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Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence

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ABSTRACT

During recent decades, studies of the carbon (C) balance of forest ecosystems have became more actual, mainly in connection with the global increase of CO_2 in the atmosphere. In the present study the stand chronosequence approach was applied to analyse C sequestration dynamics. Study was made of C accumulation both in biomass and in the soil in 6–60-year-old silver birch (*Betula pendula*) stands growing at fertile (*Oxalis*) sites.

As the growth of the studied stands was vigorous, their yield was higher than that presented in several yield tables for earlier periods. The C concentration (C%) in different compartments of the trees varied between 47% and 55%. However, the weighted average of C concentration in the silver birch trees was approximately 50% regardless of stand age. The average C concentration of the herbaceous understorey plants was 43.3 ± 0.5%.

The soil C_{org} pool was independent of stand age, and so far there occurred no C accumulation during stand succession, expressed as C_{org} values or stage of forest floor formation. This might indicate fast C_{org} turnover in the soils of the *Oxalis* site. The total C pool in a mature silver birch stand was 185 t ha^{-1} of which 50% was accumulated in the aboveground part of the trees. In young birch stands the C pool in aboveground biomass and in the soil accounted for 21–39% and 53–71%, respectively, of the total C pool of a stand. In pre-mature and mature stands the corresponding share accounted for 50–59% of the aboveground C of the trees and 29–38% of the soil C pool. Due to closed canopies, the role of herbaceous understorey plants as a C sink was modest, constituting 1% or even less of the total C pool of the older stands. The annual C flux 1.6 t ha^{-1} yr^{-1} into the soil via litter fall was the largest in the middle-age stand.

Our results show that the main C sink in fertile silver birch stands is located in the wooden parts of trees. The C pool in tree biomass increased with stand age, whereas the soil C_{org} pool remained stable. For a more profound understanding of C cycling in silver birch forest, soil respiration fluxes should be measured.

1. Introduction

Combustion of fossil fuels has caused an elevation of CO_2 concentration in the atmosphere, which leads to the global greenhouse effect. For inhibiting the increase of the concentration of atmospheric CO_2 and climate changes, more attention should be paid to reduction of CO_2 emission (through more extensive use of biofuels and renewable energy) as well as to extensive carbon (C) sequestration. Terrestrial ecosystems represent a major sink for atmospheric 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). On the other hand, elevated CO_2 could increase forest growth; according to Norby et al. (2005), the net primary production of forests increased significantly due to elevated CO_2 in the atmosphere.

In the last decade accumulation of C in different ecosystems, including forests, has been an actual topic 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). Estimation of the stock and accumulation of C in the forests is essential for assessing the role of forest ecosystems in global C budgets.

The C storage in boreal forests formed 49% of the total forest C storage (Dixon et al., 1994) and the amount of C accumulated there was appreciable (Kaipanen et al., 2004; Liski et al., 2003). Forests have a great potential to sequester C in short- or mid-term. The factors affecting the rate of C sequestration are the tree species composition of stand, stand age, site fertility and management of forests

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(Thornley and Cannell, 2000; Akselsson et al., 2004); even the impact of the understorey is significant (Vogel and Gower, 1998).

The soils of boreal forests can store a substantial amount of C, exceeding often the forest vegetation in this respect (Peltoniemi et al., 2004). Although current biomass production depends on soil conditions and vice versa, it is definitely also related to C accumulation in forest. However, relevant empirical data for different tree species are still quite scarce.

As stand age affects its C accumulation ability, the chronosequence method is widely used to clarify the effect of stand age and to estimate the dynamics of various stand development aspects. However, chronosequence studies in birch stands are still rare (Wang et al., 1996; Mälkonen and Saarsalmi, 1982).

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, birches are the most important commercial broad-leaved 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 broad-leaved tree species in Estonian forestry, birch stands accounting for approximately 30% of the total area of Estonian forests (Yearbook, 2009).

In the present study we investigated the growth, yield and carbon accumulation of a silver birch forest growing at a fertile site (*Oxalis* site type according to the local classification (Lõhmus, 1984)). During the last two decades extensive spontaneous afforestation of abandoned agricultural lands has taken place in Estonia, which has increased the area of silver birch stands. As a rule, the *Oxalis* site type will be prevalent in such areas, which will lead to an increase of the area of silver birch stands at *Oxalis* sites.

Although forests have a great potential to sequester C in midterm, their effect on C accumulation ability is still quite unclear and the few relevant literature data are inconsistent. Different reviews report an average rate of soil C sequestration of 0.3 t ha^{-1} yr^{-1} (range 0–3 t C ha^{-1} yr^{-1}) across different climatic zones in the case of afforestation of former agricultural land (Post and Kwon, 2000; Jandl et al., 2007). Deckmyn et al. (2004) simulated a long-term pattern of C in soils over 150 years with a short-rotation coppice of poplar and concluded that there would lead an increase of C up to 0.29 t ha^{-1} yr^{-1}.

The potential of silver birch for C sequestration in soils is poorly studied. In a Russian study on dark grey forest soils, birch showed the highest humus concentration in the 0–5 cm surface layer but the average humus stock was decreased as follows: oak forest > birch forest > pine forest > agroecosystem (Vladychenskii et al., 2007). To adequately understand the potential of forest C sequestration, it is necessary to investigate stands in a complex way involving trees, the understorey, the soil and litter.

The working hypotheses of the present study were: (1) the growth of silver birch stands can be more intensive than is predicted in local yield tables; (2) in the silver birch forest ecosystem carbon is accumulated evenly both in tree biomass and in the soil; (3) the soil carbon pool increases significantly during development of silver birch stands.

The main objective of the present study was to analyse C sequestration dynamics in silver birch stands growing at a fertile site by using the chronosequence approach.

The specific aims of the study were:

- to estimate the biomass and production of silver birch stands growing in the *Oxalis* site type;
- to estimate C content in different biomass fractions of silver birch stands and in the soil.

2. Material and methods

2.1. Site description

Eight silver birch stands aged between 6 and 60 years were included in the study (Table 1). One stand (Kambja) grows on abandoned agricultural land and the other stands grow on forest land. All studied stands had regenerated naturally and grew in a flat landscape in the *Oxalis* site type in Southeastern Estonia. All studied silver birch stands had closed canopies. In two young stands (Kooraste 2 and Alatskivi 1) harvesting thinning was carried out, which affected stand density. In the period 2003–2008 sanitary cutting was carried out in the Aakre stand to remove storm-damaged trees, which resulted in lower than normal stand density (305 trees per ha).

Estonia is situated in the hemiboreal vegetation zone (Ahti et al., 1968), within a transition zone from the maritime to continental climate. Annual average precipitation varies between 550 and 800 mm, and annual average temperature in Estonia is between 4.3 and 6.5 °C.

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 the steady forest floor is missing in most cases (Lõhmus, 1984).

The parent material of the Estonian soils is mainly glacial till, along with glacio-fluvial melt water sands and gravels and, to a limited extent, also ice-lake clays. The physical properties of the soil such as soil depth, soil drainage class and soil texture class are quite similar in all studied stands, except for the Järvselja site which is situated in the Peipsi lowland.

Soil taxonomy class is undoubtedly a surrogate for soil fertility and has been traditionally used for forest site indexing in Estonia. According to Lõhmus (1984), all studied stands belong to the same forest site type except for the Järvselja site with *Umbric Gleysol*. The higher C_{org} content in Järvselja, compared with the other sites, is particularly characteristic of *Gleysols*, owing to "raw humus" formed in moister conditions.

2.2. Partitioning of aboveground biomass and estimation of production

The aboveground biomass and production of a stand was always estimated at the end of August when the process of biomass formation was completed; the method of model trees (Bormann and Gordon, 1984; Uri et al., 2007a,b) was used. Sample plot were established in every stand and stand characteristics were measured (Table 1).

The stem breast height diameter ($D_{1.3}$) of all trees was measured. The trees were divided into five classes on the basis of $D_{1.3}$, and a model tree was selected randomly from each class. A total of five (in older stands) to 12 (in younger stands) model trees were felled depending on stand age and on the dimension ($D_{1.3}$) variability of the trees. In all cases sample trees were felled in the middle of the stand to avoid the edge effect. The stems of the model trees were divided into five or 10 sections depending on the size of the tree. The stems of the small model trees aged 6–18 years were divided into five sections: the first section, height 0–1.3 m, the second section, height 1.3 m up to the living crown; the living crown, consisting of three equal layers. In the case of older stands the stems of the model trees were divided into up to ten sections: the first section, height 0–1.3 m; every next section 2 m up to the beginning of the living crown; the living crown was divided into ten equal sections.

The stem sections and the larger branches were weighed in forest and smaller branches were placed in plastic bags and transported to the laboratory. From every crown section, one model