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Humus-rich topsoils in SW Norway – Molecular and isotopic signatures of soil organic matter as indicators for anthropo-pedogenesis

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ABSTRACT

Some previous studies showed that the formation of several deep dark humus-rich topsoils in Northern Europe was strongly influenced by the application of different organic materials by anthropogenic activities in former times. Such topsoils classified as plaggic Anthrosols also occurred in the Jæren region in SW Norway. However, source material and formation time of these Plaggic Anthrosols have not yet been clarified. Close to this region we found further humus-rich topsoils in the Karmøy municipality (2 sites at main island of Karmøy and 1 site at Feøy). These soils show a thick humus-rich topsoil up to 30 cm, and their formation cannot only be explained by natural conditions. We analyzed the molecular signature of the soil organic matter (SOM) by benzene polycarboxylic acids (BPCA), non-targeted bulk SOM mass spectrometry, $\delta^{34}S$ and ^{14}C AMS dating in order to determine source materials and the age of the SOM. The black carbon (BC) contents of the plaggic soils in Jæren (mean 3.4 g kg^{-1}) deliver clear evidence for inputs of combustion residues from ancient fire management and/or from settlements. The C-XANES and Py-FIMS-spectra reveal relative enrichments of aromatic C and heterocyclic N compounds in the plaggic soils corresponding to the BC contents. In contrast, the humus-rich topsoils in Karmøy seem to be unaffected by fire management due to the low BC contents (mean 0.6 g kg^{-1}) and the relative low portions of aromatic C and heterocyclic N compounds from C-XANES and Py-FIMS. The $\delta^{34}S$ isotope signature of the SOM ranged from 10.6 to 15.2‰ in the soils at the islands and 10.0 to 13.5‰ in Jæren, corresponding to the Anthrosols in the Baltic Sea region (Median: $\delta^{34}S$ = 11.5‰) and suggest an input of marine biomass ($\delta^{34}S$ of seaweed = 20‰). The AMS ^{14}C dating and complementary archaeological literature implied that the soils in Jæren and Karmøy have been formed between the Roman Iron Age (500 BC to AD 500) and the Viking Age (AD 800 to AD 1,000). Our results provide strong evidence for an anthropo-pedogenesis of the humus-rich topsoils in Karmøy and indicate parallels to the plaggic soils in Jæren as well as to Anthrosols in the Baltic Sea region. Therefore, we propose to classify the humus-rich topsoils in Karmøy as Anthrosols.

1. Introduction

Recent investigations show that development of humus-rich topsoils around the Baltic Sea were strongly influenced by the application of different organic materials (e.g. animal manure, ashes, turf, organic waste) and, thus, soils were classified as Anthrosols (Acksel et al., 2017). Humus-rich topsoils were also found in Southwest Norway and classified as Plaggic Anthrosols (Schnepel et al., 2014). The high P contents of these soils (up to 2,924.3 mg kg^{-1}) and archaeological data (Kvamme, 1982; Myhre, 1985; Opedal, 1994; Sølvberg, 1976) indicate a strong anthropogenic influence in the Viking Age, which points to a fundament soil amendment practiced earlier than those forming most Plaggic Anthrosols in Northwest Germany (Schnepel et al., 2014). The anthropogenic character of these soils corresponds to various authors who reported that different materials such as ashes, turf, organic waste and mineral soil material were used for soil amendment in Norway

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(Kvamme, 1982; Myhre, 2000; Rønneseth, 1974; Sølvberg, 1976). A combination of different materials – consisting of a wide range of possible inputs e.g. seaweed, sea sand and turfs after usage for bedding cattle – formed up to 75 cm deep humus-rich topsoils at the Orkneys (Scotland) (Davidson and Simpson, 1984). The soil organic matter (SOM) source, recent SOM quality and the soil age (by ^{14}C AMS dating) of the Norwegian Plaggic Anthrosols have not yet been clarified. Furthermore, we recently found other humus-rich topsoils in the Karmøy municipality on the islands of Karmøy and Feøy, located slightly northwest of Jæren. These soils show thick humus-rich topsoils up to 30 cm and their formation cannot be explained by natural conditions. Therefore, the question arises if the formation of the humus-rich topsoils in Karmøy also has been formed by earlier agricultural practice, e.g. plaggen management, such as the plaggic soils in Jæren.

Indicators for anthropogenic influence are high contents of soil organic matter (SOM) and phosphorus (P). Additionally, high contents of black carbon (BC) often characterize soils originating from human activity. These mainly condensed aromatic structures generally originate from biomass combustion (Kleber et al., 2003; Rodionov et al., 2006; Schmidt et al., 1999). Thus, the BC in the soil can originate from the incomplete combustion of fossil fuels (e.g. coal, oil) and/or from vegetation fires (Brodowski et al., 2007; Goldberg, 1985). For example, Acksel et al. (2016, 2017) identified large contents aromatic compounds by the determination of benzene polycarboxylic acids (BPCA), by pyrolysis-field ionization mass spectrometry (Py-FIMS) and synchrotron based X-ray absorption near-edge fine structure (XANES) spectroscopy at the carbon (C) and nitrogen (N) *K*-edges (C- and N-XANES). These were relatively enriched in the characteristic biogenically mixed "hortic" horizons of the Anthrosols in the Baltic region (18% BC of C_{org}). Acksel et al. (2016, 2017) hypothesized that BC-enrichments in these soils resulted from human activities like slash and burn or the disposal of settlement residues, because natural fires were relatively rare in Central Europe in contrast to typical steppe landscapes (Tinner et al., 1999). Humus-rich soils in SW Norway have not yet been characterized by the above methods.

Another possibility to trace the source of SOM is to measure the stable isotope composition, because the isotope distribution pattern of soils differ in natural systems (Schoenau and Bettany, 1989), mainly affected by vegetation (Freney and Williams, 1983; Krouse et al., 1991). For example, S isotope ratios in native and cultivated Chernozems in Canada reflected the $\delta^{34}S$ abundance of their predominant vegetation, grasses, herbs and field crops (Schoenau and Bettany, 1989). Acksel et al. (2017) detected high $\delta^{34}S$-values in deeper-lying horizons of Anthrosols on various islands in the Baltic Sea region (+13.5‰), corresponding to high $\delta^{34}S$-values in seaweed (+20‰). This suggested that seaweed was incorporated into the soils by humans because any direct marine influence (precipitation and sea spray) could be excluded. Therefore, it is possible that marine biomass was used as soil amendment in a wide range of coastal regions in Northern Europe which is assumed, e.g., in Norway for plaggen management (Austad et al., 2001; Sølvberg, 1976).

Besides the investigation of the SOM source the determination of soil age is another important issue. An indication for an ancient agricultural land use in Norway is the heathland expansion between 4,000 BC to AD 200 as a result of deforestation by human fire management (Prøsch-Danielsen and Simonsen, 2000). However, other authors reported that the described soil amendments were applied later from AD 400 to AD 600 (Kvamme, 1982; Myhre, 1985; Sølvberg, 1976). Therefore, it can be assumed that the soils at Karmøy and Feøy were also influenced by manuring practices at this time. However, archaeological artifacts have not been found in these soils and, thus, the time of formation could not be estimated in that way. A possibility for determining a maximum age of soils is the AMS ^{14}C dating of the humin fraction (Pessenda et al., 2001; Scharpenseel et al., 1986). The humin fraction can reveal an approximated maximum age of SOM due to removal of any recent organic materials with fulvic and humic acids. AMS ^{14}C datings of soils showed that the humin fraction was older by factor 1.2 to 1.7 than the corresponding age of the bulk SOM (Pessenda et al., 2001; Scharpenseel et al., 1986). The ^{14}C dating of the humin fraction of Baltic Anthrosols yielded ages that were about 500 years older than the bulk SOM (Acksel et al., 2017). The ^{14}C ages, and, thus, time periods of SOM formation in the humus-rich topsoils at Karmøy and Feøy and of the Plaggic Anthrosols at in Jæren are not known.

The diversity of organic material applied and indications of rather early amelioration practices (Kvamme, 1982; Myhre, 2000; Rønneseth, 1974; Sølvberg, 1976) make Norway and especially SW Norway an interesting area to study Anthrosols. However,

Anthrosols in SW Norway have been studied to a limited degree compared to the Baltic Anthrosols. To our knowledge only Schnepel et al. (2014) have published data from Anthrosols in this region. Therefore, the present study further analyzes samples from Jæren (SW Norway) collected by Schnepel et al. (2014) and additional samples collected from humus-rich topsoils at the islands of Karmøy and Feøy in Karmøy municipality (SW Norway).

The objectives of the present study were (i) to examine the SOM sources of the soils at Karmøy, Feøy and in Jæren by qualitative and quantitative BC analyses, non-targeted bulk SOM mass spectrometry and sulphur isotopic measurements, (ii) to estimate the age of SOM by AMS ^{14}C dating in order to find out evidence for an anthropogenic influence on the soil formation at Karmøy and Feøy, and (iii) to propose the consequences for soil classification according to the WRB system (IUSS Working Group WRB, 2014).

2. Materials and methods

2.1. Study areas and soil sampling

Soil samples were collected at the islands of Karmøy (59°15′N, 5°15′E, 178 m^2) and Feøy (59°23′N, 5°9′E, 1.3 km^2) in Rogaland County in South West Norway (Fig. 1). Both islands are located north of the city of Stavanger and lie in an area with maritime climate. For the 1961–1990 normal, the mean annual temperature was 7.4 °C and the mean annual precipitation 1,180 mm (Sola observation station, close to Stavanger airport; Norwegian Meteorological Institute). Highest temperatures occur in August (14.4 °C) and lowest in February (0.6 °C).

The underlying bedrock of the islands is Caledonian nappe rocks (Roffeis and Corfu, 2014), consisting dominantly of gabbro and diorites (Norges Geologiske Undersøkelse, 2017). Areas mainly along the western coast in the southern part of Karmøy are covered with marine sediments while other parts of the island are covered with till (Norges Geologiske Undersøkelse, 2017). Investigations revealed that the uppermost layer of the glacigenic material consists of clayey till from the Late Weichselian glaciation (younger than 25 ka) (Andersen et al., 1981, 1983). The southern part of the island of Karmøy became ice free before 16 ka (Gump et al., 2017).

Karmøy and the areas around have a long land use history. First settlements are from the Paleolithic (12,000–5,500 uncal. BP) and, although there are no archaeological findings of the first agriculturalists, it can be assumed that agricultural practices were carried out since about 5500 uncal. BP (Hernæs, 1997). Karmøy and Feøy belong to the agricultural region 'Coast from South Norway to Nordland [county in North Norway]' (Puschmann et al., 2004). This very diverse agricultural region is dominated by grasslands used for livestock fodder production (Puschmann et al., 2004). Currently, about 25% of the municipality of Karmøy (including Feøy) is classified as agricultural land, and about 17% of the area is classified as forests and about 5% as wetlands (Statistics Norway, 2017).

The samples of the humus-rich topsoils were collected from profiles at Sandhåland (S) and at Hillesland (Hi) at the island of Karmøy and at the island of Feøy (F). From each profile samples were taken from the upper (0–30 cm) and the underlying (30–45 cm) horizons. The German soil description system (Ad-hoc-AG Boden, 2005) has been used to