



Ecosystems carbon budgets of differently aged downy birch stands growing on well-drained peatlands



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ABSTRACT

Estimation of the carbon (C) storages and fluxes in different forest ecosystems is essential for understanding their C sequestration ability. The net ecosystem production (NEP) and the net primary production (NPP) in five downy birch (*Betula pubescens*) stands, aged between 12 and 78 years, growing on fertile well-drained *Histosols*, were studied. Drainage of swamp forests is a large-scale manipulation, which causes significant shifts at the ecosystems level, altering C and nutrient cycling a great deal. Young and middle-aged downy birch stands (12–30-year-old) acted as C sink ecosystems, accumulating 1.4–3.0 t C ha⁻¹ yr⁻¹. In the 38-year-old stand NEP was roughly zero; annual C budget was almost in balance. The over-matured downy birch stand (78-year-old) acted as a C source emitting 0.95 t C ha⁻¹ yr⁻¹. Annual woody biomass increment of the stand was the main factor which affected the forest to act as a C accumulating system. Although the highest heterotrophic respiration (Rh) values were measured in the middle-aged stands, mean soil C emission did not differ significantly between the studied stands. Annual total soil respiration (Rs) and Rh ranged from 7.4 to 8.8 t C ha⁻¹ and 4.7 to 6.2 t C ha⁻¹, respectively. Soil temperature appeared to be the dominant driver of the soil CO₂ effluxes. Temperature sensitivity (Q₁₀ value) of respiration rates (3.0–5.5), as well as the Rh/Rs (0.6–0.7) varied irrespective of stand age. Both the annual aboveground litter (1.5–1.9 t C ha⁻¹ yr⁻¹) and fine root litter (0.9–1.5 t C ha⁻¹ yr⁻¹) input fluxes were quite similar for the studied stands. However, the annual organic C input into the soil via above- and belowground litter was smaller than the annual Rh efflux, indicating that continuous mineralization of the peat layer reduces the soil organic C pool. The main share of the C stock in the drained swamp downy birch stands was soil C; the storage of C accumulated in the woody biomass of the trees accounted for only 5–20% of the total C storage of the ecosystem.

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1. Introduction

Carbon (C) accumulation in forest ecosystems is an actual topic in terms of climate change and intensive forest management (Schimel et al., 2001; Walle et al., 2007; Verlinden et al., 2013; Wu et al., 2013). Boreal and temperate forests play an important role in global C sequestration (Dixon et al., 1994; Peng et al., 2008) and have a great potential to sequester C in short- or mid-term. There are many factors which can affect the rate of C sequestration in forests: tree species, stand age, site fertility and even the impact of the understorey cannot be disregarded (Vogel and Gower, 1998). Also forest management is closely related to C sequestration, while drainage may significantly affect stands C

cycling (Ojanen et al., 2010; Lohila et al., 2011; Meyer et al., 2013; Birdsey and Pan, 2015).

Estimation of the C storages and fluxes in different forest ecosystems is an important task for understanding their C sequestration ability. Forests in the boreal and hemiboreal zones usually act as C sinks (Liski et al., 2003; Kaipainen et al., 2004) and both forest biomass and soil are considered to have a large potential for the C storage (Gower, 2003; Houghton, 2005). However, there is still a large gap in empirical data about C cycling in various forest ecosystems. Due to the large heterogeneity of different forest ecosystems, their C cycling may be highly variable. A crucial issue is the quantification and modelling of the main output and input C fluxes in different forests and in the case of different management regimes. Also the ratio of C accumulated in the soil to C accumulated into the biomass of trees has been highlighted as it determines the period of C capture (Peltoniemi et al., 2004; Uri et al., 2012).

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In northern latitudes, the amount of annual precipitation exceeds transpiration, creating favourable conditions for the paludification process and for accumulation of a significant share of the world's soil C pool in peatlands (Gorham, 1991; Martikainen et al., 1993). Thus these areas have the potential to significantly influence the global atmospheric budget of greenhouse gases (GHG) (Martikainen et al., 1993; von Arnold et al., 2005a; Leppelt et al., 2014). Draining of excessively moist soils in order to improve growth conditions for forests has been a common practice in northern regions, which has resulted in an increase of the productive forest land area. For instance, drained peatlands in Finland constitute 34% of the global area of forestry-drained peatlands (Lohila et al., 2011). In Estonia, 37% of the total forest area are located on organic soils and among them 15%, i.e. 328,000 ha, are classified under full-drained peatland forests (Yearbook Forests, 2013). As a result of the long term drainage of swamps, there has emerged a novel specific site type, named "Oxalis full-drained swamp", according to local classification (Lõhmus, 1984). Drainage is an extensive disturbance, which can cause significant shifts at the ecosystem's level and can affect C balance between photosynthesis and soil respiration (Goulden et al., 1996; Lindroth et al., 1998; Hyvönen et al., 2007). Since forest drainage in Estonia was very intensive in the second half of the 20th century, the total area of forests affected by drainage is up to 560,000 ha (Yearbook Forests, 2013). It is estimated that about 70% of all Estonian peatlands are more or less affected by drainage (Paal, 1998).

Assuming that CO₂ emission from forests growing on drained organic soils may be significantly increased due to the intensive mineralization of soil organic matter (SOM), these forests deserve special attention. Heterotrophic soil respiration (Rh), derived from decomposition of litter and SOM, is one of the largest C fluxes in ecosystems (Harmon et al., 2011) and is strongly favoured by drainage (Silvola et al., 1996). Does the ecosystem of drained forest act as a carbon sink or source, i.e. does more intensive C accumulation through increased biomass production exceed intensified Rh? This is a widely discussed issue, which is closely related to site fertility and management of drained peatland forests. Drained and nutrient rich afforested organic soils are potential sources of GHG, contributing to global warming (Leppelt et al., 2014); after drainage, some peatland ecosystems have turned from a C sink to a C source (Ilomets, 1996; Bonan, 2008).

Regarding downy birch, we did not find any earlier literature data about C budget despite the wide natural distribution area of this species on the Eurasian continent. The most abundant birch resources are located in temperate and boreal forests of Northern Europe where it is a commercially important birch species (Hynynen et al., 2010). Downy birch is also the most common tree species on lowland *Histosols* in Estonia.

The main objective of the present study was to analyse the dynamics of C cycling in downy birch stands of different ages, growing on long-term drained swamps, by applying the C budgeting approach.

To compile C budgets we aimed to estimate the above- and below-ground biomass and production, as well as soil respiration efflux in five downy birch stands.

2. Material and methods

2.1. Study sites

Five naturally regenerated pure downy birch stands, aged between 12 and 78 years, growing in fertile *Oxalis* full-drained swamp site type (Lõhmus, 1984) were included in the study (Table 1). Long lasting drainage of peatlands causes gradual

changes in site properties; the productivity and composition of understorey species change similarly to a forest growing on mineral soils, making drained areas more favourable for tree growth as well as for forest management.

All studied stands are located in the Järvselja experimental forest district in the eastern part of Estonia. The area belongs to the hemiboreal vegetation zone (Ahti et al., 1968), which is a transition zone from the temperate to boreal climate. The Järvselja forest district is an area with a long drainage history (first drainage systems from the end of the 19th century) and drained forests are widespread in this region. The *Oxalis* full-drained swamp site type made up 14% of the forest district (Korjus et al., 2015). All studied sites were drained approximately 40–50 years earlier using open ditches. As a result of drainage, the groundwater level was normally below 40 cm from surface during the vegetation period. According to the closest meteorological station of Tõravere, the annual average precipitation is 680 mm, and annual average temperature is 5.8 °C. A sample plot with an area of 0.063 ha was established in each studied stand and the main stand characteristics were determined (Table 1).

All studied stands were of natural origin and unmanaged, i.e. unthinned before the establishment of the sample plots. As typical for *Oxalis* full-drained swamp forest, mainly herbaceous plants were growing in the understorey.

All studied stands grow on drained organic soils (*Histosols*) where high C and N content (20–30% and up to 3%, respectively) as well as a thick organic horizon (>40 cm) are inherent (WRB, 2006). In all studied stands, one soil pit (depth to 0.7 m) was dug for estimation of the soil type. For estimation of the thickness of the peat layer, additional sampling from the bottom of the soil pit was done using a soil probe.

Well decomposed peat soil was dominating at all study sites; the thickness of the peat layer varied between the sites (Table 2). Although all stands belonged to the same site type, the peat layer was thinner in older stands. The C:N ratio for peat was higher for the oldest stand, which is most probably caused by the soil properties before drainage.

For estimating soil C and nutrient content, samples from 20 random points at depths of 0–10; 10–20; 20–30; 30–40 and 40–50 cm soil layers were taken over the stand to form composite samples separately for each stand. Altogether five replicates for each layer were analysed for C, nutrients and pH (Table 2).

For calculating the C and N storages in the soil, soil bulk density was determined. In the soil pit, bulk density samples were taken from different soil layers (0–50 cm) with a stainless steel cylinder ($d = 40 \text{ mm}$, $V = 50 \text{ cm}^3$) avoiding compression of the soil and preserving soil structure. Three samples were taken from each depth layer. The bulk density samples were dried at the laboratory at 105 °C to constant weight and weighed. The soil analyses were carried out at the Biochemistry Laboratory of the Estonian University of Life Sciences.

2.2. Aboveground biomass and production of the stands

The aboveground woody biomass and production of the stands was estimated in September–October 2014 when the process of biomass formation was completed; the model tree method (Bormann and Gordon, 1984; Uri et al., 2007a,b, 2012, 2014) was used. For this, a sample plot was established in each stand. All trees growing in the sample plot were measured for breast height diameter ($D_{1.3}$) and additional 10–15 trees were measured for height to estimate average stand height. 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 5–7 per model trees per stand were felled in the leafless stage and their biomass was estimated. The stems of the model trees from the youngest stand (12-year-

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