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Estimation of litter input in hemiboreal forests with drained organic soils for improvement of GHG inventories

ARTA BĀRDULE *, GUNA PETAJA, ALDIS BUTLERS, DANA PURVIŅA AND ANDIS LAZDIŅŠ

Latvian State Forest Research Institute 'Silava', Rigas str. 111, Salaspils, LV-2169, Latvia

** Corresponding author: arta.bardule@silava.lv; phone: +371 27119666*

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Abstract

Assessments of net greenhouse gas (GHG) emissions in forest land with drained organic soils conducted within the scope of National GHG Inventories require reliable data on litter production and information on carbon (C) input to soil. To estimate C input through tree above-ground litter, sampling of above-ground litter was done in 36 research sites in Latvia representing typical forests with drained organic soils in the hemiboreal zone. To estimate C input through tree below-ground litter and litter from ground vegetation, modelling approach based on literature review and data on characteristics of forest stands with drained organic soils in Latvia provided by the National Forest Inventory (NFI) was used. The study highlighted dependence of C input to soil through litter production on the stand characteristics and thus significant differences in the C input with litter between young and middle-aged stands. The study also proved that drained organic soils in the middle-aged forests dominated by silver birch, Scots pine and Norway spruce may not be the source of net GHG emissions due to offset by C input through litter production. However, there is still high uncertainty of C input with tree below-ground litter and ground vegetation, particularly, mosses, herbs and grasses which may have crucial role in C balance in forests with drained organic soils.

Keywords: forests, drained organic soils, litter production, carbon input, National GHG Inventory

Introduction

Worldwide, organic soils have large carbon (C) and nitrogen (N) stores, and they can both remove and emit greenhouse gases (GHGs), thus contributing to the atmospheric GHG concentrations (Jauhiainen et al. 2019, Ziche et al. 2019). Organic soils are formed from partially decayed plant remains in anaerobic conditions through generally slow accumulation and compaction below the high water-table (WT) in peat-forming ecosystems (Moore 1989, Jauhiainen et al. 2019). Organic soil layer accumulation depends on the equilibrium between production and decay of organic matter that is highly sensitive to major climate change and management impacts (Joosten 2015). In the Nordic and Baltic countries, peat-forming ecosystems have been widely converted into forest land (Paavilainen and Päivinen 1995, Jauhiainen et al. 2019). These land use changes commonly involve drainage by ditching to promote forest growth, but it changes soil conditions enhancing mineralization of organic matter under aerobic conditions and results in activation of soil C and N stores (Jauhiainen et al. 2019). Drainage diminishes the emission of methane (CH_4), but simultaneously increases emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) from soil. In addition, drainage ditches itself are a large source of CH_4 emissions and carry dissolved organic carbon (DOC) and other C-forms out of the ecosystem, which is then largely emitted off-site as CO_2. Furthermore, deeper drainage and warmer climates increase emissions from organic soils (Joosten 2015). Globally, 15% of the organic soils are drained (Joosten 2015), but in Europe even 48% of the organic soils are drained, especially in the temperate zone (RRR 2017). Although drained organic soils comprise about 0.4% of the global land area, these soils contribute significantly (~5%) to global anthropogenic GHG emissions (Joosten 2015).

Within the National GHG Inventory reports under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, anthropogenic CO_2, CH_4 and N_2O emissions from organic soils in forest land are reported under the Land use, Land use change and Forestry (LULUCF) sector (IPCC 2006, Tiemeyer et al. 2020). Although organic soils have a large impact on the total GHG budget in the LULUCF sector (Lazdiņš and

Lupiķis 2019) and there are growing international requirements for improved accuracy of estimates of CO_2 removals and GHG emissions from organic soils (IPCC 2014), annual GHG emission factors (EFs) from organic soils are still characterized by high uncertainty rate (Jauhiainen et al. 2019) and significant differences between regions even in the same climate zone (Lazdiņš and Lupiķis 2019).

After drainage of organic soils EFs reflect the impact of climatic conditions on the decomposition rate of organic matter. Consequently, moving from higher to lower latitude, emissions from drained organic soils increase (Biancalani and Avagyan 2014). This explains the differences between the IPCC default EFs for temperate climate/vegetation zone calculated on the basis of results obtained in the central and northern parts of Europe and recent findings in Latvia located in the hemiboreal zone – the transitional zone between the boreal and temperate forests of nemoral Europe. For instance, Lupiķis and Lazdiņš (2017) estimated that emissions from drained organic soils in forest land in Latvia equal 0.52 t CO_2-C ha^{-1} yr^{-1}, but the IPCC default EF for temperate climate/vegetation zone is significantly higher – 2.6 t CO_2-C ha^{-1} yr^{-1}. Similarly, research in deciduous and coniferous forest stands in extracted peat fields in Latvia (LIFE REstore 2020) reflected that the IPCC default EF given in the 2013 IPCC guidelines most probably overestimate emissions from organic soils in Latvia (Lazdiņš and Lupiķis 2019).

Litter production is a key parameter in estimating, modelling and predicting forest soil organic carbon (SOC) stocks and its changes responding, for instance, to management practices or climate change (Wutzler and Mund 2007, Hansen et al. 2009, Cao et al. 2019, Feng et al. 2019). Thus, GHG assessments would benefit from reliable litter production information (Neumann et al. 2018). Soil organic matter is primarily plant-derived, contributing to the accumulation of SOC due to humification after plant death, or root-borne organic substances released into the rhizosphere during the plant growth (Kuzyakov and Domanski 2000). It is important to quantify contributions from both above-ground inputs and below-ground inputs to understand the amount of C ultimately stored in the soil (Ekberg et al. 2007, Cao et al. 2020).

Although it is considered that C input through above-ground litter is well investigated (Kuzyakov and Domanski 2000), reports on relationship between inputs of plant above-ground litter and SOC dynamics are still in controversy. Numerous studies have been done to estimate regional drivers of litter production using both field measurements of litter production and modelling approaches (e.g. Wutzler and Mund 2007, Hansen et al. 2009, Becker et al. 2018, Cao et al. 2019, Ziche et al. 2019). Although forest ecosystems are highly complex and various factors exert large spatial heterogeneity (Qin et al. 2019), there are some large-scale efforts to develop litter production models and determine total litter contribution to C cycling in forests addressing climat-, region- and species-specific differences, and its temporal trends. For instance, Liu et al. (2004) determined the relationships between climatic factors and litter production in forests of Eurasia. The results indicate that annual mean temperature has a greater effect on litter production compared to the annual precipitation across Eurasian forests. Furthermore, the results highlighted a difference in climate control between coniferous and broadleaf forests at a continental scale, and consequently different litter production responses to climate change (Liu et al. 2004). Based on data obtained within pan-European forest monitoring of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP-Forests), Neumann et al. (2018) recently improved existing litter production estimation models that require climate information (Liu et al. 2004) by adding biomass abundance approach (leaf area index and stand density index) to quantify litter fluxes aggregated by bioregions and by forest types across Europe. In Latvia, continuous data on litter production in forests is available from the ICP-Forests Level II monitoring plots located in Scots pine stands, but this data set represents forest stands only on dry mineral soils.

While it is relatively easy to collect above-ground litter and estimate its production, quantification of below-ground litter still remains a challenge. The below-ground litter consists of dead roots, mycorrhizae and root exudates. Fine roots are commonly defined as non-woody, short-lived roots that are 2 mm or less in diameter and they represent one of the largest fractions of below-ground litter (Lehtonen 2005, Clemmensen et al. 2013, Leppälammi-Kujansuu et al. 2014, McCormack et al. 2015). The fine root turnover rate is a number that represents the times fine root biomass is replaced annually (Hendrick and Pregitzer, 1992). The fast turnover rates of fine roots ensure a major long-term contribution to below-ground C stocks, although fine root biomass constitutes less than 5% of the total forest biomass (Vogt et al. 1996). The direct methods to measure fine root turnover are ingrowth cores and minirhizotrons, whereas the indirect methods are C isotopic measurements, sequential soil coring, N budget, C budget and correlations with abiotic resources (Lukac 2012, Yuan and Chen 2012).

Excavation of roots for direct measurements is labour-intensive, changes the natural environment and causes artefacts, so that the measurements are no longer fully representative. Therefore, modelling approaches are widely used instead of field measurements to determine fine root biomass and turnover from other easily measurable stand variables. The input data most often include foliage and above-ground biomass, leaf area index (LAI), climate, latitude, net primary production, and land cover type (Liski et al. 2002, Liu et al. 2004, Härkönen et al. 2011, Yuan et al. 2018). The main principle of allometry is that for trees growing under the same conditions there are certain proportions between their dimensions, e.g., height and diameter, biomass and diameter. This principle can be used to predict one variable from another, using allometric equations. Remotely sensed information from satellites or inventory-based gridded forest data also can be applied to predict fine root characteristics at large scale (Yan et al. 2016, Moreno et al. 2017). Above-ground litter values can also be used to estimate below-ground litter. Chen et al. (2018) extended the pipe model analysis proposed by Shinozaki et al. (1964) and estimated that the ratio of fine root production against leaf production at the stand level is about 0.8. Fine root biomass also correlates positively with stand basal area (Vanninen and Mäkelä 1999, Helmisaari et al. 2007, Finér et al. 2011, Lehtonen et al. 2016).

Ground vegetation is another important yet less studied component of forest ecosystems. The C budgets of trees and forest soil have been modelled extensively, but vegetation is usually excluded from these analyses. According to studies carried out in pine and spruce upland forest stands in Finland, ground vegetation comprises about 4–13% of the C stock (Mälkönen 1974, Havas and Kubin 1983). Other studies show that the proportion of the C stock in ground vegetation is 1–2% (Lakida et al. 1996, Pussinen et al. 1997). Although ground vegetation constitutes only a small proportion of biomass in forests, it contributes significantly to nutrient cycles because of the fast turnover and easily decomposable litter (Mälkönen 1974, Palviainen et al. 2005). Consideration of ground vegetation biomass is particularly important during the early-successional stages of forest after clear-cutting or fire disturbances, when it is the main living vegetation component (Palviainen et al. 2005). Ignoring ground vegetation may lead to underestimation of net primary productivity, litter production and the C stock of soil. Biomass of ground vegetation decays and regenerates rapidly, therefore removals in biomass re-growth balance the emissions from decay. In peatlands the proportion of ground vegetation is mainly influenced by the WT level and the structure of the tree layer (Finér and Nieminen 1997, Minkkinen et al. 1999).

There are several methods to estimate ground vegetation biomass. The point-intercept method determines the number of contacts between plants by passing a pin through the vegetation at many positions (Levy and Madden 1933, Goodall 1952). This method gives highly accurate biomass estimates; however, it is destructive, labour-intensive and not suitable for large-scale inventories. Percentage cover analysis is a non-destructive alternative that can be applied extensively; however, it is less accurate, due to differences in visual estimates of each observer. Several studies show a relation between the percentage cover and biomass (Chiarucci et al. 1999, Röttgermann et al. 2000). Muukkonen and Mäkipää (2006) developed equations for pine, spruce and broad-leaved forest stands to calculate ground vegetation biomass using stand age and site attributes. There are models for specific vegetation types such as dwarf shrubs, herbs and grasses, mosses, lichens, total field layer, total bottom layer and all ground vegetation together. Models, where only stand age is an explanatory variable, can also be used in other boreal countries. Stand age is considered a significant predictor of ground vegetation because of the influence of structural changes stands undergo during their development. Light availability changes along with leaf area index, and there are shifts in vegetation from heliophilous species (herbs and grasses) towards species adapted to shady environments (e.g. mosses) as well as changes in abundance and occurrence of certain species (Lindholm and Vasander 1987, Luyssaert et al. 2007).

The specific aim of the study was to contribute to improvement of knowledge on C input to soil through plant litter production, including tree above- and below-ground litter and ground vegetation litter in the hemiboreal region (Latvia is a target area) to generally improve the National GHG Inventory.

Materials and methods

Tree above-ground litter collection and analysis

We conducted the study in central Latvia. Sampling of tree above-ground litter was performed in 36 research sites representing typical forests with drained organic soils in the hemiboreal region (Figure 1). The forest site types based on Bušs (1981) in the order from relatively nutrient poor to nutrient rich soils (Kārkliņš et al. 2009) are: *Callunosa turf. mel.* (relatively low soil fertility), *Vacciniosa turf. mel.* (moderate soil fertility), *Myrtillosa turf. mel.* (relatively high soil fertility), and *Oxalidosa turf. mel*. (relatively very high soil fertility). The research sites were dominated by Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.), or silver birch (*Betula pendula* Roth). The mean annual precipitation in the study region was 732 mm and the mean annual temperature was 8.1 °C in 2019 (calculated as average using data obtained from two nearest observation stations in Sigulda and Skriveri; Latvian Environment, Geology and Meteorology Centre). More detailed characteristics of the research sites are presented in Table 1.

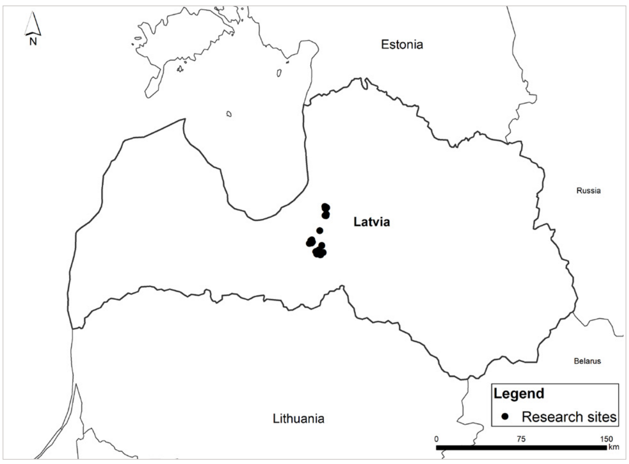

Figure 1. Location of the research sites (forest stands with drained organic soils) in Latvia

Table 1. Characteristics of the research sites located in the typical forests with drained organic soils in the hemiboreal zone in Latvia

Forest site type	Soil type	Dominant tree species (number of research sites)	Number of trees per hectare, count ha^{-1}	Diameter, cm	Height, m	Basal area, m^2 ha^{-1}	Stock, m^3 ha^{-1}	Age, years
Vacciniosa turf. mel.	Fibric histosols	Scots pine (2)	550 ± 30	22.2 ± 0.8	21.5 ± 0.1	22.4 ± 0.3	238 ± 4	90 ± 5
			(520–580)	(21.4–23.0)	(21.3–21.6)	(22.1–22.8)	(234–241)	(85–95)
Oxalidosa turf. mel.	Terric histosols	silver birch (8)	1,488 ± 295	15.2 ± 1.9	16.5 ± 1.3	26.5 ± 3.5	264 ± 50	47 ± 8
			(360–3,080)	(8.6–21.8)	(10.2–20.6)	(16.8–42.7)	(138–500)	(22–68)
		Norway spruce (10)	1,000 ± 141	20.0 ± 1.4	18.7 ± 1.0	32.9 ± 2.4	348 ± 40	51 ± 5
			(620–2,040)	(10.3–27.7)	(12.1–23.6)	(20.7–44.5)	(153–586)	(26–78)
Myrtillosa turf. mel.	Terric histosols	silver birch (5)	1,400 ± 135	14.1 ± 1.5	15.9 ± 1.1	24.6 ± 4.0	229 ± 49	60 ± 5
			(1,120–1,860)	(10.8–19.4)	(13.1–18.6)	(15.9–40.0)	(115–407)	(45–70)
		Norway spruce (1)	1,100	10.2	9.8	10.5	68	59
		Scots pine (3)	693 ± 216	23.0 ± 4.6	19.1 ± 4.5	28.2 ± 6.3	310 ± 122	63 ± 22
			(420–1120)	(14.2–29.7)	(11.3–26.9)	(18.6–40.1)	(112–533)	(23–98)
Callunosa turf. mel.	Fibric histosols	silver birch (3)	2,047 ± 704	9.5 ± 2.4	11.4 ± 1.6	13.1 ± 1.2	90 ± 17	30 ± 0
			(840–3,280)	(6.3–14.1)	(9.5–14.7)	(11.5–15.5)	(67–125)	(30–31)
		Scots pine (4)	1,460 ± 214	10.6 ± 1.8	9.7 ± 1.7	14.5 ± 3.9	93 ± 32	42 ± 12
			(980–2,020)	(6.6–13.8)	(5.4–12.6)	(5.3–23.8)	(21–163)	(21–70)
Average	-	silver birch (16)	1,565 ± 195	13.8 ± 1.2	15.3 ± 0.9	23.4 ± 2.4	221 ± 33	48 ± 5
			(360–3,280)	(6.3–21.8)	(9.5–20.6)	(11.5–42.7)	(67–500)	(22–70)
		Norway spruce (11)	1,009 ± 127	19.1 ± 1.6	17.9 ± 1.2	30.9 ± 3.0	323 ± 44	51 ± 5
			(620–2,040)	(10.2–27.7)	(9.8–23.6)	(10.5–44.5)	(68–586)	(26–78)
		Scots pine (9)	1,002 ± 181	17.3 ± 2.6	15.5 ± 2.4	20.8 ± 3.2	197 ± 51	59 ± 10
			(420–2,020)	(6.6–29.7)	(5.4–26.9)	(5.3–40.1)	(21–533)	(21–98)

Note: Mean values ± S.E. (minimum – maximum values) are summarized in the table.

Tree above-ground litter was collected using 5 litter collectors placed randomly in each research site under uniform forest canopy during the period from October 2018 till December 2019 (covering one full calendar year). Tree above-ground litter included everything falling from trees (foliage, branches, twigs, bark, fruits, seeds, rest of fruiting, fines, frass, insects, lichen, moss, etc.) excluding large dimension branches which are not perceived by collectors. This fraction of large dimension branches was not collected by collectors and is accounted under dead wood pool (natural mortality) within the National GHG Inventory. Thus, double accounting of C input to soil is avoided. The litter collector design – the collecting area of individual traps – 0.42 m^2, solid funnel (0.7 m deep) with a bag of inert material (nylon fabric) with mesh size of 0.2 mm. Above-ground litter was collected monthly (Ukonmaanaho et al. 2016). After transporting the tree above-ground litter to the laboratory, dry matter was determined by drying samples at a temperature of 105 °C to complete desiccation. Total C and N concentration of the grounded litter samples (dried at a temperature of 70 °C) were determined by total combustion at 950 °C with elemental analyser Elementar EL Cube according to the LVS ISO (2006) and ISO (1998), respectively.

Carbon input with tree below-ground litter (modelling approach using the NFI data)

Neumann et al. (2019) compiled data from 454 plots across forests in Europe and 19 estimation models of fine root biomass and production. We chose this model to estimate fine root biomass, which requires stem biomass as input data (given in Equation 1).

$$\textit{Fine root biomass } (t\ ha^{-1}) = \textit{stem biomass } (t\ ha^{-1}) \cdot 0.02 \quad (1)$$

Subsequently, we multiplied the biomass value by fine root turnover rate (yr^{-1}) to obtain the value of annual tree below-ground litter input. Yuan and Chen (2010) reviewed fine root characteristics in boreal forest ecosystems, and we used the turnover rates for *Betula* (1.22 ± 0.56), *Picea* (0.84 ± 0.07) and *Pinus* (0.61 ± 0.17) species from their study. To calculate C input with fine roots, it was assumed that the C content in biomass is 48% for broadleaves and 51% for conifers (Lamlom and Savidge 2003, IPCC 2006).

Carbon input with ground vegetation litter (modeling approach using the NFI data)

We used the equations elaborated by Muukkonen and Mäkipää (2006). Ground vegetation biomass (kg ha^{-1}) was calculated for spruce, pine and birch forest stands and for different plant forms such as mosses, lichens, dwarf shrubs, herbs and grasses separately (Equations 2–11). The input variable is stand age (years).

Pine forest stands:

Above-ground biomass (y), dwarf shrubs:

$$\sqrt{y + 0.5} = 16.68 + 0.129 \cdot \textit{stand age} - 0.0004 \cdot \textit{stand age}^2 \quad (2)$$

Above-ground biomass (y), herbs and grasses:

$$\sqrt{y + 0.5} = 11.725 - 0.098 \cdot \textit{stand age} + 0.0002 \cdot \textit{stand age}^2 \quad (3)$$

Above-ground biomass (y), mosses:

$$\sqrt{y+0.5} = 27.329 + 0.138 \cdot \textit{stand age} - 0.0005 \cdot \textit{stand age}^2 \quad (4)$$

Above-ground biomass (y), lichens:

$$\sqrt{y+0.5} = 7.975 - 0.0002 \cdot \textit{stand age}^2 \quad (5)$$

Spruce forest stands:

Above-ground biomass (y), dwarf-shrubs:

$$\sqrt{y+0.5} = 10.375 - 0.033 \cdot \textit{stand age} + 0.001 \cdot \textit{stand age}^2 - 0.000004 \cdot \textit{stand age}^3 \quad (6)$$

Above-ground biomass, herbs and grasses:

$$\sqrt{y+0.5} = 15.058 - 0.113 \cdot \textit{stand age} + 0.0003 \cdot \textit{stand age}^2 \quad (7)$$

Above-ground biomass (y), mosses:

$$\sqrt{y+0.5} = 19.282 + 0.164 \cdot \textit{stand age} - 0.000001 \cdot \textit{stand age}^3 \quad (8)$$

Broad-leaved forest stands:

Above-ground biomass (y), dwarf-shrubs:

$$\sqrt{y+0.5} = 7.102 + 0.0004 \cdot \textit{stand age}^2 \quad (9)$$

Above-ground biomass (y), herbs and grasses:

$$\sqrt{y+0.5} = 20.58 - 0.423 \cdot \textit{stand age} + 0.004 \cdot \textit{stand age}^2 - 0.00002 \cdot \textit{stand age}^3 \quad (10)$$

Above-ground biomass (y), mosses:

$$\sqrt{y+0.5} = 13.555 - 0.056 \cdot \textit{stand age} \quad (11)$$

To calculate above-ground vegetation litter, the obtained values were multiplied by the turnover rates of the respective plant forms – 0.25 for dwarf-shrubs, 1 for herbs and grasses, 0.33 for mosses and 0.1 for lichens (Muukkonen 2006). It was assumed that the proportion of the ground vegetation biomass located in the below-ground parts is 70% of the total biomass (Mälkönen 1974, Havas and Kubin 1983, Palviainen et al. 2005). To calculate C input with ground vegetation litter, it was assumed that the C fraction in biomass is 0.475 (Magnussen and Reed 2015).

The National Forest Inventory data used for calculations

Characteristic parameters of the forest stands with drained organic soils (Table 2) provided by the 3rd cycle of the National Forest Inventory (NFI) were used to model tree fine root biomass according to the Equation 1 and above-ground biomass of ground vegetation according to the Equations 2–11.

Applied soil emission factors

Table 3 summarizes the applied GHG EFs for forests with drained organic soils in the hemiboreal region. The range of basal areas in the forests, where the applied heterotrophic respiration values (GHG EFs) were measured, is from 12.8 to 28.3 $m^2\ ha^{-1}$ (mean 20.5 $m^2\ ha^{-1}$) for Scots pine stands and from 14.9 to 28.1 $m^2\ ha^{-1}$ (mean 20.7 $m^2\ ha^{-1}$) for silver birch stands (Lazdiņš and Lupiķis 2019). Forests, where the applied GHG EFs were measured, correspond to *Myrtillosa turf. mel.* (relatively high soil fertility) forest site type (Lazdiņš and Lupiķis 2019).

Net GHG emissions were calculated as a sum of GHG emission from soil and total C input to soil. Emissions are usually expressed with a positive sign, but removals including C input to soil – with a negative sign. Respectively, negative net GHG emissions mean that the system is a net sink contributing to reduction of GHG emissions, and if net GHG emissions have a positive sign – the system is a net source of GHG emissions contributing to increase of GHGs in atmosphere (IPCC 2006).

Table 2. Average characteristic parameters of the forest stands with drained organic soils in Latvia (NFI, 3rd cycle)

Parameter	Value	Dominant tree species		
		Scots pine	Norway spruce	Silver birch
Number of plots	number	349	242	503
Age of dominant tree species, years	average ± S.E.	79 ± 2	51 ± 2	41 ± 1
	range (min…max)	1–221	1–195	1–119
Total basal area, $m^2\ ha^{-1}$	average ± S.E.	26.7 ± 1.5	22.8 ± 1.5	18.0 ± 0.6
	range (min…max)	0.0079–90.7	0.0079–130.8	0.0028–85.4
Stem biomass, $t\ ha^{-1}$	average ± S.E.	210.7 ± 7.2	167.2 ± 8.5	145.3 ± 5.8
	range (min…max)	0.008–760.8	0.011–787.7	0.002–924.2

Table 3. Applied GHG emission factors for the forests with drained organic soils in the hemiboreal zone

Dominant tree species	CO_2-C *, $t\ ha^{-1}\ yr^{-1}$	CH_4-C, $kg\ ha^{-1}\ yr^{-1}$	N_2O-N, $kg\ ha^{-1}\ yr^{-1}$	CH_4 from drainage ditch ***, $kg\ ha^{-1}\ yr^{-1}$	Total GHG, $t\ CO_2$-C eq. $ha^{-1}\ yr^{-1}$
Silver birch	5.60	22.39	0.62	217	5.91
Norway spruce	5.25	–1.39 **	–0.05 **	217	5.27
Scots pine	5.25	–1.39	–0.05	217	5.27
Data source	Lazdiņš and Lupiķis 2019	Lazdiņš and Lupiķis 2019	Lazdiņš and Lupiķis 2019	IPCC 2014	Calculated

Note: * Soil heterotrophic respiration; ** Emission factor estimated for Scots pine dominated stands (Lazdiņš and Lupiķis 2019) was used; *** A fraction of the total area of drained organic soil which is occupied by ditches is 2.5% (IPCC 2014).

Data analysis

Data processing and all statistical analyses were performed in the R environment (R Core Team 2017). Statistical differences between average values were analysed with the pairwise comparison using *t* test with pooled SD (function *pairwise.t.test()*). Correlations (including their significance) between biomass of tree above-ground litter and characteristics of the forest stands were tested using Pearson's product-moment correlation test (function *cor.test()*). We considered relationships significant if *p* values were lower than 0.05. To gain a better understanding of relationships between annually produced biomass of tree above-ground litter and characteristics of forest stand, a linear equation models were constructed. For all analyses, a 95% confidence level was used.

Results

Above-ground litter of tree

The research site average annually produced biomass of tree above-ground total litter in the forests with drained organic soils was within the range from 1.08 ± 0.16 t ha^{-1} yr^{-1} in the Scots pine dominated stand which is the youngest forest stand included in the study and characterized with the lowest stem biomass parameters to 7.26 ± 0.39 t ha^{-1} yr^{-1} in the Norway spruce dominated stand with relatively high stem biomass parameters. Average annually produced biomass of tree above-ground litter in the research sites was 3.77 ± 0.23 t ha^{-1} yr^{-1}.

Table 4 summarizes statistical data on the relationships characterizing a dependence of annually produced biomass of tree above-ground litter on characteristics of the forest stands with drained organic soils. For the silver birch and Norway spruce stands strong and statistically significant correlations ($r > 0.7$, $p < 0.05$) were found between annually produced biomass of tree above-ground litter and forest stand characteristics such as average height, basal area and stock which in turn correlate with each other. For the Scots pine stands moderately strong, but statistically insignificant correlations ($0.5 < r < 0.7$, $p > 0.05$) between annually produced biomass of tree above-ground litter and average diameter and basal area of the forest stands were revealed.

Annually produced biomass of tree above-ground litter was best described by stand basal area as the most significantly influencing factor (independent variable) of nonlinear regressions. The best models for annual production of tree above-ground litter (polynomial regression for the silver birch stands and power regression for the Norway spruce and Scots pine dominated stands) are shown in Figure 2.

Average total C and N concentration, as well as average C/N ratio of tree above-ground litter are shown in Figure 3. In general, statistically significantly higher ($p < 0.001$) total C concentration was found in Scots pine (540.7 ± 2.6 g kg^{-1}) and silver birch (537.9 ± 2.1 g kg^{-1}) above-ground litter if compared to Norway spruce (521.2 ± 2.1 g kg^{-1}) above-ground litter. Total N concentration in Scots pine above-ground litter (8.0 ± 0.3 g kg^{-1}) was significantly smaller if compared to Norway spruce (14.2 ± 0.4 g kg^{-1}) and silver birch (14.2 ± 0.2 g kg^{-1}) above-ground litter. Consequently, significantly higher ($p < 0.001$) C/N ratio was found in Scots pine litter (70.6 ± 2.1) if compared to Norway spruce (37.9 ± 0.9) and silver birch (38.7 ± 0.8) above-ground litter (Figure 3).

The comparison of calculated total C and N annual input with tree above-ground litter between stands with different dominant tree species in the forests with drained

Table 4. Statistical data (correlation coefficients *r*, *p*-values, equations and adjusted R^2 of linear regressions) on the relationships characterizing dependence of annually produced biomass of tree above-ground litter on characteristics of the forest stand with drained organic soils

Tree species	Independent variable	Pearson's correlation		Linear regression	
		r	*p*	equation	adjusted R^2
Scots pine	Number of trees per hectare, count ha^{-1}	–0.37	0.330	$y = -0.00061x + 3.61$	0.012
	Diameter, cm	**0.50**	0.175	$y = 0.056x + 2.03$	0.14
	Height, m	0.42	0.258	$y = 0.054x + 2.17$	0.061
	Basal area, m^2 ha^{-1}	**0.56**	0.120	$y = 0.051x + 1.93$	0.21
	Stock, m^3 ha^{-1}	0.40	0.282	$y = 0.0024x + 2.53$	0.043
	Stand age, years	0.16	0.674	$y = 0.050x + 2.68$	–0.11
Silver birch	Number of trees per hectare, count ha^{-1}	–0.29	0.270	$y = -0.00046x + 4.76$	0.021
	Diameter, cm	0.46	0.075	$y = 0.12x + 2.45$	0.15
	Height, m	**0.71**	**0.002**	$y = 0.24x + 0.31$	0.47
	Basal area, m^2 ha^{-1}	**0.75**	**< 0.001**	$y = 0.09x + 1.88$	0.52
	Stock, m^3 ha^{-1}	**0.73**	**0.001**	$y = 0.0068x + 2.55$	0.50
	Age, years	0.46	0.073	$y = 0.32x + 2.41$	0.16
Norway spruce	Number of trees per hectare, count ha^{-1}	–0.13	0.698	$y = -00045x + 5.83$	–0.092
	Diameter, cm	**0.59**	0.055	$y = 0.17x + 2.20$	0.28
	Height, m	**0.73**	**0.011**	$y = 0.26x + 0.72$	0.48
	Basal area, m^2 ha^{-1}	**0.82**	**0.002**	$y = 0.12x + 1.65$	0.65
	Stock, m^3 ha^{-1}	**0.78**	**0.005**	$y = 0.0077x + 2.87$	0.56
	Age, years	0.10	0.771	$y = 0.096x + 4.84$	–0.10

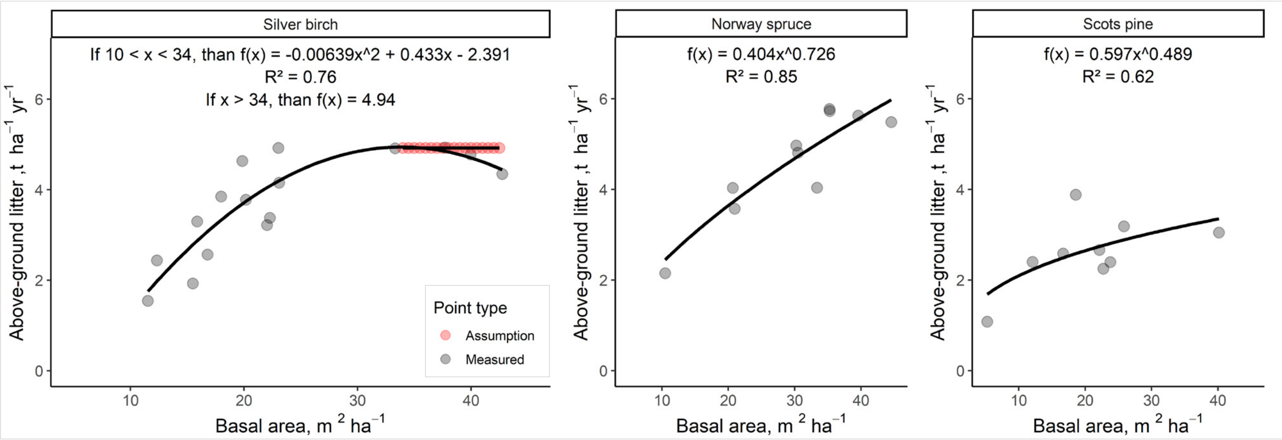

Figure 2. Nonlinear regressions describing dependence of annually produced biomass of tree above-ground litter on basal area in the forests with drained organic soils

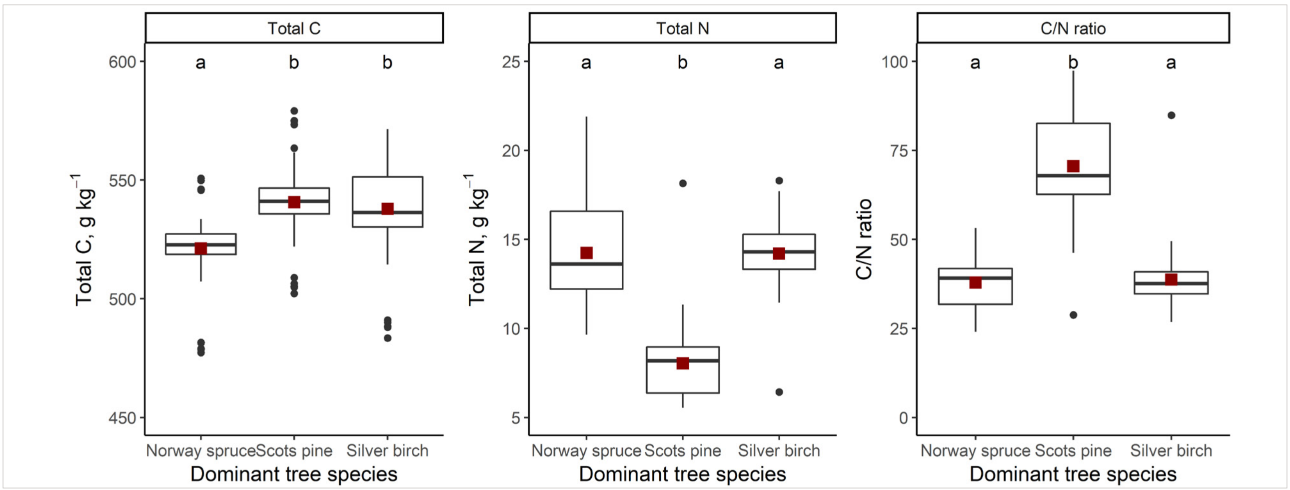

Figure 3. Total C and N concentrations and C/N ratio in tree above-ground litter in forests with drained organic soils based on field measurements

Note: In the boxplots, the median is shown by the bold line, the mean is shown by the dark red square, the box corresponds to the lower and upper quartiles, whiskers show the minimal and maximal values (within 150% of the interquartile range from the median) and black dots represent outliers of the datasets. Characters *a* and *b* label statistically significant differences ($p < 0.05$, $\alpha = 0.05$) in average values between stands with different dominant tree species.

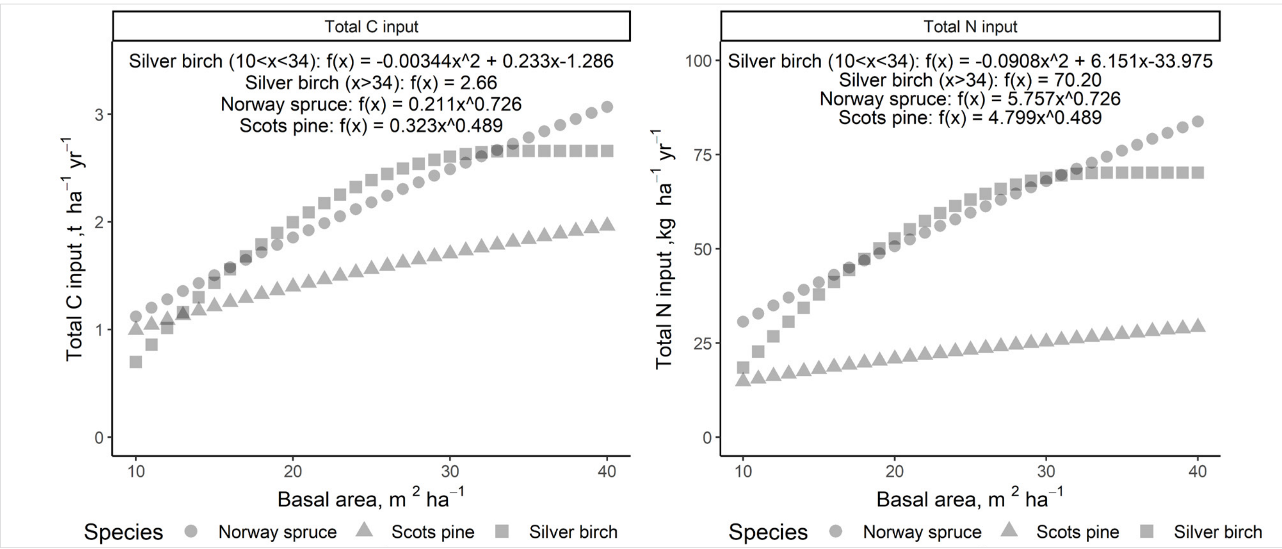

Figure 4. Calculated total C and N input through above-ground tree litter in stands characterized with basal area in the range from 10 to 40 m^2 ha^{-1} in the forests with drained organic soils

organic soils is shown in Figure 4. We calculated the input of total C and N by applying equations of nonlinear regressions of annual input of above-ground litter biomass depending on stand basal area (Figure 2) and average C and N concentrations in litter of different tree species (Figure 3). In the stands with a range of basal area from 10 to 40 m^2 ha^{-1}, the highest total C and N annual input was estimated in the Norway spruce dominated stands with a basal area of 40 m^2 ha^{-1}, but the smallest total C and N annual input was estimated in the silver birch and Scots pine dominated stands, respectively, with a basal area of 10 m^2 ha^{-1} (Figure 4).

Modelled carbon input through tree below-ground litter

Modelled C annual input through tree below-ground litter in the forests with drained organic soils based on stem biomass data provided by the NFI (3rd cycle) is shown in Figure 5. In the Scots pine dominated stands, weighted average C annual input through below-ground tree litter that takes into account the distribution of forest stands according to the NFI data was 1.31 ± 0.05 t ha^{-1} yr^{-1}. In the Norway spruce dominated stands it was 1.43 ± 0.07 t ha^{-1} yr^{-1}, but in the silver birch stands – 1.70 ± 0.07 t ha^{-1} yr^{-1}, furthermore, differences in average values between stands with different dominant tree species were statistically significant ($p < 0.003$). The highest average C annual input through below-ground tree litter (3.52 ± 0.97 t ha^{-1} yr^{-1}) was estimated in the silver birch dominated stands at the age of > 91 years, but the lowest C input was estimated in the young stands of silver birch up to 10-years age (0.07 ± 0.02 t ha^{-1} yr^{-1}).

Modelled carbon input through ground vegetation litter

The modelled total C annual input through above-ground and below-ground litter of ground vegetation (dwarf shrubs, herbs, grasses, mosses and lichens) in the forests with drained organic soils is shown in Figure 6. The modelled total C annual input through above- and below-ground litter of ground vegetation ranges up to 1.55 ± 0.18 t ha^{-1} yr^{-1} in the Norway spruce dominated stands with the age of > 140 years. The weighted average annual C input through above-ground and below-ground litter of ground vegetation that takes into account the distribution of forest stands according to the NFI data in the Scots pine dominated stands was 0.91 ± 0.01 t ha^{-1} yr^{-1}, in the Norway spruce dominated stands – 0.65 ± 0.01 kg ha^{-1} yr^{-1}, but in silver birch stands – 0.27 ± 0.01 t ha^{-1} yr^{-1}, furthermore, differences in average values between stands with different dominant tree species were statistically significant ($p < 0.001$).

In the Norway spruce and Scots pine dominated stands, mosses produce the largest share of the C input through above-ground litter of ground vegetation (61 and 68% of total C input, respectively). The second largest share of the C input through above-ground litter of ground vegetation is formed by herbs and grasses in the Norway spruce dominated stands (29% of total C input) and dwarf shrubs in the Scots pine dominated stands (25% of total C input). In the silver birch dominated stands, the largest share of C input through above-ground litter of ground vegetation is formed by herbs and grasses (52% of total C input), but the second largest share of C input through above-ground litter of ground vegetation is produced by mosses (32% of total C input).

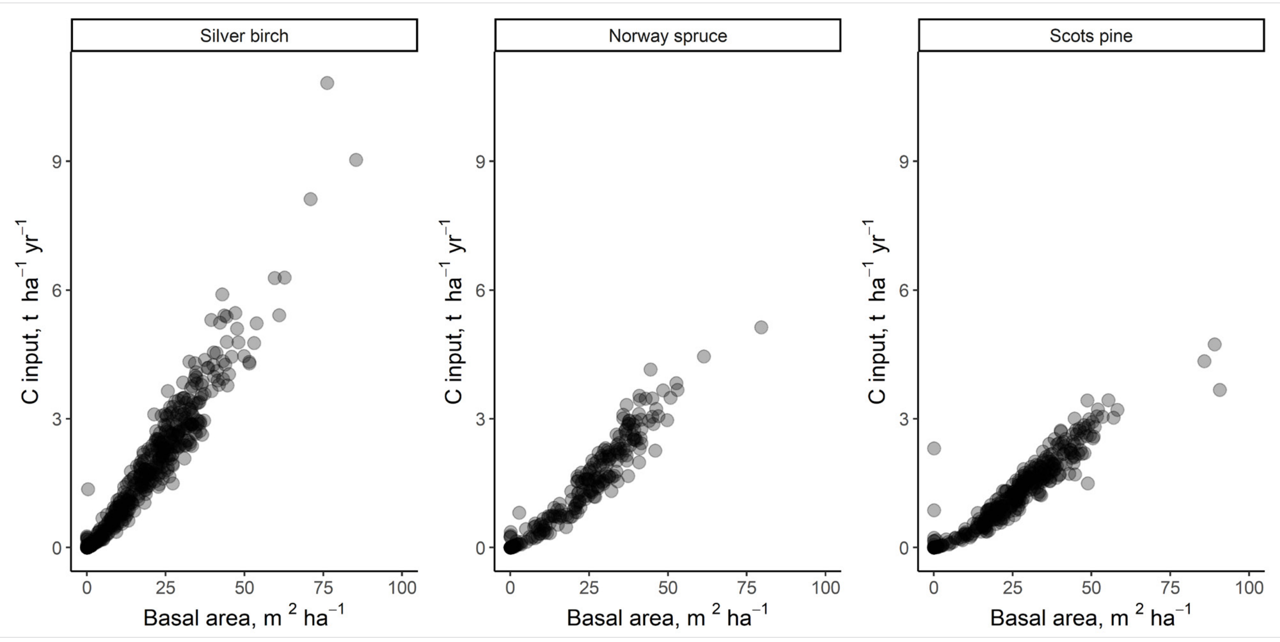

Figure 5. Modelled carbon input through below-ground tree litter in the forests with drained organic soils based on stem biomass data provided by the National Forest Inventory (3rd cycle)

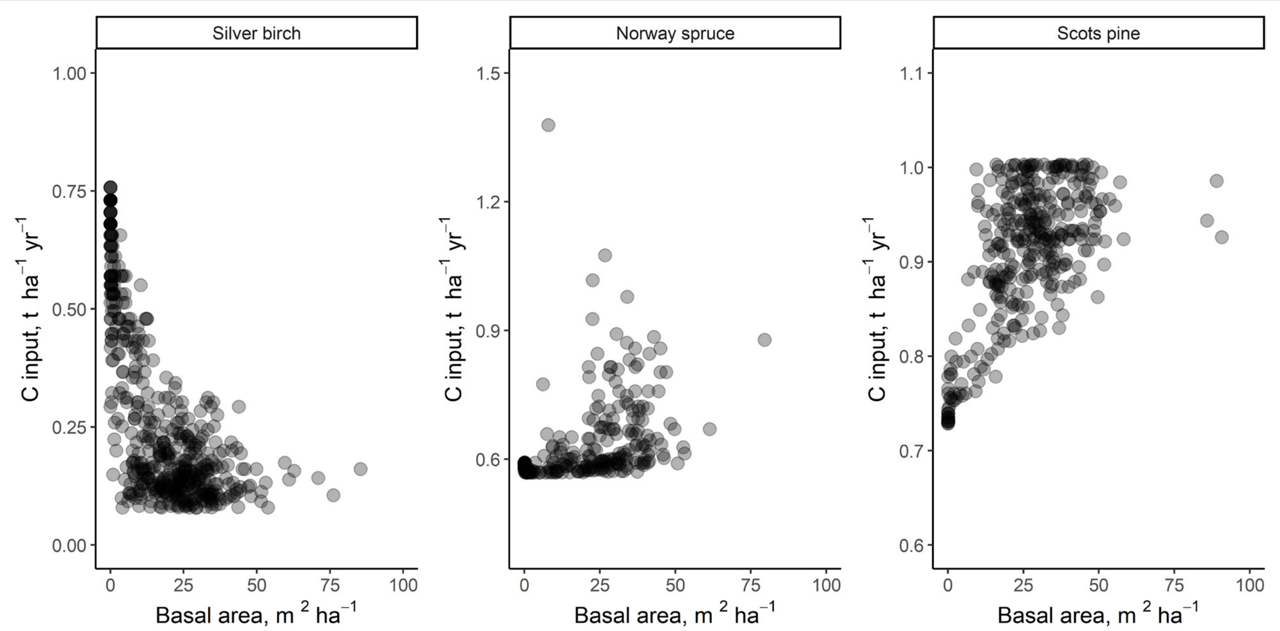

Figure 6. Modelled carbon input through above-ground and below-ground litter of ground vegetation (dwarf shrubs, herbs, grasses, mosses and lichens) in the forests with drained organic soils based on stand age distribution data provided by the National Forest Inventory (3rd cycle)

Net GHG emissions from soil

Net GHG emissions from soils in the forests with drained organic soils were calculated for stands characterized with basal area in the range between 10 and 40 m^2 ha^{-1} (Figure 7). In the forest stands within this basal area range, the calculated individual net GHG emissions from soils ranged from 4.30 t CO_2-C ha^{-1} yr^{-1} to –2.15 t CO_2-C ha^{-1} yr^{-1} (both minimum and maximum value detected in the silver birch dominated stands). Weighted average net GHG emissions that takes into account the distribution of forest stands according to the NFI data were 1.54 ± 0.05 t CO_2-C ha^{-1} yr^{-1} in the Scots pine dominated stands, 0.70 ± 0.10 t CO_2-C ha^{-1} yr^{-1} in the Norway spruce dominated stands and 1.47 ± 0.08 t CO_2-C ha^{-1} yr^{-1} in the silver birch dominated stands.

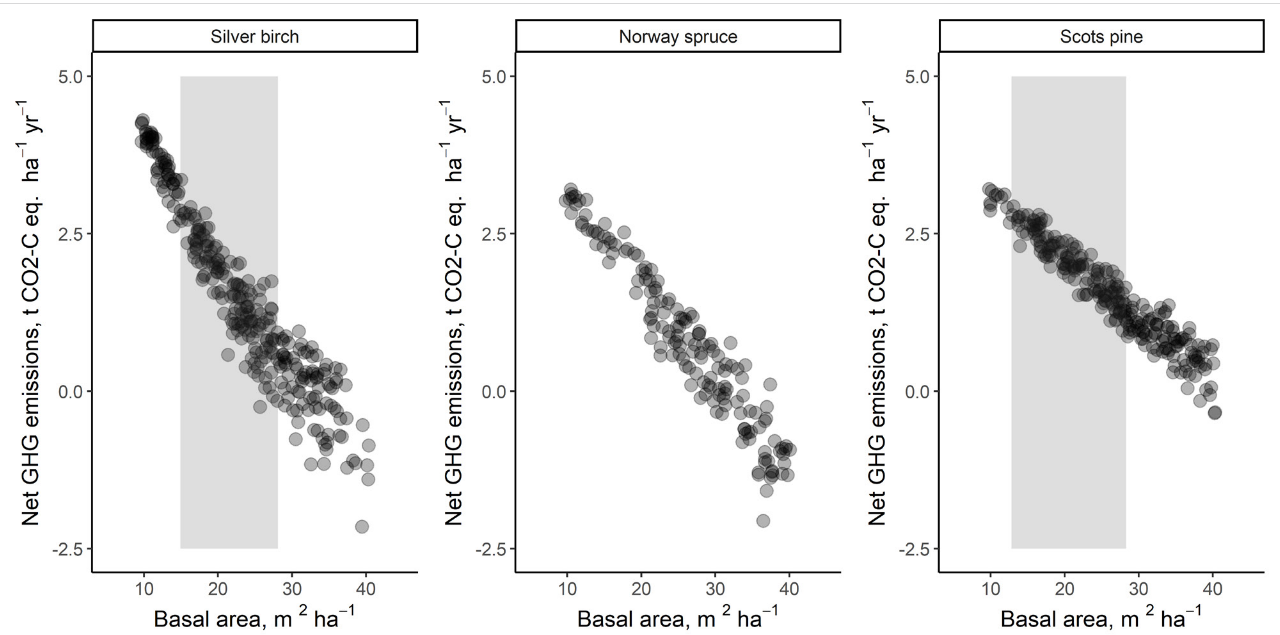

Figure 7. Net GHG emissions from soil in stands characterized with basal area in the range from 10 to 40 m^2 ha^{-1} in the forests with drained organic soils

Note: A grey area indicates the range of basal areas in the forests where the applied heterotrophic respiration (GHG emission factors, Table 3) values were measured.

In general, drained organic soils in the silver birch and Norway spruce stands with basal area in the range from 10 to 32 and 31 m^2 ha^{-1}, respectively, and in the Scots pine stands with basal area in the range from 10 to 40 m^2 ha^{-1} were source of net GHG emissions. But drained organic soils in the silver birch stands with basal area in the range from 32 to 40 m^2 ha^{-1} and in the Norway spruce stands with basal area in the range from 31 to 40 m^2 ha^{-1} were sink of net GHG emissions. In stands within these basal area ranges (32–40 m^2 ha^{-1} for silver birch and 31–40 m^2 ha^{-1} for Norway spruce stands), weighted average net GHG emissions were –0.29 ± 0.09 t CO_2-C ha^{-1} yr^{-1} in the silver birch stands and –0.61 ± 0.09 t CO_2-C ha^{-1} yr^{-1} in the Norway spruce. Underestimation or overestimation of total net GHG emissions might have occurred in stands with basal area ranges not covered by estimates of soil heterotrophic respiration (uncoloured area in Figure 7).

Discussion

Biomass of tree above-ground litter

Litter production is a significant process in the global C and nutrient cycles of terrestrial ecosystems (Liu et al. 2004, Feng et al. 2019). Tree species and climate are key drivers for litter production; thus, litter production rates are usually estimated by biogeoclimatic zones using equations including climatic parameters (e.g. Berg and Meentemeyer 2001, Liu et al. 2004) and information on biomass abundance (e.g. Neumann et al. 2018) as predictors. For instance, Berg and Meentemeyer (2001) developed regressions for European coniferous forests against a set of climatic parameters, and the best simple relationships were obtained with annual actual evapotranspiration and other parameters including temperature, whereas, for example, precipitation gave lower *r* values. Based on the review of original publications over litter production in Eurasian forests Liu et al. (2003) calculated that average total litter production rate in boreal forests is 2.61 ± 1.08 t ha^{-1} yr^{-1} with a range from 0.27 to 5.08 t ha^{-1} yr^{-1}. They developed regression model that uses annual mean temperature and annual precipitation as independent variables (Liu et al. 2004). Similarly, as Berg and Meentemeyer (2001), Liu et al. (2004) also concluded that annual mean temperature has a greater effect on litter production compared to annual precipitation across the Eurasian forests. The mean values from the data provided by the ICP Forests Level II network covering the full geographical range of European forests (Neumann et al. 2018) are higher than calculated by Liu et al. (2004). Neumann et al. (2018) calculated that average annual litter production rate for northern Europe (Fennoscandia and Baltic states, mainly boreal forests) is 3.22 ± 2.01 t ha^{-1} yr^{-1} for conifers and 2.76 ± 1.27 t ha^{-1} yr^{-1} for broadleaves. Further they concluded that the best developed regression model for total litter production uses temperature, precipitation and biomass abundance (stand density and leaf area index) as independent variables (Neumann et al. 2018). We developed country-specific regression model for total tree above-ground litter production in the stands with drained organic soils using stand basal area as an independent variable; climatic parameters were omitted from the models due to narrow coverage of climate transect by the research sites. Field observations showed tree above-ground litter production rate in the forests with drained organic soils in the range from 1.08 ± 0.16 to 7.26 ± 0.39 t ha^{-1} yr^{-1} depending on dominant tree species and forest stand biomass parameters.

Most of the regional evaluations of litter production rates carried out so far do not differentiate forests with organic soils, although forest stands with organic soils may structurally differ from stands on mineral soils (Laiho et al. 2003, Laiho et al. 2008). According to the 3rd cycle of the NFI data, 73% of the Scots pine stands and 65% of the Norway spruce stands with drained organic soils in Latvia correspond to the basal area range from 10 to 40 m^2 ha^{-1} and average litter production (biomass) rate in these stands is 2.90 ± 0.03 and 4.33 ± 0.08 t ha^{-1} yr^{-1}, respectively (calculated based on the regression models developed within the study). Most of the silver birch stands with drained organic soils (60%) correspond to the basal area range from 10 to 40 m^2 ha^{-1} as well, and average litter production (biomass) rate in these stands is 3.86 ± 0.06 t ha^{-1} yr^{-1}. These calculated values of average litter production rate in the forests with drained organic soils in Latvia are significantly higher than those calculated using, for instance, the regression models developed by Liu et al. (2004) which use annual mean temperature and annual precipitation as independent variables (1.48 t ha^{-1} yr^{-1} for broadleaves and 1.88 t ha^{-1} yr^{-1} for conifers if annual mean temperature is 8.1 °C and annual precipitation is 732 mm).

Carbon input through tree above-ground litter

Mostly, C content in conifers is higher than in broadleaves due to higher lignin content in coniferous wood (Lamlom and Savidge 2003), but exceptions are observed in northern Europe (Neumann et al. 2018) which was also confirmed by our results. The default IPCC (2006) C content for temperate and boreal regions in above-ground forest biomass of 48% for broadleaves and 51% for conifers (Lamlom and Savidge 2003, IPCC 2006) provides estimates, which are about 12% lower for broadleaves and about 4% lower for conifers than C content estimates in litter determined within our study. Thus, based on our results, we can support the use of both tree species- and region-specific C content values within estimations of C flows through litter production since C content in litter differs significantly between tree species and biogeoclimatic zones.

A high C/N ratio may indicate slower decomposition rates due to high lignin/N ratios that retard the decomposition processes (Berg et al. 2000). Furthermore, litters rich in N (with a low C/N ratio) not only decompose faster, but also increase the decomposer activity (C-use efficiency), resulting in C transportation, incorporation and ultimately stabilization into the deeper soil matrix (Zhou et al. 2019). Results of our study indicated that the Norway spruce and silver birch stands produce litter with a significantly higher total N content and lower C/N ratio if compared to Scots pine litter, which theoretically can promote higher SOC accumulation rate in the Norway spruce and silver birch stands.

Neumann et al. (2018) estimated that the average C input through total tree above-ground litter in the forests of northern Europe is 1.7 ± 1.1 t C ha^{-1} yr^{-1} for conifer stands and 1.5 ± 0.7 t C ha^{-1} yr^{-1} for broadleaved stands. Our average estimates of C input for conifer and silver birch stands characterized with basal area in the range from 10 to 40 m^2 ha^{-1} (1.82 ± 0.02 t C ha^{-1} yr^{-1} and 2.07 ± 0.03 t C ha^{-1} yr^{-1}, respectively) are within the range of their estimates. Our average estimates for C input through tree above-ground litter in the stands with basal area in the range from 10 to 40 m^2 ha^{-1} were about 1.5 times higher for conifers, comparing with the input from tree below-ground litter. For silver birch, average estimates for C input through tree above-ground litter were quite like C input through tree below-ground litter (average difference in C input between tree above- and below-ground litter was –0.13 t C ha^{-1} yr^{-1}).

Carbon input through tree below-ground litter

Our estimates fall within the range of the results of other studies carried out in the boreal region and show a tendency for below-ground litter to increase with increasing stand basal area. According to our estimates, the below-ground litter input also tends to increase along with stand age. The highest litter input was observed in the silver birch stand (with the age of > 50 years). Underestimation or overestimation may have occurred because there were no LAI or foliage biomass data available and estimation models that require these parameters as input variables offer the most accurate results.

According to a study carried out in southern Sweden, the estimated fine root litter input was the highest in spruce stands (1.3 t C ha^{-1} yr^{-1}) followed by pine (1.06 t C ha^{-1} yr^{-1}) and birch (0.77 t C m^{-2} yr^{-1}) stands (Hansson et al. 2011). Also, in a study carried out by Ågren et al. (2007) using data from the Swedish forest inventories it was concluded that fine root turnover influenced C sequestration in spruce forests more significantly than in pine forests. Other aspects that should be considered along with the dominant tree species are nutrient availability and soil temperature. In a nutrient manipulation experiment carried out in a Norway spruce stand in northern Sweden Leppälammi-Kujansuu et al. (2014) found that the fine root lifespan was significantly shorter in warmer and more nutrient-rich soil and the litter input increased. This aspect should be considered in the context of global warming and increasing soil temperatures. In the control treatment the C input with fine root litter was 0.51 t C ha^{-1} yr^{-1}. Fertilization or warming alone increased the amount of below-ground litter production (1.476 and 1.45 t C ha^{-1} yr^{-1}, respectively), whereas both treatments simultaneously increased the fine root litter input 4.4-fold (2.246 t ha^{-1} yr^{-1}). Along with improving nutrient availability trees invest less in nutrient acquisition and more resources are invested in above-ground biomass production (Vanninen and Mäkelä 1999, Iivonen et al. 2006).

Carbon input through ground vegetation litter

Our results show a weak positive association between C input with ground vegetation litter and stand basal area in the conifer stands. The trend is more pronounced in pine stands. In the silver birch stands there is a logarithmic trend for C input to decrease along with increasing stand basal area. C input varies between stands of each dominant tree species because of differences in ground vegetation composition and abundance of certain species. Studies pursued by other researchers show that ground vegetation composition is strongly linked to stand age and differences in canopy cover (MacLean and Wein, 2011, Bäcklund et al. 2015, Majasalmi and Rautiainen, 2020). The lower ground vegetation litter production in the birch stands could be explained by poorer light availability resulting from denser canopy. Also the difference between pine and spruce-dominated stands may have occurred due to lower light levels that reach the understory of the latter. The ground vegetation abundance in spruce stands is generally lower than in pine and it decreases rapidly with increasing stem density (Hedwall et al. 2013, Bäcklund et al. 2015, Tonteri et al. 2016). In pine stands light is rarely the limiting factor, and ground vegetation is primarily influenced by competition (Tonteri et al. 1990). Other studies conducted in boreal forests show that the field layer (dwarf shrubs, herbs and grasses) of ground vegetation declines with increasing stand basal area, whereas no conclusions can be drawn regarding the C stock in the moss layer (Muukkonen and Mäkipää 2006, Hansson et al. 2011). Some studies show that the cover of grasses tends to decline with reduced light availability under a dense canopy, whereas the cover of dwarf shrubs tends to initially increase, then decrease and eventually bryophytes dominate (Hedwall et al. 2013, Felton et al., 2020). Overstory effects also depend on interspecific competition and soil condition (Kuusipalo 1985). Our results confirm that biomass of herbs declines with increasing stand age and that dwarf shrub biomass is slightly increasing. While the decline of vascular plants has a considerable impact on ground vegetation litter production and annual C input because of fast turnover rates, the increase in dwarf shrub biomass has a negligible impact. The biomass of mosses is slightly decreasing along with increase of stand basal area.

Kristensen et al. (2015) studied above- and below-ground C pools in boreal forests using LiDAR and found that 1.64–3.31 t C ha^{-1} is in the ground vegetation compartment. Lehtonen et al. (2016) estimated that the mean C input from ground vegetation is approximately 0.473 and 0.863 t ha^{-1} C for the southern and northern parts of Finland, respectively, which correspond to our results obtained in the spruce stands, but are lower than our estimates for the pine stands and higher than those for the birch stands. Hansson et al. (2011) estimated that litter production by shrubs and ground vegetation was higher in birch (0.84 t C ha^{-1} yr^{-1}) and pine (0.71 t C ha^{-1} yr^{-1}) than in spruce stands (0.24 t C ha^{-1} yr^{-1}), however the values are difficult to compare with our results, when mosses are excluded.

As it was indicated in the study conducted by Muukkonen and Mäkipää (2006), equations including site attributes like latitude, longitude, elevation, temperature sum, nutrient level, stem volume, number of trees per 1 ha, basal area and stand age – as input variables offer more accurate estimates than the equations with stand age alone as an input variable, however these equations are country-specific and can be applied only in Finland. The equations used in our study were originally developed for upland forest stands, which could be another reason for inaccuracies in our estimations. Additionally, ground vegetation is a variable component of the forest ecosystem, therefore it cannot be predicted with conventional site attributes only. Site disturbances as well as interspecies' relationships can significantly influence the species composition and biomass of the ground vegetation.

To obtain more accurate estimates of C input with ground vegetation, it is required to investigate which site attributes can be used to predict ground vegetation biomass and to develop country-specific ground vegetation biomass equations for peatland forests in Latvia.

Net GHG emissions from soil

Litter production is one of the most important ecological processes in forest ecosystems, influencing the C and nutrient transfer from vegetation to the soil (Liu et al. 2004), but organic matter stored in soil may be significantly affected by different land management practices or changes in the predominant climatic patterns (Laiho et al. 2008). Any land management-mediated changes in SOC stock and GHG emissions from soils need to be estimated and reported within the National GHG Inventories. Boreal and temperate forests with drained organic soils may act either as a sink (e.g. Minkkinen and Laine 1998, Ojanen et al. 2013, Lupiķis and Lazdiņš 2017, Ojanen et al. 2019) or a source of C (e.g. Simola et al. 2012, Pitkänen et al. 2013, Hommeltenberg et al. 2014) depending on the case, but the combinations of factors controlling this variation are still insufficiently understood (Laiho et al. 2008).

Results of our study obtained by combining field observations (C input through tree above-ground litter), modelling approach (C input through tree below-ground litter and litter of ground vegetation) and NFI data on characteristics of forest stands with drained organic soils showed that drained organic soils in the silver birch and Norway spruce stands with basal area in the range from 10 to 32 and 31 m^2 ha^{-1}, respectively, and in the Scots pine stands with basal area in the range from 10 to 40 m^2 ha^{-1} were a source of net GHG emissions. At the same time, drained organic soils in the silver birch stands with basal area in the range from 32 to 40 m^2 ha^{-1} and in the Norway spruce stands with basal area in the range from 31 to 40 m^2 ha^{-1} were a sink of net GHG emissions (-0.29 ± 0.09 t CO_2-C ha^{-1} yr^{-1} in the silver birch stands and -0.61 ± 0.09 t CO_2-C ha^{-1} yr^{-1} in the Norway spruce stands). Furthermore, it should be noted that C input through natural mortality of tree biomass (including large dimension branches and parts of stumps and roots), which is a significant source of C to soil, was not included in the assessment of net GHG emissions from the system. According to the Latvia's National Inventory Report, the weighted average natural mortality in 2017 was 2.01 m^3 ha^{-1} yr^{-1} in Latvia, and it corresponds to 0.72 t C ha^{-1} yr^{-1}. Thus, net GHG emissions from drained organic soils calculated within the study could be overestimated. Considering that C input through natural mortality was not included, the results obtained within this study approach the results reported by Lupiķis and Lazdiņš (2017) who concluded that in the hemiboreal vegetation zone drainage of organic soils is not always causing C storage reduction.

Although soil heterotrophic respiration increases with increasing litter production (soil fertility impact) (e.g., Ojanen et al. 2013), we used the constant GHG EFs for the forests with drained organic soils without division into fertile and poor sites (Table 3) due to lack of more stratified GHG emission data corresponding to the hemiboreal zone. This could underestimate or overestimate total calculated net GHG emissions in stands with basal area range not covered by estimates of soil heterotrophic respiration. To obtain more accurate estimates of net GHG emissions from the forest stands with drained organic soils, it is required to include dynamic data of soil heterotrophic respiration depending on stand fertility and dynamics of litter production in calculations.

Conclusions

Drained organic soils in silver birch, Scots pine and Norway spruce dominated stands in hemiboreal conditions may act either as a sink or a source of net GHG emissions depending mostly on characteristics of the stand (both stand age, growing stock and basal area); furthermore, the variation in calculated net GHG emissions was relatively large. It highlights the need to include the stratified EFs for drained organic soils depending on dominant tree species and stand characteristics in the National GHG Inventories.

It is necessary to conduct further research to get a better understanding of C flows in drained organic soils covering forest stands with a wider range of basal area stratified by soil fertility and GHG fluxes in forests with naturally wet organic soils. It would contribute not only to more accurate estimates of net GHG emissions for the National GHG Inventories, but also to the development of a more sustainable management of forests with organic soils.

Acknowledgements

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