Impact of the spatial resolution of soils data on climate reporting for organic soils using the example of Germany

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SUMMARY

As a result of the climate conferences in Durban (2011) and Doha (2012), voluntary accounting for greenhouse gas emissions from organic soils is now possible in national climate reporting. The quality of the data describing the spatial extent of organic soils and their relevant soil properties thus becomes particularly important. For climate reporting issues, maps for organic soils at different scales and levels of detail are used. In Germany, for example, the soil map at scale 1:1,000,000 is the basis for the emission inventory (NIR 2013). In contrast, the national inventory report of The Netherlands is based on a soil map at scale 1:50,000 (Coenen *et al*. 2013). This leads to questions about the optimal level of detail or scale for climate reporting.

Datasets with scales ranging from 1:25,000 up to 1:1,000,000 were used to derive the spatial distribution of organic soils in two characteristic areas of the temperate zone, one in northern and one in southern Germany. Comparison of the results shows large differences in both areal and spatial accuracy, depending on the origin and quality of the data as well as on scale and landscape characteristics. In southern Germany, for example, only 50 % of the organic soils derived from smaller-scale maps can be verified by detailed data, in contrast to more than 70 % in northern Germany. In combination with the partially poor spatial accuracy, these differences have a strong impact on the calculation of greenhouse gas emissions from organic soils, leading to errors of more than 60 %.

As a result, for the temperate zone we recommend a minimum scale of 1:200,000 for maps of organic soils. However, in mountainous regions with higher geomorphic heterogeneity, more detailed data may be necessary.

KEY WORDS: GIS; greenhouse gas; scale; soil maps; temperate zone

INTRODUCTION

Even though the long-term effects of greenhouse gas emissions will be felt globally, the ongoing worldwide debate on this topic is strongly influenced by national interests and this affects prospects for achieving an objective and widely accepted knowledge base. This observation is especially pertinent for organic soils, as the processes in these are more complex and of higher uncertainty than, for example, the processes underlying emissions from industry or road traffic. It applies to both the spatial distribution of organic soils and land use specific emission factors.

According to the IPCC (2006) Guidelines, organic soils are characterised by an organic carbon content of more than 12 % in the uppermost horizon, up to a depth of 20 cm. This is not completely congruent with German classification schemes, which usually require a thickness of more than 30 cm and an organic carbon content of more than 15 %.

In their natural state, sites with organic soils are carbon sinks, mainly due to high water supply. Dead material from specialised plants like mosses, sedges and reed is incompletely decomposed and accumulates *in situ*, resulting in high soil carbon content. Worldwide estimates of organic carbon stored in soils range from 1,115 to 2,200 Pg (petagram = 10^{15} grams) carbon (Batjes 1992, Eswaran *et al*. 1993). Referring to organic soils alone, estimates range from 330 to 550 Pg (Gorham 1995, Batjes 1996). These carbon deposits are in danger of being partly released primarily by changes in the water balance. When they are subjected to drainage, often accompanied by the application of fertilisers, the microbial degradation of organic material and the release of greenhouse gases like CO_2 and N_2O re-starts, and the former carbon sink changes into a carbon source (Kalbitz *et al*. 2001, Blodau & Moore 2003, Drösler 2005).

The carbon release rate depends strongly on the type and intensity of land use. The release of CO_2 due to tillage of fens, for example, is 41.1 t ha^{-1} and more than double that from fens which are used as meadows, where CO_2 emissions are approximately 15–17 t ha^{-1} (Oleszczuk *et al*. 2008). Therefore, a reliable estimate of greenhouse gas emissions from organic soils must take land use information into account. This implicitly requires similarly accurate information on the extent of organic soils, because the areas under different land uses may otherwise be miscalculated. In contrast to soils data, land use information is, in most cases, available at large scales.

One action of the 2011 Durban climate conference (United Nations Climate Change Conference COP17/CMP17) was to enable voluntary accounting for emissions from organic soils in national climate reporting. In Germany, data about the spatial distribution of these soils is spread over a multitude of surveys and data sources that differ greatly in scale and thematic content (Behrens & Scholten 2006). Some of them are geologically oriented while others are focused on pedological, agricultural or forestry interests.

In contrast to many mineral soils, the spatial extent of organic soils can be delineated rather sharply on the ground. Organic soils are composed of characteristic substrates such as peat, and they often follow geomorphic or hydromorphic features like depressions, slope toes or stream networks. This strong relationship with topographical elements suggests that organic soils could be delineated with sufficient accuracy for climate reporting, even in small-scale data.

Climate reporting for organic soils in Germany has been based hitherto on the soil map at scale 1:1,000,000 (NIR 2013). This dataset is also part of the European Soil Database, which was used to describe the distribution of peatland within Europe by Montanarella *et al*. (2006). More detailed data were used in, for example, Ireland and The Netherlands. A map of peatlands in Ireland was derived from soil and peatland maps with scales ranging from 1:127,560 to 1:575,000 (Connolly *et al*. 2007). In The Netherlands, a map of organic soils was compiled using, mainly, the soil map of The Netherlands at scale 1:50,000 and recent soil monitoring data (Kuikman *et al*. 2003).

Generally, the impact of scale in digital soil mapping is well known (McMaster & Shea 1992, Goodchild 2011). Depending on the initial purpose of the underlying survey, the information is subject to generalisation and aggregation during the map-making process. Geometry-based generalisation often leads to over-estimation of large units because small structures tend to be eliminated (Rapalee *et al*. 1998). Because organic soils in the temperate zone often occur in relatively small patches, they are highly vulnerable to the elimination process. This leads to possible under-estimation of the extent of organic soils, especially in smaller-scale maps. Aggregation is another relevant procedure in map making. In our case it involves the combination of similar soil types into higher soil classes. It is always accompanied by a loss of information. In the case of organic soils, aggregation may be of particular importance for non-peat soils with high carbon content. These soils are possibly in danger of being absorbed into map units with mineral soils, even if they cover large areas.

Few working groups have analysed scale-dependent effects in the process of delineating organic soils and their properties. The impact of generalisation on soil maps is confirmed by Zhao *et al*. (2006). The areal fraction of bog soils in their test area decreased from 0.55 % at scale 1:500,000 to 0.46 % at 1:1,000,000 and 0.44 % at 1:2,500,000. Davidson & Lefebrve (1993) calculated the soil organic carbon for a test area in Maine, in the north-eastern United States. Unlike Zhao *et al*. (2006), they found that the apparent extent of Histosols was 21 % higher when derived from soils data at scale 1:250,000 than when it was calculated from a more detailed dataset at scale 1: 20,000.

The aim of the work reported in this article was to compare the accuracy and completeness of different datasets that delineate organic soils in Germany, and thus to demonstrate how the choice of data source would impact on estimates of greenhouse gas emissions attributable to agricultural and forestry land use. To achieve this, parts of the datasets were compared using GIS techniques.

METHODS

Two large test areas were available, one in the north-east and the other in the south-west of Germany (Figure 1). To evaluate differences in the delineation of organic soils within these test areas, available national pedological and geological datasets were compared with detailed reference data from the Map of Organic Soils (MOS). The MOS is a synthesis of differently detailed geodata (Table 1) and a site-specific pedological characterisation based mainly on geomorphology and hydrology. It is being developed in the context of climate reporting issues as part of the Joint Research Project "Organic Soils" (funded by the Thünen-Institut), and will eventually cover the whole of Germany.

The national datasets used were the Soil Map of Germany SM1000 (BGR 2013) and the Geological

Map of Germany GM1000 (BGR 1993), both at scale 1:1,000,000; and the Soil Map of Germany SM200 (BGR 2000–2011) and the Geological Map of Germany GM200 (BGR 1983–2003), both at scale 1:200,000. These were compared with the MOS as well as with highly precise land use information derived from ATKIS (Authoritative Topographic-Cartographic Information System) (AdV 2005). Because our focus was on the quality of data for soils, other sources of land use data were not considered, even though they might lead to different results (Trepel 2007).

Figure 1. The test areas in Germany: Mecklenburg-Vorpommern (MV) in the north-east and Baden-Württemberg (BW) in the south-west.

Scale-dependent analyses were conducted in GIS for the two large test regions (Figure 1), within which a range of typical geomorphological conditions are represented.

The north-eastern test area covers the entire Federal State of Mecklenburg-Vorpommern and extends to 23,200 km². It is mainly composed of sediments from the late Weichselian glacial. The typical pattern of geomorphic structures such as ground moraines, terminal moraines, aprons and glacially initiated stream networks can be found. Large areas with organic soils appear mostly in valley situations or in coastal lowlands. A multitude of relatively small organic soil patches are bound to lakeshores or local depressions with relatively high groundwater levels. The climate is characterised by a transition from oceanic climate in the north and west to more continental climate in the south-east. The average annual precipitation ranges from 700 mm in coastal areas to 500 mm farther inland (Hurtig 1957).

The second test area covers the Federal State of Baden-Württemberg, with an area of 35,750 km². The landscape diversity is much higher than for the north-eastern test area. The western part of Baden-Württemberg is dominated by the sediment-filled initial rift valley of the Rhine. To the east of this rift valley lie the mountain ranges of the Black Forest (up to 1,500 m) and the Odenwald (up to 600 m),

Table 1. Main input data for the Map of Organic Soils (MOS) for the two test areas. ATKIS: Authoritative Topographic-Cartographic Information System.

north-eastern test area	south-western test area
Geological Map of Prussia, 1:25,000	Soil Map, 1:25,000
Conceptual Soil Map of the local soil survey, 1:25,000	Soil Map, 1:50,000
Agricultural soil maps (Bodenschätzung) for quality assurance issues	Agricultural soil maps (Bodenschätzung), ~1:10,000
Digital Terrain Model, 25 m × 25 m grid	Digital Terrain Model, 25 m × 25 m grid
Hydrology (rivers and lakes) from ATKIS data	Hydrology (rivers and lakes) from ATKIS data
	Forest soil maps (Forstliche Standortkartierung), ~1:10,000
	Mire inventory (Moorkataster)

which are composed mainly of silicate rocks. Farther east there is the Swabian Alb with its limestones. The foothills of the Alps in the south are composed of glacial sediments. The majority of sites with organic soils are situated in the foothills of the Alps and in the valleys of large rivers like the Danube and the Rhine. Bogs can be found in the Black Forest region. Annual precipitation in the mountain regions is up to 1,000 mm, and much higher than in the lowlands (600–700 mm). The average annual temperature ranges from 4 °C to 10 °C, depending mainly on altitude. Temperatures in the lowlands, at least, are significantly higher than in the northern parts of Germany (Rosner 2008, Eberle *et al*. 2010).

From all available source data, those datasets with relatively sharp delineation of organic soils were selected. Simplified, organic soils have to meet the criterion of more than 12 % organic carbon in a mixed sample taken from the uppermost 20 cm of the soil profile (IPCC 2006). With respect to the German soil classification (AG Boden 2005), non-peat organic soils with a carbon content of 9–15 % in the upper layer were included as well.

In the case of the SM1000 we extracted all datasets describing fens and bogs. Soils with less organic carbon that are still considered to be organic soils according to the IPCC definitions are included in other soil classes and, therefore, are not spatially extractable. The SM200 is more detailed and supports the extraction of non-peat organic soils as well. The GM1000 distinguishes bogs, fens and non-peat organic soils. The GM200 follows the same taxonomy as the GM1000.

To verify the chosen soil classes, ground verification with respect to organic carbon content was carried out. Results from the north-eastern test area show that approximately 50 % of the non-peat organic soils still have 9 % or more organic carbon in the upper soil and fulfil the requirements of the adapted definitions for greenhouse gas reporting for organic soils in Germany, despite the partly old data (Table 2).

All data were pre-processed using GIS techniques, then intersected with the MOS and ATKIS land use data. Descriptive statistics were calculated, and spatial analyses were carried out in GIS.

RESULTS

According to the MOS, 328,696 ha of the north-eastern test area are covered by organic soils. This equates to 14 % of the total area, of which 85 % is peatland and 15 % non-peat organic soils (Table 3).

Table 2. Ground verification results: carbon content (%) in a mixed sample taken from the uppermost 20 cm. CV = coefficient of variation (%); n is the number of sampled sites.

site characteristic	mean	avg.	min.	max.	CV	n
non-peat organic soil	9.0	11.7	1.2	40.2	79.7	29
shallow fen	22.0	21.4	1.3	43.2	58.1	44

Table 3. Areas of bog, fen and non-peat organic soil in the north-eastern test area, from different sources.

site characteristic	MOS ha	SM1000 ha	SM200 ha	GM1000 ha	GM200 ha
bog	5,389	-	4,811	3,631	3,851
fen	274,144	361,373	232,492	217,903	249,554
non-peat organic soil	49,163	-	400,0	-	34,729
total	328,696	361,373	237,703	221,534	288,134

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000.

Comparing the total areas of organic soils in the north-eastern test area shows that the small-scale pedological map SM1000 over-estimates the area covered by organic soils by 10 % whereas the geological map GM1000 under-estimates this statistic by 32.6 %. In contrast, the medium-scale pedological map SM200 under-estimates the occurrence of organic soils by 27.7 % and the GM200 by 12.3 %. Even though this comparison shows huge differences in the total areas of organic soils, it is of limited value because it ignores the question of spatial accuracy (Figure 2).

Therefore, all data sources were intersected with the more detailed MOS. Only 40 % of the SM1000 organic soils can be confirmed by the MOS, showing that 60 % are not organic soils at all. A clearly higher spatial accuracy is achieved by the SM200 and the GM200, with more than 70 % agreement. The GM200 is more complete, with an intersection of 207,155 ha (Table 4).

Taking detailed land use data derived from ATKIS into account, it is obvious that a decreasing spatial accuracy of soils data leads to an over-estimation of arable land use on organic soils. According to the MOS, the proportion of arable land on these soils is about 10 %, and this is three times over-estimated using the SM1000 (Table 5).

According to the MOS, 52,077 ha (1.5 %) of the south-western test area is covered by organic soils, of which 74 % are peatland and 26 % non-peat organic soils. The small-scale pedological map SM1000 under-estimates the extent of organic soils by approximately 70 % whereas the GM1000 under-estimates it by just 14 %. The medium-scale SM200 over-estimates the fraction of organic soils by 20 %, whereas the area of organic soils in the geological map GM200 is almost identical to that in the MOS (Table 6).

The GIS-based intersection with the MOS again clarifies aspects of spatial accuracy. Only 52 % of the organic soils delineated in the GM200 can be verified by the MOS. For the SM200, SM1000 and GM1000, similar results are achieved (Table 7).

Taking land use into account, the direct link between scale and spatial accuracy is evident. The fraction of arable land increases in proportion to scale and spatial error. The SM1000, for example, over-estimates the proportion of arable land by three times (Table 8) and also under-estimates the total area of organic soils by a factor of three.

An example calculation of greenhouse gas emissions (C-equivalents) based on emission factors according to Höper (2007) illustrates the huge impact of soil data quality (Table 9).

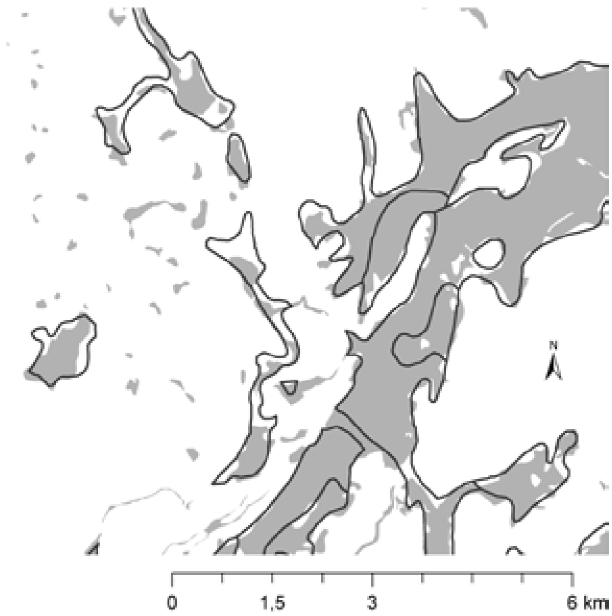

Figure 2. Overlay of MOS and GM200 (MOS: grey fill; GM200: black boundary).

Table 4. Intersection of organic soil inventories and the MOS in the north-eastern test area.

site characteristic	SM1000	SM200	GM1000	GM200
total area of organic soils	361,373 ha	237,703 ha	221,534 ha	288,134 ha
organic soils congruent with the MOS	145,956 ha 40.4 %	174,012 ha 73.2 %	130,289 ha 58.8 %	207,155 ha 71.9 %
organic soils not congruent with the MOS	215,417 ha 59.6 %	63,691 ha 26.8 %	91,245 ha 41.2 %	80,979 ha 28.1 %

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000.

Table 5. Land use (ATKIS data) on organic soils in the north-eastern test area.

data	arable land %	grassland %	forest %	unused %	rest %
MOS	9.8	58.6	18.5	9.8	3.1
SM1000	29.7	38.0	19.3	5.3	7.7
SM200	10.5	58.2	17.3	9.9	4.2
GM1000	18.4	49.7	16.1	7.4	8.5
GM200	13.0	55.9	18.0	8.4	4.7

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000; ATKIS: Authoritative Topographic-Cartographic Information System.

Table 6. Areas of bog, fen and non-peat organic soil in the south-western test area, from different sources.

site characteristic	MOS ha	SM1000 ha	SM200 ha	GM1000 ha	GM200 ha
bog	4,145	4,176	2,551	2,356	3,237
fen	34,423	11,506	45,935	42,277	35,981
non-peat organic soil	13,509	-	14,688	-	12,825
total	52,077	15,682	63,174	44,633	52,043

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000.

Table 7. Intersection of organic soil inventories and the MOS in the south-western test area.

site characteristic	SM1000	SM200	GM1000	GM200
total area of organic soils	15,682 ha	63,174 ha	44,633 ha	52,043 ha
organic soils congruent with the MOS	7,888 ha 50.3 %	34,759 ha 55.0 %	20,805 ha 46.6 %	27,002 ha 51.9 %
organic soils not congruent with the MOS	7,794 ha 49.7 %	28,415 ha 45.0 %	23,828 ha 53.4 %	25,041 ha 48.1 %

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000.

Table 8. Land use (ATKIS data) on organic soils in the south western test area.

data	arable land %	grassland %	forest %	unused %	rest %
MOS	9.7	40.1	26.5	20.9	2.6
SM1000	26.5	24.4	9.5	29.6	10.2
SM200	14.1	37.2	21.6	18.3	8.9
GM1000	21.2	34.2	17.8	16.3	10.6
GM200	16.9	35.7	19.7	17.9	9.6

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000; ATKIS: Authoritative Topographic-Cartographic Information System.

Table 9. Land use specific greenhouse gas emissions* for fen soils in the two test areas, derived using ATKIS land use data.

site characteristic	north-eastern test area kg C-equ.$a^{-1}ha^{-1}$			south-western test area kg C-equ.$a^{-1}ha^{-1}$		
	MOS	SM1000	GM200	MOS	SM1000	SM200
arable land	273,060	1,267,755	345,401	29,168	43,800	57,179
grassland	933,127	770,700	806,082	83,680	16,017	108,394
forest	228,131	330,962	201,563	39,529	5,477	44,133
unused	23,041	33,427	20,358	3,992	553	4,457
total	1,457,359	2,402,844	1,373,404	156,370	65,847	214,163

MOS: new Map of Organic Soils; SM1000: Soil Map at scale 1:1,000,000; SM200: Soil Map at scale 1:200,000; GM1000: Geological Map at scale 1:1,000,000; GM200: Geological Map at scale 1:200,000; ATKIS: Authoritative Topographic-Cartographic Information System.

*****Emission factors for German peatlands according to Höper (2007): fen/arable land = 11,809 kg C-equ. a^{-1} ha^{-1}; fen/grassland = 5,618 kg C-equ a^{-1} ha^{-1}; fen/forest = 4,746 kg C-equ. a^{-1} ha^{-1}; fen/unused = 101 kg C-equ. a^{-1} ha^{-1}.

According to the MOS, the total greenhouse gas emissions of the northern test area accumulate to an annual sum of 1,457,359 t CO_2 equivalents. Calculations based on the GM200 under-estimate the emissions by a mere 5.8 % whereas calculations based on the SM1000 over-estimate the emissions by 65 %.

Different results are achieved for the southern test area. Compared to the MOS, the SM200 over-estimates the emissions by 37 % whereas calculations based on the SM1000 under-estimate the emissions by 58 %.

DISCUSSION

The small-scale SM1000 and GM1000 seem to be of limited value for the objective of deducing a complete and spatially accurate database for the organic soils. The medium-scale SM200 and GM200 are clearly better. As geological data lacks information on pedological processes, the degree of aggregation is lower than in pedological data and maps. This partly explains the higher proportion of non-peat organic soils in the GM200, as well as its substantial intersection with the MOS. In pedological data, soils with less than 15 % organic carbon are in danger of becoming part of mineral soils classes. Additionally, the MOS for the northern test area is mainly composed of large-scale geological data, and perhaps for this reason exhibits a greater intersection with geological data.

The *ex ante* hypothesis that, due to their specific type of genesis, organic soils can be delineated with sufficient accuracy even on the basis of medium- and small-scale maps is not generally confirmed by our analyses. Over- and under-estimations can be observed in both test areas, but the medium- and small-scale data for the north-eastern area deliver clearly better results than those for the south-western test area. Differences in landscape diversity may be a key factor here. The widespread organic soils of the north-eastern test area, with its relatively homogeneous glacial landscape, are in less danger of being merged with mineral soils in the course of map aggregation than the organic soils of the diverse landscape of south-west Germany. Thus, depending on the specific landscape, even medium-scale geodata may be suitable for deriving an inventory of organic soils.

The results obtained here demonstrate the need for detailed soils data to establish reliable inventories of organic soils. Small-scale data, regardless of whether they are pedological or geological, are inadequate for climate change reporting. Furthermore, it could be shown that, in addition to scale, aspects of landscape diversity have a great impact on the suitability of geodata. For homogeneous landscapes with widespread organic soils, medium-scale (1:200,000) geological or pedological data may be sufficiently accurate for climate reporting purposes. For diverse landscapes however, large-scale data are essential.

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