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Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands

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ABSTRACT

An essential carbon (C) pool of forest ecosystems is stored in belowground tree biomass; however, data about belowground C and nutrient accumulation is scarce. It is crucial to involve belowground part for developing regional and global C or nitrogen (N) budgets for different forest ecosystems.

Fine root ($D < 2.0$ mm) biomass and spatial allocation as well as coarse root ($D \geqslant 2.0$ mm) biomass were studied in a chronosequence in four silver birch (*Betula pendula* Roth) stands aged 6–60 years.

The soil coring method was used for estimation of birch fine root biomass and necromass in the upper 40 cm topsoil layer. Stump biomass and coarse root biomass were estimated by excavation of the root systems of model trees in a 6-year-old stand and in a 32-year-old silver birch stand. For a 14-year-old stand and for a 60-year-old stand, the developed root-shoot ratio approach was used. Carbon and nitrogen accumulation in belowground biomass was estimated as well.

Fine root biomass varied between 103 g m^{-2} and 409 g m^{-2} and fine root necromass, between 22 g m^{-2} and 93 g m^{-2}; both increased with stand age. Fine root vertical distribution showed a gradual decrease with soil depth in all profiles, however, fine root biomass shifted more to the deeper soil layers with increasing stand age. The fine root live/dead ratio decreased hyperbolically with stand age while the change was most rapid before pole age.

The most active part of the fine root system – ectomycorrhizal biomass (EcMB) – was estimated for three stands (6-, 14- and 32-year-old); EcMB per basal area varied between 8 and 14 kg m^{-2} and was not related to stand age.

Coarse root biomass increased with stand age from 7.9 Mg ha^{-1} in the 6-year-old stand to 40.2 Mg ha^{-1} in the 60-year-old stand. The root-shoot ratio decreased in silver birch stands drastically between 6 and 14 years but stabilized thereafter. Hence the use of a root-shoot ratio of 21% for calculation of belowground biomass from aboveground biomass for silver birch stands is justified.

Carbon accumulation in the belowground tree biomass of silver birch stands varied between 4.0 Mg ha^{-1} and 19.8 Mg ha^{-1}, being the highest in the 60-year-old stand. The C accumulated in belowground biomass accounted for 3–4% of the total C storage of the total C storage of the forest ecosystem in the young stands and for 9.5–11% in the middle-aged and mature stands. Fine root mortality and the corresponding C flow as fine-root litter input increased with stand age. As the biomass of the trees was the main C sink, a significant share (3–28%) of C was accumulated in the belowground part of the stand. C accumulation in the fine roots was low in chronosequence birch stands; however the C flux into the soil through fine root litter may be considerable.

1. Introduction

Terrestrial ecosystems represent a major sink for atmospheric carbon (C) (Schimel et al., 2001) and boreal and temperate forests play an important role in global C cycling and in C sequestration (Dixon et al., 1994; Peng et al., 2008). In the last decade the issue of accumulation of C in different terrestrial ecosystems, including forests, has become more relevant around the world and the stock of C bound in biomass and in the soil has been estimated in numerous studies (Cannell, 1999; Pussinen et al., 2002; Mund et al., 2002; Laiho et al., 2003; Paul et al., 2003; Ågren and Hyvönen, 2003).

An essential C pool of forest ecosystems is sequestered in belowground tree biomass (Peichl and Arain, 2006; Helmisaari et al., 2002; Cairns et al., 1997), however, data about belowground C and nutrient accumulation is scarce. This is mainly due to methodological problems: estimation of belowground biomass is always more laborious and costly than estimation of aboveground

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biomass. Most study methods, especially those developed for coarse roots are also destructive and have the potential to damage or destroy trees. On the other hand, it is impossible to compile C or nitrogen (N) budgets for different forest ecosystems without taking into account the belowground part of stands. Studies focusing on different tree species are needed, because the current literature suggests the share of belowground biomass of trees as a proportion of total tree biomass highly varying, ranging between 18% and 45% (Santantonio et al., 1977; Fogel, 1983). For instance in young grey alder stand belowground biomass formed 18% of the total tree biomass (Uri et al., 2002), but in lodgepole pine stand the respective value may reach over 30% (Litton et al., 2003).

The processes related to the roots, especially the fine roots ($D < 2.0$ mm), are important for understanding the carbon and nutrient cycling of forest ecosystems, since fine root growth, death and decomposition, represent major pathways of C and N in boreal forests (Bohm, 1979; Berg, 1984; Persson, 1986; Joslin and Henderson, 1987; Garkoti and Singh, 1992; Hendrick and Pregitzer, 1993; Helmisaari et al., 2002).

According to a widely accepted definition, the limit between the coarse roots and the fine roots is 2 mm (Vogt et al., 1996). However, some authors have pointed out that a standard definition of the fine roots is inadequate to determine the most dynamic portion of the root population, because it lumps together populations of roots that cycle C at significantly different rates (Gill and Jackson, 2000; Wells and Eissenstat, 2001; Gaudinski et al., 2001).

Despite the relatively small biomass (Keyes and Grier, 1981; Vogt et al., 1996), fine roots have an enormous surface area, growing and turning over rapidly, which is important in terms of substance cycling and energy flow in the forest ecosystem (Zhou et al., 2007). Hence, fine roots, including structures of mycorrhizal fungi, contribute significantly to soil C fluxes and hence to the soil C storage, as well as to the belowground recycling of nutrients such as nitrogen (N), phosphorus (P), magnesium (Mg) and calcium (Ca) (Brunner and Godbold, 2007).

As belowground biomass in the tree roots may account for a remarkable portion of total forest biomass and may provide an additional essential C pool, inclusion and advancement of root biomass assessment for carbon budgets is indispensable (Kurz et al., 1996; Cairns et al., 1997; Peichl and Arain, 2006).

Silver birch (*Betula pendula* Roth) has a wide natural distribution area on the Eurasian continent, ranging from the Atlantic to Eastern Siberia. In Northern Europe and also in the Baltic countries birches are the most important commercial broadleaved tree species (Hynynen et al., 2010). Although silver birch occurs almost throughout the whole of Europe, the most abundant birch resources are located in the boreal and temperate forests of Northern Europe. In the Baltic and Nordic countries, the proportion of birch in the total volume of the growing stock varies between 11% and 28%. Silver birch is also the most important deciduous tree species in Estonian forestry; birch stands account for approximately 30% of the total area of Estonian forests (Yearbook Forest, 2009). Despite the wide distribution and high silvicultural importance of silver birch stands, studies of their belowground biomass and of the role of roots in C sequestration have been scanty (Mamayev, 1977; Uri et al., 2007).

In the present study we investigated belowground biomass (including fine root biomass) in four silver birch chronosequence stands in Southern Estonia. This study forms part of a larger research aimed to compile carbon and nitrogen budgets in silver birch stands the first results of which were published in Uri et al. (2012). The present study is focused on estimation of belowground biomass and C as well as N accumulation in the belowground biomass of the same stands. This allows a more adequate estimation of C accumulation in silver birch stands and their role in C budgets of forests in the boreal region. The obtained knowledge serves as a basis for development of carbon cycling models both on the regional and global scales.

The working hypotheses of the present case study were: (1) the share of accumulated C in belowground part of the total stand C storage increases with increasing stand age. (2) Necromass of fine roots is lower at young age and the live/dead ratio changes according to stand age. (3) Fine root biomass will increases with stand age.

To test these hypotheses, the main objective of the study was to analyse the role of belowground part in the dynamics of C and N accumulation in silver birch stands by the chronosequence approach. The specific aims were: (1) to estimate coarse root biomass of 6-, 14-, 32- and 60-year-old silver birch stands; (2) to estimate fine root biomass and its depth distribution in the topsoil of chronosequence silver birch stands.

2. Materials and methods

2.1. Site descriptions

This work was conducted in a chronosequence of silver birch stands in Estonia. Estonia is situated in the hemiboreal vegetation zone (Ahti et al., 1968) within a transition area from the maritime to continental climate. According to the Estonian Meteorological and Hydrological Institute, annual average precipitation varies between 550 and 800 mm, and annual average temperature is between 4.3 °C and 6.5 °C. Four silver birch stands aged between 6 and 60 years (Table 1), were included in this study. The stands represented different stages of development: young (6-year-old), pole (14-year-old), middle-aged (32-year-old) and mature (60-year-old).

All studied stands grew in a flat landscape in the *Oxalis* site type in South-eastern Estonia. In the *Oxalis* site type, stands are highly productive; acidic soils have a relatively thick A layer, moisture conditions for plant growth are suboptimal, the soils are well drained and there is no appreciable O-horizon in most cases (Lõhmus, 1984). All studied stands belong to the same forest soil type except for the 6-year-old site with *Umbric Gleysol* (Table 1). The higher C_{org} content in the 6-year-old stand, compared with the other sites, is particularly characteristic of *Gleysols*, owing to the presence of "raw humus" formed in moister conditions.

All studied stands had regenerated naturally and had closed canopies. In the 14-year-old stand thinning was carried out, which affected stand density. In the period 2003–2008 sanitary cutting was done in the 60-year-old stand to remove storm-damaged trees, which resulted in lower than normal stand density (305 trees per ha).

For estimation of the main stand characteristics and above-ground biomass, one sample plot without replicates was established in each stand. The following stand characteristics were recorded: stand age, mean height and diameter, density, basal area and stem volume (Table 1) (Uri et al., 2012). A description of the herbaceous understorey plants and estimation of their biomass are presented in Uri et al. (2012).

2.2. Estimation of fine root biomass and necromass

Fine root biomass and necromass were estimated with the soil coring method (Vogt et al., 1981; Uri et al., 2007). Twenty soil cores were taken randomly over the whole stand with a cylindrical corer with a diameter of 38 mm. To avoid compression of soil layers, the internal diameter of the upper part of the auger was 1.6 mm larger than the diameter of the cutting edge. The soil cores were divided into four layers (0–10; 10–20; 20–30 and 30–40 cm), placed in