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DOES SOIL TILLAGE BEFORE AFFORESTATION CONTRIBUTE TO HIGHER CARBON STOCKS?

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ABSTRACT

Afforestation of former agricultural land contributes to the higher carbon (C) stocks in aboveground biomass and dead organic matter. Soils contain major C stocks and are of great importance for C sequestration. Soil preparation prior to planting tree seedlings, especially if deep soil cultivation is applied, causes significant disturbances in the soil profile. Therefore, the afforestation can alter organic C budgets, both in soil and forest biomass. This study analyzed the influence of deep soil tillage up to 40–60 cm depth on the SOC stocks in Arenosols (20 years post afforestation) and Planosols (10 years post afforestation) of Scots pine plantations in comparison to non-ploughed soils in naturally regenerated Scots pine stands. The samples of forest floor and mineral soil in different layers up to 80 cm depth were analyzed. The results showed no differences in forest floor C contents between deep ploughing and non-ploughed sites. The SOC stocks increased at deeper mineral soil layers in relation to the upper mineral soil layers. The total SOC stocks, calculated by summing the SOC values obtained in forest floor and mineral soil layers up to 80 cm depth, were higher in deep ploughing sites than in non-ploughed sites. Therefore, this demonstrated the positive effect of deep soil tillage not only on SOC retaining in the deeper soil layers but also showed the continuous SOC accumulation in the new topsoil. Potentially, soil C sequestration in the deeper layers for a longer period could also be important in the context of climate change.

Keywords: *deep ploughing, organic carbon, carbon concentration, carbon stock.*

INTRODUCTION

The discussions on more intensive land use management in the context of climate change are initiating an assessment of the carbon (C) balance in terrestrial ecosystems at various levels. The management of CO_2 emissions from the energy and transport sectors and the C sequestration following different land use categories and land-use change practices, including afforestation, are among the main challenges for the sustainable management of environmental systems in Europe (IPCC, 2007; Ellison *et al.*, 2011). The C sequestration in both plant biomass and terrestrial soils reduces atmospheric CO_2 concentrations over time

(Lal, 2004; 2010; Smith *et al*., 2013). Existing research recognizes that the stocks of soil organic carbon (SOC) are about three times higher than in terrestrial plant biomass, and soil is exclusively valued as a long-term SOC stock in the biosphere (Guggenberger, 2010; Palosuo *et al*., 2016; FAO, 2017). Additionally, the higher SOC stocks positively contribute to climate change mitigation (UNFCCC, 1997; IPCC, 2007). The existing studies show that C sequestration and SOC stock management are related to various land use management practices (Mayer et al., 2020). It is obvious, that the afforestation of former agricultural land leads to higher C stocks in the aboveground plant biomass and a higher amount of dead organic matter. However, at the ecosystem level, the response of soil chemical composition to afforestation, especially when different soil cultivation techniques are applied prior to tree planting, is likely to be a more complex process.

For higher environmental sustainability and biodiversity, the afforestation of abandoned and former agricultural lands is one of the priorities in increasing overall forest cover in Lithuania. The previous studies identified the increased or unchanged SOC stocks in infertile sandy soils during the 30 years after afforestation (Bárcena *et al*., 2014; Varnagirytė-Kabašinskienė *et al*., 2021). The different afforestation techniques could potentially have a stronger positive effect on climate change management for a long time. When agricultural land is evaluated as a potential land for afforestation, a layer of compacted soil could potentially inhibit tree growth by slowing down root penetration and water penetration (Malinauskas and Urbaitis, 2008). When the deep soil ploughing practice is used, the soil is deeply mixed throughout the profile and the upper carbon-rich soil horizon is buried in deeper soil layers (Schneider *et al*., 2017). Usually, deep soil ploughing is performed up to 50–60 cm in depth as compared to ordinary soil ploughing up to 20 cm. A slower decomposition of additional SOC inputs in the subsoil compared to the topsoil was indicated in the previous studies (Wordell-Dietrich, 2016). This was explained by a lower density of decomposing microorganisms followed by a lower possibility of SOC mineralization (Don *et al.*, 2013). The higher SOC stability in the subsoil was also demonstrated due to lower oxygen concentration in the subsoil and lower changes in humidity and temperature regimes (Rumpel and Kögel-Knabner, 2011). The development of new forest plantations leads to new carbon input from an annual litter of leaves or needles, dead wood and roots slowly entering the subsoil. In this study, we analyzed the influence of deep soil ploughing up to 55–60 cm depth on the SOC stocks in Arenosols 20 years after afforestation and in the Planosols 10 years after afforestation with *Pinus sylvestris* plantations in comparison to naturally regenerated *P. sylvestris* stands on non-ploughed soils. We presumed that the deep soil ploughing could be considered when afforestation is planned on low fertility sandy soils.

MATERIAL AND METHODS

For this study, two experimental regions were selected: the first, the Druskininkai region located in southern Lithuania (54°40’ N; 23°39’ E), and the second, the

Širvintos region located in eastern Lithuania (54°91’ N; 24°93’ E). For estimation of SOC stocks under different soil cultivation techniques, 20 years old Scots pine (*Pinus sylvestris* L.) sites on Arenosols and 10 years old Scots pine sites on Planosols were sampled in August of 2020 and 2021, respectively. In the Druskininkai region, the sites represented four treatments: deep soil ploughing up to 60 cm depth; soil cultivation by 40 cm × 40 cm microsites when the surface soil layer is removed; soil ploughing by making furrows up to 20 cm depth; and naturally regenerated forest stand on non-ploughed Arenosols. This study region was established after the application of different soil cultivation methods prior to afforestation in 2000. In the Širvintos region, there were two treatments, including deep soil ploughing up to 55 cm depth; and naturally regenerated forest stand on non-ploughed Planosols, established in 2012.

For mass determination, the forest floor was sampled with a metal frame of 25 cm × 25 cm. The four samples of the forest floor were composed of five subsamples in the field; then dried at 105 °C to a constant mass and weighed in the laboratory. The mineral soil was sampled with a metallic soil auger from the 0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm soil layers. The four composite samples were combined from five subsamples, collected systematically at each site of each study region. For the assessment of bulk density ($g \cdot cm^{-3}$) of fine (<2 mm) mineral soil, the four composite samples from the 0–10 cm, 10–20 cm, 20–40 cm, and 40–80 cm layers were taken from five subsamples using a metal cylinder. Then, the samples were passed through a 2 mm sieve to remove stones and gravel and dried at 105 °C to a constant mass (ISO 11272:1998). The organic C concentration was determined in forest floor and mineral soil samples using a dry combustion method with a total carbon analyzer Analytic Jena multi EA 4000 Germany (ISO 10694:1995). The SOC stocks in the forest floor were calculated by multiplying the concentrations by the forest floor mass. The SOC stocks in the mineral soil layers were calculated according to the methodology given by Vesterdal et al. (2008), which included the value of bulk density, the thickness of the soil layer, and the SOC concentration of the layer. The total SOC stocks for the mineral soil profile up to 80 cm depth were obtained by summing the values in all mineral soil layers.

The data were analyzed for differences between the sites representing different soil cultivation methods by Kruskal–Wallis analysis of variance (ANOVA). The STATISTICA 12.0 (StatSoft. Inc, Tulsa, OK, USA, 2007) software with a level of significance of $p < 0.05$ was used.

RESULTS AND DISCUSSION

The SOC concentrations obtained in the forest floor were different from the remaining soil layers for both Arenosols and Planosols (Table 1). In Arenosols, the SOC concentrations in the forest floor found for the sites afforested after deep soil ploughing were comparable to non-ploughed sites but slightly lower than for the sites afforested after making furrows. In Planosols, the SOC concentrations in the sites of deep ploughing were lower than in the naturally regenerated Scots pine stand.

Table 1. The concentrations of soil organic carbon (SOC) ($g \cdot kg^{-1}$) in the forest floor and mineral soil layers at the sites representing different treatments on Arenosols and Planosols. Different letters indicate statistically significant differences in mean concentrations of mineral soil layers between the sites within the same soil type ($p < 0.05$).

Treatment	Forest floor	Mineral soil layer (cm)			
		0–10	10–20	20–40	40–80
Arenosols					
Afforested, deep ploughing	227.7 ± 24.0	6.2±0.2ab	5.5±0.3a	7.2±0.6b	6.3±0.4ab
Afforested, microsites	214.3 ± 12.5	8.4±1.0c	6.4±0.5b	4.6±0.3ab	4.1±0.2a
Afforested, furrows	271.8 ± 17.6	9.8±0.6b	8.3±0.6b	7.0±0.2ab	5.7±0.5a
Naturally regenerated, non-ploughed	220.1 ± 31.4	9.1±0.9c	7.0±0.4b	5.1±0.5a	4.7±0.5a
Planosols					
Afforested, deep ploughing	204.1±8.3	4.5±1.3a	5.0±0.4ab	7.7±0.6b	4.6±1.5a
Naturally regenerated, non-ploughed	227.4±20.9	9.8±1.9c	7.0±1.5a	5.9±1.5ab	3.0±0.1a
Croplands, furrows	-	6.6±0.4b	6.7±0.3b	6.4±0.6ab	4.2±0.3a

The estimated SOC concentrations varied among the mineral soil layers up to 80 cm in depth for both study regions (Table 1). In deeply ploughed soils, the SOC concentration in the 20–40 cm layer was slightly higher for the Arenosols and by 1.5-1.7 times for the Planosols compared with the remaining soil layers. In the Arenosols, relatively similar SOC concentrations of 6.2–6.3 g kg^{-1} were found in the upper 0–10 cm and the deepest 40–80 cm layers but lower concentrations were found in the 10–20 cm layer. The SOC concentrations in the remaining study sites showed a consistent decreasing trend from the upper soil layer to a profile depth of 80 cm for both soil types.

In this study, we compared the SOC stocks in different mineral soil layers in both soil types (Figure 1). The comparison of different treatments showed an uneven distribution of SOC stocks in the soil profile. The highest SOC stock values in the Arenosols were obtained in the deepest 40–80 cm mineral soil layers, which varied from approximately 20 $t \cdot ha^{-1}$ in the sites afforested by making microsites to 34 $t \cdot ha^{-1}$ in the deeply ploughed sites (Figure 1A). The SOC values obtained in the upper 0–10 cm and 10–20 cm soil layers were from 2.3–2.6 to 4.3–4.8 times lower than in the 20–40 cm and 40–80 cm layers, respectively. These data demonstrated a clear trend for higher carbon accumulation in deeper soil layers following deep soil ploughing. Not as clearly expressed as in the sites with deep ploughing, but still, quite a similar trend was obtained in the sites afforested after making furrows. However, in the non-ploughed sites, the SOC stocks were similarly distributed among the 0–10 cm, 10–20 and 20–40 cm layers with the higher values found in the 40–80 cm layer.

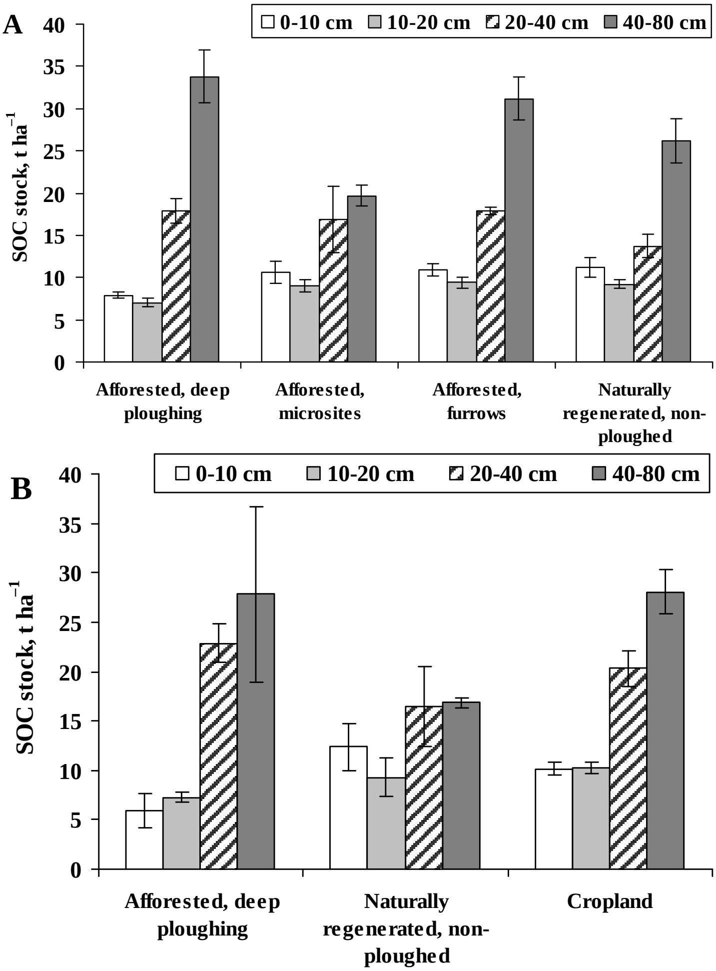

Figure 1. The stocks of soil organic carbon (SOC, t·ha^{-1}) in the mineral soil layers in the different treatments on Arenosols (A) and Planosols (B)

In the Planosols, the comparable SOC values of 23–28 t·ha^{-1} were obtained for the 20–40 cm and 40–80 cm layers of afforested soil at deeply ploughed sites (Figure 1B). The distribution of the SOC stocks in the soil profiles representing different treatments was different. The deep soil ploughing caused lower SOC stocks for the topsoil layers and higher SOC stocks for the subsoil layers. There were no significant differences among the SOC values in different layers of the non-ploughed sites. While the SOC stocks in different soil layers of the croplands were distributed as follows: 10 t·ha^{-1} in both 0–10 cm and 10–20 cm layers; 20 t·ha^{-1} in the 20–40 cm layer, and 28 t·ha^{-1} in the 40–80 cm layer.

In comparison to non-ploughed sites, the total SOC stocks for the whole mineral soil profile up to 80 cm depth showed from 7 t·ha^{-1} to 9 t·ha^{-1} higher SOC stock in the deep ploughed Planosols and Arenosols, respectively.

The most obvious finding to emerge from the analysis was that deep soil ploughing significantly increased the SOC stocks in the 20–40 cm layer while it did not facilitate SOC sequestration to a significant extent for the whole soil profile. Comparable trends were obtained for both studied soil types – Arenosols and Planosols, which were 20 and 10 years, respectively, after afforestation with *P.sylvestris*. This finding was contrary to some previous studies which have suggested that intensive ploughing resulted in the SOC loss (Lal 2007) or showed that the SOC stocks in the former plough layer decreased in the first decade after afforestation, and only later increased (Smal et al. 2019). More often, the use of deep soil ploughing prior to afforestation is highlighted as an effective tool for long-term SOC sequestration (Alcántara et al. 2016). Furthermore, the added value of this soil ploughing is that the topsoil carbon enters the deeper layers and remains for a longer time in a non-fully mineralized matter, additionally, the SOC begins to accumulate as a new litter layer after afforestation (Alcántara et al. 2016). Several studies outline, that deep soil ploughing prior to afforestation facilitates deep rooting, therefore, the SOC stocks can be expected to increase over time. These findings suggest a higher potential to increase the SOC sequestration after the application of deep ploughing for a longer period at least in the soils of lower fertility, therefore, it could be useful in the context of climate change.

CONCLUSIONS

This study has discussed the effect of deep soil ploughing up to 55–60 cm depth on the SOC stocks in the Arenosols and Planosols two and one decade, respectively, after afforestation with *Pinus sylvestris* plantations in comparison to non-ploughed soils and other land uses. We found no differences in the SOC content in the forest floor layer between deep ploughing and non-ploughed sites. However, the SOC stocks increased in the subsoil layers at a depth of 40–80 cm in comparison to the mineral topsoil layers up to 20 cm in depth. The deep ploughing induced 7–9 t·ha^{-1} higher SOC stock in the entire mineral soil profile up to 80 cm depth, compared to the non-ploughed sites. Overall, we assumed that there is a positive effect of deep soil ploughing on the SOC retaining in the deeper soil layers with a potential to accumulate new SOC in the litter layer after afforestation of former agricultural land.

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