RESEARCH NOTE

Estimating root system biomass from breast-height diameters

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Summary

Estimates of tree root system biomass are important to understanding the dynamics of forest systems and tree growth. The difficult and time-consuming extraction of woody roots is often a limiting factor when estimating the below-stump biomass. Regression equations of root system biomass on diameter at breast height derived from other studies might be useful for applications in forestry and as a simple input variable for growth models. Data for developing regression equations and, where possible, equations were taken from the recent literature for *Picea abies*, *Pseudotsuga menziesii*, *Pinus sylvestris*, *Pinus radiata*, *Pinus taeda*, *Fagus sylvatica*, *Quercus ilex* and *Quercus douglasii*. The equation for *Quercus petraea* was developed using data from European research projects.

Introduction

Root system development is important for stability, anchoring, water uptake and nutrient supply (Polomski and Kuhn, 1998; Coutts *et al*., 1999). Estimates of root system biomass (root system is here defined as an architectural construction of woody roots; cf. Sutton and Tinus, 1983) are required in many areas of forest management, tree or forest growth models and forest ecosystem studies (Santantonio, 1990; Kurz *et al*., 1996; Laiho and Finer, 1996; Millikin and Bledsoe, 1999; Bartelink, 2000; Lacointe, 2000; Lebaube *et al*., 2000). Recent studies show that the radial increment and volume growth in structural roots is strongly influenced by environmental changes (Urban *et al*., 1994; Drexhage *et al*., 1999b). However, the knowledge of root system biomass and structural root architecture is limited because of the difficulties encountered when sampling woody roots, especially those of large trees. Thus, it would be useful to create an allometric model for estimating root system biomass directly from the diameter at breast height (d.b.h.). This relationship is based on the hypothesis that the growth of structural roots depends on stem diameter and that the above- and below-stump development of trees maintains an allometric balance (Köstler *et al*., 1968; Santantonio, 1990; Lacointe, 2000). Studies providing the relationship between d.b.h. and root biomass are rare and consequently are restricted to the stands where the trees had been sampled. Santantonio *et al*. (1977) compiled allometric regressions of root system biomass on d.b.h. for a large number of tree species. Such relationships might be very useful for predicting root system biomass as they rely on easily obtainable above-stump parameters (Bartelink, 1998; Drexhage and Gruber, 1999; Millikin and Bledsoe, 1999; Le Goff and Ottorini, 2001).

The purpose of this paper is to present some recent developments in allometry research and to recall that d.b.h. might be used as a simple variable for estimating root system biomass.

Material and methods

The allometric equations developed in this paper were derived from data and relations taken from the literature for the following species: Norway spruce (*Picea abies* (L.) Karst.), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Monterey pine (*Pinus radiata* D. Don), loblolly pine (*Pinus taeda* L.), Scots pine (*Pinus sylvestris* L.), European beech (*Fagus sylvatica* L.), holm oak (*Quercus ilex* L.) and blue oak (*Quercus douglasii* Hook. and Arn.). Age, d.b.h., site and soil type for selected trees were taken from the literature (Table 1).

The equation for sessile oak (*Quercus petraea* Liebl.) was developed from original data obtained in recent European research projects. Seventy-one trees were selected from two adjacent 150 m^2 plots in naturally regenerated stands in the state forest of Champenoux, located in north-eastern France, 15 km east of Nancy. The trees were felled in 1994, 1995 and 1997, leaving a 1 m high stump. The procedure of root system extraction always followed the same protocol: the main lateral roots were exposed at the stem–root base by excavation before winching the stumps over. A 1 m deep soil trench was carefully dug 1 m away from the stump by a small caterpillar tractor with a mechanical shovel fitted with a special tooth. The root system was pulled slowly out with a chain connected to the stump and the shovel of the tractor. All broken roots were completely excavated and tagged, and the soil was removed from the root plate. Fifty-five root systems extracted in 1994 and 1995 were weighed after 3 years of air-drying and biomass was calculated after determining the mean moistures. Sixteen root systems extracted in 1997 were oven-dried to a constant weight at 105°C. For further details about the sampling and measurement methods, refer to Drexhage (1998), Drexhage *et al.* (1999a), and http://www.chez.com/mdrexhage.

The relationship between root biomass (y) and d.b.h. (x) is generally best fitted by a power function. The log-transformation of the data is usually taken to obtain linear allometric relations, to stabilize the variability, and to allow the fitting of a linear least square regression in the standard use of random errors with equal variances. The values of the coefficient of log-log transformed equations were taken to compare several species from different sites.

In our study, the relationship between root system biomass and stem diameter at breast height was developed for 20- to 28-year-old sessile oak trees from natural regeneration (Figure 1).

In the equations, d.b.h. (cm) was used as the independent variable (x) in a simple regression of root biomass (kg) as dependent variable (y). Logarithmic transformations of both the response and predictor variables were applied:

$$\log y_i = \beta_0 + \beta_1 \log x_i \quad (1)$$

where β_0 is the intercept coefficient and β_1 is the

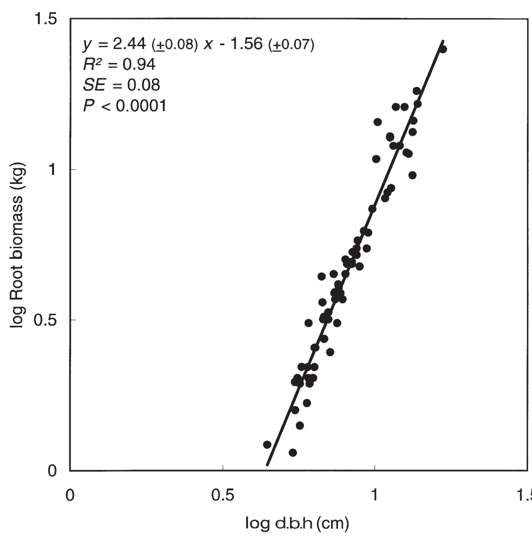

Figure 1. Log of root system biomass against log d.b.h. for 71 sessile oak trees from neighbouring 20- to 28-year-old natural regeneration plots in the state forest of Champenoux, north-eastern France.

Table 1: Diameter at breast height (d.b.h.), site and soil type for Norway spruce, Douglas fir, Monterey and loblolly pine without stump (–), and for Douglas fir, European beech, sessile oak, holm oak and blue oak with stump (+)

No.	Species	Age (years)	d.b.h. (cm) min–max	Site	Stand	Soil type FAO	Source
1	*Picea abies* (–)	10–40	5–25	Northern Germany	Plantation	Podsol–Cambisol	Drexhage and Gruber, 1999
2	*Pseudotsuga* (–)	12–37	5–27	Central Netherlands	Plantation	Podsol–Cambisol	Kuiper and Coutts, 1992
3	*Pseudotsuga* (+)	45–70	22–53	Western Oregon, USA	Plantation	Cambisol	Thies and Cunningham, 1996
4	*Pinus sylvestris* (+)	8–55	4–24	Southern Finland	Nat. Reg.*	Gleysol	Laiho and Finer, 1996
5	*Pinus radiata* (–)	8–25	12–60	North-western N. Zealand	Plantation	Cambisol	Watson and O'Loughlin, 1990
6	*Pinus taeda* (–)	48	15–40	South Carolina, USA	Plantation	Cambisol	Kapeluck and Van Lear, 1995
7	*Fagus sylvatica* (+)	100–115	12–47	Northern Germany	Nat. Reg.	Rendzina	Pellinen, 1986
8	*Fagus sylvatica* (+)	24–35	3–20	North-eastern France	Nat. Reg.	Gleyic Luvisol	Le Goff and Ottorini, 2001
9	*Quercus petraea* (+)	20–28	7–17	North-eastern France	Nat. Reg.	Gleyic Podsol	Drexhage *et al.*, 1999a; this study
10	*Quercus ilex* (+)	60–90	7–23	North-eastern Spain	Nat. Reg	Xerosol	Canadell and Roda, 1991
11	*Quercus douglasii* (+)	40–90	8–33	California, USA	Nat. Reg.	Haplic Xerosol	Millikin *et al.*, 1997

* Natural regeneration.

slope coefficient. Reverse transformation will yield an underestimate of value (*y*) on an arithmetic scale (Baskerville, 1972). To eliminate the systematic bias in the predicted values, correction factors (CF) were calculated (Krämer *et al*., 1996) for Norway spruce and sessile oak from original data of Drexhage and Gruber (1999) and Drexhage *et al*. (1999a) or cited from literature for Douglas fir calculated by Thies and Cunningham (1996). Regressions between the populations were compared by using multiple regression analysis (Neter *et al*., 1990; Drexhage *et al*., 1999a) where raw data were available, i.e. for Norway spruce, Douglas fir, loblolly pine, European beech, sessile oak and blue oak. As the root weight of these conifers had been determined without stump (see definition in Sutton and Tinus, 1983) and that of broadleaved species with stump, which results in different biomass values, the regressions were separately compared within these two classes.

Results

Regression equation coefficients for d.b.h. and root weight are given in Table 2 and the regressions plotted are given in Figure 2 for five coniferous and four broadleaved species covering a wide range of diameters and site conditions. The regressions obtained from different sites and determined with different methods are similar but not identical.

Discussion and conclusion

The regressions for the conifer species differ significantly from each other ($P < 0.001$), with one exception: Drexhage and Gruber (1999) had already found that the regressions for Norway spruce measured by them and those for Douglas fir measured by Kuiper and Coutts (1992) were not different. The latter authors found that their data fit with those on natural Douglas fir stands in the Pacific Northwest (Santantonio *et al*., 1977). The root weight of Douglas fir trees in western Oregon had been calculated with stump (Thies and Cunningham, 1996), and the d.b.h. values of their trees were higher than in the Netherlands (Kuiper and Coutts, 1992) and higher than Norway spruce, so the dataset is inadequate for comparing the regression lines.

The fit of the regression is highly dependent on the root extraction technique. After comparing their results with data from other researchers, Watson and O'Loughlin (1990) emphasized that their pine trees, which were extracted carefully, have higher root biomass than trees which had been partially excavated and winched.

As no root system excavation could be done for their study on root biomass changes of Scots pine in peatland, Laiho and Finer (1996) used existing allometric data for peatland sites from other publications to calculate an equation relating the biomass of stumps and coarse roots to d.b.h. They found a strong relationship between stump and coarse root biomass and tree diameter even when the data came from different sites.

Consistent relationships between root system

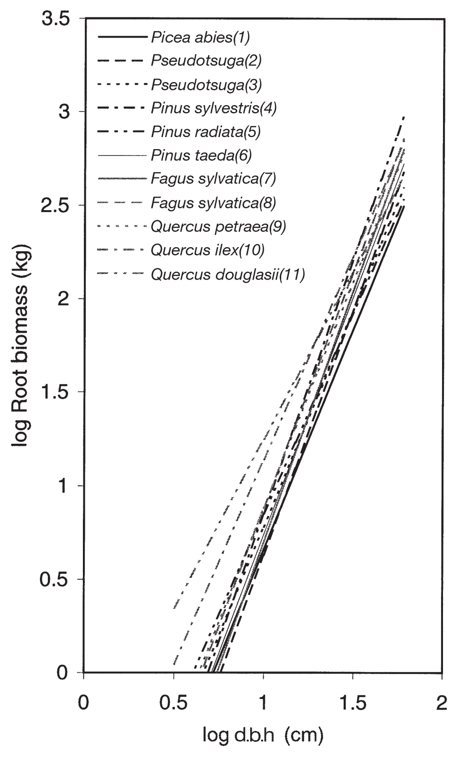

Figure 2. Log of root system biomass against log d.b.h. plotted for five coniferous and four broadleaved species. Regression equation coefficients are given in Table 2.

Table 2: Regression and correlation coefficients of log–log regressions of diameter at breast height (d.b.h.) and coarse-root weight, (1) without stump for Norway spruce, Douglas fir, Monterey and loblolly pine; (2) with stump included for Douglas fir, Scots pine, European beech, sessile oak, holm oak and blue oak (refer to Figure 2); the equations are calculated or re-calculated after citation in the references in Table 1

No.	Species	n	β_0	β_1	CF	R^2
1	*Picea abies* (1)	15	–1.70	2.36	0.01	0.79
2	*Pseudotsuga* (1)	21	–2.00	2.63	n.a.	0.96
3	*Pseudotsuga* (2)	52	–1.55	2.33	0.03	0.86
4	*Pinus sylvestris* (2)	20	–1.89	2.74	n.a.	0.99
5	*Pinus radiata* (1)	13	–1.31	2.16	n.a.	0.96
6	*Pinus taeda* (1)	15	–1.81	2.55	n.a.	0.94
7	*Fagus sylvatica* (2)	8	–2.00	2.70	n.a.	0.98
8	*Fagus sylvatica* (2)	16	–1.66	2.54	n.a.	0.99
9	*Quercus petraea* (2)	71	–1.56	2.44	0.003	0.94
10	*Quercus ilex* (2)	32	–1.05	2.19	n.a.	0.73
11	*Quercus douglasii* (2)	6	–0.56	1.81	n.a.	0.89

The general equation is $\log y = \beta_0 + \beta_1 \log x$; y is root dry weight (kg), x is d.b.h. (cm), β_0 and β_1 are constants.
The measured d.b.h. range is given in Table 1.
n is the number of samples.
CF is the correction factor for reverse transformation and is given where raw data were available.

biomass with stump included and d.b.h. are found for the four broadleaved species, which had all grown in areas of natural regeneration. The tested regressions differ significantly from each other ($P < 0.001$) except for beech. Le Goff and Ottorini (2001) found that total root biomass is closely linked to tree dimension, independently from tree age and site. Holm oak trees in a Mediterranean forest have higher root : shoot ratios than the other temperate species (Canadell and Roda, 1991). However, Canadell and Roda (1991) found that the values of root system biomass predicted for holm oak are close to those derived from the mean regression for coniferous trees, but higher than those from the mean regression for deciduous trees compiled by Santantonio *et al*. (1977). Although no statistical comparisons could be made, Millikin *et al*. (1997) considered allometric relationships between height, d.b.h. and root biomass for *Q. douglasii*, *Q. ilex* and *Q. robur* to be similar. However, the sample size of *Q. douglasii* was very small and their 'trench excavation method' certainly underestimated the root biomass.

The possibility of estimating below-stump biomass by using an easily obtainable above-stump parameter such as d.b.h. has already been tried for a large number of tree species (Santantonio *et al*., 1977). Allometric equations are a useful tool for estimating plant biomass by component in forests (Santantonio, 1990; Laiho and Finer, 1996). Based on allometric relationships like these, Bartelink (1998) recently developed a growth model describing the dynamics of dry matter distribution in Douglas fir and beech trees.

The regression equations developed might be used to estimate root system biomass from d.b.h., which is a simple variable to measure. For applications in forestry inventories and as an input variable for entire tree-growth models, the equations might be extremely useful for a simple estimation of root system biomass without the need for extraction of root systems. However, the researchers will need to agree on whether the stump should be considered as part of the root system or not. In our opinion, the stump is the interface between stem and root system with a high contribution to tree stability but which presents to a lesser extent the functional properties of the supporting roots. Thus, it is suggested that the stump and the below-stump part of the root system should be considered separately and the biomass of both parts of the root system should also be estimated separately.

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