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A comparison of soil organic carbon stock in ancient and modern land use systems in Denmark

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Summary

During the South Scandinavian Early Bronze Age about 3300 years ago, thousands of burial mounds were constructed of sods from fallow ground used for grazing in Denmark and northern Germany. In some of these mounds a wet, anaerobic core developed, preventing the decomposition of organic matter. A comparison of the organic matter content in these mound cores and the plough layer in modern farmland offers an opportunity to compare the soil organic carbon (SOC) stocks in ancient and modern land use systems and to evaluate the long-term trends in carbon (C) sequestration in relation to modern farmland with varying inputs of manure and inorganic fertilizers. In the present paper we compare SOC stocks based on integrated horizon-specific densities and SOC contents in three 3300-year-old buried farmland soils, representing the land use system at that time, with results from soil surveys representing modern land use systems with low and high inputs of manure. Results show that, within the upper 0.28 m, which is the average depth of present day plough layers in Denmark, soils receiving manure from intensive pig or cattle production hold *c*. 60% more SOC than the ancient soils from the South Scandinavian Bronze Age. In contrast, modern arable soils mainly receiving limited inputs of manure hold a SOC stock similar to that of the ancient soils.

Introduction

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

Thus, in the ongoing debate on climate change resulting from increased emission of greenhouse gases into the atmosphere, soils play an important role because of the possibility of C sequestration in SOC. The SOC stock is strongly influenced by soil characteristics such as texture, pH and drainage but also by environmental factors such as climate and by human activities (Jones *et al*., 2004). While the soil characteristics and the climate maintain or change the SOC stock slowly over time, human activity can change the SOC stock quickly; for example by manuring, inorganic fertilization, ploughing, drainage and liming. This is clearly demonstrated by the long-term experiments at Rothamsted (Jenkinson, 1990; Johnston, 1991; Poulton, 1995).

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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 C sequestered in the soils, estimates of the SOC stock have been made at global (Post *et al*., 1982; Batjes, 1996) and at country scales (e.g. Great Britain (Smith *et al*., 2000), Canada (Tarnocai, 1994), France (Arrouays *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 C we can expect to store in the soil by changes in land use. For example, Krogh *et al*. (2003) estimated that to the depth of 1 m, the well-drained agricultural soils in Denmark contained *c*. 3 kg m^{-2} less C than forest soils. Afforestation is therefore likely to sequestrate C. Similarly, intensively farming land with a high input of manure seems to increase the SOC content, as demonstrated by the long-term experiment at Rothamsted (Jenkinson, 1990; Johnston, 1991; Poulton, 1995).

Schlesinger (1984) calculated that on a worldwide basis, the pool of SOC held within the soils of the Earth is *c*. 1515 Pg and that human activity is causing a net release to the atmosphere of *c*. 0.8 Pg annually. Bellamy *et al*. (2005) have recently shown a net SOC loss in the UK in modern agriculture and other land uses. When discussing long-term decrease or increase of the SOC stock in farmland soils it is important to have some accurate measurements of the SOC stock in ancient times. Current databases cover the last few decades, but over longer time scales there is a lack of data, particularly for SOC stock in prehistoric agricultural systems. This is because the best-suited soils to agriculture are well drained and aerobic. The organic matter in these soils has a fast turnover time, hence the rarity of 'frozen' agricultural SOC stocks.

From 3700 to 3100 BP, and especially during 3400–3300 BP, thousands of burial mounds were built of turf sods in Denmark and northern Germany. Botanical analyses of pollen and plant macro-fossils show that the sods generally came from areas used for extensive grazing and were procured from the immediate vicinity of the barrow (Andersen, 1999; Prangsgaard *et al*., 1999; Karg, 2008). The frequent occurrence of plough marks (ard furrows) and occasionally signs of settlements underneath the barrows indicate a form of rotation system, probably with a few years of cereal production followed by a long and irregularly grazed fallow. This land use system is thought to be representative of the predominant agricultural strategy in southern Scandinavia during the Bronze Age (Thrane, 1991; Rasmussen, 1993, 1995; Odgaard, 1994).

In a few cases, an anaerobic bluish wet core has developed in the centre of these mounds. The core is totally encapsulated by a thin, strongly cemented and impermeable iron pan (Breuning-Madsen & Holst, 1998; Holst *et al*., 1998; Breuning-Madsen *et al*., 2001, 2003). From some of these cores, well-preserved oak log coffins containing human bodies together with their clothing have been excavated, indicating very slow rates of decomposition of the organic matter (Holst *et al*., 2001). Furthermore, the presence of undecomposed plant remnants and soil animals on the upper surfaces of the individual constituent sods has often been reported (Aner & Kersten, 1973). This shows that the development of anaerobic conditions in the mound core happened quickly. Experimental work by Breuning-Madsen *et al*. (2001, 2003) shows that the development of anaerobic conditions in the mound core can happen within days. Therefore the sods in anaerobic cores offer a unique opportunity to quantify the original SOC content in ancient soils without major concerns about partial decomposition of the organic matter after burial, as is normal in well-drained paleosols (Crowther *et al*., 1996). The SOC content in the anaerobic cores gives a unique opportunity to test the statement of Schlesinger (1984) that modern agriculture has resulted in a net SOC loss, by comparing the SOC content in the present day plough layers with that in the plough layers of the past.

Our paper aims to quantify the SOC stocks in a 3300 year-old land use system in Denmark and northern Germany based on C data from the anaerobic cores in burial mounds and the soil horizon sequence in the buried soil below, and to evaluate long-term trends in soil organic matter by comparing the prehistoric SOC stocks with modern land use systems based on results from modern nationwide soil surveys.

Materials and methods

Soil sampling

Three burial mounds with a blue anaerobic core have been excavated during the last decade: Bredhøj east of Kolding, Skelhøj northeast of Ribe, both in Denmark, and Hüsby west of Schleswig in northern Germany, close to the Danish border (Figure 1). Bredhøj was excavated in 1996, while Skelhøj and Hüsby were excavated in 2002–2003. Skelhøj was a 6 m-high protected mound partly demolished by grave robbers, while Bredhøj and Hüsby were ploughed burial mounds on arable land and not more than 2 m high. Figure 2 shows the Hüsby burial mound with a pronounced blue core below an aerobic mantle, and Figure 3 shows the lower anaerobic core with distinct sods and the buried soil below at Skelhøj.

The cores and the ancient soil profiles below were described according to the FAO manual (FAO, 1990). Bulk soil samples were taken from all soil horizons, air-dried and sieved through a 2-mm sieve prior to analysis. The texture was determined with the hydrometer method for the silt and clay fractions and dry-sieving of the sand fractions. Soil pH was determined potentiometrically in a suspension of soil and 0.01 M $CaCl_2$ at a soil-liquid ratio of 1:2.5. Total C content was determined by dry combustion at 1250 °C in oxygen (ELTRA, 1995). Low pH-values (<4.6) indicate that there are no carbonates, so that the measured C represents only organic C. The content of iron and aluminium sesquioxides was determined by the dithionite-citrate-bicarbonate method (DCB) (Mehra & Jackson, 1960). The presence of ferrous iron was tested by means of the αα dipyridyl method (Childs, 1981). Triplicate core samples of 100 cm^3 were taken from the horizons for bulk density determination. Skelhøj and Hüsby were dated by AMS ^{14}C-dating of plant and insect remains found in the barrows, while the age of Bredhøj was determined by typological dating of the artefacts in the primary burial tomb.

SOC contents and stocks in modern well-drained agricultural soils with low and high inputs of manure have been evaluated from the Danish nationwide pedological database (Madsen *et al*., 1992). This comprises data from soil profiles sited on a nationwide orthogonal 7 km grid during 1987–1990. Bulk samples for texture and chemical analyses were collected, and triplicate core samples of 100 cm^3 were taken from the natural horizons for bulk density determination. The samples were analysed according to the same methodology as described above for the burial mound samples. The information on

Figure 1 Map showing the location of the burial mounds, in Ribe county and Zealand.

texture, total C content, depths of soil horizons, bulk density and land use (Madsen *et al.*, 1992) are extracted for the comparisons in the present paper

Results and discussion

Description of the burial mounds

Table 1 is a description of the soil layers through the central part of the Skelhøj mound. For the construction of this mound *c.* half a million sods have been used, corresponding to the removal of the top 10 cm from *c.* 3 ha land. The sods have mainly been taken from grazed land. In the upper metre of the almost 5 m high mound the sod structure has almost disappeared because of bioturbation, and an incipient podzol has developed (Appendix S1). An Ap horizon was absent, indicating that no ploughing of the mound has taken place. Below the top metre there was an aerobic mantle with distinct sods (Appendix S2). In some cases the sods consisted solely of A horizon materials but in others they contained A- and B/C-materials. In a few cases only B/C-materials were used. This is probably because sods have been taken from the same field more than once. The lower border of the mantle is the upper iron pan (Appendix S3). It is semi-permeable and was not as strongly developed as the lower iron pan, but chemically they are identical.

The central core of the mound can be divided into two parts: an upper aerobic core with fossil gley features that have become oxidized after intrusions by grave robbers, and a lower anaerobic core where the individual sods contain well-preserved plant and insect fragments (Figure 3; Appendix S4). The intrusions by the grave robbers may have happened during the Bronze Age, shortly after the construction of the mounds, or later. Many mounds were excavated in the 19th century by archaeologists or private grave robbers, before the Danish Parliament passed a protection act in 1937. Despite intrusions into the cores, the lower parts of the central cores have remained

Figure 2 Ploughed-over Hüsby burial mound. (1) Modern plough layer. (2) Aerobic mantle. (3) Previously anaerobic core, now aerobic with gley. (4a, b) Upper and lower iron pans. (5) Anaerobic core.

wet and bluish with no or few red mottles (Figure 3). The lower core tested positive for the presence of ferrous iron, which indicated that the cores were still anaerobic. This is supported by the presence of undecomposed vegetation on the sod surfaces. At Hüsby, the vegetation on the sod surfaces was dominated by grasses, heather and other herbs; at Bredhøj mosses and grasses dominated (Prangsgaard *et al*., 1999); and at Skelhøj young heather and grasses dominated (Karg, 2008). Well-preserved plant remnants were observed on the sod surfaces at Skelhøj (Appendix S5) and some complete insects, including a well-preserved dung beetle, were also found (Appendix S6). The age of beetle and plants was determined by ^{14}C to 3400–3300 BP (calibrated). This fits well with the fact that most of the Bronze Age mounds were constructed in that period. The well-preserved vegetation and insects show that the cores have been anaerobic since shortly after construction and that the C content in the sods can be used to indicate the SOC content in the ancient 3300 year-old plough layers. Furthermore, the vegetation shows that the sods in all three mounds have been collected from fallow ground.

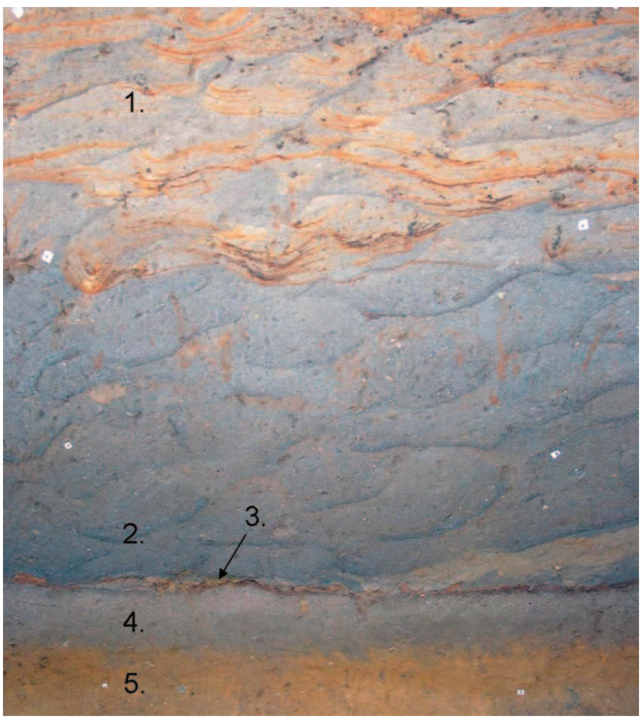

Figure 3 Core, the lower iron pan and the buried soil from Skelhøj burial mound. (1) Previously anaerobic core, now aerobic with gley. (2) Anaerobic core. (3) Lower iron pan. (4) Apb – 3300-year old buried plough layer. (5) Bwb – the buried B-horizon.

The anaerobic core rested on the strongly cemented and impermeable lower iron pan (Breuning-Madsen *et al*., 2000). The DCB-soluble iron contents in the iron pans were *c*. 5%, which is more than tenfold higher than those found in the other soil horizons (Table 2). There are no comparable peaks for aluminium and organic C in the iron pan, indicating that it was formed by redox processes rather than podzolization. This has also been demonstrated by Holst *et al.* (1998) and Breuning-Madsen *et al.* (2000). Figure 4 shows a scanning electron micrograph of the lower iron pan at Skelhøj, and a scanning electron micrograph of the thinner upper iron pan is shown in Appendix S7. The impermeable part of the pan was not more than 1 or 2 mm thick.

The two other mounds investigated, Hüsby and Bredhøj, have not been protected, and have been ploughed and show a distinct Ap-horizon (Figure 2). A greater part of the mantle has been ploughed away, the depth of which today is *c*. 1 m. The upper iron pan is semi-permeable and not as strongly developed as the lower one. As at Skelhøj, the central core of the mounds can be divided into two parts, an upper aerobic core with fossil gley features that have become oxidized after intrusions into the core by grave robbers, and a lower anaerobic core. These tested positive for the presence of ferrous iron, indicating anaerobic conditions, and the individual sods contain well-preserved plant and insect fragments.

The ancient soils and their carbon content

The lower iron pan separated the mound core from the Bronze Age buried soil profile, which was thus protected against leaching. The buried soil can therefore give information on the soil profile development in the Bronze Age and, to some degree, also the nutrient status of the soils at that time.

Table 1 shows that the buried soil below the anaerobic core of Skelhøj (Figure 3) was a well-drained soil without gleying. Roots and other plant remnants in the soil have decomposed. The ancient Ap horizon is 15 cm thick and there was a lighter coloured Bw horizon below. Table 2 shows that all three burial mounds were built of coarse sandy sods. The texture of the core

Table 1 Profile description of the central part of the burial mound Skelhøj and the 3300-year-old buried soil below. Depths in cm from the top of the mound (see Figure 3)

A (0–3): black (10YR 2.1 dry) clayey sand; high humus content; many roots, very few stones; horizon boundary abrupt and smooth.
E (3–16): very dark greyish brown (10YR 3/2 dry) clayey sand with bleached sand grains; medium humus content; weak subangular blocky; many roots; very few stones; horizon boundary clear and smooth.
Bvs (16–37): brown (10YR 4/3 dry) clayey sand; low humus content; weak subangular blocky; many roots; very few stones; horizon boundary gradual and smooth.
C (37–100): brown (10YR 4/3 dry) clayey sand; low humus content; very weak subangular blocky; many roots; very few stones; horizon boundary diffuse.
Aerobic mantle (100–323): sods of Ap-material or A-material and B/C-material. The dominant colours are dark greyish brown (10YR 4/2 moist) or dark brown (10YR 3/3 moist) for the A-material and dark yellowish brown (10YR 4/6 moist) or yellowish brown (10YR 5/6 moist) for the B/C material; coarse sand; medium to low humus content; weak subangular blocky; few roots; few stones; horizon boundary abrupt and smooth.
Upper iron pan (323–325): reddish brown (5YR 4/4 moist) to red (2,5 YR 4/8 moist) partly cemented continuous iron pan.
Aerobic core (325–425): bluish grey (10B 5/1 moist) aerobic core with many gley features mainly as yellowish red (5YR 4/6 moist) horizontal bands formed after the drainage of the upper part of the anaerobic core due to grave robber intrusions; some of the bands are cemented; coarse sand; medium humus content; weak subangular blocky; very few roots; few stones; horizon boundary abrupt and smooth.
Anaerobic core (425–485): dark bluish grey (5B 4/1 wet) well-defined sods; coarse sand; medium humus content; well-preserved roots, flowers and soil animals; weak subangular blocky; few stones; horizon boundary abrupt and smooth.
Lower iron pan (482–485): red (2,5 YR 4/8 moist) strongly cemented continuous iron pan.
Apb (485–500): dark brown (10YR 3/3 moist), greyish brown (10YR 5/2 dry); coarse sand, with many bleached sand grains; medium humus content; weak subangular blocky; no roots; very few stones; abrupt and smooth boundary to:
Bwb (500–525): dark yellowish brown (10YR 4/6 moist) coarse sand; low humus content; weak subangular blocky; no roots; very few stones; clear and smooth boundary to:
C1b (525–550): yellowish brown (10YR 5/8 moist) coarse sand; low humus content; very weak subangular blocky; no roots; very few stones; horizon boundary clear and smooth abrupt and smooth boundary to:
C2(g)b (550–570): yellowish brown (10YR 5/6 moist) coarse sand; low humus content; very weak subangular blocky; no roots; no stones; very weak traces of gley features.

and the Bronze Age Apb below were similar, indicating that the mound consisted of sods taken from the immediately surrounding areas. The soil material in the lower anaerobic core and the soil below had pH values less than 5.0 and it is therefore likely that the soils in the Bronze Age had low nutrient contents. The three underlying sandy Bronze Age paleosols are all Arenosols (IUSS Working Group WRB, 2007), although they show some signs of incipient podzolization. For example, the

Table 2 Texture, bulk density (BD), pH, soil organic carbon (SOC), and total Fe and Al by dithionite-citrate-bicarbonate (DCB) extraction

Depth /cm	Clay <2 μm	Silt > 2–50 μm	Fine sand 50–125 μm	Medium sand 125–250 μm	Coarse sand 250–2000 μm	BD /kg m^{-3}	pH $CaCl_2$	%SOC today	% SOC in Bronze Age[a]	Fe / %	Al / %
	/%										
Skelhøj											
Lower core	6	12	7	14	61	1520	4.6	1.79[a]		0.30	0.11
Lower iron pan	ND	ND	ND	ND	ND	ND	4.4	1.97		8.45	0.06
Apb 0–15	5	10	7	13	65	1570	4.3	0.74	1.79	0.50	0.06
Bwb 15–40	5	10	5	9	71	1590	4.3	0.31	0.75	0.47	0.13
C1b 40–65	3	3	2	7	85	1600	4.5	0.13	0.31	0.27	0.08
Hüsby											
Lower core	3	12	8	25	52	1520	4.2	1.74		0.28	0.35
Lower iron pan	ND	ND	ND	ND	ND	ND	4.6	1.65		7.78	0.50
Apb 0–15	6	10	10	27	47	1540	4.4	0.60	1.74	0.48	0.13
Bwb 15+	4	8	7	21	60	1420	4.6	0.31	0.90	0.58	0.75
Bredhøj											
Lower core	7	16	9	20	48	1270	4.5	1.18		0.32	0.06
Lower iron pan	ND	ND	ND	ND	ND	ND	4.8	1.38		4.85	0.12
Apb 0–15	3	12	7	20	58	1310	4.5	0.34	1.18	0.47	0.08
Bwb 15+	0	3	1	18	78	1350	4.6	0.15	0.52	0.26	0.11

[a]% C Apb (Bronze Age) = %C anaerobic core. % C Bwb (Bronze Age) = %C Bwb (current) * %C anaerobic core/%C Apb (current).
ND, no data.

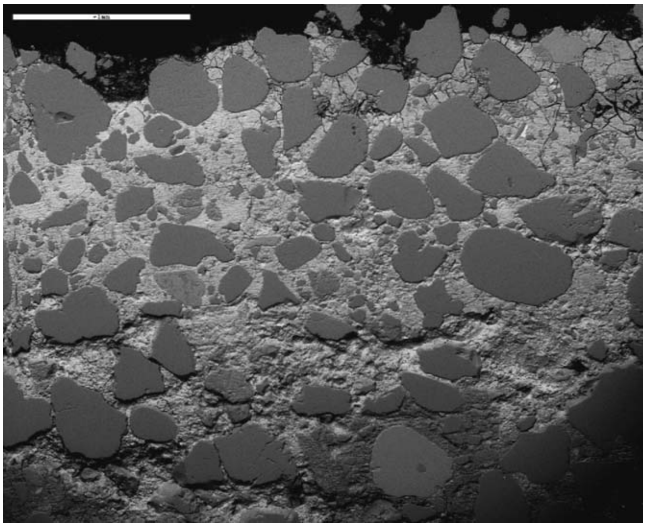

Figure 4 Scanning electron micrographs of the lower iron pans in Skelhøj. The grey particles are quartz grains with white iron hydroxide cement making the iron pan impermeable to water. Bar = 1 mm.

DCB-aluminium content increases from Apb to Bwb in all three profiles (Table 2). The 15 cm thick Apb horizon at all three sites was typical for Bronze Age plough layers in Denmark and northern Germany (Aner & Kersten, 1973). Below the Apb plough (ard) marks were recognized (Figure 5), showing that the soils were cropland before they turned into grassland. This indicates that the soils were part of the agricultural system with long-term fallows that is believed to have been the norm in the Bronze Age. Thus the C content in the mound sods investigated can be considered as a measure for the C content in the Bronze Age soils.

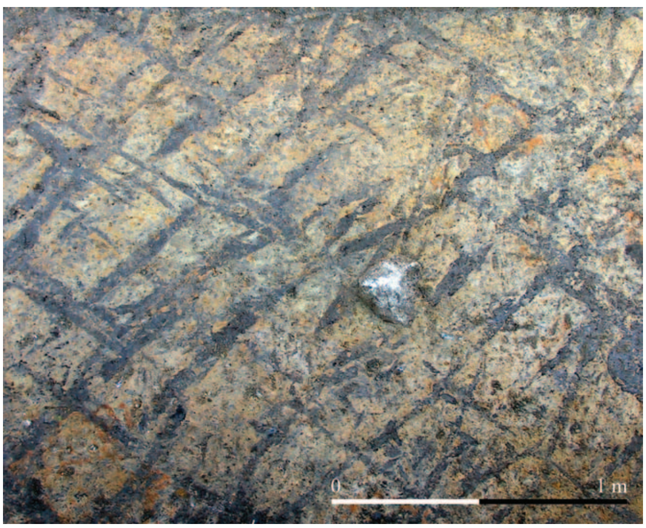

Figure 5 Plough marks in two perpendicular directions below the 15 cm thick Bronze Age plough layer under a Bronze Age barrow in Jutland. The plough marks are dark grey lines in the bright coloured subsoil.

Biological processes have taken place in the aerobic soil material below the iron pan encapsulated anaerobic core. This is clear from: (i) the lack of roots in the buried Apb that must have been decomposed after the mound construction, and (ii) the low SOC content in Apb compared with the anaerobic core (Tables 1, 2). During 3300 years, the SOC content in Apb has apparently been reduced to *c*. 30–50% of the SOC content in the anaerobic core. Thus, an estimation of the SOC content in the ancient soil's Ap horizon is best based on that in the sods of the undecomposed organic matter of the anaerobic core. For determination of the SOC content in horizons below the Bronze Age plough layer, the unmodified measured SOC content in the Bwb and Cb horizons cannot be used because of partial decomposition since burial. An estimate can, however, be obtained if we assume that the ratio between the SOC concentration of the undecomposed anaerobic core and the SOC concentration in the partly decomposed Apb-horizon is a measure of the degree of decomposition in the whole of the buried soil below the lower iron pan. This ratio can be used as a correction factor in the estimation of the SOC concentration of the sandy Bronze Age soils, Bwb as well as Ap horizons (Table 2), giving estimates of *c*. 1.5% SOC in a 15 cm Apb and *c*. 0.7% SOC in the Bwb.

Carbon content in modern farmland soil

The Danish Soil Classification carried out in 1975–79 determined the C content in approximately 36 000 plough layers. The average SOC concentration of the well-drained plough layers with less than 10% clay was *c*. 2.0%, while for soils with 10–25% clay the SOC concentration was *c*. 1.7% (Madsen & Platou, 1983). The data indicate large regional variations. In regions with intensive cattle production, and consequently a high input of manure, the SOC concentration is larger than in arable regions dominated by crop production. Cattle production mainly takes place on sandy soils in Jutland, and this accounts for the higher SOC concentration in the sandy plough layers.

There are municipal scale data on manure application rates for 1989 (Statistics Denmark, 1990), the last year of the 3 years when profile data were compiled for the national orthogonal 7 km soil sampling grid. For our comparisons, we used data from: (i) 34 well-drained sandy sites on farmland in Ribe County in western Jutland, which is a region with high rates of manuring, corresponding to 96 kg N ha^{-1} and (ii) 18 well-drained sandy sites on farmland in Zealand, which is a region with low manuring rates, equivalent to 41 kg N ha^{-1} (Figure 1). The soils are all Arenosols or Podzols (IUSS Working Group WRB, 2007). The dominant land use in Ribe County is cattle and some pig production and the main crops are cereals, grass, fodder beets or maize, while in Zealand the dominant land use is crop or pig production and the main crops are cereals, rape, sugar beet and grass seed. The average SOC concentration in the plough layer in the three Bronze Age mounds is

Table 3 Means and standard deviations of SOC concentrations (%) and SOC stock (kg m^{-2}) for well-drained Bronze Age sandy soils and modern well-drained sandy arable soils. Number of samples in parentheses

	Bronze Age land use system	Present-day land use system, high manure input	Present-day land use system, low manure input
% C in Ap	1.57 ± 0.32 (3)	2.16 ± 0.56 (34)	1.42 ± 0.50 (18)
kg m^{-2} C in Ap	3.40 ± 1.00 (3)[a]	8.36 ± 1.94 (34)[b]	5.64 ± 1.75 (18)[b]
kg m^{-2} C in Ap + (Bw) 0–28 cm	5.03 ± 1.04 (3)	8.36 ± 1.94 (34)	5.64 ± 1.75 (18)

[a]0–15 cm.
[b]0–28 cm.

c. 70% of the average modern well-manured plough layer in Ribe County, but was larger than in the Zealand low-manured topsoils (Table 3).

SOC stock in Bronze Age soils and modern farmland soil

As well as SOC concentrations, estimation of SOC stocks requires information on the thickness of the plough layer and the bulk density. Below the three mounds, the thickness of the plough layers was approximately 15 cm, whereas the present-day plough layers on sandy soils in Jutland are 28.2 ± 5.5 cm ($n = 288$) and 28.7 ± 3.9 cm ($n = 23$) in Zealand. Values of bulk density in the modern topsoils are 1410 ± 120 kg m^{-3} ($n = 270$) and 1430 ± 130 kg m^{-3} ($n = 23$), respectively. Estimated SOC stocks (Table 3) show that the sandy plough layers from 3300 years ago hold less than half the amount of SOC compared with present-day plough layers with high inputs of manure. This results mainly from the thickness of the plough layer, which was only half as deep in the Bronze Age compared with the present-day plough layer. When depths to 28 cm are compared, the Bronze Age soils contained *c.* 60% of the amount of SOC found in the modern much-manured arable soils. In areas with low inputs of manure like Zealand, present-day SOC stocks were similar to those in the Bronze Age soil (Table 3).

Conclusion

This study demonstrates that wet anaerobic cores developed in burial mounds constructed of sods from fallow ground used for grazing about 3300 years ago offer possibilities to determine the SOC stock in an ancient land use system and to compare this with SOC stocks in modern agricultural land use systems.

The results show that the SOC in the anaerobic core was more than twice as much as that found in the aerobic buried Ap-horizon below. Therefore, a substantial amount of organic C has been decomposed, and we can conclude that a calculation of the SOC stock in ancient farmland systems based on measured values of buried aerobic Ap horizons is problematic and should be avoided.

A comparison of the soils in the ancient and modern land use systems shows that the thickness of the plough layer has almost doubled since the Bronze Age, and the SOC has increased significantly in the modern land use system with large inputs of manure compared with the ancient land use system, while it has remained at almost the same level in the modern land use system with low manure inputs. The net effect of these long-term trends is that modern intensive farming using animal manure as a major nutrient input to soils has resulted in a more than 60% increase in the SOC stock compared with the ancient land use system. In areas with low manure inputs and large inputs of inorganic fertilizers, the SOC stock has remained at almost the same level.

Our findings show that the impact of modern farming on the SOC/C sequestration compared with ancient land use systems is positive, especially for land use systems with high input of manure. We can therefore conclude that generalizations about the detrimental effects of modern farming with respect to SOC stocks are not universally valid, and that a change in land use system from low to high input of manure will give rise to C sequestration.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Photographs showing the soil profile development in the top of the burial mound Skelhøj. Below the incipient podzol the different sods in the aerobic mantle are pointed out

Appendix S2. Photograph showing a part of the aerobic mantle at Skelhøj. The sods are placed with the top downwards.

Appendix S3. The mantle, the upper iron pan, the upper aerobic core, the middle aerobic core and the top of the anaerobe lower core at Skelhøj. The aerobic core with gley has developed from the anaerobic core due to grave robbers' intrusions that fractured the iron pan leading to drainage of the upper part of the core.

Appendix S4. The lower part of the aerobic middle core, the anaerobic lower core, the lower iron pan and below the palaeosol from the Bronze Age.

Appendix S5. Flowers of *Calluna vulgaris*. Left: Two uncarbonized flowers of *Calluna vulgaris* from Skelhøj. Right: One modern flower. Photo: Sabine Karg and Jan Andreas Harild, NNU, see also Karg (2008).

Appendix S6. A 3300-year-old dung beetle found in the anaerobic core of Skelhøj. (1) Elytra from a 3300-year-old dung beetle. (2) Leg from a 3300-year-old dung beetle.

Appendix S7. Scanning electron micrographs of the thin upper iron pan in Skelhøj. The grey particles are quartz grains with white iron hydroxide cement making the iron pan impermeable to water. Bar = 1 mm.

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