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Estimating vulnerability of agriculturally used peatlands in north-east Germany to carbon loss based on multi-temporal subsidence data analysis

Holger Fell *, Niko Roßkopf, Albrecht Bauriegel, Jutta Zeitz

Faculty of Life Science, Institute of Agriculture and Horticulture, Division of Soil Science and Site Science, Humboldt-Universität zu Berlin, 14195 Berlin, Germany

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ABSTRACT

Agriculturally used peatlands are prone to carbon loss and soil degradation. The intensity of the underlying processes differs locally with respect to land management practices as well as hydro-geomorphic setting and soil conditions. A reliable assessment of the site specific vulnerability to carbon loss is important information to enable effective and precise agricultural and environmental policy. In the frame of a research project to derive an updated map of peatland soils for the Federal State of Brandenburg, located in the North-East of Germany, 7725 soil investigations on peatland sites were carried out thereof 3729 were suitable for peatland subsidence analyses. These data, together with extensive legacy data consisting of approx. 246,650 soil profiles, allow for robust carbon loss estimations based on peatland subsidence records. Observed carbon losses amount to 0.234 $kg/m^2 * yr$ at (presently) uncultivated sites, 0.562 $kg/m^2 * yr$ for grassland and 0.645 $kg/m^2 * yr$ for arable land. These figures agree well with recently published data for similar landscapes and land management practices. Taking into account additional information on the initial peat thickness, the type of underlying substrate and the presence or absence of a mineral top layer, a robust site-specific assessment of vulnerability to carbon loss for agriculturally used peatlands has been done. It is shown that >50% of agriculturally used peatlands in Brandenburg are characterized by medium or high vulnerability to carbon loss.

1. Introduction

The increased degradation of agriculturally used peatlands is of great concern in the context of both greenhouse gas emissions as well as their role as agricultural production sites. Under aerobic conditions, naturally accumulated peat is microbially decomposed, leading to the release of the greenhouse gases carbon dioxide (CO_2) and nitrous oxide (N_2O) into the atmosphere. This process is accompanied by corresponding changes in the soil profile. The magnitude of observed changes differs from site to site. This is an indicator of site-specific vulnerability resulting from the site affecting stressors and the individual ability to cope with these.

The goal of this work is to evaluate the vulnerability of agriculturally used peatlands in Germany to carbon loss based on area-representative peatland subsidence records. Reliable information on this is relevant in the frame of climate and soil protection. The results presented herein could be used to prepare, develop or implement optimized management approaches or support instruments leading to more-sustainable land use in peatlands.

1.1. Peatland subsidence as a proxy for carbon stock changes

Different approaches to measure or estimate carbon loss from peatlands exist. Methods based on peatland subsidence observations or by measuring the CO_2 flux, for example, are described by Kasimir-Klemedtsson et al. (1997).

To derive area-representative results for carbon stock changes, we will focus here on peatland subsidence (Eggelsmann, 1976; Leifeld et al., 2011) data as a proxy. This is well founded by the enormous amount of data available. For the investigated area in Brandenburg solely, approx. 246,650 soil profiles with a direct link to peatland soils distributed over the whole region were made available. It is this dense information that enables area-representative results and helps avoid errors that easily occur with small sample sizes, heterogeneous site conditions and/or undocumented historical changes in land use.

The drainage of a formerly water-saturated peat layer is accompanied by compaction, shrinkage and mineralization (oxidation) of the organic material (Eggelsmann, 1976). As a direct consequence of groundwater lowering, compaction prevails in the first years. The missing buoyant force in the drained part increases the vertical compressive stress and results in the compaction of soil particles up to the water-saturated zone of the soil profile (Zeitz and Velty, 2002). Compression in the water-saturated zone may considerably exceed the proportion

* Corresponding author.
E-mail address: holger.fell@agrar.hu-berlin.de (H. Fell).

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of shrinkage on peatland subsidence (Drexler et al., 2009; Price and Schlotzhauer, 1999; Schothorst, 1977). Shrinkage occurs only in the drained part of the soil profile. It is the result of concave menisci with isotropic pull on surrounding soil particles. Later, the decomposition of peat by soil organisms and the proceeding pedogenesis in the upper soil predominate, leading to the development of soil aggregates, compaction and an overall greater surficial area. The intrinsic mineralization (oxidation) of the organic material is a microbial process, driven mainly by bacteria and fungi which use the pre-decomposed peat in their metabolism. Carbon dioxide and simple inorganic compounds are the final products (Höper, 2007; Renger, 2002). Any further drainage triggers these processes again, with decreasing intensity of compression and shrinkage. Reliable estimates on annual peatland subsidence rates rely on the observation of large time periods to fully reflect the described processes and to account for repeated water management adjustments.

The coexistence of mineralization, compression and shrinkage prevent the deduction carbon loss based solely on subsidence data. Beside reliable estimates on the share of mineralization, additional information on dry bulk densities and carbon contents are required (Grønlund et al., 2008; Kluge et al., 2008). Carbon stocks then can be calculated in the following form:

$$C_{stock} = \sum_{i=1}^{n} BDi * Ci * Zi \quad (1)$$

BD is the bulk density, C the carbon content, *Z* the soil layer thickness and *i* the number of the consecutive soil layers.

Rarely is such data available with sufficient quality for two points in time to calculate carbon loss, but robust estimates can be made based on statistically derived characteristic peat carbon contents and dry bulk densities for different time periods in the past.

1.2. Vulnerability

Vulnerability generally refers to "a measure of the extent to which a community, structure, service or geographical area is likely to be damaged or disrupted, on account of its nature or location, by the impact of a particular disaster hazard" (UN, 1997). Here, we will focus on the vulnerability of peatlands to the loss of carbon. Taking peatland vulnerability as a measure for potential carbon loss, the most important fact is that they require high (ground) water levels to develop and persist. This can be seen as the system's internal dimension as its sensitivity and poor adaptive capacity lie here (Füssel and Klein, 2006). Primary stressors to the system are those with a negative impact on the site's water regime. One can distinguish between local, regional and supra-regional stressors. They may be anthropogenically induced or of natural origin (Table 1).

Secondary stressors apply to already disturbed systems. They have an impact on the magnitude of the system's damage. In the context of managed peatlands, most of them affect the type and intensity of land use and hence the resulting (ground-) water level and intensity of microbial activity (Table 1).

Both primary and secondary stress factors have to be seen in the given socioeconomic context. Poverty may force people to start agriculture on more complex-to-handle sites like peatlands. But on the other hand, a missing industrial level of agriculture can also be limitative. The contrary is observed in well developed countries with their largely public supported agriculture and forestry. If their supporting instruments lack aspects of sustainability or nature protection, they are the main drivers for peatland degradation, as they solely create the opportunity for a profitable management on these sites.

Only pristine fens or bogs bear a limited ability to resist changing (ground-) water levels due to their oscillating capabilities (Table 2). Drained peatlands almost entirely lack this natural resilience.

In the context of vulnerability, the ability to adapt is of great importance. With respect to managed peatlands, this ability exists only in a socioeconomic point of view (Table 3). The peatland itself is not able to adapt to ongoing low water levels, but the management of these sites can be modified. This applies to general support, soil protection instruments or nature protection laws, which can be added or changed to support more-sustainable land use.

The site-specific degree of vulnerability can be seen as a function of the potential carbon loss under the given natural and socioeconomic conditions. In other words, the higher the carbon loss was at a given site in the past, the higher its vulnerability is under these specific conditions. If we could robustly quantify the carbon loss for different time periods in the past and verify that these processes are similarly ongoing, we could apply this knowledge to analogous situations today, enabling the detection of areas of actually higher or lesser vulnerability.

2. Methods and materials

The Federal State of Brandenburg, in north-east Germany, covers an area of approx. 29,650 km^2. It is built up mainly of glacial sediments. Typical patterns of geomorphic structures such as ground moraines, terminal moraines, aprons and glacially initiated stream networks can be found. Large areas with organic soils predominantly appear in valley situations. A multitude of relatively small organic soil patches are bound to lakeshores or local depressions with high groundwater levels (Roßkopf et al., 2015). According to the updated map of organic soils, overall 1660 km^2 in Brandenburg are declared as peatland soils (Bauriegel, 2014). The climate is characterized by a transition from oceanic in the west to a more continental climate in the east. Mean annual temperatures range between 7.8 and 9.5 °C (Drastig et al., 2010). With precipitation of approx. 600 mm/year, fens are the most common source for peatland soils. Bog soils are missing.

The systematic drainage of lowland areas in Brandenburg for the purpose of agriculture started in the 17th century. As a consequence of the industrialization and mechanization of agricultural processes at the end of the 19th century, as well as during the socialistic economy of the GDR in the 20th century, land use on former fens was constantly

Table 1
Primary and secondary stress factors for peatlands with respect to carbon loss.

Parameter		Attribute	Local	Regional	Supra-regional	Natural	Anthropogenic
Water level drawdown	Primary	Drainage	x				x
		Modification of catchment area	x	x	x	(x)	x
		Climate change	x	x	x	(x)	x
Land use	Secondary	Arable	x				x
		Forestal	x	(x)			x
		Grassland	x				x
		Fertilization	x				x
		Tillage	x				x
Climate		Precipitation	x	x	x	x	(x)
		Temperature	x	x	x	x	(x)
Socio-economic context		Poverty	x	x	x		x
		Fin. support, Legislation	x	x	x		x