Charles University, Faculty of Science

Department of Physical Geography and Geoecology

Study programme: Physical geography and geoecology

Summary of the Doctoral thesis

The variability of soil organic carbon pool and the potential of ground-penetrating radar in its estimating

Variabilita zásob uhlíku v půdě a možnost využití GPR radaru k jejich zjišťování

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Praha, 2022

Abstract

In the context of currently ongoing climate change, more attention is given to soil and its organic carbon pool because soil can act as an essential long-term carbon sink or carbon source. Therefore, the doctoral thesis aims to bring new knowledge about the soil organic carbon pool and the factors controlling the pool in temperate forests. However, the main objective was to test the usability of the ground-penetrating radar to estimate forest floor and topsoil thicknesses because conventional soil sampling for soil organic carbon pool estimation includes measuring forest floor depth and bulk density, and taking soil samples for carbon concentration analysis. The thesis examines the variability of soil organic carbon pool n a regional scale across the Czech Republic and its driving factors and the variability of forest floor and topsoil thicknesses and their driving factors on a local scale at a site of 1 km^2. Subsequently, we surveyed shallow soil stratigraphy using ground-penetrating radar on two contrasting soil types repeatedly under different moisture conditions. The study of the driving factors found climatic conditions, vegetation, and acid deposition to control the soil organic carbon pool and the forest floor and topsoil thicknesses at both scales. The best predictors, however, differed between scales. The ground-penetrating radar approach did not detect the boundary between the forest floor and topsoil, but it was successful for the topsoil/mineral soil boundary. The average error of the thickness estimation was about 25%. However, the mean thickness at the transects applicable for soil organic mass estimation showed a mean measurement error of only up to about 9%. The average measurement errors were slightly lower under wetter conditions, but the mean thickness estimation was more accurate under the driest conditions.

Abstrakt

V souvislosti s probíhající klimatickou změnou je stále více pozornosti věnováno výpočtu organického uhlíku v půdě a možnostem jeho sekvestrace, protože půda je největším terestrickým zásobníkem uhlíku. Předkládaná disertační práce si klade za cíl přispět k poznání zásob organického uhlíku v půdě a faktorů, které je ovlivňují a dále ověřit metodu měření mocnosti půdních horizontů pomocí GPR radaru v temperátních lesích, protože konvenční sběr dat za účelem odhadů zásob uhlíku v půdě sestává z měření mocností horizontů a odběru vzorků pro stanovení obsahu organického uhlíku a objemové hmotnosti půdy. Disertační práce proto zkoumá variabilitu zásob organického uhlíku v půdě s faktory, které je ovlivňují a následně variabilitu hloubek organických horizontů a jejich řídící faktory. Zásoby uhlíku v půdě byly zkoumány na regionální úrovni celé České republiky, mocnost organických horizontů byla zkoumána detailněji v rámci lokality o rozloze 1km^2. Následně proběhlo měření mocnosti organických horizontů radarem GPR na dvou odlišných půdních typech za různých vlhkostních podmínek. Výsledky ukázaly vliv klimatu, vegetace a kyselé atmosférické depozice na zásoby uhlíku v půdě i mocnost organických horizontů na obou studovaných úrovních, ale proměnné, které daný faktor charakterizovaly, se lišily. Měřením pomocí GPR radaru se nepodařilo detekovat rozhraní jednotlivých humusových horizontů, ale rozhraní humusových horizontů a minerální půdy bylo odhadnuto s průměrnou chybou kolem 25%. Odhad průměrné mocnosti na celém měřeném transektu vykazoval chybu jen do 9 %. Průměrná chyba měření mocností byla mírně nižší za vlhčích podmínek, ale odhad průměrné mocnosti byl nejpřesnější za nejsušších podmínek.

Introduction

In the context of currently ongoing climate change, attention is paid to soil organic carbon because soil can act as an essential long-term carbon sink or carbon source (Lal, 2004). Therefore, numerous soil surveys and studies focus on the accuracy of soil organic carbon pool estimation and monitoring its changes in all environments. Special attention is paid to forests because forests store large amounts of organic carbon in the biomass and the organic soil horizons (Pan et al., 2011). Conventional soil sampling for soil organic carbon pool estimation and modelling includes manual soil sampling, forest floor depth measurements, and soil carbon concentration analysis. These works are time and labour demanding. Therefore, there is an effort to develop precise models predicting the carbon pool based on its driving factors that would limit the amount of fieldwork. The models often use remote sensing data. There is an effort to estimate soil organic carbon concentration from spectral characteristics of the soil (e. g., Hong et al., 2020). Nevertheless, another variable still needed to assess the soil organic carbon pool is the thickness of the soil profile or individual soil horizons. The thickness can be hardly determined from remote sensing data (Sothe et al., 2022), and it has to be measured in the field. However, some geophysical methods, especially the ground-penetrating radar, being engaged to estimate the horizon depths non-destructively look promising and could provide the thickness information in greater detail with less effort than manual sampling.

Aims and objective

This doctoral thesis aims to contribute to soil organic carbon pool estimation and modelling effectiveness. The intention is to determine whether the factors suggested by previous studies: climate, elevation, soil moisture, topography, parent material, vegetation, soil type, soil texture, and soil acidification drive the soil organic carbon stock on the regional and local level in temperate forests in the Czech Republic and what factors are the most important. Next, the thesis focuses on estimating the forest floor and topsoil thicknesses. We study whether the forest floor and topsoil thicknesses are affected by the same factors as the organic carbon pool in the mineral soil, and we test the possibility of using ground-penetrating radar in horizon thicknesses estimation. We further compare the ground-penetrating radar measurements performed under different moisture conditions to recommend optimal conditions for such surveys.

Material and Methods

Most of the surveys were performed within 14 long-term monitored catchments, coordinated by the Czech Geological Survey across the Czech Republic (Fig. 1). Most of the catchments are dominantly covered by Cambisols (60%) and Podzols (22%). Soil organic carbon pool was determined in all catchments. Studied driving factors included elevation, mean annual temperature, annual precipitation, geochemical reactivity, forest age, the proportion of broadleaf trees, soil texture and nitrogen and sulphur depositions. Thicknesses of forest floor and topsoil were sampled in detail in one of the 14 catchments called Liz. Studied environmental factors included soil edaphic category, forest age, dominant tree species, forest floor cover (needles, leaves, graminoids, moss, bilberries, spruce seedlings), topography described by elevation, slope and topography wetness index, and soil moisture in the subsoil.

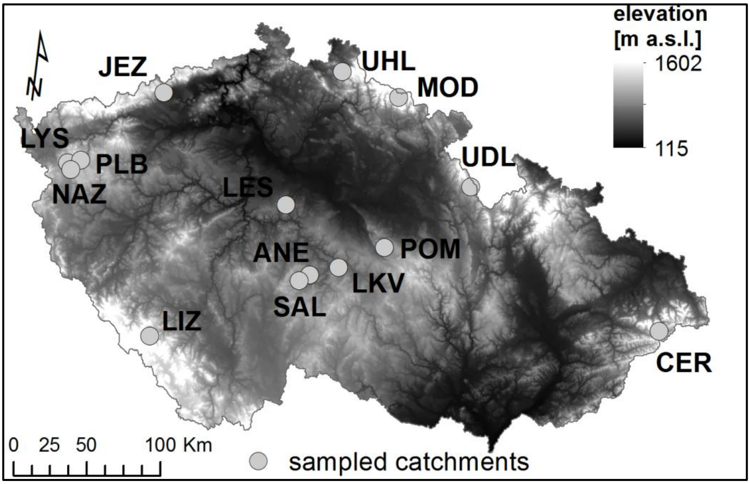

Fig. 1 Localization of long-term monitored catchments used as study sites

Source: Chuman et al., 2021

The role of environmental factors on the soil organic carbon pool size was modelled using a linear mixed-effect model, and the role of those on the forest floor and topsoil thicknesses using geographically weighted regression (Fotheringham et al., 2002).

Subsequently, we surveyed shallow soil stratigraphy using ground-penetrating radar with an 800 MHz antenna at a shorter transect on Dystric Cambisol in the Liz catchment and in addition on a profile of Arenic Podzol near the town of Bělá pod Bězdězem in northern Bohemia, repeatedly under different moisture conditions. The ground-penetrating radar survey was designed after we had reviewed 130 papers published on the Web of Science and SCOPUS from 1995 to 2018. The keywords were: ground-penetrating radar and soil.

The ground-penetrating radar data were processed and interpreted in one-dimensional analysis trace by trace. They had not been filtered to show individual reflections of the ground-penetrating radar signal and their oscillations better. Time-depth conversion of the ground-penetrating radar data was made using the velocity of electromagnetic waves calculated from the dielectric permittivity of the soil measured during the survey by means of GS3 Soil Moisture Sensor by Decagon Devices, Inc. working on the principle of capacitance. The determined thicknesses were used for a detailed reconstruction of the forest floor plus topsoil thickness along the survey transect and compared with the actual depth measured manually at the field at check points.

Major findings

The forest floor contains only 25% of the soil organic carbon pool of the total pool contained in the forest floor and mineral soil down to 80cm depth in the temperate forest; however, the forest floor soil organic carbon pool is an essential part of the total soil organic carbon pool as it changes more dynamically. It is controlled by soil acidification legacy (sulphur deposition) and subsequently by the proportion of broadleaved trees, compared to the total soil organic carbon pool controlled mainly by elevation. The total soil organic carbon pool increases with elevation. In the forest floor, this effect is amplified by the acidification legacy. The higher the sulphur deposition was in the past, the higher the forest floor thickness and organic carbon pool are nowadays. Besides the historical sulphur deposition on the regional level, the forest floor thickness variability could be partly explained by forest floor cover and soil moisture on the local level. The overall spatial variability of the soil organic carbon pool and forest floor thickness is high. A thorough literature review indicates that the forest floor and topsoil thicknesses could be estimated using ground-penetrating radar. This method could allow sampling of larger areas in a shorter time. The simplest and most often used ground-penetrating radar data treatment approaches are based on image filtering of reflected electromagnetic signals. The interpretation can be subjective and needs visible reflections of electromagnetic signal. Contrastingly, our approach based on the one-dimensional analysis proved to detect the boundary between soil horizons even if the difference in the dielectric permittivity was low. The thickness of the forest floor plus the topsoil was estimated with an average error of around 25%, and the mean thicknesses at the entire measured transects finally used for soil organic carbon pool modelling were estimated with an average error of up to 9%. Slightly higher accuracies for point values at check points were under moister conditions, but the mean thicknesses were more accurate under the driest conditions.

Discussion

The results showed that elevation was the main factor controlling the total soil organic carbon pool. The elevation was suggested to substitute climatic variables in regional studies (Wiesmeier et al., 2019). Therefore our findings are in line with previous studies that conclude that higher elevations reduce organic matter decomposition and lead to the accumulation of soil organic carbon due to lower temperatures and higher precipitations retarding microbial activity (Meier and Leuschner, 2010; Wiesmeier et al., 2013). Nevertheless, the effect of elevation was amplified by soil acidification because the historical atmospheric sulphur deposition was higher at higher elevations. The sulphur depositions were accompanied by nitrogen depositions, which were excluded from the analysis due to correlation with sulphur deposition. Increased nitrogen availability favoured biomass production and slowed its decomposition (Berg and Matzner, 1997; Hobbie, 2008; Janssens et al., 2010; Liu and Greaver, 2010; Waldrop et al., 2004). Similarly, increased sulphur concentrations inhibited organic matter decomposition (Oulehle et al., 2018). Thus, higher nitrogen and sulphur contents led to higher thicknesses of the forest floor and increased its organic carbon pool (Mulder et al., 2001; Oulehle et al., 2008).

Tree species and forest floor cover are other important factors controlling the forest floor carbon pool, resp. their thicknesses. The proportion of broadleaf trees was found to drive the carbon pool of the forest floor and upper layers of the mineral soil at a regional scale, but there was no effect on the forest floor and topsoil thickness on a local scale. We suggest that it is better substituted by forest floor cover (needles, leaves, graminoids, moss, bilberries, spruce seedlings) on a local scale. Forest floor cover differs among tree species, and it represents the variability of litter inputs and their recalcitrance. Studies by Cremer et al. (2016), Jonard et al. (2017), Labaz et al. (2014), Rothe et al. (2002), Vesterdal et al. (2013, 2008) reported increased forest floor thickness and its carbon pool under coniferous trees compared to broadleaf trees. These results are in line with our results on the regional level. However, the forest floor and topsoil thicknesses did not differ pronouncedly under the forest floor cover of needles and leaves. The content of recalcitrant lignin in beech litter does not have to differ from that of spruce under certain conditions (Vesterdal, 1999). The forest floor and topsoil thicknesses were the lowest under graminoids. Compared with pine needles, lower forest floor thickness under gramineous species was also observed by Bens et al., 2006 and compared to moss and heather by Anschlag et al. (2017). They both argued for better decomposability of gramineous litter.

The found relation of the thicknesses to soil moisture measured in the subsoil is in line with low decomposition rates at wet sites that were already discussed above. At a local scale, it is appropriate to use soil moisture as a proxy variable representing climate because it expresses micro-climate variability. The elevation suggested as a proxy variable of climate for regional-level studies (Wiesmeier et al., 2019) was also included in the local study, but no effect was found.

The thickness of the forest floor plus the topsoil using ground-penetrating radar was estimated with an average error of around 25%. The best comparable study by Winkelbauer et al. (2011) presents the forest floor plus topsoil thickness estimation with a mean measurement error of 15%. However, they excluded the sites of bigger stones or tree roots from the analysis (Winkelbauer et al., 2011). Doolittle and Butnor (2009) reviewed numerous studies of soil stratigraphy using ground-penetrating radar and estimating depths of argillic, spodic and placic horizon or bedrock. These studies showed mean measurement errors between 2 and 40% (Doolittle and Butnor, 2009). The (topsoil)mineral soil/C horizon boundary or soil/bedrock boundary are the most often detected by ground-penetrating radar (e. g., Zhang et al. 2014; Ikazaki et al. 2018; Šamonil et al. 2020; Schaller et al. 2020; Schiavo et al. 2020) but there are only a few studies focusing on the depth of the forest floor or topsoil (Li et al., 2015; Winkelbauer et al., 2011). We intended to measure the thicknesses of the forest floor and the topsoil separately, but the first boundary we detected corresponded to the topsoil/mineral soil boundary. The same result brought the study of

Winkelbauer et al. (2011). They argued that this failure resulted from the insufficient thicknesses of the respective organic horizons relative to the antenna resolution and insignificant differences in the dielectric permittivity. However, the dielectric permittivity differences between the forest floor and the topsoil were more significant than that between topsoil and mineral soil in some cases during our measurements. The insufficient thickness of the topsoil in Dystric Cambisol and that of the forest floor in Arenic Podzol could be the main reason why the boundaries were not detected. The topsoil/mineral soil boundaries were detected, although the dielectric permittivities differed less than between the forest floor and the topsoil. Corradini et al. (2020) also detected a boundary between layers showing a minimal dielectric permittivity difference, but they noticed that the reflection was weak. We could not distinguish these boundaries with low dielectric permittivity differences in the 2D radargrams but we distinguished them using the numerical analysis of individual traces in one-dimension.

The surveys were performed under several assumed soil moisture conditions at each site. However, the moisture finally differed less significantly than expected based on weather conditions. The moisture conditions at the field capacity, suggested advantageous by van Dam et al. (2002), were almost met at the Cambisol site, but the thickness estimation error at the point values was only slightly lower. Other studies (Curioni et al., 2017; van Dam et al., 2002; Zhang et al., 2014) showed better results under wetter conditions. By contrast, we could see better deeper parts of irregular horizon boundaries under drier conditions because of the limited signal attenuation. Surveying during dry conditions was, for this reason, suggested by Li et al. (2015).

The mean thicknesses at the entire measured transects were estimated with errors of up to 9%, and they were more accurate under the driest conditions. We suggest this method to facilitate the estimation of soil organic carbon pool. The accuracy of the soil organic carbon stock estimation depends not only on the accuracy of the thickness estimation using the presented ground-penetrating radar approach but also on the accuracy of data on the organic carbon concentration and bulk density. The laboratory methods used to determine both are well established, but the uncertainty arises from the spatial variability of these parameters in the field. Similarly, soil horizon thickness is highly spatially variable, as was found in this study. Therefore, uncertainty in the thickness arises not only from the thickness estimation using the ground-penetrating radar but also from the ability to cover its spatial variability.

High variability of the parameters inevitably influences the uncertainty of the soil organic carbon stock estimation because uncertainties of all variables propagate. A hypothetical uncertainty of the estimation of soil organic carbon stock in the forest floor plus topsoil at the Liz catchments was illustrated according to Taylor (1982). The uncertainty of estimating soil organic carbon stock in the forest floor plus topsoil using the thickness measured by ground-penetrating radar exceeded 80% if expressed as the standard deviation in the value relative to the average thickness. However, the uncertainty of the stock estimation using the thickness measured manually in the field at more than 164 random sampling pits per 1 km^2 reached almost 60%. It follows that the major uncertainty originates in the spatial variability of the soil properties. In absolute values, the soil organic carbon stock in the forest floor plus topsoil at the Liz catchment was estimated to be 61.5 t/ha using the thickness from sampling pits. In comparison, the estimation based on the thickness acquired by ground-penetrating radar was 57 t/ha. The difference between these two approaches is less than 8%.

Conclusions

Forest floor carbon pool represents only 25% of the total soil organic carbon pool down to 80 cm depth, and it is the least recalcitrant part that is subject to the most rapid changes. Therefore, its estimation is essential for monitoring soil organic carbon pool changes. The forest floor and topsoil thicknesses are highly variable, and thus the soil organic carbon pool is variable accordingly. Several factors controlling this variability were identified at the regional and local scale: elevation, soil moisture, historical soil acidification, tree species, forest floor cover, and soil texture. Although the processes acting at both scales are similar, the best predictors slightly differ. We found that the elevation can be used as a variable representing climate for soil organic carbon modelling in regional studies in Central Europe, but in local studies, it is better to use soil moisture that shows the microclimate of a site. At the regional scale, the vegetation expressed as the proportion of broadleaf trees and conifers was a significant predictor of the forest floor organic carbon pool. In contrast, at the local scale, forest floor cover (needles, leaves, graminoids, moss, bilberries, spruce seedlings) predicted the thicknesses of the forest floor and topsoil better.

Ground-penetrating radar can help estimate the forest floor and topsoil thickness and thus model their organic carbon pool. We proposed an approach to treating the reflection amplitudes trace by trace. This method still does not reveal the forest floor and topsoil boundary. The topsoil/mineral soil boundary was detected with a mean measurement error of 25%, with slightly higher accuracy under wetter conditions. However, when using mean thicknesses for a several metres long transect, the measurement error is only up to 9%, with more accuracy under the driest conditions when deeper parts of irregular horizon boundaries could be better detected as well.

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Currriculum vitae

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2019 –2021 Ekologické služby, s. r. o (”Ecological surveys”); Tichá 784, 268 01 Hořovice

2016 –2019 Czech Geological Survey; Klárov 3, 118 21 Praha 1

Education:

since 2014 *Ph. D. study of Physical geography and geoecology* at Faculty of Sciences, Charles University

Doctoral thesis: The variability of soil organic carbon pool and the potential of ground-penetrating radar in its estimating

2012 – 2014 *master study of Physical geography and geoecology* at Faculty of Sciences, Charles University

Master thesis: Soil characteristics in relation to relief and land-use changes around St. Helena village in Banat, Romania

January – June 2014 ERASMUS at University of Strasbourg

2009 – 2012 *bachelor study of Geography and Cartography* at Faculty of Sciences, Charles University

Bachelor thesis: Physical-geographical aspects of vegetation succession and soil development with focus on abandoned mining sites

2001 – 2009 Gymnazium Ústavní 400, Praha 8
1998 – 2001 Elementary school with extended language education, Žernosecká, Praha 8
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Languages:

English – C1; French – C1 (II/2015 DALF C1); Russian – B1; Spanish – A2

Publications:

Zajícová, K., Chuman, T., 2019. Effect of land use on soil chemical properties after 190 years of forest to agricultural land conversion. Soil and Water Research. 2019, 1–11.

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