Root spatial distribution and biomass partitioning in *Quercus robur* L. seedlings: the effects of mounding site preparation in oak plantations

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Abstract In a reforestation field experiment undertaken in southern Sweden and planted with pedunculate oak, three site preparation treatments (herbicide application (H), mounding site preparation (MSP) and combined herbicide and mounding treatment (H + MSP)) were compared to an undisturbed control (C). We analysed root spatial and biomass distribution in 48 harvested seedlings. Compared to the control, both MSP and H treatments resulted in a significantly higher root system biomass (means C: 16.4 g, H: 45.7 g, MSP: 41.4 g, MSP + H: 102.2 g). The proportion of lateral root biomass increased from 38% (C) to 62% (MSP + H), while the two remaining treatments (H, MSP) attained percentages of 48% and 51%, respectively. The treatments did not alter seedlings' allometry and root:shoot ratio significantly. However, biomass distribution of different root system parts varied among treatments, so that lateral root biomass increased relative to leaf biomass from C to MSP + H variant. Site preparation treatments (MSP, MSP + H) increased the horizontal extension

of root biomass, compared to C and H variants. We conclude that mounding site preparation is an efficient method for the reforestation of pedunculate oak stands. Due to the comparative positive effects on root system development, MSP presents an alternative to herbicide treatment, particularly at sites where the use of chemicals is restricted.

Keywords Pedunculate oak · Herbicide · Site preparation · Root collar diameter · Lateral root length · Root system biomass · Allometry · Root:shoot ratio

Introduction

Oaks (*Quercus* spp.) are major components of European temperate vegetation types, and oak forests previously covered larger areas than today (Bradshaw and Lindbladh 2005). For Europe, climate models project prolonged, and more frequent summer droughts in areas such as southern Scandinavia, central Europe and the Mediterranean, and an increased frequency of major storm events (Schär et al. 2004; Luterbacher et al. 2004; Leckebusch et al. 2006; Christensen and Christensen 2007; IPCC 2007). Oaks are among the most wind-stable and drought-tolerant tree species (Ellenberg 1988; von Lüpke and Spellmann 1999). Like other broadleaved tree species, they may become more competitive than several conifers like Norway spruce (*Picea abies*) and can attain higher production potentials due to increased air temperature and prolonged growing seasons (Koca et al. 2006). Thus, oaks are a preferred tree genus in any adaptation strategies to climate change for both ecological and economic reasons in these regions, and the oak forest area may increase in the future (Berg et al. 1994; Larsen 1995).

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Oaks are normally cultivated on fertile sites, where the natural herb and shrub vegetation is abundant and interferes strongly with newly planted tree seedlings (Löf 2000). Moreover, herbaceous vegetation on regeneration sites provides an environment suitable for voles, which may damage seedlings. The consequent low survival and poor growth of seedlings may result in substantial economic losses in forest management. Therefore, vegetation control on open sites during reforestation is needed and is usually achieved by using herbicides, mechanical site preparation, mulching or prescribed burning (e.g. Davies 1988; Dey et al. 2008). Due to their relatively high effectiveness combined with low cost, herbicides are often preferred. However, increased environmental awareness has urged a discussion on available alternatives (Willoughby et al. 2009). Mounding site preparation, i.e. inverted mounds on humus to create elevated planting spots, is an old mechanical site preparation technique that again is attracting attention (Sutton 1993). It presents an alternative, especially in boreal coniferous forest sites, where low soil temperature, high water table and competing herb vegetation are serious problems (Hawkins et al. 1995; Hallsby and Örlander 2004; Pennanen et al. 2005). Less research has been done on mounding site preparation in temperate zones for broadleaved species (Dey et al. 2008). Though results of several root studies provide insight into the rooting behaviour of oaks seedlings in competition with herbaceous and grass vegetation (e.g. Harmer and Robertson 2003; Collet et al. 2006), we lack knowledge about the effects of mechanical site preparation on root system characteristics for oak seedlings. Since root development plays a major role in competition among tree individuals (e.g. Leuschner et al. 2004; Bloor et al. 2008) and in competition between young trees and herbaceous vegetation for limited soil resources (Löf 2000; Coll et al. 2003, 2004), information about biomass partitioning to roots and root system extension forms the basis for appropriate evaluations of regeneration success.

The present study was conducted on a temperate forest site in southernmost Sweden to increase the efficiency of oak stand establishment. Following our discussion of

growth and survival (Löf et al. 2006), this paper focuses on seedling root development in mounding site preparation treatments with and without herbicide application. The specific objectives of this study were (1) to analyse whether herbicide and mounding site preparation treatments changed seedling allometry and biomass partitioning in various plant compartments above and below ground, (2) to examine treatment effects on the horizontal and vertical root system extension and (3) to evaluate any benefits of mounding site preparation with or without herbicide application on seedling development.

Materials and methods

Site and experimental design

The study was conducted in the Skarhult experimental forest (55°50'N/13°24'E, 90 m a.s.l.), Scania (southern Sweden), which has been subjected to wind-throw damage. The 4.3 ha study site comprised a 32-year-old hybrid larch (*Larix * eurolepis* Henry) stand planted in 1970, which replaced a European beech (*Fagus sylvatica* L.) stand damaged by wind-throw in 1967, and which subsequently was wind-thrown in December 1999.

The mean monthly temperature and precipitation at Lund, 15 km west of Skarhult, ranged from −0.3 to 17.9°C and from 67 to 87 mm in January and July, respectively. During the study, no extreme low or high precipitation periods occurred (Anonymous 2002–2004).

Soil type was a gleyic cambisol (Gleyic B., FAO 1988, Table 1) developed from loose moraine sediments. A sandy loam soil texture prevailed to a depth of 60 cm with a 25–43% sand, 40–50% silt and 17–25% clay content (Ad-hoc-AG Boden 2005). The potential tree rooting zone is seasonally water saturated as the height of the groundwater table varies from 40 to 60 cm depth.

Soil fertility was classified as moderate with a medium C/N ratio (Table 1). The soil was acidic with a moderate to low cation exchange capacity (CEC) and a moderate CEC saturation of the base cations K, Mg and Ca.

Table 1 Chemical soil properties of the organic layer and the rooted mineral soil

	pH (KCL)	C/N ratio	CEC ($\mu\text{eq g}^{-1}$)	Al (% CEC)	K + Ca + Mg (% CEC)
Oh (organic layer)	4.2	17.8	–	–	–
Ah (min. soil 0–10 cm)	3.8	17.9	71	63.7	17.4
Bv (min. soil 10–27 cm)	4.1	–	30	84.9	8.6
Bv-Go (min. soil 27–58 cm)	4.1	–	24	87.0	7.8

Oh humified organic layer containing amorphous organic material, Ah humified mineral top soil horizon, Bv cambic mineral soil horizon, Bv-Go cambic/gleyic mineral soil horizon (AK Standortskartierung 1996), CEC effective cation exchange capacity, Al exchangeable aluminium ions, K + Ca + Mg sum of exchangeable base cations

A randomised block experimental design was adopted on the fenced experimental site comprising four blocks each with four variants: herbicide (H), mounding site preparation (MSP), mounding site preparation plus herbicide (MSP + H) and untreated control (C). The blocks were 27×25 m (0.067 ha) in size, spaced 4 m apart and were located approx. 20 m from the nearest forest edge. At the end of April 2002, each variant was planted with 25 bare-root pedunculate oak seedlings (*Quercus robur* L., 1/0, 15–25 cm, Visingsö-Herrängen, southern Sweden, $58^{\circ}02'N/14^{\circ}19'E$, 110 m a.s.l.) in three randomly placed rows 1 m apart using a planting spade. The provenance from Visingsö is considered of high quality, but initially different seed sources from southern Sweden was used to establish this stand in 1865, why the exact seed origin is rather blurred. The distance between rows and treatments was approx. 2 m. The mounding site preparation treatments (MSP), also called bedding (Sutton 1993), were prepared in early April 2002, with an excavator forming approx. 25 m long, 2 m wide and 20 cm high inverted mounds on humus. In the herbicide treatments (H), glyphosate (0.3 g m^{-2} active gradient) was applied in early June and mid-July during the 2002, 2003 and 2004 growing seasons. The herbicide was applied in strips approx. 25 m long and 1 m wide along the planting rows alongside the seedlings.

Root extractions and additional assessments

In early December 2004, three growing seasons after commencement of the experiment, three oak seedlings were selected from each block (no. 5, 6 and 7 in the first row). The root collar (d_0) was marked to indicate northerly direction on the shoot and the boundary between the above- and below-ground plant compartments. Thereafter, we extracted carefully the entire root systems with coarse and fine root parts by digging and manually removing soil material around the roots using small hand tools. The root systems were washed under running water in the field, and the length and orientation of the three longest roots were recorded for each seedling. In the laboratory, the root systems were divided into sections representing (1) horizontal 10 cm distance classes from stem axis, (2) vertical 10 cm distance classes from soil surface and (3) four ordinal classes of root system orientation, i.e. NE, SE, SW and NW (Fig. 1). The remaining stump part located below ground was analysed separately. The dry mass component of the seedling stem and the roots in each section was determined after drying at 70°C for 72 h. In addition, data for the above-ground seedling components of leaf and stem biomass, used for reference purposes in the analyses, were derived according to the methods described in Löf et al.

Fig. 1 Schematic illustration showing the framework for recording coarse root dimensions, based on the *horizontal* and *vertical* sectioning of the root systems

(2006). Leaves from the seedlings were sampled at the end of September 2004.

Data analysis and distribution modelling

Allometry assessments were performed to describe the relationships between root collar diameter (RCD) and the root structural traits of maximum lateral root length (MRL) or dry weight of total root system biomass (TRB). A linear function (Eq. 1) was fitted with a simple least square regression using transformed variables (cf. Le Goff and Ottorini 2001; Bolte et al. 2004):

$$\ln y = \beta_0 + \beta_1 \ln x, \quad (1)$$

where y = maximum lateral root length [MRL, cm] or total root system biomass [TRB, g dry weight]; x = root collar diameter [RCD, cm]; β_0 , β_1 = empirical parameters.

Finney (1941) suggested a bias correction function (Eq. 2) be applied to estimate the bias due to the use of transformed variables in the regression analysis.

$$K = e^{s_{\ln}^2/2} \left\{ 1 - \frac{s_{\ln}^2}{4n} (s_{\ln}^2 + 2) + \frac{s_{\ln}^4}{96n^2} (3s_{\ln}^4 + 44s_{\ln}^2 + 84) \right\} \quad (2)$$

where $s_{\ln}$ = standard deviation of $\ln$ -transformed values ($\ln x$, $\ln y$), n = number of samples.

We performed a non-parametric Kruskal–Wallis H test for comparisons of biomass partitioning between the above- and below-ground plant compartments, as well as of root structure data among the different horizontal and vertical sections of the different variants.

Horizontal biomass distribution of sapling root systems was modelled for all treatments separately by fitting

horizontal section biomass values to a logistic model distribution (Eq. 3); root collar diameter and distance from stem centre were the predictor variables. The first 10 cm section (0–10 cm distance from stem centre) also included stump biomass below ground. Nielsen and Mackenthun (1991) used a similar model approach for modelling vertical fine root distribution of old-growth Norway spruce and European beech.

$$z = \frac{\beta_0 \cdot x^{\beta_1}}{1 + \beta_2 \cdot e^{(\beta_3 \cdot y)}} \quad (3)$$

where z = root section biomass incl. stump [RSB, g dry weight]; x = root collar diameter [RCD, cm]; y = horizontal distance from stem centre (mean of 10 cm section) [HD, cm] or soil depth (mean of 10 cm section) [SD, cm]; $\beta_0, \beta_1, \beta_2, \beta_3$ = empirical parameters.

All derived data were stored in a MS Access database. We used Statistica 7.1 (StatSoft Inc. 2005) for all statistical analyses and modelling purposes. In the comparisons, $P < 0.05$ was considered significant.

Results

A positive treatment effect on both root and seedling biomass (cf. Löf et al. 2006) was observed 3 years after the experiment commenced. The combined use of mounding site preparation and herbicide (MSP + H, Table 2) led to a significantly higher above- and below-ground oak biomass, almost six times higher than for the control variant (C). A significantly higher root system biomass was found also in the herbicide application (H) and the site preparation treatment (MSP). This increase was less clear for above-ground biomass and different root system fractions (lateral roots, tap roots). Differences between H and MSP treatments were small. The proportion of lateral roots of the entire root system biomass rose from 38% (C) to 62%

(MSP + H). The herbicide (H) and site preparation (MSP) treatments attained similar values of 48% and 51%, respectively.

Allometric relationships were found between root collar diameter (RCD) and either total root system biomass (TRB, dry weight) or maximum lateral root length (MRL) for all pedunculate oak saplings (Table 3, Fig. 2a, b). Linear regression functions obtained from log-transformed data [Eq. (1)] attained medium to high coefficients of determination. The residuals are normally distributed according to a Shapiro–Wilk normality test ($P < 0.05$). No clear indication was found of a difference in relationships between the different site preparation treatments (Fig. 2a, b).

Moreover, treatment effects on biomass distribution patterns between above- and below-ground plant compartments were less obvious, and even inconsistent for total biomass or plant fractions. Whereas the root:shoot ratio was not affected significantly by the different treatments compared to control (Fig. 3, cf. Löf et al. 2006), and remained quite constant over the entire root biomass spectrum (Fig. 4a), biomass partitioning to lateral roots increased relative to partitioning to leaves along the gradient from control (C) to mounding site preparation combined with herbicide application (MSP + H, Fig. 4b). This resulted in a significant difference in biomass ratios of lateral root to leaf fractions when comparing the most intensive treatment (MSP + H) with the control (C, Fig. 3).

Analyses of the root system orientation revealed no significant variation in root system biomass in the four ordinal direction classes (NE, SE, SW, NW; Kruskal–Wallis test, control: $P = 0.07$; MSP: $P = 0.19$; H: 0.80; MSP + H: 0.52), and thus no root anisotropy. Therefore, all direction classes were merged for further analyses of spatial root distribution.

Horizontal root system extension and biomass distribution varied between the different treatments. In the

Table 2 Root system and biomass distribution traits of the oak seedlings ($n = 48$)

	Treatment			
	C	H	MSP	MSP + H
Max. lateral root length* (cm)	29.8 ^a ± 8.8	42.6 ^a ± 11.9	38.8 ^a ± 8.7	49.8 ^b ± 11.0
Lateral roots (g)	6.3 ^a ± 5.8	22.1 ^{a,b} ± 16.5	20.9 ^b ± 12.1	63.4 ^b ± 46.3
Taproot (g)	10.1 ^a ± 5.5	23.7 ^b ± 13.4	20.5 ^a ± 10.9	38.8 ^b ± 12.3
Total root system biomass (g)	16.4 ^a ± 8.0	45.7 ^b ± 29.3	41.4 ^b ± 18.9	102.2 ^c ± 46.5
Total biomass above ground (g)	29.9 ^a ± 28.8	69.6 ^a ± 44.3	72.4 ^{a,b} ± 42.6	173.4 ^b ± 84.1
Total biomass (g)	46.2 ^a ± 36.3	115.3 ^a ± 73.0	113.8 ^a ± 60.3	275.6 ^b ± 126.7

Mean values ± SD are displayed. Means followed by different letters (a, b or c) resulted in significant differences between treatments ($P < 0.05$, Kruskal–Wallis H test); treatment description: C control, H herbicide application, MSP mounding site preparation, MSP + H combination of mounding site preparation and herbicide application

*Mean of the three longest lateral roots

Table 3 Regression equations for predicting root structural traits from root collar diameter (*RCD*)

Root collar diameter [<i>RCD</i>]	Total root system biomass [<i>TRB</i>]	Max. lateral root length [<i>MRL</i>]
$\beta_0 \pm SE$	-2.29 ± 0.34	1.72 ± 0.24
$\beta_1 [\ln RCD] \pm SE$	2.06 ± 0.12	0.67 ± 0.08
<i>N</i>	48	48
R^2	0.87	0.59
<i>S</i>	0.30	0.21
<i>K</i>	1.04	1.02

All equations are of the form $\ln y = \beta_0 + \beta_1 \ln x$, see Eq. (1), y = total root system biomass (*TRB*, g) or y = maximum lateral root length (*MRL*, cm), x = root collar diameter (*RCD*, cm), β_0 , β_1 = regression coefficients (empirical parameters, rounded to two decimals) with standard errors in parentheses ($\pm SE$). R^2 = coefficient of determination (R^2), s = standard deviation of residuals (“standard error” of estimation) and K = bias correction factor, see Eq. (2), are displayed. All model parameters were statistically significant ($\alpha = 0.05$) in accounting for variation in *RCD*

Fig. 2 Relationships between root collar diameter ($\ln RCD$) and **a** total root system biomass ($\ln TRB$), **b** maximal lateral root length ($\ln MRL$). Scatter data are differentiated into different treatments. For descriptions of treatments, see text. The equations of the regression lines are presented in Table 3

horizontal root distributions modelled from the median seedling *dbh* (Fig. 5a, b), seedlings in the control (C) and the herbicide treatment (H) exhibited a stem-centred root biomass distribution. In the C treatment, 83% of root system biomass was found within 10 cm of the stem centre, and only small root biomass proportions were found at distances 20 cm beyond the stem. Seedlings in the H treatment also showed this rooting pattern (73% root biomass <10 cm stem distance). In contrast, MSP and MSP + H treatments induced a higher biomass partitioning to lateral roots. This resulted in a more extensive root system, and, compared to the C treatment, higher proportions of root biomass in >10 cm distance from stem centre (MSP: 30%, MSP + H: 39%) and considerable root biomass at distances up to 30 cm from stems.

Less variation was found in the general shape of the vertical rooting distribution (Fig. 5c, d). Mean rooting depth increased from 30 cm in the C treatment to about 60 cm (MSP + H). The treatments with site preparation (MSP) and herbicide application (H) attained similar mean rooting depths of 40 cm and a comparable vertical rooting distribution.

Discussion

Mounding site preparation has considerable positive effects on both the size and extension of the root system. This strongly supports previous experimental results (Löf et al. 2006), which focussed on site preparation effects on survival and above-ground performance of seedlings. The results emphasise the applicability of mounding site preparation for efficient reforestation. Similar conclusions have been reached in several previous studies of conifer and broadleaved tree species (Sutton 1993; Gemmel et al. 1996; Nilsson and Örlander 1999; Patterson and Adams 2003; Hallsby and Örlander 2004; Pennanen et al. 2005).

Regarding whole seedling development, less interference from ground vegetation compared to the control (C, vegetation cover 2004: 95.9%, see Löf et al. 2006) is reputedly the main reason for seedling superiority in repeated herbicide treatments with and without site preparation (H, vegetation cover: 12.4%, MSP + H, vegetation cover: 6.7%) (e.g. Davies 1988; Löf 2000; Collet et al. 2006). However, in this study, mounding site preparation without herbicide application (MSP) and higher vegetation

Fig. 3 Biomass ratio below and above ground. Mean $\pm$ S.D. *Blank bars*: ratio of total root biomass and shoot biomass (root:shoot ratio), *grey bars*: ratio of lateral root biomass and leaf biomass, in g g^{-1} , dry weight. Treatments followed by different letters (greek for compared root:shoot ratios, latin for compared sub-fractions) resulted in statistically significant differences ($P < 0.05$, Kruskal–Wallis H test). For descriptions of treatments, see text

cover (95.9%) also resulted in seedling development similar to that in the herbicide treatment (H, Table 2). Moreover, the higher horizontal root extension and higher lateral root biomass compared to the control (C) and the herbicide treatment (H, Fig. 5a, b) indicate a specific effect of the MSP treatment on the seedlings. This is particularly obvious when comparing seedlings with the same root collar diameter (Fig. 5b). Weed reduction in the seedlings' first year, and the improvement in soil conditions by increasing the fine texture, organic matter content and humus mineralisation in the top soil may be the reasons

(Örlander et al. 1990; Carlquist 2000; Löf et al. 2006). Thus oak seedlings seem to follow a root foraging strategy by extending their root system into soil nutrient hot spots (De Kroon and Mommer 2006, p. 114; Grime and Mackey 2002) and into soil areas with fewer roots from competitors (Grime 1979; Bauhus and Messier 1999; Bolte and Villanueva 2006). Moreover, at cool sites with temporary water-logging, like ours, mounding site preparation may increase heat absorption and consequently create better conditions for lateral root growth (Lyr and Garbe 1995; Lyr 1996; Carlquist 2000).

In contrast to MSP seedlings, those treated with herbicides (H) had a significantly higher taproot biomass (Table 2), but both MSP and H seedlings showed similar vertical rooting patterns. Considerably deeper and laterally more extensive rooting was found for seedlings treated with both herbicide (H) and mounding site preparation (MSP; Fig. 5c, d).

As mounding may result in a break down in soil capillarity, when mineral soil is loaded onto humus, dry soil conditions may result and have been reported to influence seedling growth and survival (e.g. Hallsby and Örlander 2004). Although we did not find any low soil water potentials in this study (Löf et al. 2006), particularly dry sites probably should be avoided when using mounding.

Diameter at breast height (*dbh*), or root collar diameter, commonly is used in tree allometry to estimate root biomass for young trees (e.g. Drexhage and Colin 2001; Le Goff and Ottorini 2001; Hoffmann and Usoltsev 2001; Knapp et al. 2006). A comparison of the results of this study (Table 3) with recent compilations of allometric relationships between trunk size and root system biomass for oak species (*Quercus* spp.) (Zianis et al. 2005; Muukkonen and Mäkipää 2006) reveals that similar regression equations demonstrate the consistency of this relationship for oak independent of site and competitive

Fig. 4 Variation in biomass above ground versus biomass below ground; **a** Root:shoot ratio, i.e. total root system biomass ($\ln \text{TRB}$, g, dry weight) versus total biomass above ground ($\ln \text{TBA}$, g, dry weight). The displayed regression line and function (*) does not include three outliers with a root:shoot ratio above 1; **b** lateral root biomass ($\ln \text{RB}_{\text{lat}}$, g, dry weight) versus leaf biomass ($\ln \text{LB}$, g, dry weight). The regression line and function includes all values. The scattered lines represent the 1:1 ratio for the compared parameters

Fig. 5 Modelled spatial distribution of root section biomass [RSB]: (a, b) horizontal rooting; displayed lines represent either saplings' median RCD per each treatment sampling (a) or all saplings' median RCD = 1.85 cm (b); (c, d) vertical rooting, displayed lines represent

either saplings' median RCD per each treatment sampling (c) or all saplings' median (d); CD_{lin} : Non-linear coefficient of determination. The distributions are results of the fitting to the logistic model distribution shown in Eq. (3)

conditions (cf. Santantonio et al. 1977). This is in accordance with the notion of a 'unifying allometric theory' (Niklas 2004), and hence also with Machado et al. (2003) and Curt et al. (2005) who reported no evidence of variation in biomass partitioning among compartments above and below ground in seedlings of five conifer species and European beech, respectively, due to different soil resource limitations. However, contradicting to this, other authors found recently variations of root–shoot's allometry and biomass partitioning in pine species due to tree age or height (Peichl and Arain 2007) or soil compaction and organic matter removal (Ludovici 2008). Moreover, the reputed alternation of biomass distribution between aerial and non-aerial tree organs, expressed e.g. as a root:shoot ratio, due to changing soil fertility (Axelsson and Axelsson 1986; Keyes and Grier 1981; Paz 2003), varying light regime (Ammer 2003), different interspecific competition regimes (McConnaughay and Coleman 1999; Bolte et al. 2004) and environmental stress (Ericsson et al. 1996) may

conflict with this theory. Variations from an assumed functional balance between root and shoot systems are interpreted as adaptations to a resource supply limited by site conditions and competition according to the optimality theory (Bloom et al. 1985; Wilson 1988). However, they can be also the result of ontogenetic drift, and thus may be misinterpreted as plasticity of biomass partitioning (Reich 2002). In the present study, mounding site preparation (MSP) and combined MSP and herbicide treatment (MSP + H) lowered root:shoot ratios slightly, but not significantly (Fig. 3), compared to control (C), whereas oak seedling size and growth above ground increased remarkably (Löf et al. 2006). Thus, clear signals for an adjustment in oak biomass partitioning to adapt to soil resource limitations arising from grass competition (cf. McConnaughay and Coleman 1999; Collet et al. 2006) or soil compaction (Ludovici 2008) are absent in this study.

The increase in the biomass fraction ratio of lateral root biomass to leaf biomass with intensified treatment

(Fig. 4b) points to a dominance of biomass repartitioning among root fractions over a biomass partitioning shift between root and shoot systems. This is underlined by the significant rise ($P < 0.05$) in the lateral to total root biomass ratio from the control (C: 0.35 ± 0.22) to the combined site preparation—herbicide application treatment (MSP + H: 0.57 ± 0.14 , Table 3). In comparison, the ratio of leaf to total shoot biomass was unaffected (C: 0.32 ± 0.06 ; MSP + H: 0.32 ± 0.04). On the one hand, these results suggest that light supply is not the primary resource constraint for oaks and that root competition between the saplings and herbaceous vegetation is more decisive (cf. Löf et al. 2006). This is in line with results from Picon-Cochard et al. (2006) from competition studies between grass vegetation and Scots pine seedlings. On the other hand, our results support Reich's (2002) assumption that the root:shoot ratio is a rather insensitive indicator for phenotypic adaptation to variations in resource supply.

Conclusion

Our results demonstrate that mounding site preparation is an efficient method for the reforestation of oak stands. After three growing seasons, mounding site preparation was found to have a positive effect on root system and seedling development, similar to that of repeated herbicide application, exceeding the performance of the control seedlings significantly in almost all traits. Plant allometry did not change with different treatments. However, a root biomass repartitioning to the lateral roots, and a more extensive root system point to a higher performance of oak seedling below ground under mounding site preparation compared to repeated herbicide application. Therefore, mounding site preparation is a preferable method at cool sites with a high ground-water table, and particularly at sites, and in areas where ecological vulnerability makes restrictions to chemical use essential. However, attention should be paid to possible nutrient losses arising from enhanced humus mineralisation with possible negative effects on nutrient cycling and ground-water eutrophication.

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