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A comparison of soil organic carbon stocks in Viking Age and modern land use systems in Denmark

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ABSTRACT

A comparison of the organic matter content in anaerobic soil horizons in burial mounds and the plough layer in modern farmlands offers a unique opportunity to compare the soil organic carbon (SOC) stocks in ancient and modern land use systems and to evaluate the long term carbon sequestration in modern farmlands during thousands of years in relation to inputs of manure, fertilizers, liming and drainage.

In this paper the SOC stocks from anaerobic soil horizons in two big loamy burial mounds from the Viking Age, representing the land use system 1000 years ago, are compared with results from ancient sandy soils, loamy soils surrounding the mounds and nation-wide soil surveys representing modern land use systems with low and high inputs of manure. Results show that within the upper 0.28 m of the soil, which is the average depth of present day plough-layers in Denmark, the carbon stock in the farmland soils surrounding the mounds is roughly 85% of that in Viking Age. Intensively manured loamy soils in West Jutland contain about the same carbon stock as the ancient soils from the Viking Age. In contrast, modern arable loamy soils in Southern Zealand and adjacent islands, receiving low input of manure, contain a SOC stock of roughly 60% of the level in the loamy Viking Age soils. The carbon loss since the Viking Age in the surrounding soils is believed to be due to liming and drainage that has increased the decomposition of organic matter in the soils. This loss can be balanced by present day land use systems with high input of manure. Compared to ancient sandy soils that do not show any SOC loss during the past 3000 years, there is a clear SOC loss from the loamy soils, probably about 40% during the last 150 years, where most of the loamy soils have been drained.

1. Introduction

Soil organic carbon (SOC) plays an important role in the overall carbon cycle as it is the primary terrestrial pool for organic carbon. It accounts for more than 75% of the Earth's terrestrial organic carbon and contains between 4 and 5 times the amount of C stored in living vegetation (Lal, 2004). Therefore, even small changes in the SOC stock may influence the greenhouse gas concentration in the atmosphere. In that respect soils can act as a source for greenhouse gases by CO_2 and CH_4 emissions or as a sink for atmospheric CO_2 by carbon sequestration in soil organic matter.

The SOC stock is strongly influenced by soil characteristics such as texture, pH and drainage conditions but also by environmental factors like climate, vegetation and human activities (Brady and Weil, 2002; Jones et al., 2004). While the soil characteristics and hereby the SOC stock only change slowly over time due to changes in climate and natural vegetation, human activity can change the SOC stock rather quickly due to changes in crop rotation, liming, manuring, inorganic fertilization, ploughing and drainage. This is clearly demonstrated by the long-term experiments at Rothamsted (Jenkinson, 1990; Johnston, 1991; Poulton, 1995) and similar experiments for more than 100 years at Askov Research Station in Denmark (Christensen et al., 2006).

Because of the impact of human activity on SOC, there is a growing interest in regulating land-use strategies in an attempt to increase SOC sequestration or prevent CO_2 emission. In order to assess the total amount of carbon sequestered in the soils, estimates of the SOC stock have been made at global scale for example by Batjes (1996), Buringh (1983), Post et al. (1982), and Schlesinger (1984). Based on these investigations the total amount sequestrated is about 1500 Pg. At country level similar calculations have been made in e.g. Great Britain (Smith et al., 2000), Canada (Tarnocai, 1994), France (Arouays et al., 2001), and Denmark (Krogh et al., 2003). If these stocks are given for individual landscape types, they can be used to determine how much carbon we can expect to store in the soil by changes in land use. For example, Krogh et al.

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(2003) estimated that to the depth of 1 m, the well-drained agricultural soils in Denmark contained about 3 kg m^{-2} less carbon than forest soils. Afforestation is therefore likely to sequestrate C, but not necessary always, because Krogh et al. (2003) did not distinguish between heavily manured farmland soils and fertilized farmland soils.

Bohn (1976, 1978), Buringh (1983), Rosenberg and Izaurralde (2001), and Schlesinger (1984) calculated the SOC balance on a worldwide basis. They found a yearly net SOC loss from slightly above 4 Pg to slightly below 1 Pg mainly due to human activity. This discrepancy is probably due to lack of accurate measurements of the SOC stock in ancient times, particularly for SOC stocks in prehistoric agricultural systems. This is due to the fact that the best suited soils for agricultural production are well drained and aerobic. Such soils have a fast SOC turn over time, hence the rarity of 'frozen' agricultural SOC stocks from ancient time. Breuning-Madsen et al. (2009) calculated the SOC-stock in 3300 year old sandy soils from the South Scandinavian Bronze Age and compared them to samples collected in present days farming systems with high and low input of manure. The 3300 years old samples were collected from iron pan encapsulated anaerobic cores in burial mounds built of turfs (Breuning-Madsen and Holst, 1998; Breuning-Madsen et al., 2001, 2003; Holst et al., 1998). The turfs were topped with un-decomposed plant remnants upon extraction showing that decomposition of the organic matter in the soil was neglectable. Furthermore, the composition of the vegetation indicated that the turfs originated from areas used for extensive grazing in a former shifting cultivation system, which was the predominant agricultural strategy in southern Scandinavia during the Bronze Age (Odgaard, 1994; Rasmussen, 1995; Thrane, 1991). The result showed that the SOC stock in the Bronze Age was at the same level as found in present days farmlands with low input of manure, while in areas with high input of manure the SOC stock was more than 50% higher than in the Bronze Age. This study showed that there has not been any SOC loss in the Danish sandy soils for more than 3000 years which is contradictory to the findings of Bohn (1976,1978), Buringh (1983), Rosenberg and Izaurralde (2001), and Schlesinger (1984) about SOC loss from farmlands since ancient times.

The findings of Breuning-Madsen et al. (2009) are only valid for sandy soils and it is questionable to use the findings on loamy soils because of differences in soil physical and chemical properties affecting the SOC stock. However, it will be possible to determine changes in the SOC stock in loamy soils relative to the SOC stock in modern loamy farmland soils with low and high inputs of manure since ancient time, if data is available from loamy burial mounds with anaerobic cores. In 2009 several borings were carried out in the two royal burial mounds in Jelling (Breuning-Madsen et al., 2012). They were built in mid 900 AD and had thick anaerobic cores, which offer a unique possibility to determine the SOC stock in loamy ancient soils and compare this finding with the SOC stocks in ancient sandy soil in Denmark and with SOC stock in modern loamy farmland soils with low and high inputs of manure.

Thus, this paper aims at quantifying the SOC stock in a 1000 year-old land use system on loamy soils in Denmark and compares this with SOC stocks in ancient sandy farmland soils and in the modern farming system around the mounds. Furthermore, based on results from nation-wide soil databases, the SOC in the 1000 year-old land use system is compared with the SOC stock in modern loamy farmland soils with low and high inputs of manure.

2. Materials and methods

2.1. Site description

Jelling is located in Eastern Jutland in Denmark, Fig. 1, in a relatively level bottom moraine landscape consisting of loamy tills and melt water deposits from the late Weichsel Glaciation. In minor depressions wetlands have developed due to the loamy tills' low permeability and in few places bogs have developed. West of Jelling aeolean sand deposits cover great areas, and south of Jelling a distinctive melt water valley was developed. The average temperature is 7–8 °C and the mean annual precipitation is about 750 mm.

In the bottom moraine landscape two huge burial mounds were constructed in the Viking Age (700–1066 AD). The mounds were built by turfs collected in the vicinity, and the turfs were about 10 cm thick, 20 wide and 30 cm long. Both mounds are flat-topped, truncated and cone-shaped. The oldest one, the north mound, was probably constructed in year 958 or 959 AD according to dendrochronological dating (Krogh, 1993). It is approximately 60 m in diameter, 7.5 m tall and constructed from more than 2.5 million mainly sandy loamy turfs. The youngest mound, the south mound, was built shortly after 970 AD according to dendrochronological dating of a centre post in the mound. It is about 70 m in diameter, 9.5 m high and constructed from more than 3.0 million loamy or sandy loamy turfs. According to macro-fossil analyses of plant remnants on the turf surfaces the vegetation was heather (*Calluna vulgaris*), grasses and mosses. Immediately after the construction of the north mound was finished, an intrusion was made from the top of the mound and the grave was emptied. However, the south mound remained untouched. In 19th and 20th centuries extensive intrusions have been made into both mounds (Dyggve, 1942; Krogh, 1993).

2.2. Soil sampling

In 2009 several borings were carried out in the two mounds in order to describe the soil physical and chemical composition of the building material and to study the preservation condition within the mounds. Six borings were carried out in the undisturbed parts of the north mound and three in the south mound. The borings were carried out using a hand-driven auger for stony soils with an auger head of 7 cm in diameter and a length of 15 cm. All borings reached the yellowish brown subsoil below the mounds, and the deepest boring was 9.4 m. At each down lead and uptake, a 10–15 cm long sample was extracted and described according to the soil profile description system developed for Danish burial mounds (Breuning-Madsen and Holst, 2003). Special emphasis was placed on texture, distinctness of the turfs, wetness, gley, artefacts and plant remnants on the turf surfaces.

About 120 disturbed soil samples were collected for analyses from the nine borings.

In order to compare the SOC stock at Viking Age with present day agriculture in the vicinity, more than 50 sites were chosen on farmlands close to the mounds and disturbed soil samples from the plough layer were collected for determination of SOC, textural composition and pH. At 16 sites triplicate undisturbed samples for bulk density determination were collected each in 100 cm^3 metal rings. Wetlands were excluded from the sampling.

2.3. Analyses

The soil samples were air dried and sieved through a 2 mm mesh before analyses for soil chemical and physical parameters were initiated. The following analyses were carried out on selected samples:

- Soil texture was determined by dry sieving for the sand fraction and the hydrometer method for the silt and clay fraction (Day, 1950).
- Total carbon content was determined by dry combustion at 1350 °C in an Eltra CS500-analyzer (ELTRA, 1995).
- Soil pH was determined in a soil suspension in 0.01 M $CaCl_2$ at a soil–liquid ratio of 1:2.5.