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Legacy of medieval ridge and furrow cultivation on soil organic carbon distribution and stocks in forests

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ABSTRACT

Land management history can influence soil organic carbon (SOC) stocks over centuries. In this study, the impact of medieval ridge and furrow cropland management on SOC in forests was assessed. Continuous clockwise ploughing in rectangular fields moved topsoil from the outer part of strip-shaped fields towards the centre, thus forming a corrugated microtopography with peripheral furrows and central ridges. This tillage technique led to the burial of former topsoil under the ridges.

The effect of this human-created microtopography and the centuries old topsoil burial on forest SOC spatial distribution and stocks was investigated. Five sites with ridge and furrow field strips under deciduous forests on soils of differing texture in Germany were sampled, with three orthogonal transects of the field strips and a defined reference position where neither net soil removal nor accumulation occurred. Reforestation took place between the 17th and 19th century.

At 0 to 10 cm depth, average SOC content was 28 ± 3 g kg^{-1} at ridges, 37 ± 3 g kg^{-1} at reference positions and 47 ± 5 g kg^{-1} at furrows. SOC stocks were 7 ± 5% lower at ridges and 8 ± 4% higher at furrows than at reference positions. Enhanced C input at furrows through leaf litter accumulation was indicated by higher SOC content in the free light fraction at furrows (10 ± 5 g kg^{-1}) than at ridges (6 ± 3 g kg^{-1}), higher specific SOC mineralisation (37 ± 4 μg CO_2-C g^{-1} SOC at furrows and 31 ± 3 μg CO_2-C g^{-1} SOC at ridges) and wider C/N ratio at furrows (18 ± 1) compared with ridges (17 ± 1).

Buried topsoil under ridges (20 to 33–52 cm depth) did not contain significantly less SOC than corresponding samples at furrows and reference positions. However, SOC content was 0.4 to 0.9 g kg^{-1} higher at ridges than at reference positions, indicating long-term preservation of former topsoil SOC by burial under ridges, although enhanced SOC stocks at ridges due to carbon burial could not be significantly confirmed for all sites. It can be concluded that preserved microtopography over centuries and ancient topsoil burial, a legacy of medieval ridge and furrow cultivation, still influences forest SOC spatial distribution and stocks.

1. Introduction

Human activity has been modifying ecosystems since the Neolithic Age through land management and land use changes (Price, 2000). These have affected the global carbon (C) cycle through either C losses to the atmosphere or C sequestration in biomass and soils. In particular, soil C dynamics do not respond rapidly to land cover change, but C stocks and fluxes may display a long-lasting effect (Houghton et al., 2012; IPCC, 2013). Primary emissions of 63 Gt C have been estimated to result from anthropogenic disturbance of the natural land cover in preindustrial times until 1850 arising mainly from Europe, India and China (Pongratz et al., 2009). By late medieval times, 4.6 × 10^6 km^2 land world-wide, equivalent to 5% of the area potentially covered by vegetation, was under agricultural use (Pongratz et al., 2008) and atmospheric CO_2 exceeded its natural range of variation (Pongratz et al., 2009).

In Central and Western Europe, forest clearance for cultivation increased continuously between 1000 BCE and industrialisation in the 19th century, with two main interruptions after the decline of the Roman Empire in the 5th century and the Black Death in the 14th century (Kaplan et al., 2009). During these times, many villages and their associated agricultural land were abandoned and forest was able to re-establish (Abel, 1955).

Ridge and furrow cultivation was a widespread, possibly dominant, agricultural practice in Europe during the Middle Ages and continued

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up to the 19th century (Eyre, 1955; Frank, 1912; Hartmann, 1882; Mortensen, 1957; Trächsel, 1962). It consisted of ploughing a strip-shaped field clockwise using a simple mouldboard plough and draught animals. Through the repeated use of a ploughing pattern turning soil to the centre of the field (Epperlein, 1975), the topsoil towards the outer part of the field (furrows) was ploughed up and deposited towards the inner part of the field (ridges) (Fig. A.1). After some decades, a corrugated land surface was formed, with a furrow in the outer part of the rectangular field and a convex ridge in the inner part. In this way, topsoil was buried under the ridges. Ridges were sometimes built up by hand prior to cultivation. Between the ridge and furrow positions, several decimetres height difference were built up (Meibeyer, 1969). The possible benefits of this land use practice were many, including (i) higher fertility of the ridges through organic matter accumulation by topsoil depth enlargement, (ii) a drainage effect of the furrows in wet soils, (iii) improved water storage in sandy soils, (iv) incorporation of unweathered subsoil containing nutrient-rich minerals and (v) establishment of clear field borders, thus minimising loss of topsoil to neighbouring fields (Bartussek, 1982; Meibeyer, 1977). However, since ridge and furrow fields were established on all types of soils, irrespective of drainage conditions, the most likely reason for their establishment was as a risk management strategy that helped to ensure a certain level of yield in dry (enhanced yields in furrows) and wet (enhanced yields on ridges) years. Crop growth was concentrated on the ridges (Bartussek, 1982). The fields were mostly used according to the three-field system rotating winter cereals (wheat or rye), summer crops (barley, oats or peas) and fallow for grazing (Küster, 1995).

Ridge and furrow fields were mostly located in the vicinity of villages (Niemeier, 1967). If a village was abandoned, cultivation of the fields was often abandoned too and the ridge and furrow microtopography was preserved over centuries under the subsequently established forest (Sittler, 2004). Some ridge and furrow fields have also been preserved under grassland (Beeresford and St Joseph, 1979). However, at most agricultural sites the ridges were levelled off in the late 19th and early 20th century with the growing use of earthenware tiles as subsurface drains and of drainage channels, as well as technological advances allowing deeper ploughing and thus higher accumulation of organic matter (Bartussek, 1982). The ridge and furrow legacy is thus not only present in abandoned fields under forest and grassland, but also in modern arable fields. Fossil, C-enriched Ap horizons have been observed at ridge and furrow sites under forest, reflecting the former agricultural history of these sites (Meibeyer, 1969; Niemeier, 1967; Well, 1989). However, consequences of this land use history on soil organic carbon (SOC) stocks are completely unknown. The microtopography may have influenced the spatial distribution of SOC over time, for example via preferential accumulation of litter in the furrows or effective long-term SOC storage under the ridges.

With the development of ridge and furrow systems and the anthropogenic creation of microtopography, SOC-rich topsoil material was buried deeper than the recent forest Ah horizon. Carbon burial has been suggested as an effective measure to store additional SOC in subsoils on a long-term basis (Chaopricha and Marín-Spiotta, 2014; Hoffmann et al., 2013; Van Oost et al., 2012; VandenBygaart et al., 2015). Translocation of SOC to greater soil depth has been described as a promising SOC sequestration measure due to the low SOC contents in subsoils with high apparent SOC ages, their high content of unsaturated mineral surfaces and their consequently assumed high SOC storage capacity (Baldock and Skjemstad, 2000; Beare et al., 2014). Large-scale SOC storage through burial has been reported in depositional footslopes (VandenBygaart et al., 2015), volcanic deposits (Basile-Doelsch et al., 2005) and deep ploughed arable soils (Alcántara et al., 2016).

In this study we investigated the legacy of medieval ridge and furrow cultivation on the forests that now occupy these sites, including the effects of topsoil burial and the impact of the microtopography on SOC. The following questions were addressed:

1.) Does ridge and furrow microtopography lead to preferential litter input into furrows, and thus shape the distribution of recent SOC stocks under forest?
2.) Does topsoil burial under ridges result in higher SOC stocks compared with reference positions caused by high stability of the buried SOC?

2. Materials and methods

2.1. Selection of study sites and soil sampling

Five forest sites with a documented and approximately dated ridge and furrow land use history were selected for sampling. All sampled ridge and furrow fields were associated with former villages that were deserted between the 13th and 16th century. We searched in particular for the most suitable sites with respect to historical documentation, as much time as possible since abandonment, a high degree of conservation of the ridge and furrow systems and a relief height difference of at least 30 cm between ridge and furrow. A soil texture range from loamy sand to silty loam was covered (Table 1). The five sites were located in northern and central Germany.

Sampling design was based on the ridge and furrow description according to Meibeyer, 1969. The highest position within the undulating rectangular field strip was identified as the ridge and the lowest as the furrow (Fig. 1). At a certain position within the transverse profile of the rectangular field strips, the elevation of the soil surface remained unchanged and neither net topsoil excavation nor net accumulation took place (Fig. A.1). This was taken as the reference position and was assumed to be located at 57% of the distance between ridge and furrow, based on the shape of ridge and furrow systems documented by Meibeyer (1969). He determined a reference position on the original land surface as the position at which the soil mass (measured as drawn area of a ridge and furrow profile) lacking at the furrow was equal to that accumulated at the ridge. Sampling at each site comprised two ridges, two furrows and four reference positions. In addition, a position between ridge and reference (middle 1, Fig. 1) and a position between reference and furrow (middle 2, Fig. 1) were sampled.

Samples were collected to 100 cm depth at the ridge positions and the equivalent depth at the middle 1, reference, middle 2 and furrow positions.

Ploughing depth was assumed to be a maximum of 20 cm (Meibeyer, 1969). The deepest limit of the buried topsoil under the ridges was marked in the field by fixing of a string at two reference positions to each side of the ridge, at 20 cm depth, in order to obtain a straight line parallel to the original surface and marking the maximum depth of initial ploughing. At the ridge position, the depth increment between 20 cm and the string was taken as the buried topsoil (increment 3), which was sometimes >20 cm because its thickness depended not only on the maximum ploughing depth but also on the amount of accumulated soil at the ridge. The following depth increments were thus sampled (Fig. 1): (1) recent Ah horizon developed under forest within the former plough layer (0 to 10 cm), (2) last active ploughed layer down to maximum ploughing depth (10 to 20 cm), (3) buried topsoil as relictic Ap horizon (ridge and middle 1: 20 to 33–52 cm depth), (4) non-tilled subsoil with equivalent depth of buried topsoil horizon at ridge (ridge and middle 1: 33–52 to 46–84 cm depth, reference, middle 2 and furrow: 20 to 33–52 cm depth) and (5) down to 100 cm at ridges. At the Eddessen site, the last 20 cm (80 to 100 cm) were sampled separately because a pedogenic horizon with stagnic properties and high clay content was identified.

Soil cores with a fixed volume were retrieved from three parallel transects 15 m apart, which were set orthogonal to the ridge direction. A soil coring probe with 60 mm inner diameter, driven by an electric jackhammer (Wacker EH 23, Wacker Neuson, Munich Germany), was used for sampling, as recommended by Walter et al. (2016). Each transect comprised two ridges, four middle 1 positions, four reference positions, four middle 2 positions and two furrows. Thus, a total of 16 soil