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SOIL CARBON STOCK IN FERTILIZED FOREST STANDS WITH MINERAL SOILS

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Abstract
Forest mineral soil is one of the terrestrial carbon pools, and changes in forest management practices can affect the carbon stock in forest soil. The purpose of the study is to estimate temporal fertilization impact on mineral soil organic carbon stock, depending on fertilizers applied, forest stand type, different dominant tree species of the stands. Coniferous and birch forest stands with mineral soil in the central and eastern part of Latvia were selected for the experiment. The fertilizers used were wood ash and nitrogen containing mineral fertilizer. No significant differences in organic carbon stock in O horizon were detected 2–5 years after fertilization. A tendency of smaller organic carbon stock in upper mineral soil layers (0–10 cm, 10–20 cm) was found in most part of objects. Significantly smaller organic carbon stock was found in upper mineral soil layers (0–10 cm and 10–20 cm) in birch stands with wet mineral soil treated with ammonium nitrate if compared to the control plots, possibly due to a different soil moisture regime of forest stands. The positive and significant correlations between soil organic carbon and nitrogen stocks were found in most part of the objects.
Key words: wood ash, nitrogen containing mineral fertilizer, organic carbon, forest soil.

Introduction

Forests have an essential role in the global carbon cycle, and forest soil is one of the terrestrial carbon pools. Changes in carbon stock of boreal forest soils are mainly the result of global warming, deforestation and occasional periods of drought and fire. On average, circa 60% of carbon is stored in soil of boreal forests (Pan *et al.*, 2011), and mineral soil is the second important carbon pool, reaching 31% of total forest ecosystem carbon, right after the living tree biomass – 59% (Ķēniņa *et al.*, 2019). Organic matter has an impact on quality and structure of soil, chemical and biological properties (Walsh & McDonnell, 2012).

Several local studies have been carried out in this field. A research in regard to the impact of surface fire on O layer in a dry Scots pine forest indicated a significant impact on reduction of a carbon stock in O layer in fire affected forest areas, while no significant changes were detected in mineral soil layers (Bārdule *et al.*, 2017). A study conducted in over-mature Norway spruce stands showed no significant differences between forest site types (Ķēniņa *et al.*, 2018). Furthermore, a study in over-mature Scots pine stands showed no trends in O horizon and mineral soil carbon stock changes regarding the stand age, within the range of 163–218 years (Ķēniņa *et al.*, 2019).

Forest soil fertilization can improve the growth of trees on nutrient-poor site and reduce deficiency of nutrients. Forest fertilization can be commenced during the whole rotation or 10–15 years before the regenerative felling, respectively, forest fertilization can be conducted once during the rotation period or can be repeated to ensure continuously high growth rates (Högberg *et al.*, 2006). Studies in Latvia have reported a short-term impact of forest soil fertilization with wood ash on the growth of stand (Okmanis *et al.*, 2016; Okmanis *et al.*, 2018) while other studies reported a long-term effect of forest soil fertilization on growth of trees (Jansons *et al.*, 2016; Libiete *et al.*, 2016; Petaja *et al.*, 2018).

Long-term boreal forest fertilization experiment with repeated application of nitrogen containing fertilizer has showed a positive effect on the growth of trees and, as a result, carbon sequestration (Högberg *et al.*, 2006). It has been estimated that by forest soil fertilization in Latvia can be cumulatively reduced 635,000 CO_2 eq. in 10 years (Petaja *et al.*, 2018).

Soil quality and the content of organic matter of soil have been relevant topics of studies. The topicality of this study is based on necessity to increase CO_2 removals in forest ecosystem and considerable short- and long-term greenhouse gas (GHG) mitigation potential of forest fertilization in hemi-boreal forest stands (Federici *et al.*, 2015). The aim of the research is to evaluate temporal impact of fertilization with wood ash and ammonium nitrate on soil organic carbon stock in forests stands with mineral soils.

Materials and Methods

Study sites and treatment

In total, 49 research sites were established in the central and the eastern part of Latvia (Table 1). The dominant tree species in the study sites are Scots pine (*Pinus sylvestris L.*), Norway spruce (*Picea abies (L.) H.Karst.*) and birch (*Betula spp.*). In order to estimate the possible impact of treatment on the organic carbon (C_{ORG}) stock in forest soil, the plots were established in the forest stands with dry mineral soil, naturally wet mineral soil and drained mineral soil. The experimental sites received the following treatment: wood ash (WA), wood ash and ammonium nitrate ($WA+NH_4NO_3$) or

Table 1

Description of research objects and fertilization

Soil type and moisture conditions	Dominant tree species	Number of forest stands	Age of stands	Dose: t *WA or **NH4NO3 ha^{-1}	Fertilizer spreading	Date of treatment
wood ash treatment						
Dry mineral soil	Norway spruce	3	50-54	2; 3 t WA	mechanically	11.2014; 05.2017
Drained mineral soil	Norway spruce	3	44-53	3; 4; 6; 8 t WA	manually/ mechanically	10.2016; 12.2016; 05.2017
wood ash and ammonium nitrate treatment						
Drained mineral soil	Norway spruce	2	36-38	3 t WA + 0.44 t NH4NO3	mechanically	02.2017; 07.2017
Drained mineral soil	Scots pine	3	51-67	3 t WA + 0.44 t NH4NO3	mechanically	02.2017; 07.2017
Drained mineral soil	birch	2	34-37	3 t WA + 0.44 t NH4NO3	manually/ mechanically	10.2016; 02.2017; 06.2017; 07.2017
ammonium nitrate treatment						
Dry mineral soil	Norway spruce	7	25-83	0.44 t NH4NO3	manually/ mechanically	09.2015; 07.2017
Dry mineral soil	Scots pine	21	24-130	0.44 t NH_4NO_3	manually/ mechanically	09.2015; 06.2017; 07.2017
Dry mineral soil	birch	3	44-72	0.44 t NH_4NO_3	manually/ mechanically	06.2017; 07.2017
Wet mineral soil	birch	2	23-48	0.44 t NH_4NO_3	manually/ mechanically	05.2017; 06.2017
Drained mineral soil	Norway spruce	2	28-37	0.44 t NH_4NO_3	manually/ mechanically	09.2015; 06.2017

*wood ash; **ammonium nitrate

ammonium nitrate (NH_4NO_3). Control plots (C) were left without the treatment. Wood ash used in this study were taken from local heating- and power plants: NewFuels RSEZ, Ltd.; Latgran, Ltd.; “Graanul Invest, Ltd. and Salaspils siltums, Ltd.

Collection and analysis of soil samples

Collection of samples was conducted in 2019, namely, 2-5 years after the fertilization. Two replicates of 10 cm x 10 cm large O horizon samples were collected in each plot. Soil samples were collected at fixed depths: 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm. The samples were taken at each plot, ensuring 2 replicates per plot.

Collected O horizon samples were milled till fine powder, soil samples were manually comminuted and sieved through 2 mm sieve. Fine fraction was used for analyses assuming coarse fraction to be free of C_{ORG} and nitrogen (N). The samples were prepared according to the ISO 11464:2005. Bulk density was determined according to ISO 11272:2017. Content of total carbon (C_{TOT}) content was determined using elementary analysis according to ISO 10694:2006 and inorganic carbon (C_{CARB}) – by volumetric method according to ISO 10693:2014. Concentration of C_{ORG} was calculated as the difference: C_{TOT} – C_{CARB}. The concentration of total nitrogen (N_{TOT}) was determined using elementary analysis according to ISO 13878:1998.

Data analysis

The C_{ORG} stock was calculated for different soil layers: 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm. In addition to these soil layers, the average C_{ORG} stock in soil from control and fertilized plots was compared in the following soil layers: 0–20 cm, 0–40 cm and 0–80 cm. The C_{ORG} stock was calculated according to the formula (1):

$$(1)\ CS = \frac{SBD \times H \times (100\% - P_{2mm})}{100(cm)} \times \frac{SOC}{1000}, \text{ where:}$$

CS – content of C_{ORG} in 1 ha of the soil/O horizon (t C_{ORG} ha^{-1});
SOC – C_{ORG} content (g kg^{-1});
SBD – bulk density (kg m^{-3});
H – thickness of a soil/O horizon layer (cm);
P_{2mm} – volume of the fraction of > 2 mm particles in the sample (%).

Table 2

Impact of forest soil fertilization on C_{ORG} stock (t ha^{-1}) in O horizon (mean values ± standard error of the mean)

Type of fertilizer	Wood ash		Wood ash and ammonium nitrate	Ammonium nitrate		
Soil type and moisture conditions	Dry mineral soil	Drained mineral soil	Drained mineral soil	Dry mineral soil	Wet mineral soil	Drained mineral soil
Control plots	14.0 ± 6.5	6.4 ± 2.4	12.9 ± 1.6	13.3 ± 0.9	7.8 ± 2.3	7.2 ± 0.9
Fertilized plots	12.5 ± 3.0	11.2 ± 3.0	9.9 ± 1.3	11.6 ± 0.7	8.8 ± 2.3	8.2 ± 1.3

Normal distribution was tested by Shapiro-Wilk normality test. The data ranges were not normally distributed; therefore, non-parametrical test was used. The non-parametrical Wilcoxon rank sum test with continuity correction was used to compare the C_{ORG} stock among control plots and plots, where fertilizers were applied. The Spearman's rank correlation was used to compare relationship between C_{ORG} and N_{TOT} stock of the trial objects. The strength of correlation coefficient was evaluated according to Akoglu (2018). Tests were conducted at a 95% confidence level in program *R* (R Core Team, 2018).

Results and Discussion

The results are summarized according to the applied fertilizer and forest stand type. Table 2 summarizes the average C_{ORG} stock in O horizon. No statistically significant differences were found between control and fertilized plots. No trends in results were found among the trials or forest stand types. No significant impact on O horizon was reported in similar study with wood ash application (Libiete *et al.*, 2016). The differences in C_{ORG} stock among the plots can be explained with the natural O horizon variability. The average C_{ORG} stock in O horizon is smaller in comparison to average values in Latvia estimated earlier – 21 t ha^{-1} (Bārdule *et al.*, 2009) or average C_{ORG} stock in O horizon in European forests – 22.1 t ha^{-1} (De Vos *et al.*, 2015). These differences in average C_{ORG} stock in O horizon may be explained with different site conditions of the experiments, because the organic matter content in O horizon depends on different factors, such as disturbances (Bārdule *et al.*, 2017), moisture regime of the stand (Błońska & Lasota, 2017) and the dominant tree species of the stand (Butlers & Lazdins, 2020) while the calculated C_{ORG} stock is quite similar to the mean value determined in a study carried out in local Scots pine stands with dry mineral soil – 15.2 t ha^{-1} (Ķēniņa *et al.*, 2019).

The average C_{ORG} stock in different soil layers in the research objects after the fertilization are summarized in Table 3. Statistically significant differences ($p < 0.01$) in average C_{ORG} stock were found in upper soil layers (010 cm and 1020 cm) in forest stands with wet mineral soil. The average C_{ORG} stock in control plots in stands with wet mineral soil is 44.4 ± 5.3 and 19.4 ± 3.8 t ha$^{-1,}$ and C_{ORG} stock in plots fertilized with N containing mineral fertilizer is 29.6 ± 4.1 and 11.0 ± 1.6 t ha^{-1} – in 0–10 cm and 10–20 cm soil layers, respectively. The soil samples were collected in the second year after the ammonium nitrate application in these two birch stands. The soil moisture regime of these trial objects differs from other experimental sites. The average C_{ORG} stock of mineral soil determined in this study is comparatively smaller than the average value estimated in the earlier study in Latvia – 195 t ha^{-1} (Bārdule *et al.*, 2009). But the calculated value is quite similar to results of other local studies – 88.4 t ha^{-1} in Norway spruce stands with dry mineral soil, 88.0 t ha^{-1} in stands with wet mineral soil (Ķēniņa *et al.*, 2018) and 90.0 t ha^{-1} in Scots pine stands with dry mineral soil (Ķēniņa *et al.*, 2019). The calculated values of cumulative C_{ORG} stock in 0–80 cm soil layer varies among different plots, but the average value is close to C_{ORG} stock determined in European forests in 0–100 cm mineral soil layer – 108 t ha^{-1} (De Vos *et al.*, 2015).

A trend of smaller C_{ORG} stock in upper soil layer (0–10 cm) of fertilized plots was detected, and to a lesser extent – in 10–20 cm soil layer. If C_{ORG} is summarized at multiple layers, on average the calculated C_{ORG} stock is smaller in fertilized plots, except for ammonium nitrate treated plots in forest stands with drained mineral soil. The difference is not statistically significant in the most cases.

The results of Spearman rank correlation between C_{ORG} and N_{TOT} in O horizon is shown in Table 4. The table summarizes only statistically significant ($p < 0.05$) results. All relationships detected are positive and ranges from moderate to very strong. The correlation found confirms that the N_{TOT} stock is higher in plots with higher content of organic matter in soil.

Table 3

Impact of forest soil fertilization on C_{ORG} stock (t ha^{-1}) in different mineral soil layers

Soil type and moisture conditions	Plot	Mean soil C_{ORG} stock in different soil layers (mean values ± standard error of the mean), t ha^{-1}				Cumulative soil C_{ORG} stock in different soil layers, t ha^{-1}		
		0–10 cm	10–20 cm	20–40 cm	40–80 cm	0–20 cm	0–40 cm	0–80 cm
Wood ash experiment								
Dry mineral soil	[1]C	40.5 ± 6.7	22.5 ± 5.2	16.2 ± 4.6	15.5 ± 5.5	63.0	79.2	94.7
	[2]WA	38.4 ± 9.2	18.1 ± 2.7	17.5 ± 5.4	18.2 ± 3.3	56.5	74.0	92.2
Drained mineral soil	C	66.7 ± 15.4	30.6 ± 9.3	19.0 ± 6.3	52.3 ± 12.2	97.3	116.2	168.6
	WA	43.8 ± 16.2	41.1 ± 5.4	31.8 ± 5.7	33.1 ± 5.1	84.8	116.7	149.8
Wood ash and ammonium nitrate experiment								
Drained mineral soil	C	62.9 ± 5.1	36.3 ± 6.7	29.3 ± 9.9	41.1 ± 16.1	99.2	128.5	169.6
	WA+N	54.5 ± 4.8	36.0 ± 6.7	34.6 ± 14.5	25.3 ± 6.4	90.5	125.1	150.4
Ammonium nitrate experiment								
Dry mineral soil	C	30.7 ± 2.3	15.7 ± 1.3	12.1 ± 1.0	16.8 ± 2.3	46.4	58.5	75.3
	[3]N	30.9 ± 2.1	12.8 ± 0.8	12.4 ± 1.0	15.4 ± 1.7	43.7	56.2	71.6
Wet mineral soil	C	[a]44.4 ± 5.3	[a]19.4 ± 3.8	7.1 ± 2.4	12.6 ± 3.7	63.8	71.0	83.6
	N	[a]29.6 ± 4.1	[a]11.0 ± 1.6	8.9 ± 3.1	29.0 ± 10.8	40.7	49.5	78.6
Drained mineral soil	C	63.8 ± 9.8	32.8 ± 2.3	14.6 ± 4.1	15.2 ± 3.8	96.6	111.2	126.4
	N	61.9 ± 6.7	45.7 ± 5.7	32.7 ± 8.8	21.2 ± 5.3	107.5	140.2	161.4

[1]control; [2]wood ash; [3]ammonium nitrate; a $p < 0.05$

Table 4

Significant Spearman rank correlations (r_s, p<0.05) between C_{ORG} and N_{TOT} stock in O horizons

Type of fertilizer	Wood ash		Wood ash and N fertiliz.	Ammonium nitrate		
Soil type and moisture conditions	Dry mineral soil	Drained mineral soil	Drained mineral soil	Dry mineral soil	Wet mineral soil	Drained mineral soil
Control plots	[b]0.73	-	[a]0.89	[a]0.85	[b]0.94	[a]0.98
Fertilized plots	[b]0.76	-	[a]0.54	[a]0.58	-	[a]0.79

[a] $p < 0.01$; [b] $p < 0.05$

Table 5 summarizes only statistically significant correlation between C_{ORG} and N_{TOT} stock in forest soil. The relationship between C_{ORG} and N_{TOT} is positive and is found in nearly all soil layers, plots and forest stand types. The correlation found between organic matter and N_{TOT} can be estimated as moderate or mostly – very strong.

These findings are in line with the results of demonstration project *BioSoil* (Bārdule *et al.*, 2009), where relationship between the content of C_{ORG} and N_{TOT} in forest mineral soil was detected (R2 = 0.82).

Significant relationship between relative C_{ORG} and N_{TOT} stock in forest soil is shown in Table 6. In comparison to the correlation found between C_{ORG} and N_{TOT} stock (Table 5), correlation between the relative element stocks was found only in a part of stands. A larger N_{TOT} stock in mineral soil layer is related to a larger carbon stock.

Conclusions

1. No significant trends were found in average carbon stock in O horizon among experimental groups or different growth conditions.
2. In comparison to the control plots, a smaller C_{ORG} stock in 0–10 cm mineral soil layer was detected in the most of the fertilized plots. A statistically significant difference between control and fertilized plots was found in upper soil layers (0–10 cm and 10–20 cm) of birch stands with wet mineral soil, indicating a possible impact of ammonium nitrate on mineralization of organic matter. However, the differences may be explained also with different moisture regime and initial C_{ORG} stock in these experimental sites.
3. There is no significant difference between soil C_{ORG} stock in control plots and plots fertilized with wood ash and nitrogen. Similarly, no significant

Table 5

Significant Spearman rank correlations (r_s, p<0.05) between C_{ORG} and N_{TOT} stock in mineral soil layers

Soil type and moisture conditions	Plot	0–10 cm	10–20 cm	20–40 cm	40–80 cm	0–20 cm	0–40 cm	0–80 cm
Wood ash experiment								
Dry mineral soil	[1]C	[a]0.89	[a]0.92	[a]0.87	[b]0.69	[a]0.95	[a]0.94	[a]0.87
	[2]WA	[a]0.91	[a]0.95	[a]0.79	-	[a]0.96	[a]0.92	[a]0.85
Drained mineral soil	C	[b]0.94	[b]0.89	[b]0.89	-	[a]0.94	[a]0.93	[a]0.90
	WA	[a]0.92	[a]0.87	[a]0.82	[a]0.67	[a]0.92	[a]0.92	[a]0.86
Wood ash and ammonium nitrate experiment								
Drained mineral soil	C	[a]0.74	[a]0.92	[a]0.83	[a]0.86	[a]0.87	[a]0.91	[a]0.90
	WA+ [3]NH_4NO_3	[a]0.71	[a]0.92	[a]0.83	[a]0.80	[a]0.87	[a]0.91	[a]0.91
Ammonium nitrate experiment								
Dry mineral soil	C	[a]0.96	[a]0.93	[a]0.74	[a]0.56	[a]0.96	[a]0.87	[a]0.71
	NH_4NO_3	[a]0.94	[a]0.92	[a]0.81	[a]0.70	[a]0.95	[a]0.88	[a]0.75
Wet mineral soil	C	[b]0.68	[a]0.99	[a]0.73	[b]0.66	[a]0.90	[a]0.95	[a]0.91
	NH_4NO_3	[a]0.76	[a]0.79	[b]0.72	[a]0.74	[a]0.89	[a]0.85	[a]0.81
Drained mineral soil	C	[a]0.89	[a]0.95	[a]0.91	[a]0.75	[a]0.93	[a]0.97	[a]0.96
	NH_4NO_3	[a]0.94	[a]0.97	[a]0.94	[a]0.83	[a]0.97	[a]0.98	[a]0.97

[1]control; [2]wood ash; [3]ammonium nitrate; a $p < 0.01$; b $p < 0.05$

Table 6

Significant Spearman rank correlations (r_s, p<0.05) between relative organic carbon and nitrogen stock (in comparison to the control plots, %) in mineral soil layers

Soil type and moisture conditions	0–10 cm	10–20 cm	20–40 cm	40–80 cm	0–20 cm	0–40 cm	0–80 cm
Wood ash experiment							
Dry mineral soil	-	-	-	-	-	[b]0.94	[a]0.95
Drained mineral soil	-	-	-	-	[b]0.94	[a]0.86	[b]0.61
Wood ash and ammonium nitrate experiment							
Drained mineral soil	-	-	-	[b]0.89	[a]0.85	[a]0.83	[a]0.84
Ammonium nitrate experiment							
Dry mineral soil	[a]0.92	[a]086	[a]0.53	[a]0.53	[a]0.90	[a]0.78	[a]0.72
Wet mineral soil	-	-	-	-	-	-	[a]0.88

[a] $p < 0.01$; [b] $p < 0.05$

reduction or increase of N_{TOT} stock is found in plots fertilized with wood ash and nitrogen.

4. On average, forest fertilization with wood ash and/or ammonium nitrate does not have a significant impact on C_{ORG} stock in mineral soil 2–5 years after the fertilization.
5. A relationship between C_{ORG} and N_{TOT} stock in mineral soil was found practically in all plots – both control and fertilized, and in most of the plots – a relationship between the stock in O horizon.
6. The study has to be continued because 2–5 years period is too short to acquire the impact of fertilization on soil C_{ORG} stock.

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