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Carbon stock changes in drained arable organic soils in Latvia: results of a pilot study

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Abstract. Drained arable organic soils in the most of European countries represent a minor part of the total area of farmlands, but these soils contribute significantly to national greenhouse gas budgets. The aim of the pilot study is to demonstrate methodology for determination of the changes of soil organic carbon stock after drainage of arable land on organic soil by evaluation of subsidence of the land surface from detailed historical pre-drainage topographic maps created during designing of drainage systems and LiDAR. Results of a pilot study show that ground surface level in arable land on organic soil has decreased by 0.8 cm annually after drainage, but soil organic carbon stock has decreased by 4.2 ± 3.3 tonnes C ha^{-1} yr^{-1}. The results of a study show that pre-drainage topographic maps are suitable for estimation of organic layer subsidence after drainage. The estimated mean CO_2 emissions are about 47% less than the default emission factor for drained arable organic soils in boreal and temperate climate zone provided by Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories. The results substantiate the necessity to develop national methodology to estimate emissions from drained organic soils in cropland and grassland.

Key words: carbon stock, drained agricultural land, LiDAR, organic soil, subsidence.

INTRODUCTION

Peatlands are the most effective terrestrial ecosystems at sequestering C over millennial timescales (Leifeld et al., 2011; Loisel et al., 2017). Although they cover only about 3% of the global land area, during the Holocene (the last ca. 11,700 years), high latitude peatlands have accumulated approximately 500 Pg C (Pg = 10^{15} g), which is equivalent to approximately 30% of global soil organic C, and nearly equal to the pre-industrial atmospheric C reservoir (Gorham, 1991; Yu, 2012; Mathijssen et al., 2016). Farmed organic soils in most European countries represent a minor part of the total agricultural area, but these soils contribute significantly to national greenhouse gas (GHG) budgets (Kasimir-Klemedtsson et al., 1997; Fell et al., 2016). Carbon fixed in plant residues through photosynthesis may enter anoxic settings and accumulate as peat, serving as a reservoir in the global C cycling (Joosten & Clarke, 2002). In the warm boreal and temperate zones, many peatlands have been and are still drained to make them usable for agriculture (Luan & Wu, 2015; Bader et al., 2017). When organic soils are drained, the organic soil loses the mechanical support of the water (flotation) and the initial subsidence is rapid, augmented by the pressure from the drained but still water-holding top layer of the peat (consolidation). The dry organic matter is decomposed by microorganisms resulting in tighter compaction, increased bulk density and continuous subsidence (shrinkage) (Fell et al., 2016). Organic soils subside at a rate of 2–20mm yr^{-1} due to oxidation, i.e. microbial respiration emitting CO_2 and continue to subside until the water table reaches the soil surface or until all the peat is oxidised (Berglung, 2011). Cultivation of organic soils (repeated ploughing of the soil, fertilization, liming, increase in pH and mineral soil addition) allows oxygen to enter the soil, which initiates decomposition of the stored organic material, and CO_2 and N_2O emissions increase while CH_4 emissions decrease (Kasimir-Klemedtsson et al., 1997; Maljanen et al., 2007; Grønlund et al., 2008; Musarika et al., 2017). It is known that in organic agricultural soils the decomposition of organic matter is faster than the uptake of CO_2 by plants and therefore there is a net loss of CO_2 from the drained organic agricultural soils (Kasimir-Klemedtsson et al., 1997; Maljanen et al., 2001; Lohila et al., 2004; Maljanen et al., 2004; Musarika et al., 2017). Drainage of organic soils for agricultural purposes increases the emissions of greenhouse gases (CO_2, CH_4, and N_2O) by roughly 1 tonne CO_2 eq. ha^{-1} per year, compared to undrained soils (Kasimir-Klemedtsson et al., 1997). Previous estimates from Denmark, Finland, Sweden, Norway, and the Netherlands indicated that organic soils under agricultural management with cereals, row crops, and grasses are net emitters of CO_2, with fluxes ranging from 0.8 to 31 tonnes C ha^{-1} yr^{-1}(Kasimir-Klemedtsson et al., 1997; Maljanen et al., 2001, 2003a, 2003b; Lohila et al., 2004; Regina et al., 2004; Maljanen et al., 2007; Grønlund et al., 2008; Elsgaard et al., 2012).A recent study by Evans et al. (2016) measured GHGs fluxes from both cultivated peat soils and a near intact peat in East Anglia, finding the cultivated soils to be a source of 25.34–28.45 t CO_2 ha^{-1} yr^{-1} while the near intact fen was a sink measuring −5.13 t CO_2 ha^{-1} yr^{-1} (Musarika et al., 2017). Large uncertainties are associated with considerable variation of CO_2 flux and lack of data, especially in Baltic States.

GHG emissions from agricultural organic soils are included into the National Inventory Report under the United Nations Framework Convention on Climate Change (UNFCCC). In Latvia, the reported share of organic soils in cropland and grassland is 5.18 ± 0.5% according to summaries of land surveys (L.U. Consulting, 2010). The annual emission of CO_2 from agricultural organic soils in Latvia was estimated by Latvian State Forest Research Institute 'Silava' (LSFRI Silava) using the Tier 1 method of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006; IPCC, 2014), i.e., by multiplying national activity data (area of organic soils) and default emission factor. The default CO_2 emission factor for drained organic soils in cropland for boreal and temperate climate zone used for reporting is 7.9 tonnes CO_2-C ha^{-1} yr^{-1}(IPCC, 2014), and it is not validated in Baltic States. Moreover, drained organic soil is one of the key sources of GHG emissions in Latvia. In 2015, the total GHG emissions from agricultural organic soils were estimated to be 3,902.5 kt CO_2 eq. which corresponded to 95% of the total emissions from cropland and grassland (Gancone et al., 2017).

Managed organic soils are a large source of both CO_2 and nitrous oxide (N_2O) emission, due to the degradation (oxidation) of the parent material. The results of degradation is measurable as descending (subsidence) of the ground surface (Kasimir-Klemedtsson et al., 1997; Berglund & Berglund, 2010). One of the historically used field methods to estimate C losses from cultivated peat soil is subsidence rate measurements (Kasimir-Klemedtsson et al., 1997; Grønlund et al., 2008). Peat subsidence after drainage and cultivation results from the combined effects of compaction and soil loss through soil organic matter mineralization. In theory, the exact C loss from peat can be calculated from initial and final peat depths, C concentration profiles and bulk density profiles (Grønlund et al., 2008). Grønlund et al. (2008) estimated C losses from cultivated peatlands in West Norway by three independent methods: (1) long-term monitoring of subsidence rates, (2) changes in ash contents, and (3) soil CO_2 flux measurements. The three methods yielded fairly similar estimates of C losses from Norwegian cultivated peatlands (Grønlund et al., 2008).

The aim of the pilot study is to demonstrate methodology for determination of the changes of soil organic carbon stock after drainage of arable land on organic soil by evaluation of subsidence of the land surface from detailed historical pre-drainage topographic maps created during designing of drainage systems and LiDAR.

MATERIALS AND METHODS

Study site

Study was conducted in 2016 in agricultural land in the central part of Latvia, Jaunmārupe (geographic coordinates: 56.864 N, 23.925 E), the object was drained in 1982 by establishing a pipe drain system. The current thickness of organic topsoil layer in the selected sampling area is 20–40 cm (50–70 cm before). The land is used to cultivate corn for last two years. No historical information is available about long term use of field. Naturally afforested (after 1930–1940) undrained forest stand corresponding to *Dryopterioso-caricosa* site type near the study site was used as a control (Fig. 1). Old topography maps from 1930–1940 shows that both, drained and undrained, sites were open and treeless fields, at least trees did not form tree stand. The mean thickness of the organic layer in sampling area in the undrained forest is about 60–100 cm.

Figure 1. Location of study site.

Determination of subsidence rate

The subsidence of topsoil was calculated as a difference between the ground surface level before drainage and the current surface level. The initial elevation data were obtained from a topographic maps (measurements according to BAS-77 height system) created during the designing of drainage systems. Ground surface elevation is measured with optical level tool with 0.5 cm precision. The current ground surface levelling data are obtained using LiDAR based terrain model (measurements according to LAS-2000, 5 height system, based on European Vertical Reference System).

Soil surface height values from topographic maps were digitalized in QGIS and digital elevation model (DEM) was created in R by krigging interpolation method using krige.conv function built in geoR package (Ribbeiro Jr & Diggle, 2015). The result was transferred to QGIS for further analysis. Raster calculator in QGIS was used to calculate difference between two surface height models, thereby obtaining mean difference. Pixel size was 0.5 m x 0.5 m.

Mean height differences between initial and current mean height of DEM in sampling area is subtracted from differences in auxiliary sample area on mineral soil located within the same drainage system. Subsidence equals to this difference between sampling area on organic soil and auxiliary sample area on mineral soil. It was assumed that organic topsoil layer must be shallower than 10 cm (before drainage, data on topographic maps) to consider the soil in area to be mineral soil.

Difference between initial and current depth of organic soil layer is used for auxiliary validation of calculated subsidence. At stage of drainage system designing the depth of organic layer was measured in 10 cm steps and measurement point density was many times smaller than height measurement points. Therefore, it is used just for auxiliary validation, but not to calculate carbon stock changes.

Determination of soil organic carbon content and stock

In 2016, sample sets, taking undisturbed soil samples at 0–10, 10–20, 20–40 and 40–80 cm depth using soil sample probes (steel cylinder with a 100 cm^3 volume), in three replicates on 8 sample plots (total 24 sample sets) were collected. Sampling design consists of two transects of four sample plots on each transect. Distance between transects is 100 m and between sample plots on transect 50 m. Dry bulk density (the mass of a unit volume of oven dry soil, the volume includes both solids and pores) were determined. Samples were dried until constant mass at 105 °C and weighted after in the Forest Environment Laboratory of LSFRI Silava.

The regression equation describing relationship between organic C content in soils and soil bulk density ($R^2 = 0.96$) was constructed using soil monitoring (BioSoil 2012) data to estimate the current organic carbon content in soil (Fig. 2).

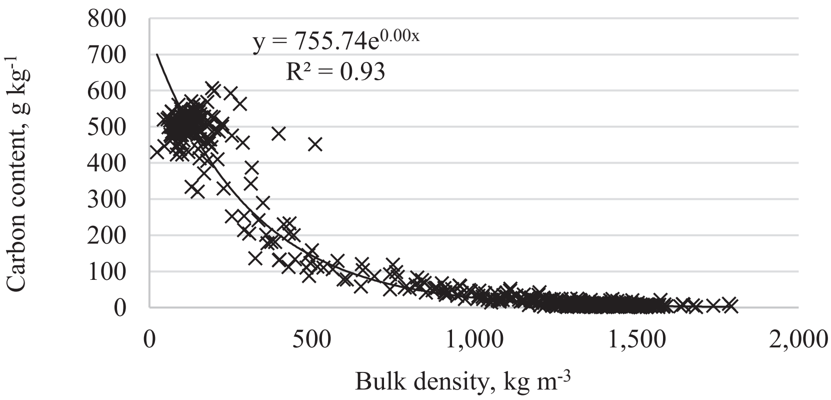

Figure 2. Relationship between soil organic carbon content and soil bulk density according to Biosoil data.

Soil organic C stock was calculated according to equation:

$$SOCS = SOC * SBD * H * (1 - P_{2mm}) * 100^{-1} \tag{1}$$

where: $SOCS$ – soil organic carbon stock per unit area, tonnes ha^{-1}; SOC – organic carbon content in soil (according to constructed regression equation), g kg^{-1}; SBD – soil bulk density, kg m^{-3}; H – thickness of the soil layer, m; P_{2mm}– volume fraction of > 2 mm particles in the soil (assumed to be zero as the value is negligible in most soils), %.

Soil organic C stock pre-drainage profile for the drained site was constructed from the profile of undrained site. It was assumed that average depth of organic layer before drainage was 60 cm, as it was not possible to calculate depth more precisely because of poorly distinguishable boundary between organic and mineral layer at drained site.

Organic C profile from control site was proportionally adjusted to pre-drainage profile for drained site, as there is a slight difference of the depth of organic layer between drained and undrained site. Carbon stock in depth of 80 cm in undrained site corresponds to 60 cm depth on pre-drainage profile, 40 cm in undrained corresponds to 30 cm in drained etc. Simple second order polynomial equation was created to characterize pre-drainage carbon stock in organic layer (Fig. 3).

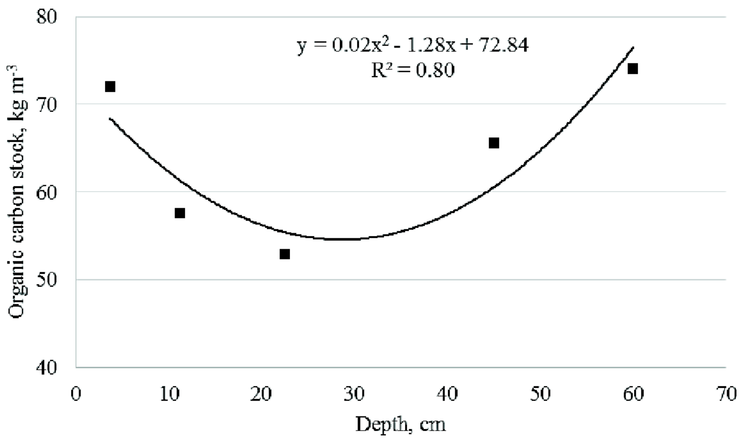

Figure 3. Pre-drainage organic carbon stock profile.

Pre-drainage C stock was calculated as definite integer of created polynomial equation.

$$SOCS^{0-60}_{pre-drainage} = \int_{0}^{60} (ax^2 + bx + c) \tag{2}$$

where: x – depth, cm; a, b, c – coefficients of regression equation.

Carbon stock changes after drainage equals C stock in drained site down to 60 - Δh depth subtracting from pre-drainage carbon stock.

$$\Delta SOCS_{stock} = SOCS^{0-60}_{pre-drainage} - SOCS^{0-(60-\Delta h)}_{drained} \tag{3}$$

where: Δh – subsidence, cm; $SOCS^{0-(60-\Delta h)}_{drained}$ – carbon stock in drained site down to $60 - \Delta h$ depth.

In order to show the uncertainty of carbon stock changes, confidence interval (CI) of carbon stock changes is calculated to show variability of the result. It is assumed to calculate CI as for normally distributed data with significance level of 0.05. CI for carbon stock changes is a sum of:

1) CI of carbon stock in drained site down to 0 – $(60 - \Delta h)$ cm;

2) CI of carbon stock in undrained site down to 60 cm;

3) Uncertainty of subsidence multiplied with average carbon stock in kg m^{-3}. It is assumed that uncertainty of subsidence is ± 0.05 m;

4) Uncertainty due to the use of BioSoil data to estimate carbon content in peat (± 7%, Fig. 2). Uncertainty is multiplied with carbon stock in t ha^{-1} in pre-drainage peat profile.

RESULTS AND DISCUSSION

Subsidence of organic layer

Drainage and cultivation of organic soils increase soil aeration and reverse the carbon flux, resulting in soil subsidence. The initial descending of soil surface after drainage of organic soils is mainly due to physical processes (Bergund, 2011).The primary consolidation is followed by secondary subsidence caused by shrinkage, compaction, wind and water erosion, fire and microbial oxidation of the organic matter (Heathwaite et al.,1993; Berglund & Berglund, 2010). The main factors influencing the oxidation rate on drained organic soils are peat type, climate, cultivation intensity and water table level (Eggelsman, 1976; Berglund & Berglund, 2010).

Results of a pilot study show that ground surface level in arable land on organic soil decreased by 28.6 ± 11.3 cm (mean ± 1 SD) during 34 years or 0.8 cm annually after drainage. In Norway, Grønlund et al. (2008) reported that subsidence of cultivated peat soils averaged about 2.5 cm yr^{-1}. Subsidence rates due to different cultivation intensities under Swedish conditions have been roughly estimated to be 0.5 cm yr^{-1} for pasture (extensive land use and trees),1.0 cm yr^{-1} for managed grassland,1.5 cm yr^{-1} for annual crops except row crops and 2.5 cm yr^{-1} for row crops (Berglund & Berglund, 2010).

Subsidence in this study is determined as a change in ground surface level between initial height (before drainage) and current height. However, absolute height can be highly varying depending on height reference system (Adam et al., 2000; Ihde & Sánchez, 2005), reference point used for height measurements with optical level tool and movement of tectonic plates during longer time span (England & Molnar, 1990; Teixell et al., 2009). The spatial analysis shows that height difference between DEM before drainage and current DEM created from LIDAR data in sampling area is positive (+ 3 cm), thus the elevation of soil surface has increased. This is a sum of measurement and data processing errors and those factors mentioned above which needs to be fixed.

The impact of errors and those factors can be excluded if the relative height differences are analysed throughout relatively small area, where no impact of geological processes or impact of reference point used in measurements can occur. That why, height difference between DEM before and after drainage in sampling area was calibrated, by using auxiliary data on differences between pre-drainage soil surface model and current soil surface model on mineral soil nearby sampled area. The idea is that there should not occur any significant subsidence of mineral soil. Subsidence of the organic layer equals to changes on relative height difference between initial (before drainage) height measurements and current measurements (LiDAR) between organic site and nearby site with mineral soil. It is calculated by mean differences between initial and LiDAR data on organic soil subtracting from mean differences on mineral soil. The result estimated by this method (28.6 cm) is in good accordance to changes in depth of organic layer – 25–35 cm (from 50–70 cm before to 25–35 cm now). Depth of organic layer is also measured during the designing of drainage systems, but the density of depth measurements is too low with an accuracy of 10 cm incremental steps. The density of depth measurements is around 300x300 m and the surface between the organic layers is uneven.

It is crucial to have all the necessary information about conditions, equipment and reference point for height measurements to use old topographic maps from designing of drainage systems if subsidence is calculated as a difference between two DEM. If there is missing all the necessary information, then the approach described in this paper may be applied. It demonstrates good results and can be used to determine subsidence if long term subsidence measurement data are not available, but detailed topographic maps are accessible.

Bulk density and carbon stock changes

Soil bulk density in the drained sites is twice as large on topsoil (0–10) and even bigger in deeper layers in comparison to undrained sites (Fig. 4). Explanation of the difference is not only the natural changes in soil occurring after drainage, but also mechanical impact due to tillage and addition of fertilizers. Organic layer was rather shallow (25–35 cm) during the study and agricultural practices can cause mixing of mineral soil particles with the organic material in topsoil.

In all cases there was a considerable admixture of mineral particles at a depth of 20–40 cm in drained sites (bulk density > 400 kg m^{-3}, mean 520 kg m^{-3}), but the mean bulk density on topsoil (0–20 cm) were less than 400 kg m^{-3}. Due to this reason we didn't collected soil samples from deeper layers at drained sites. Mean bulk density in undrained site varied from 130 to 300 kg m^{-3}.

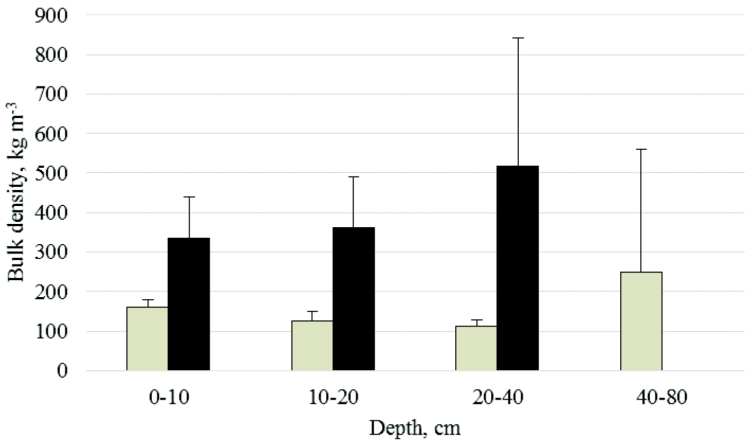

Figure 4. Soil bulk density in drained and undrained sites in different soil layers. Error bars shows 1 SD.

Pre-drainage profile of organic C stock was modelled to calculate the changes in C stock (Fig. 5). Mean C stock in topsoil at drained site through different soil layers have increased by about 50 kg m^{-3}compared to pre-drainage state. The difference of C stock between those two profiles is C loss after drainage. The study results demonstrate that after drainage soil organic C stock has decreased by 137 ± 113 tonnes C ha^{-1} (mean ± CI) during 34 years or 4.2 ± 3.3 tonnes ha^{-1} yr^{-1}.The subsidence of the organic layer caused increase on soil C carbon stock in the upper soil layers due to compaction of organic topsoil (Fig. 3). Approximately 27% of decrease of the ground surface level can be explained by soil compaction. However, the most of the subsidence (73%) observed is due to decomposition of organic matter resulting in CO_2emissions.

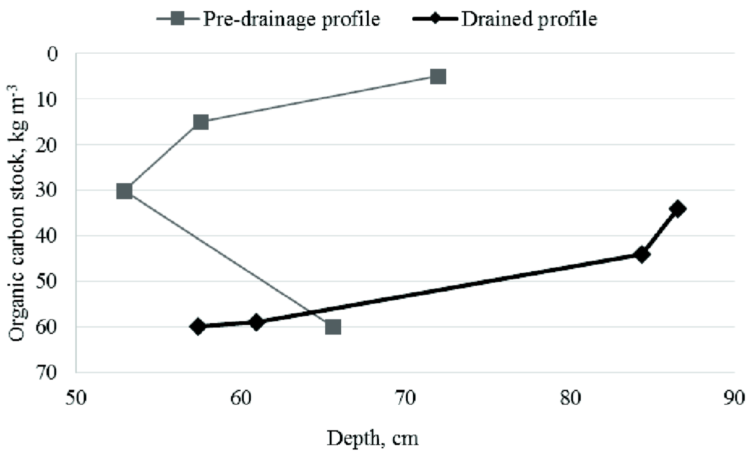

Figure 5. Soil organic carbon stock in different soil depth in drained and control plots.

Emissions estimated during this pilot study are close to those, 4.0–5.5 tonnes CO_2-C ha^{-1} yr^{-1}, estimated earlier for boreal organic agricultural soils (Kasimir-Klemedtsson et al., 1997). Annual CO_2 fluxes from cultivated organic soils in Finland range from 0.8 to 11 tonnes CO_2-C ha^{-1} yr^{-1}(Maljanen et al. 2001, 2003a, 2003b, 2004; Lohila et al. 2004, Regina et al. 2004), but Maljanen et al. (2007) have comparably more recently reported that annual CO_2 fluxes from cultivated organic soils in Finland range from 4.1 to 5.9 tonnes CO_2-C ha^{-1} yr^{-1}. Grønlund et al. (2008) estimated C losses from cultivated peatlands in West Norway by three independent methods. Based on these estimates the corresponding C losses equal 6.0–8.6 tonnesCO_2-C ha^{-1} yr^{-1}.

The estimated CO_2 emissions (4.2 tonnes CO_2-C ha^{-1} yr^{-1}) is by 47% less than the currently applied default emission factor for arable land (7.9 tonnes C ha^{-1} yr^{-1}) provided by IPCC Guidelines for National Greenhouse Gas Inventories. The obtained results substantiate importance of development of the national emission factors for CO_2 to avoid overestimation or underestimation of the GHG emissions from managed organic soils.

Although the method used in this study seems suitable for determination of C stock changes, there are strong limitations to it. Firstly, large uncertainty of carbon stock change should be considered when results are used to drive any conclusions. Uncertainty could be reduced if carbon content would be measured not modelled and sample size (soil samples collected) needs to be several times larger than in this study. Secondly, it is crucial to have detailed and accurate pre-drainage topographic maps. In many cases topographic maps are not available or accuracy of height measurements is too low to use them to calculate subsidence. Thirdly, finding an appropriate control site can be challenging too. Use of historical soil maps could be a useful tool to find an appropriate control sites in agricultural land. Nevertheless, most of the fertile organic soils historically were drained for agriculture. Therefore, availability of reliable control sites is limited.

CONCLUSIONS

After drainage ground surface level in arable land on organic soil has decreased by 0.8 cm annually, but soil organic carbon stock in the study area has decreased by 4.2 ± 3.3 tonnes ha^{-1} yr^{-1}. The estimated CO_2 emissions are by about 47% less than according to the default emission factor for drained arable organic soils in boreal and temperate climate zone provided by IPCC Guidelines for National Greenhouse Gas Inventories. The study results approve credibility of the evaluated methods and substantiate the importance of elaboration of national methodology for accounting of the CO_2 emissions from drained organic soils in cropland and grassland. The subsidence of organic layer due to drainage can be determined if detailed pre-drainage topographic maps are available for the drained site. However, large uncertainty of carbon stock changes points out deficiencies of the study, which needs to be addressed in further studies.

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