BALTIC FORESTRY
https://balticforestry.lammc.lt
ISSN 1392-1355
eISSN 2029-9230
Baltic Forestry 2024 30(2): 150–155
Category: Research article
https://doi.org/10.46490/BF776

Preliminary assessment of stock of organic carbon in mineral soils of hemiboreal forests in Latvia

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Ķēniņa, L., Bārdule, A., Bičkovskis, K., Desaine, I. and Jansons, Ā. 2024. Preliminary assessment of stock of organic carbon in mineral soils of hemiboreal forests in Latvia. *Baltic Forestry* 30(2): 150–155; https://doi.org/10.46490/BF776.

Received 25 September 2024
Revised 21 December 2024
Accepted 21 December 2024

Abstract

The European Union (EU) Nature Restoration Law requires increasing trends for soil organic carbon stock (SOC stock) in the mineral soil at a depth of 0 to 30 cm and in the litter layer (O horizon) in forest ecosystems until satisfactory level is reached, thus assessing and monitoring this indicator remains challenging at the national scale. This report aims to characterize and compile existing data to estimate SOC in mineral soils (O horizon and 0–30 cm layer) of hemiboreal forests in Latvia. Despite limited observations – particularly on wet and drained mineral soils, and for deciduous trees at different ages – preliminary assessment show that SOC stock in mineral soil differs significantly among forest types, while dominant tree species and stand age affects SOC stock in O horizon. Although several detailed studies in Latvia had gathered SOC stock data in forests, comprehensive monitoring system is needed to ensure complete understanding of soil and O horizon SOC stock to detect long-term trends to achieving EU climate and biodiversity targets.

Keywords: soil organic carbon stock; litter layer (O horizon); stand age; forest type; EU Nature Restoration Law

Introduction

Soil provides a range of crucial ecosystem services including nutrient cycling, climate regulation, habitat, and water purification (Panagos et al. 2022, Meurer et al. 2024). In mean time soil is a fragile resource that must be carefully managed and safeguarded for future generations. In recent years, the European Union (EU) has been intensively working on soil governance system, focusing on the legal framework to protect soil and promote its sustainable use, and improve its quality. The new EU Soil Strategy and the EU mission "A Soil Deal for Europe" set a long-term vision emphasizing the importance of conserving soil organic carbon stock (SOC stock) (Ålmas et al. 2024, Wellbrock et al. 2024). To achieve these objectives, the Soil Monitoring Law has been proposed to monitor and assess soil health, establish a comprehensive and coherent monitoring framework, and enable greater coordination of existing and future environmental monitoring programs for soil (Wellbrock et al. 2024). Forest soil monitoring is in line with the EU Nature Restoration Law (2024), which requires member states to establish and implement measures to improve the state of natural habitats by 2030. This also includes a demand for a positive trend in several indicators to enhance biodiversity and maintain habitats in forest ecosystems. One of these specific indicators is the organic carbon stock in mineral soil (0–30 cm depth) and litter (EU Nature Restoration Law 2024). By litter is meant the soil litter layer or O horizon which is dominated by organic material, consisting of fresh, partially or completely decomposed litter (such as leaves, needles, twigs, mosses, and lichens) that has accumulated on the soil surface (FAO 2006, Cools and De Vos 2020).

Awareness of the importance of soil in various EU policy sectors, both current and future, has increased, along with the need for accurate soil data (Leeuwen et al. 2017). Numerous case studies have provided soil data; however, due to differences in measurement methods and accounting practices, it is challenging to address comparable SOC stock data, and detect long-term trends resulting from changes in management and other factors (Ålmas et al. 2024). Previous studies show that forest SOC stock within a particular climate zone varies with soil type, spatial variability and groundwater level, and is affected by stand development stage, tree species, soil depth, and other factors that have significant effects on SOC stock (Uri et al. 2022, Savaci and Doğan 2023). The mineral soils of northern and northeastern Europe are rich in carbon, though not the richest compared to European temperate forests (Bono et al. 2024). Furthermore, across the chronosequence of stand age, SOC stock is highly variable due to the natural heterogeneity of the sites (Ražauskaite et al. 2020, Uri et al. 2022, Bono et al. 2024). Studies show that SOC stock forms the major share of the total carbon in young stands (Uri et al. 2022). Over time, the share of SOC stock decreases, and carbon storage in tree biomass increases (Uri et al. 2022, Savaci and Doğan 2023). A study in hemiboreal old-growth stands shows that mineral soil is the second-largest carbon pool after overstory biomass (Ķēniņa et al. 2023). Moreover, differences in litter production, influenced by various factors including forest management strategy, significantly affects the input of SOC and thus its stock (Mäkipää et al. 2023).

Although soil mapping in Latvia has rather long history, forest soil mapping (1 : 10 000 scale) has been almost nonexistent (Kasparinskis 2012). However, during the last decade, some studies have analyzed distribution and forest soil properties in Latvia (Kukuļs et al. 2019, Ivanovs et al. 2024). The most detailed studies of forest soils to date were conducted as part of regional forest monitoring (1990– 1992) (Laiviņš et al. 1993) and forest soil monitoring BioSoil (2006–2012) (Bārdule et al. 2009). To this day, obtaining and monitoring nationwide estimations of forest SOC stock remains a significant challenge, as the process is complex, expensive, and time-consuming (Ražauskaite et al. 2020, Bellassen et al. 2022). Nevertheless, several datasets have become available through the research projects to gather data on forest soil carbon in Latvia, including across different stand development stages and forest types (Lazdiņš et al. 2013, Bārdule et al. 2021). While the case studies conducted are of high importance, the results need to be integrated into a single system to ensure a complete understanding of SOC stock and trends in its changes. Therefore, this report aimed to characterize and compile existing data to estimate SOC in mineral soils (O horizon and 0–30 cm layer) of hemiboreal forests in Latvia.

Materials and methods

Geographic scope and description

The hemiboreal zone is in a transition between the boreal and temperate forest of nemoral Europe, hosting a variable mixture of boreal coniferous and temperate deciduous tree species and a diverse soil and biota (Lõhmus and Kraut 2010). The climate is cool and moist, influenced by the Baltic Sea and the North Atlantic. According to data from the Latvian Environment, Geology and Meteorology Centre, the long-term (1991–2020) mean annual sum of precipitation is 685 mm, and the mean annual air temperature +6.8°C.

Data from Latvian National Forest Inventory (NFI) show that 55% of Latvia is covered by forest (3.6 Mha forest land), and forest growing conditions are highly variable. Specifically, 51% of the total forest area is on naturally dry mineral soils, 9% on wet mineral soils, 11% on peat soils, and 29% on drained land (drained mineral soils comprised 17%). Overall, two thirds of Latvian forests are on mineral soils (2.5 Mha). More than half (56%) of the forests on mineral soils are dominated by coniferous trees – Scots pine (*Pinus sylvestris* L.) (591 kha) and Norway spruce (*Picea abies* (L.) Karst.) (534 kha). Among the deciduous-dominated forests on mineral soil, birch (*Betula pendula* Roth, *Betula pubescens* Ehrh.) stands (635 kha) and European aspen (*Populus tremula* L.) stands (247 kha) are the most common.

Soil data

We used different existing data sources containing soil sampling results from forests on mineral soils, available through the Latvian State Forest Research Institute 'Silava'. These included the forest soil monitoring BioSoil: Demonstration Project for Monitoring European Forest Soils and Biodiversity (2006–2012) data (Bārdule et al. 2009), a dataset from old-growth forest stands and mature control stands (Ķēniņa et al. 2023), and data from the project "Research program on improvement of forest growth conditions 2016–2021", which focused on forest fertilization (Silava n.d.). Additionally, we used freely available EU Land Use and Cover Survey 2018 (LUCAS) topsoil dataset (Panagos et al. 2022). After reviewing the LUCAS data, we found that of the 331 samplings in Latvia, only 131 were from forests (categorized as woodland, forestry), but soil bulk density values necessary for carbon stock calculations were available only for 45 samples. It was not clear from the LUCAS data, whether these topsoil data (only 0–20 cm depth) included O horizon soil organic carbon or not. Also, it was not possible to categorize the data by forest site types (dry, wet, drained), or stand age, and clear information on dominant tree species was not available (categorized as mixed woodland, coniferous woodland, pine dominated mixed woodland, other mixed woodland etc.). As a result, we were unable to incorporate the LUCAS data into the further analysis in this study to assess required indicator values of EU Nature Restoration Law.

We generated a joint dataset (Table 1) from the remaining data pools and grouped available data according to the dominant tree species (birch, aspen, pine, spruce), age groups (young, middle-age, premature, mature, old-growth; see Table 2). We grouped nationally classified (Bušs 1997) forest site types based on soil moisture conditions and productivity: dry mineral soils and wet mineral soil (freely draining and periodically waterlogged mineral soil, respectively), and drained mineral soils.

Table 1. Data available (number of samples) for assessment of the stock of organic carbon in the O horizon and in the mineral soil in forest ecosystems

Stand age group	Forest type group					
	Dry		Wet		Drained	
	soil	O horizon	soil	O horizon	soil	O horizon
Young	90	90	3	3	34	34
Middle-age	174	174	11	11	155	155
Premature	54	54	1	1	4	4
Mature	132	91	0	0	3	3
Old-growth	79	84	1	1	1	1
TOTAL number of samples	529	493	16	16	197	197

Table 2. Age groups of assessed tree species (years)

Tree species	Age group					
	Young	Middle-age	Premature	Mature*	Over-mature*	Old-growth**
Scots pine	1–40	41–80	81–100	101–140	141–160	163
Norway spruce	1–40	41–60	61–80	81–120	121–160	170
Birch	1–20	21–60	61–70	71–90	91–120	123
Aspen	1–20	21–30	31–40	41–60	61–100	104

Notes: * – determined according to rotation age in national legislation, but not according to the stand quality;
** – the minimum age of the stands which were used in this study.

SOC stock calculation and data analysis

The SOC stock for the mineral soil and O horizon was calculated using available soil data. The SOC stock was calculated by multiplying SOC content (g kg^{-1}) in soil by thickness of the soil layer (0–10 cm, 10–20 cm, and 20–40 cm depth), and soil bulk density (kg m^{-3}) (Savaci and Doğan 2023). The SOC stock of the 20–40 cm layer was divided in half, and SOC stock of 20–30 cm layer was obtained. For SOC stock calculation in O horizon layer thickness (cm) was used in equation. The total SOC stock in the 0–30 cm layer was obtained by summing the SOC stocks in each depth.

The data analysis was performed using R software, version 4.4.0 (R Core Team 2024). The R libraries lme4 (Bates et al. 2015) and lmerTest (Kuznetsova et al. 2017) were used to implement the linear mixed-effects models (LMER). There were insufficient number of observations in certain groups (Table 1), resulting in imbalanced dataset. Therefore, analysis was performed on individual factors with different amount of observations. Differences in the soil and O horizon carbon stock between age groups were evaluated only for dry mineral soils. LMER were used to test the effect of forest site type as an independent variable on the dependent variables – the soil and O horizon carbon stocks only for middle-age forest data. To test tree species effect on the soil and O horizon carbon stocks, only data from mature and old-growth stands was used, also due to imbalanced dataset between other age and forest site type groups. The stand identification was used as a random factor, as there were multiple plots per stand. Analysis was conducted using a significance level of $p < 0.05$. The R library emmeans (Lenth 2021) was used to calculate and pairwise compare the estimated marginal means of SOC stocks.

Results

Analysis of available datasets

Our study showed that the coverage of current data on SOC stock has some gaps. The soil SOC stock data obtained from available databases exhibited considerable variability, and in some defined groups, there was an insufficient number of observations both for mineral soil and O horizon. Due to the very low number of samples (see Table 1), most of the data on wet and drained soil and O horizon SOC stock were excluded from further analysis.

The most extensive dataset was for dry mineral soil, and therefore, these data were used for to assess SOC stock in both the mineral soil and the O horizon. When evaluating data availability by tree species, the most comprehensive dataset was available for pine, while the least data were available for aspen and birch. Some age groups were missing for deciduous tree species, and for most tree species, there was insufficient data on SOC stocks in wet mineral soils.

Estimations of SOC stock

To estimate the relationship between SOC stock and stand characteristics, we used information on three stand variables: forest site type group, age groups, and dominant tree species. The mineral soil SOC stock (0–30 cm) was significantly affected by forest site type (LMER; $F = 38.0$, $P < 0.001$). However, mineral soil SOC stock depends neither on age group (LMER; $F = 1.9$, $P = 0.11$) nor on dominant tree species (LMER; $F = 0.6$, $P = 0.63$). In middle-aged stands, the pairwise comparison test showed that wet mineral soil (estimated mean ± 95% confidence interval 104 ± 48 t C ha^{-1}) and drained mineral soil (114 ± 18 t C ha^{-1}) stored significantly ($P < 0.01$) more SOC stock than dry mineral soil (54 ± 14 t C ha^{-1}) (Figure 1). In dry mineral soils there were no trend among the examined age groups and no significant difference ($P = 0.53$) in the estimated mean SOC stock between young (61 ± 17 t C ha^{-1}), middle-age (55 ± 9 t C ha^{-1}), mature (61 ± 7 t C ha^{-1}) and old-growth (61 ± 8 t C ha^{-1}) stands. The highest estimated mean for SOC stock was found in the premature (71 ± 15 t C ha^{-1}) stands.

The SOC stock in the O horizon was affected by the age group (LMER; $F = 5.4$, $P < 0.001$) and dominant tree species (LMER; $F = 9.2$, $P < 0.01$), but not by forest site type (LMER; $F = 1.71$, $P = 0.18$). The O horizon SOC stock distribution across different age groups according to dominant tree species in the analyzed dataset, is shown in Figure 2. The pairwise comparison test of O horizon data from forests on dry mineral soil revealed that the significantly ($P < 0.01$) lower estimated mean SOC stock was found in young and middle-aged stands (9 ± 6 t C ha^{-1} and 14 ± 3 t C ha^{-1}, respectively) compared to estimated means in mature (21 ± 3 t C ha^{-1}) and old-growth (18 ± 2 t C ha^{-1}) stands. We found that in mature and old-

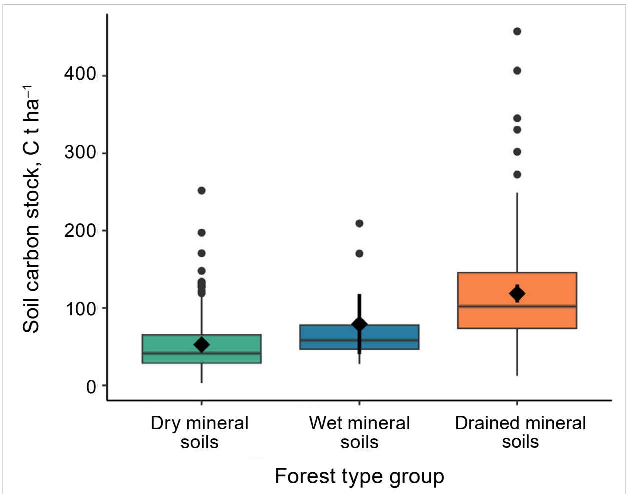

Figure 1. Mineral soil (0–30 cm) carbon stock distribution in different forest type groups (analysis included only middle-age forest stands)

The box shows 25th and 75th percentile, median (horizontal line), whiskers shows minimal and maximal value or 1.5 time the interquartile range if outlier values present (points). The lower and upper Gaussian confidence limits based on the t-distribution, outliers (black points). Diamond with lines shows the mean and its 95% confidence interval.

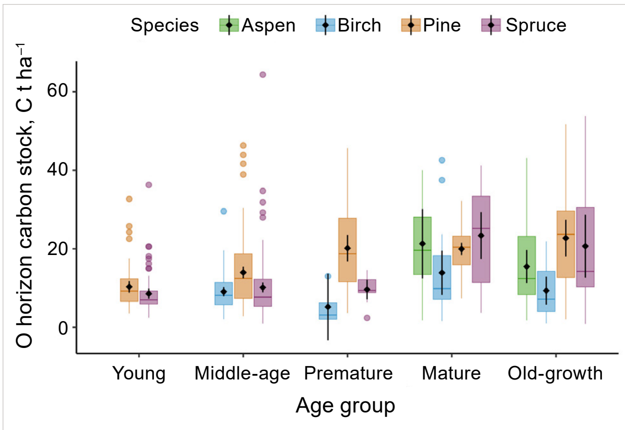

Figure 2. O horizon carbon stock distribution across different age groups according to dominant tree species

The box represents 25th and 75th percentile, median (horizontal line), whiskers shows minimal and maximal value or 1.5 time the interquartile range if outlier values present (points). The lower and upper Gaussian confidence limits based on the t-distribution, outliers (points). Diamond with lines (black) shows the mean and its 95% confidence interval.

growth stands dominant tree species had a significant (LMER; $F = 7.7$, $P < 0.001$) influence on SOC stock size of the O horizon. According to pairwise comparison test, the mean SOC stock in O horizon in pine (21 ± 3 t C ha^{-1}) and spruce (23 ± 4 t C ha^{-1}) stands was significantly higher ($P < 0.05$) compared to aspen (17 ± 4 t C ha^{-1}) and birch (11 ± 4 t C ha^{-1}) stands.

Discussion

There is a considerable diversity in soil types, fertility, species composition, and climatic conditions across forests in Latvia. Combined with the impact of stand age-specific or applied management effects on SOC stock changes, soil monitoring in Latvia, as in other EU countries, is particularly resource-intensive requiring significant financial and human effort (Ražauskaite et al. 2020, Bellassen et al. 2022). We used three existing local datasets containing soil sampling results from forests on mineral soils to assess SOC stock of the mineral soil (0–30 cm) and O horizon as required in the EU Nature Restoration Law. There was an insufficient number of observations in certain groups – specifically for all analyzed tree species on wet and drained mineral soils. Additionally, data were generally lacking for deciduous species, although birch is the most common deciduous tree species in Latvia. In the existing dataset, all tree species had missing data across various age groups, particularly in younger forest stands. In the future, it will be essential to create a more comprehensive national soil dataset, including currently uncovered features (e.g. forest stand characteristics, climate, soil types), obtaining data from deeper soil layers, and increasing the number of soil and O horizon samplings to reduce the random sampling error (Leeuwen et al. 2017, Meurer et al. 2024). Such additions are significant to monitor forest soils' health and provide incentives for sustainable forest management practices (Leeuwen et al. 2017, Lindross et al. 2022).

In our dataset, several relations were tested: impact of forest site type, stand age, and dominant tree species on SOC stock in mineral soil and O horizon. Our data revealed that the forest site type had a significant effect on the SOC stock in mineral soil (0–30 cm). Our results indicated that for middle-aged stands, SOC stock is significantly lower in dry mineral soils compared to wet and drained mineral soils (Figure 1). However, due to the limited availability of SOC stock in wet and drained soils, estimated mean SOC stock values may lead to overestimation or underestimation (Butlers and Lazdins 2020).

No clear impact of stand age or dominant tree species on carbon stock in mineral soil was found in this study. Also, when evaluating the effect of age on SOC stock in dry mineral soils, we did not find an increase in soil carbon stock with increasing age, therefore, it can be assumed that soil is a relatively stable carbon pool. Previous studies in Finland have shown that soil carbon stock increases with stand age (Lindross et al. 2022), thus the knowledge of the variation in soil carbon storage with stand age is controversial (Xiang et al. 2022). For example, Uri et al. (2022) calculated a forest C budget for Scots pine in the hemiboreal zone and found that SOC storage in the forest soil was independent of stand age, as in his earlier study of silver birch forest (Uri et al. 2012).

The O horizon is considered an important transfer point between the aboveground and soil carbon pools (Jandl et al. 2007). Study results revealed a tendency of increase of mean SOC stock in O horizon with increasing stand age in forest stands on dry mineral soils, however, data in some age groups in other forest site types were insufficient to further examine this relationship. Nevertheless, a similar result has also been observed for drained and naturally wet forests on organic soils (Butlers and Lazdins 2020). In the present study, coniferous stands compared to deciduous stands in all analyzed age groups tend to store more SOC in the O horizon (Figure 2). At the same time, considerably higher O horizon SOC stock was detected in aspen stands compared to birch stands. Other researchers have also reported that dominant tree species is one of the factors affecting SOC stock in O horizon (Hansson et al. 2011, Butlers and Lazdins 2020, Ķēniņa et al. 2023). In Sweden, Hansson et al. (2011) found that O horizon SOC stock in coniferous stands is higher than in deciduous stands due to slower needle decomposition compared to leaf decomposition. It has been reported that coniferous species admixture in deciduous-dominated stands can significantly boost the SOC stock in O horizon in long-term (Butlers and Lazdins 2020). Therefore, we could speculate that considerable O horizon SOC stock differences between birch and aspen-dominated stands are related to the level of coniferous species admixture within these stands. However, further testing is required to provide practically usable recommendations through forest management practices that encourage such admixture and/or formation of second-layer and restoration that may be beneficial to promote carbon sequestration in tree biomass and mineral soil.

Conclusions

Although existing local datasets containing soil sampling results from forests are available, providing an overview of SOC stock in mineral soil (0–30 cm) and O horizon, further studies should increase the number of sample plots to better characterize the impact of different age groups and tree species (addressing current data gaps and obtaining data of uncovered features such as forest stand characteristics, climate, and soil types). Additionally, the number of soil and O horizon samplings should be increasing to reduce the random sampling error. This would enable also to obtain more comprehensive national-level SOC stock estimates and allowing to shifting from average to weighted average estimations, as well as evaluating the impact of various factors, such as forest management on SOC stock over time. Despite limitations in the number of observations for certain parameters, the study found that SOC stock in mineral soil was significantly influenced by the forest site type, while dominant tree species and stand age groups were factors affecting O horizon SOC stock. In future, complementary soil monitoring system is needed to supplement already existing national forest soil datasets, ensuring a comprehensive understanding of soil and O horizon SOC stock to detect long-term trends necessary of achieving EU climate and biodiversity targets.

Acknowledgments

This study was funded by Forest Development Fund Project "Proposals for improving the biological diversity of forest ecosystems using the indicators included in the Nature Restoration Regulation project: the common forest bird population index, the volume of dead wood, the proportion of forests with uneven age structures, forest connectivity, organic carbon stock, the proportion of forests dominated by autochthonous tree species, and tree species diversity" (No. 24-00-S0MF01-000002) and State research program "Forest4LV – Innovation in Forest Management and Value Chain for Latvia's Growth: New Forest Services, Products and Technologies" (No. VPP-ZM-VRIIILA-2024/2-0002). This study used part of data obtained in projects "Carbon Cycle in Forest Ecosystems" (No. 5_5.9.1_0081_101_21_87) and "Socio-economic assessment of actions to be implemented to achieve climate change mitigation goals of the Latvian Land Use, Land Use Change and Forestry (LULUCF) sector for reducing greenhouse gas (GHG) emissions and promoting carbon dioxide (CO_2) sequestration in forest management" (No. 24-00-S0INZ03-000033).

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