



Contents lists available at ScienceDirect

## Forest Ecology and Management

journal homepage: [www.elsevier.com/locate/foreco](http://www.elsevier.com/locate/foreco)

## Modelling fine root biomass of boreal tree stands using site and stand variables

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## ARTICLE INFO

## Article history:

Received 28 February 2015

Received in revised form 17 June 2015

Accepted 18 June 2015

Available online xxx

## Keywords:

Below-ground biomass

Boreal forests

Tree biomass

*Pinus sylvestris*

*Picea abies*

*Betula* sp.

## ABSTRACT

Quantification of fine root biomass is needed for estimating the role of roots as carbon (C) stores and sources of C input into the soil, as well as for modelling of forest nutrient cycling. Due to the laborious nature of root biomass determinations, there is a need to develop indirect methods that would allow fine root biomass to be estimated using data on easily measurable stand and site variables. We developed models for estimating tree fine root (diameter  $\leq 2$  mm) biomass of boreal forests by compiling data from 95 Finnish forest stands (55 on upland soils and 40 on drained peatlands). Stand basal area predicted fine root biomass ( $R^2$ -adj. = 0.35,  $p < 0.001$ ) better than any other stand variable alone. A model that included stand basal area, dominant tree species group [birch/other], soil type [upland soil/draind peatland], temperature sum and the interaction of soil type and temperature sum accounted for 46% of the variation in fine root biomass. Stand basal area, the C:N ratio of the organic layer or upper 0–20 cm peat layer and the dominant tree species group together explained 45% of the variation in fine root biomass. Temperature sum correlated with fine root biomass in opposite ways in upland soils and in drained peatlands: fine root biomass increased with decreasing temperature sum in upland soil sites, whereas in peatlands fine root biomass decreased as the temperature sum decreased. Although the models were based on a large dataset representing well the variation in stand age, basal area, site fertility and climatic conditions in northern European boreal forests, half of the variation in fine root biomass remained unexplained. More comprehensive fine root biomass sampling in relation to spatial and temporal variation in the forthcoming studies, for example in connection with monitoring campaigns, and additional predictors such as soil texture, successional stage and the fine root biomass of ground vegetation might improve the predictive power of fine root biomass models.

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### 1. Introduction

Fine roots, i.e. small-diameter (traditionally classified as  $\leq 2$  mm) roots, are responsible for the water and nutrient uptake of plants and play an important role in carbon (C) and nutrient dynamics of forest ecosystems (McClougherty et al., 1982; Helmisaari et al., 2002; Ruess et al., 2003; Yuan and Chen, 2010; Clemmensen et al., 2013). Fine root production has earlier been estimated to contribute from 33% to 75% of the annual net primary production in forest ecosystems (Grier et al., 1981; Santantonio and Grace, 1987; Vogt, 1991; Jackson et al., 1997), and more recent estimates suggest these percentages to be from 13% to 27% (McCormack et al., 2015b). Fine roots represent one of the largest litter inputs to the soil, especially in boreal forests (Vogt

et al., 1986; Lehtonen, 2005; Clemmensen et al., 2013; Leppälampi-Kujansuu et al., 2014; Ojanen et al., 2014). Unfortunately, the quantity of fine roots and their lifespan are poorly known (Brunner et al., 2013) compared to aboveground compartments, and this may lead to severe uncertainties in ecosystem simulation models and C budget estimates (Peltoniemi et al., 2006; Strand et al., 2008; Smithwick et al., 2014; McCormack et al., 2015a). In order to estimate litter input from fine roots to soil, it is necessary to estimate both the quantity and the lifespan of fine roots; in this study we improve the fine root quantity estimation. The United Nations Framework Convention on Climate Change, the Kyoto Protocol and the EU greenhouse gas (GHG) monitoring mechanism require member states to monitor and report their annual GHG emissions and C sinks. Thus, comprehensive information about the C stock and sequestration in forest ecosystems is needed. Dynamic soil C models are used with GHG inventories and also with earth system models, both to report current C

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stock changes and to predict future biosphere C sinks and sources (e.g. Palosuo et al., 2012; Todd-Brown et al., 2014). It is essential to present the level and trends of C flow (e.g. fine root litter) from vegetation to soils reliably in these models in order to avoid biased estimates of soil C stocks and changes.

Different countries use different approaches in their GHG inventories. Hitherto, fine root biomass in the GHG inventories of Finnish upland forests has been estimated using statistical models that describe the relation between modelled foliage and measured fine root biomass using data from 16 sites on upland soils across Finland (Helmisaari et al., 2007). Foliage biomass is the most difficult aboveground biomass pool to model and the systematic errors of foliage biomass estimates can be high (Lehtonen, 2005; Somogyi et al., 2007).

Determination of fine root biomass is laborious and costly, which has increased interest in developing indirect methods that would allow fine root biomass to be estimated using data on easily measurable stand variables. Allometric biomass functions have successfully been developed for coarse roots for different species and geographical regions (Pettersson and Ståhl, 2006; Ouimet et al., 2008; Repola, 2009; Brassard et al., 2011). For fine roots, it has proved problematic to develop such functions because it is difficult to assign fine roots to individual trees. The relationships between fine root biomass and stand and environmental characteristics in boreal forests have been investigated in only a few studies (Helmisaari et al., 2007; Kalliokoski et al., 2010; Yuan and Chen, 2010; Finér et al., 2011). Fine root biomass varies with stand age and tree species (Vanninen and Mäkelä, 1999; Makkonen and Helmisaari, 2001; Børja et al., 2008; Kalliokoski et al., 2010), and the fine root biomass of deciduous trees is generally greater than that of conifers (Finér et al., 2007; Kalliokoski et al., 2010). The fine root biomass of Scots pine and Norway spruce, which are the dominant tree species of the European boreal region, generally decreases with increasing site fertility (Finér and Laine, 1998; Helmisaari et al., 2007; Kalliokoski et al., 2010). Fine root biomass has been shown to correlate strongly and positively with the stand characteristics, mainly with basal area of forest stand (Vanninen and Mäkelä, 1999; Helmisaari et al., 2007; Finér et al., 2007, 2011). Factors such as temperature, precipitation and the density, compaction and aeration of soil also affect the growth and biomass of fine roots (Persson, 1992; Puhe, 2003; Helmisaari et al., 2007; Murphy et al., 2009; Yuan and Chen, 2010).

Upland soils and peat soils differ with respect to soil texture, bulk density, aeration, water regime and nutrient concentrations and contents (Westman and Laiho, 2003; Päivänen and Hännel, 2012), but little is known about whether fine root biomasses differ between upland and peatland stands (Laiho et al., 2014). In Finland, 34% of the forestry land area (8.7 million ha) consists of peatlands, of which ca. 4.7 million ha is drained (Finnish Statistical Yearbook of Forestry, 2013). However, the fine root biomass models for peatlands that can be applied with variables measured in forest inventories have been lacking.

The aim of this study was to develop models for tree stand fine root biomass estimation in boreal forests by using commonly and easily measurable stand and site variables as predictors. This component of modelling is urgently needed to improve soil C stock change estimation in GHG inventories and for future predictions. For this purpose, a database covering 95 Finnish stands from the literature and from a few unpublished studies was compiled. Our hypotheses were that (1) fine root biomass depends positively on the aboveground tree biomass, and negatively on site fertility. Moreover, we hypothesized that (2) fine root biomass per woody biomass is highest with birch stands and lowest with Scots pine stands, compared to Norway spruce stands. We also hypothesized that (3) drained peatlands have more fine root mass than upland soils due to their more extensive woody root systems.

## 2. Material and methods

### 2.1. Material

We collected published and unpublished data of tree stand living fine root (diameter  $\leq 2$  mm) biomass from Finnish Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and birch (*Betula* sp.) dominated and mixed forests (mixed stands being here defined as mixtures of Norway spruce, Scots pine and broadleaved species), see Table 1 and Fig. 1. The compiled dataset represented 95 sites (55 upland stands and 40 drained peatland stands). Values from 11 sites were unpublished studies from a sub-sample of NFI (national forest inventory) plots (Makkonen and Helmisaari, 2004) but the field and laboratory methods were similar to those in other publications by these authors (Makkonen and Helmisaari, 1998, 2001). The data from all the other sites were published earlier (Laiho and Finér, 1996; Finér and Laine, 1998; Helmisaari and Hallbäck, 1999; Vanninen and Mäkelä, 1999; Makkonen and Helmisaari, 2001; Finér et al., 2003; Taskinen et al., 2003; Palviainen et al., 2004; Helmisaari et al., 2007; Ohashi et al., 2007; Ostonen et al., 2007; Kalliokoski et al., 2010; Ojanen et al., 2010, 2012; Leppälampi-Kujansuu et al., 2014). The study sites were located in the boreal vegetation zone between 60 and 69°N, covering a wide range of variation in climatic conditions, site type and stand characteristics. The upland data consisted of 25 Scots pine, 17 Norway spruce, 1 birch dominated and 12 mixed stands, and the drained peatland data of 24 Scots pine, 11 Norway spruce, 4 birch dominated and 1 mixed stands. Stands were unfertilized and their age ranged from 15 to 200 years. Managed and a few semi-natural old-growth forests were included in the dataset. The stand characteristics are presented in Table 1.

The long-term (1981–2010) mean annual temperature sum (i.e. sum of daily mean temperatures exceeding +5 °C in degree days (dd)) for the study sites varied between 658 and 1452 dd, while annual precipitation varied between 326 and 1015 mm. The site types in upland sites range from fertile herb-rich *Oxalis-Myrtillus* (OMT) type to nutrient poor xeric *Calluna* (CT) and *Empetrum-Calluna* (ECT) types (Cajander, 1949; Hotanen et al., 2008). Site types in the peatland sites from the most fertile to the nutrient poorest were: *Herb-rich* (*Rhtkg*), *Vaccinium myrtillus I and II* (*Mtkg I and II*), *Vaccinium vitis-idaea I and II* (*Ptkg I and II*), *Dwarf shrub* (*Vatkg*) and *Lichen* (*Jätkg*) (Laine, 1989; see Vasander and Laine, 2008). Soils in the upland sites are podzols

**Table 1**

Characteristics of the study sites. Annual mean precipitation and temperature sum are for the period 1981–2010. Temperature sum equals the sum of differences between daily mean temperatures and the threshold of +5 °C.

	Volume (m <sup>3</sup> ha <sup>-1</sup> )	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Soil C/N ratio	Temperature sum
<i>Mineral soils</i>				
Mean	175	21.0	33.9	1157
Min.	9.9	3.8	19.0	658
Max.	354	36.6	52.7	1452
SD	104	8.3	8.0	200
N	55	54	55	55
<i>Drained peatlands</i>				
Mean	126	19.1	28.1	1199
Min.	10	2.8	16.9	944
Max.	286	38.0	43.8	1420
SD	76	9.4	7.1	140
N	40	39	39	40
<i>All sites</i>				
Mean	155	20.3	31.5	1175
Min.	10	3	16.9	658
Max.	354	38	52.7	1452
SD	96	8.8	8.1	178
N	95	93	94	95

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