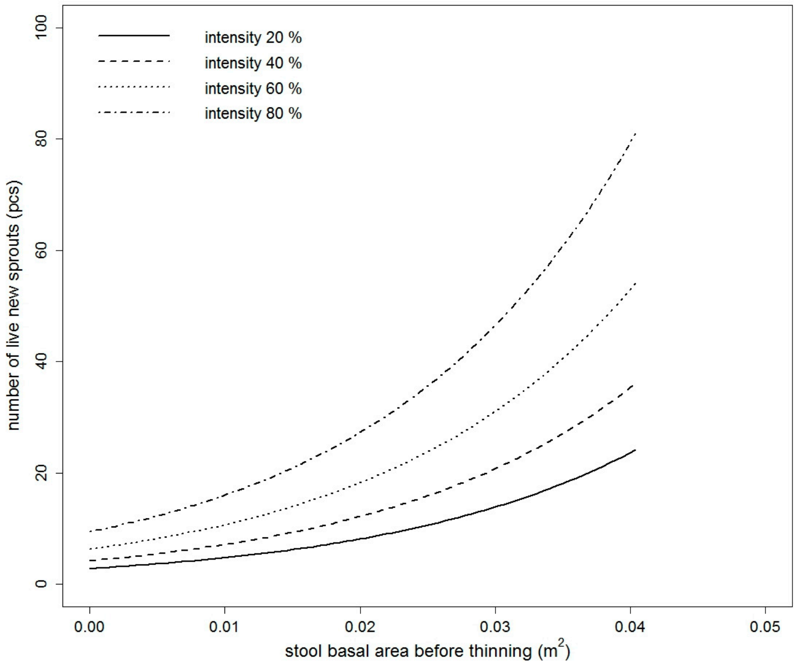

Figure 1. Fitted values of the number of live new sessile oak sprouts model based on the stool basal area before thinning and thinning intensity (2016).

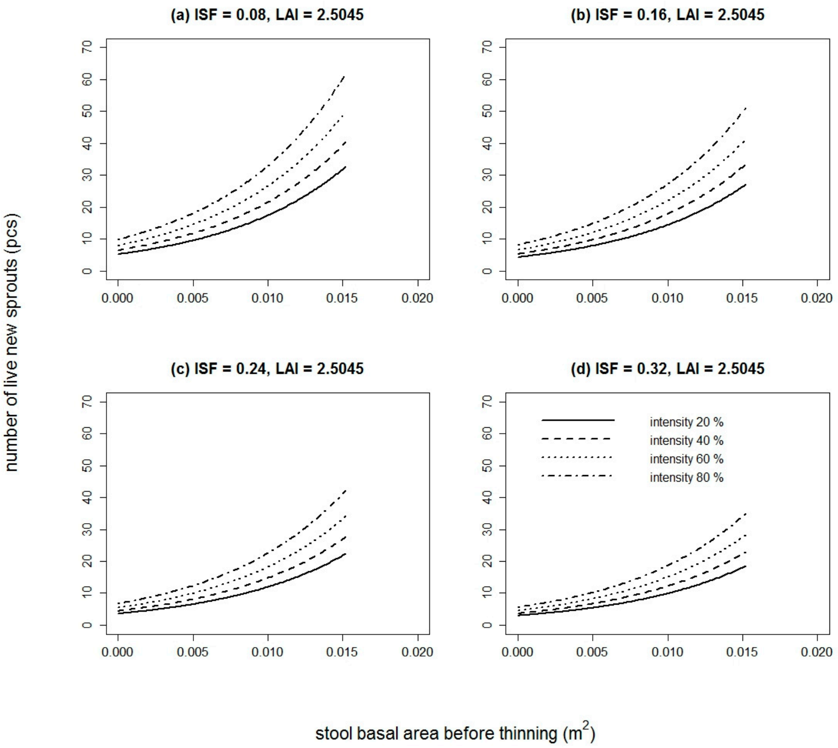

Figure 2. Fitted values of the number of live new European hornbeam sprouts model based on the stool basal area before thinning, thinning intensity, indirect site factor, and leaf area index (2016) (for the purpose of this figure, the mean value of LAI for European hornbeam stools is used).

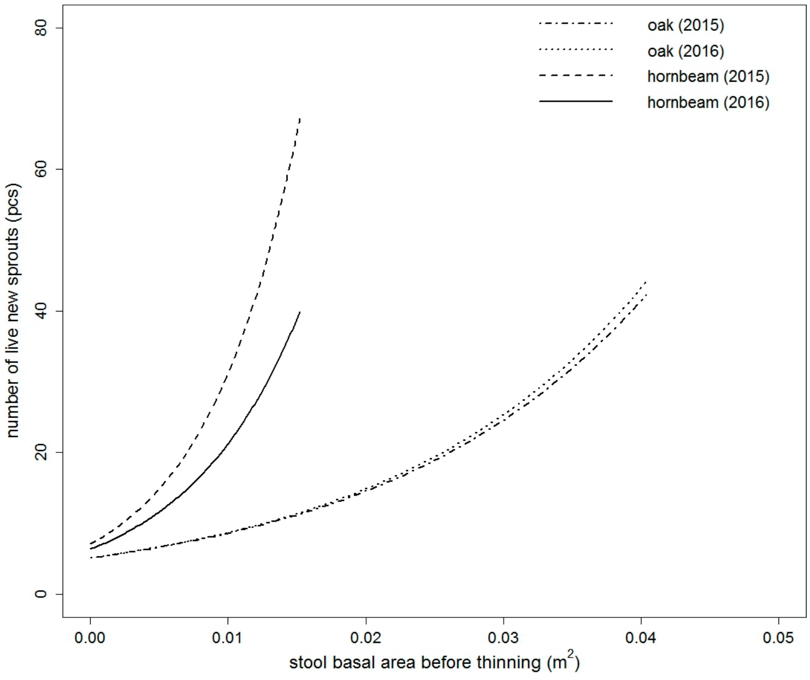

Figure 3. Comparison of fitted values of the live new sprouts model of sessile oak and European hornbeam in both studied years. Models are based on the stool basal area before thinning and thinning intensity (for both species) and indirect site factor and leaf area index (only for European hornbeam) (for the purpose of this figure, thinning intensity = 50% for both species and both years, ISF = 0.1313 for only European hornbeam in both years, LAI = 2.5045 for only European hornbeam in year 2016).

3.3. Dead New Sprouts

None of the tested independent variables were statistically significant for the number of dead new sprouts of sessile oak model in both studied years (all tested models had values of $p > 0.05$). The number of dead new sprouts of European hornbeam was influenced by BA_{bt}, BA_t, BA_{at}, and I_t in both studied years and in 2015, and GF and OP were also statistically significant (Table S3). The best model for European hornbeam in 2015 was fitted by BA_{bt} in combination with I_t as explanatory variables (Table 5). The false zeros part of the model was only influenced by BA_{bt}. The European hornbeam model in 2016 only had BA_{bt} (without the intercept in the false zeros part of the model) as an independent variable. The parameter estimates for the selected final models are shown in Table 6. The number of dead European hornbeam sprouts increased between 2015 and 2016 (Figure 4).

Table 5. The goodness of fit characteristics of the number of dead new sprouts model.

Species	Year	Predictor	χ^2 (DF)	p	ps. R^2	AIC
European hornbeam	2015	$BA_{bt} + I_t$	53.42 (3)	<0.0001	0.3411	337.3
	2016	BA_{bt}	128.42 (1)	<0.0001	0.6045	717.8

χ^2—likelihood ratio χ^2 test value, DF—degrees of freedom, ps. R^2—pseudo R^2, AIC—Akaike information criterion, BA_{bt}—stool basal area before thinning, I_t—intensity of thinning.

Table 6. The parameter estimates for the best model fit of the number of dead new sprouts.

Species (year)	Predictor	Parameter	Estimation	SE	z	p
European hornbeam (2015)	$BA_{bt} + I_t$	β_0	−1.1881	0.5304	−2.240	0.0251
		β_1	174.6932	27.6850	6.310	<0.0001
		β_2	0.0193	0.0083	2.336	0.0195
		γ_0	1.3417	0.4788	2.802	0.0051
		γ_1	−134.7950	69.8329	−2.041	0.0412
		γ_2	-----	-----	-----	-----
European hornbeam (2016)	BA_{bt}	β_0	0.6750	0.1017	6.637	<0.0001
		β_1	146.5458	12.8754	11.382	<0.0001
		γ_0	-----	-----	-----	-----
		γ_1	−280.8806	48.6000	−5.780	<0.0001

z—z-test value; SE—standard error; β_0, β_1, β_2, γ_1, γ_2—model parameters; BA_{bt}—stool basal area before thinning; I_t—intensity of thinning.

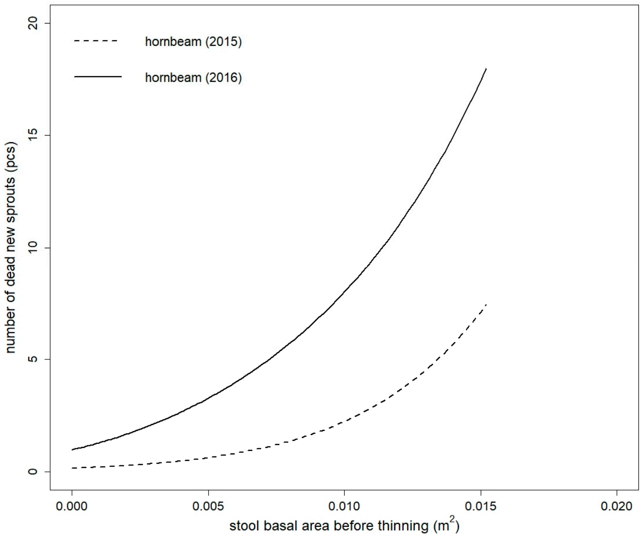

Figure 4. Comparison of fitted values of dead new sprouts model of European hornbeam in both studied years. Models are based on the stool basal area before thinning (for both years) and thinning intensity (only for year 2015) (for the purpose of this figure, thinning intensity = 48.8586%—mean value for European hornbeam).

3.4. Height of New Sprouts

The height of the new sprouts model differed in statistically significant variables between the two species (Table S4). For sessile oak, all biometric variables (BA_{bt}, BA_{at}, BA_t, I_t, LAI) were statistically significant. Of the variables representing light conditions, only GF, OP, and ISF were significant. Of the biometric variables, the height of new sprouts was best explained by BA_t. ISF had the greatest influence of the light characteristics. From all tested combinations, according to our evaluation criteria, the best model was based on BA_{bt} and ISF (without an intercept).

The height of the sessile oak sprouts increased with higher BA_{bt} and ISF values. The goodness of fit characteristics of the selected model are shown in Table 7, and the model-estimated parameters are listed in Table 8. For European hornbeam, the height of new sprouts was significantly influenced by GF, OP, ISF, DSF, TSF, and LAI (Table S4). Neither of the European hornbeam models explained more than 10% of the height variability of new sprouts. According to the goodness of fit characteristics, the best European hornbeam model was based on LAI (Table 7). The estimates of the model parameters are shown in Table 8; according to the estimates, the height of the European hornbeam sprouts decreased with increasing LAI. The mean heights of the European hornbeam and sessile oak sprouts (Table 2) were significantly different (t value = 3.0213, df = 152.2195, p value = 0.0029).

Table 7. The goodness of fit characteristics of the new sprouts height models.

Species	Predictor	F (DF)	p	R^2	AIC
sessile oak	ISF + BA_{bt}	230.862 (2, 82)	<0.0001	0.3166	514.4
European hornbeam	LAI	14.133 (1, 137)	0.0003	0.0935	840.1

F—F test value, DF—degrees of freedom, R^2—coefficient of determination, AIC—Akaike information criterion, ISF—indirect site factor, BA_{bt}—stool basal area before thinning, LAI—leaf area index.

Table 8. The estimated parameters of the new sprouts height models.

Species	Predictor	Parameter	Estimation	SE	t	p
sessile oak	ISF + BA_{bt}	β_0	—	—	—	—
		β_1	223.339	18.046	12.376	<0.0001
		β_2	2097.330	413.649	5.070	<0.0001
European hornbeam	LAI	β_0	119.124	16.499	7.220	<0.0001
		β_1	−24.600	6.544	−3.759	0.0003

SE—standard error; t—t test value; β_0, β_1, β_2—model parameters; ISF—indirect site factor; BA_{bt}—stool basal area before thinning; LAI—leaf area index.

4. Discussion

4.1. Probability of Stump Sprouting

Data are scarce concerning the re-sprouting probability in the selection system (selective thinning)-managed coppices. Conversely, there are much more data available on the probability of re-sprouting in forests managed by clearcutting [24–28] or by alternatives to clearcutting, including thinning, partial harvesting methods, and site-preparation activities [29–32].

We evaluated the probability of re-sprouting of newly established sessile oak and European hornbeam selective coppices in Drahanská vrchovina in the southeast region of the Czech Republic. For both tree species, re-sprouting was essentially 100% (resp. 96.4% for sessile oak in 2015) two years after selective thinning. We could not confirm the influence of the tested variables on the re-sprouting probability of the studied species. We assume that this can be explained by a small range of stump diameters (in selective low thinning, many thin sprouts are harvested), as in the study [33].

4.2. Live New Sprouts

In traditionally managed coppices (clearcut management) of *Quercus petraea*, *Carpinus betulus*, and *Tilia cordata* Mill., the number of new sprouts per stool depends on the stump diameter and species [30]. The relationship between tree size and the number of sprouts has been described in other species (*Quercus pubescens* Willd. or *Castanea sativa* Mill.) [34,35].

Similar results have been found in selective coppicing. The number of surviving sprouts per stool was significantly correlated with age and stool size after the partial thinning of sprouts in a holm oak coppice [36,37]. Taller trees have a more developed root system and therefore more sprouts per stump in European aspen and birch selective coppicing [6].

Our results indicate that the effects of the stool basal area (equivalent to diameter) before thinning, intensity of thinning, LAI, and light conditions (ISF) under the canopy on the initial development of sprouts (number of new live sprouts per stool) were statistically significant. With an increasing size of the root system (expressed by the stool basal area before thinning), sessile oak and European hornbeam increased the number of sprouts per stool. The increasing thinning intensity resulted in a higher number of new sprouts. The number of new sprouts depended on the thinning intensity and had different patterns in the two species. For example, in 2016 at a lower thinning intensity (20%), the number of live sprouts of European hornbeam (16) in thin stools (with BA_{bt} 0.01 m^2) was more than three times higher than that of sessile oak (5). With increasing stool BA_{bt}, the difference in the number increased. At an intensity of approximately 80%, the number of European hornbeam sprouts (98) (on stools with $BA_{bt} = 0.02$ m^2) was nearly four times higher than that of sessile oak (27). These results are valid for European hornbeam stools with mean values of LAI (2.5045) and ISF (0.1313).

The difference in the number of new sprouts between European hornbeam and sessile oak is perhaps because some tree species allocate more resources to the roots than to the sprouts [38]. Another reason for the different numbers of new sprouts could be the different demands of both tree species for ambient light. Our results confirmed a higher tolerance of European hornbeam to shade; with increasing diffuse radiation (ISF), the number of new European hornbeam sprouts decreased. In this method of regeneration (re-sprouting under the canopy), it is necessary to consider the differential intolerance of the species to shade (especially in sessile oak, even though it had a nearly 100% success rate) because many of the potential stands for such restoration in Central Europe are dominated or co-dominated by sessile oak [30]. If we wish to conserve more light-demanding species, we will need to open the canopy at relatively short intervals. Otherwise, more shade-tolerant species (European hornbeam) will predominate in the lower tree layer.

4.3. Dead New Sprouts

Within-stool sprout mortality can be generally attributed to a declining root:sprout ratio, resulting in increasingly longer periods for roots and sprouts to restore functional balance following periods of sprout elongation and expansion [39]. As documented in several coppice yield studies, the mortality curve has an exponential trend and declines rapidly during the life cycle of a coppice [34,37]. On the other hand, mortality can gradually increase after a disturbance, as documented in holm oak, where mortality was low after the first year of disturbance and then rapidly increased (42–56%) in the second year [37]. A 75% mortality rate for young sprouts that were higher than 1 m at four years of age is documented in a *Castanea sativa* coppice [34]. This finding is in accordance with the behaviour of European hornbeam in our study, in which the mortality had an increasing trend within the first two years of observation. Increasing mortality can be attributed to increasing competition and interference between sprouts [40–43]. The initial advantage of numerous sprouts is rapidly lost by increasing crowding, which induces self-thinning at a very young stage [41,44] that may also be supported by our results of European hornbeam.

The thinning method may have a significant impact on the growth and survival of sprouts. Single-tree selection significantly reduced stump sprout survival 10 years after harvesting in upland oak species compared with group selection and clearcutting [45]. For plantations of cherry bark oak and water oak, heavy silvicultural thinning treatments resulted in greater sprout survival than light thinning treatments [44,46,47].

In addition, the mortality of young sprouts can be affected by their distribution around the stump. Sprouts distributed unevenly around the stump cannot maintain the complete parent root system, so the survival and growth of the sprouts are significantly lower than those of stumps with evenly distributed sprouts [48]. This effect, when considered in survival analysis, could explain a large amount of data variance in future research.

4.4. Height of New Sprouts

In general, the tree canopy is opened after harvest, and tree crowns start to expand rapidly [49]. The greatest height increment of oaks is commonly observed in the first season after thinning [44].

Seedling height of a generative origin has been well studied [50–52], but for sprouts of vegetative origin, there are fewer studies.

The heights of sprouts of European aspen and birch were higher in traditional coppices than in selective coppices [6]. This may be a consequence of the lower light intensity in the residual stand and higher competition for available water and nutrients. According to our results, European hornbeam was only influenced by LAI. The height of new sprouts decreased with increasing LAI. We believe that the reason for this is related to the retained sprouts, which reduce the growth rate of the newer sprouts. In sprouts that developed under the light overstory, a decrease in average height was observed. Thus, there is evidence that canopy closure may have caused the reduced growth [31,44,45,53]. However, several studies claim that shading does not affect the total height, but does affect the crown surface [54]. For sessile oak, the height model of new sprouts was related to BA_{bt} in combination with ISF. This model explained more than 31% of the height variability of new sprouts. The height of new sprouts was greater with increasing BA_{bt}. New sprout height and maximum sprout diameter were correlated with the basal area and height of the retained stool [55]. New sprout height is supported by non-structural carbohydrates (starch is released from the lignotuber) and nutrients [8,10]. Selective thinning also influenced the height and diameter growth of retained sprouts of Mediterranean oaks (*Quercus ilex* and *Quercus cerris*) [56].

The height of new sprouts is closely related to mortality; smaller sprouts are less able to survive in dense and tall stands [6,49]. It is also known that taller trees have a more developed root system and therefore more sprouts per stump [6].

5. Conclusions

The present study describes the growth of new sprouts in an oak-hornbeam selective coppice after low thinning. Our aim was to find the relations between the sprouting probability, number, and height of new sprouts of sessile oak and European hornbeam and stool biometric characteristics (BA_{bt}, BA_t, BA_{at}, LAI), thinning intensity, and light conditions, and to compare the results of the two species. All stumps of both species sprouted two years after selective thinning, and the sprouting probability did not depend on any of the tested variables. The number of live new sprouts models for both species (for both studied years) was significantly influenced by BA_{bt} and I_t. European hornbeam models were influenced by LAI in both years and by ISF in 2016. The fitted number of live new sprouts was higher for European hornbeam. The number of dead new sprouts of sessile oak was not influenced by any of the tested variables in either of the studied years. The number of dead new sprouts of European hornbeam depended on BA_{bt} (in 2016) and on BA_{bt} and I_t (in 2015). The height of the new sprouts of sessile oak depended on ISF and BA_{bt}. The height of European hornbeam was only influenced by LAI in the best-fitted model. The mean height of European hornbeam was significantly higher than the mean height of sessile oak.

At comparable sites and for the examined tree species, the forest manager can obtain a realistic picture of the probability of re-sprouting, the number of new live and dead sprouts, and the expected heights of the sprouts with respect to the thinning intensities.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/9/308/s1, Table S1: The goodness of fit characteristics of the number of live new sessile oak sprouts model, Table S2: The goodness of fit characteristics of the number of live new European hornbeam sprouts model, Table S3: The goodness of fit characteristics of the number of dead new sprouts model, Table S4: The goodness of fit characteristics of the new sprouts height models.

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