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Soil carbon stock change in the forests of Denmark between 1990 and 2008☆

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ABSTRACT

Soils of the forests in Denmark were sampled in permanent plots in 1990 (t1) and resampled (N = 124) in 2007–9 (t2). The soils were classified according to the carbon concentration in the uppermost mineral soil horizon (0–25 cm) at t1 and according to subsoil texture and presence or absence of $CaCO_3$ in the subsoil. Soil organic carbon (SOC) stocks in forest floor + mineral soil (0–100 cm) at t2 had a median of 15.9 kg C m^{-2} (range 4.1–68.9 kg C m^{-2}). There was no detectable overall change in SOC during the 18-year period, but different trends were observed within the subsoil texture classes. SOC stocks decreased with increasing initial SOC content (except calcareous mineral soils), consistently with reports from other inventories of SOC change. Unlike coarse and medium textured soils, fine-textured soils (>10% clay in subsoil) with less than 4.1% C in the 0–25 cm layer gained 2.1 ± 1.1 kg C m^{-2} (lsmean and 95% confidence limit) during the 18 year period (0.11 kg C m^{-2} $year^{-1}$). With only two observation points in time, SOC changes could not be safely interpreted as true changes for subsets of the data, e.g. distinct soil types. Initially very C rich mineral soils and organic soils (C% > 12) on average lost 4 and 7 kg C m^{-2}. These C losses from very C rich mineral (4.1 < C% < 12) and organic soils are highly uncertain due to large sampling uncertainty and thus a possible effect of regression to the mean. However, decreased C concentrations in either topsoil or subsoil layers may also reflect net C mineralization as an adaptation to the current more aerobic drainage regime of soils that were frequently water saturated in previous centuries. Plots afforested after 1954 and ranging in stand age from 7 to 42 years had accumulated forest floors with an average stock of 0.3 ± 0.1 kg C m^{-2}, which was still significantly lower than forest floor stocks in soils of the forests remaining forests. On afforested sites the mineral SOC stock did not show any significant increase between t1 and t2, but SOC redistribution due to deep ploughing was observed in a few sites. The minimum detectable difference for the national soil C stock in forests was estimated to 0.3 kg C m^{-2} over two decades equivalent to a change of 0.015 kg C m^{-2} $year^{-1}$. We conclude that the average forest SOC stock remained unchanged over two decades for soils <4.1% C in the top mineral soil, whereas the sink/source status of very carbon rich and organic soils remains uncertain.

1. Introduction

Forest ecosystems are in focus as potential sinks for carbon, and carbon stocks and dynamics of soils of the forest, hereafter termed forest soils, are differ from those of other land uses. The northern hemisphere has a net terrestrial C sink which has mainly been attributed to carbon sequestration in forests (Janssens et al., 2003). In the recent years many studies have assessed soil organic matter (SOC) pools in forests, but specific knowledge of temporal changes in SOC pools is scarce although such knowledge is needed to support reporting of changes in forest carbon stocks under the Climate Convention and the Kyoto Protocol (Smith, 2004; Jandl et al., 2007). Most estimates of SOC stock changes (sinks) at the European scale have been indirect and vary from 0.01–0.1 kg C m^{-2} $year^{-1}$ due to increasing inputs (changed management) and N deposition (Liski et al., 2002; De Vries et al., 2006, 2009). Schils et al. (2008) cited various national studies, mostly based on modelling, that for the most part indicated a sink rather than source behaviour of boreal and temperate European forest soils: estimates differed from study to study ranging from 0.001 to 0.08 kg C m^{-2} $year^{-1}$ for managed forest land, and from 0.002 to 0.045 kg C m^{-2} $year^{-1}$ after conversion of cropland to forest. These estimates were not related to a uniform soil depth.

In the case that countries have elected article 3.4 under the Kyoto Protocol, documentation of SOC changes in forests is a prerequisite for acceptance of carbon credits. Article 3.4 addresses forests that were

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also forest prior to 1990. Moreover, all signatory countries will have to account for land-use change effects on soil C stocks under article 3.3 of the Protocol, i.e. afforestation and deforestation since 1990. The basis for documentation of SOC changes can be repeated soil inventories or modelling validated by inventory data (Smith, 2004; Lindner and Karjalainen, 2007). In temperate managed forests the soil may contain more than twice as much C as the living biomass (Eswaran et al., 1993; Goodale et al., 2002), yet few inventory studies have attempted to assess changes over time. This is largely due to limited time passed since the baseline sampling (Rodeghiero et al., 2010; Baritz et al., 2010), lack of baseline data or limitations in baseline data to conduct a true repeated inventory of SOC stocks, e.g. only C concentration data are available in some cases (Lal, 2005).

Repeated inventory studies of arable and grassland soils reported a negative relationship between initial carbon stock and carbon stock change of soils (Heidmann et al., 2001; Saby et al., 2008; Riley and Bakkegard, 2006; Hanegraaf et al., 2009), that can partly be attributed to changed management practices and lower inputs (Goidts and van Wesemael, 2007), and partly may reflect regression to the mean (Barnett et al., 2005). Regression to the mean (RTM) has been debated as a statistical effect causing artefact losses from initially C-rich soils (Lark et al., 2006, 2009; Potts et al., 2009) and SOC gains in soils with initially low C stocks. In a debate on UK soil inventory carbon data, Lark et al. (2009) end their response to Potts et al. (2009) by concluding that the average SOC stock change of an unbiased national sample would not be affected by RTM. Erroneous estimates of change (bias) due to RTM may, however, arise when change estimates are based on observed changes in the tails of the SOC distribution of a soil population. Statistical models developed from data with only two measurements in time will suffer from this bias if the baseline is poorly determined (Barnett et al., 2005). It is well known that soils are highly variable in their development depending on climate, organisms, relief, parent material and time according to the model by Jenny (1941). Variability in SOC stock is typically associated with different soil types, e.g. weakly developed soils (Entisols) versus podsolised soils (Spodosols) or organic soils (Histosols) (Vejre et al., 2003). If soils are regarded as one population, a large natural variability in total stock and in the location of SOC in different horizons may be expected.

The demand for transparent and verifiable reporting of SOC stock changes in forest ecosystems under the Climate Convention and the Kyoto Protocol created a need for new information on the state of and change in forest SOC stocks, i.e. C stocks in the forest floor and mineral soil as well as C stocks in organic soils (IPCC, 2003). In Denmark, existing information on forest SOC stocks to 1 m depth has come from soil profile databases (1 soil pit per site) based on spatially non-systematic (Vejre et al., 2003) and systematic sampling designs (Krogh et al., 2003). The reported C stocks differed based on these two designs; soil C stocks in forest floor and mineral soil to 1 m were on average 12.5 kg C m^{-2} in the spatially non-systematic study based on 106 soil profiles from well-drained experimental sites, but 16.7 kg C m^{-2} in the study of 101 forest soil profiles in a 7 × 7 km grid including a wider range of soil moisture regimes (Krogh et al., 2003). This difference was mainly attributed to greater representation of historically moist and wet soils with higher soil C stocks in the systematic grid design (Krogh et al., 2003). Such soil types are usually omitted for experimental management purposes (i.e. the sites included in Vejre et al., 2003), but the discrepancy is also likely to be caused by uncertain estimates of forest floor C stocks or other methodological issues.

The SINKS project was initiated in 2008 with the aim to estimate SOC stock changes in Danish forest soils for supporting Kyoto Protocol reporting under article 3.4. Forest SOC stock changes over 18 years were assessed by based on archived soil samples from an existing 7 × 7 km monitoring grid and by resampling the same sites using similar methodology. The Square Grid for Nitrate Investigations in Denmark was established in 1987 by the Danish agricultural extension service and is now managed by SEGES P/S. This monitoring grid allowed us to evaluate SOC changes in plots in forest remaining forest (art. 3.4) and in plots that experienced land-use change from cropland to forest (art. 3.3) during the 18-year period and previous decades. Our null hypothesis was that SOC stocks in forests remaining forests did not change between 1990 and 2007–9 to 1 m depth.

For cropland converted to forest, we hypothesized that soil C stocks would increase due to ceased agriculture and development of forest floor C pools as reported from Danish chronosequence studies (Vesterdal et al., 2002, 2007; Barcena et al., 2014a) as well as from global and regional meta-analyses (Poeplau et al., 2011; Nave et al., 2013; Barcena et al., 2014b). We further aimed to assess the power of the soil inventory to detect national scale changes in average SOC at the timescale of two decades in terms of the minimum detectable difference (MDD).

2. Materials and methods

2.1. The Danish monitoring network Square grid for nitrate investigations

Denmark has an Atlantic, cool temperate climate with 500–900 mm annual precipitation and annual regional mean temperatures in the range 7.2–8.4 °C (1961–1990). Between 2000 and 2010 the annual average precipitation has been 600–1000 mm, and regional mean temperatures ranged from 8.0 to 9.6 °C (Danish Meteorological Institute, 2015). Forest cover in 2012 was 14% or 608 kha of which 41% is broadleaved forest, some of seminatural origin, and 40% are coniferous plantations. Many plantations have been established since the mid 19th century on former *Calluna* heathland. Ditching of forest areas has been carried out from mid 19th century, e.g. water-logged soils in low positions in the landscape in order to improve forest production (Johannsen et al., 2013).

Soil archives from forest sites are not generally available at the national scale, but the ‘Square Grid for Nitrate Investigations’ designed for nitrate monitoring and management on agricultural land in a 7 × 7 km grid across Denmark also included forest sites. In 1990 (t1) about 1000 sites covering all of Denmark were sampled (Østergaard and Mamsen, 1990). Each plot was 50 × 50 m. This soil archive was chosen for a resampling study (1990 to 2007–9) of soil carbon in forests remaining forest (FRF) and sites afforested since 1954 (AFF). Effects of cropland to forest conversion on SOC stocks are known to be slow and lasts more than a tree generation (Poeplau et al., 2011), and the 1954 land-use baseline (as given by the first high resolution aerial photos) allowed us to study these more long-term effects of afforestation. Aerial photos of the plots and databases were studied for detecting land-use changes, e.g. afforestation, during the period. A total of 126 sites were now forest, and 124 of these sites could be sampled. Ten forest sites in the grid were not chosen for resampling due to missing data. The number of sites with SOC observations included under forest remaining forest (FRF) and afforestation (AFF) at t1 that could be resampled at t2 for paired observations were 95–98 FRF and 20–21 AFF sites depending on missing values in the depth compartments 0–25 cm of 0–100 cm. Further observations at t1 and t2 are unpaired. The slightly lower number of sites for each variable in Table 1 owes to missing carbon data in one or more soil depths for resampled sites and two sites with t1 data available that could not be resampled at t2. The six AFF sites afforested in the period 1954–1989 were included in the analysis of stock changes in FRF mineral soil between 1954 and 2007–9 as presented in Table 1, results and figures throughout the manuscript.

Following site inspections and soil profile descriptions qualitative classifications of drainage class and ditches was made. Twenty-five sites had ditches near or within the plot, and 6 sites were very poorly drained judged by presence of groundwater gley within 40–80 cm below terrain or higher. Some of these poorly drained sites were organic soils. For some sites no information on drainage class and presence of ditches was given, and we assumed that drainage was satisfactory and ditching not present. Twenty two per cent of the sites were in flat