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Pore water velocity and ionic strength effects on DOC release from peat-sand mixtures: Results from laboratory and field experiments

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ABSTRACT

Organic soils are the most important source of dissolved organic carbon (DOC) in surface water. To date, most studies have focused on natural and re-wetted peatlands, but in Central Europe a large proportion of organic soils are drained and under agricultural use. Furthermore, measures such as deep ploughing or sand addition have been conducted to improve trafficability and have resulted in topsoil horizons consisting of a peat-sand mixture. Very little is known about DOC losses from such soils. Moreover, peat soils frequently feature both mobile zones, characterised by active water and solute transport, and immobile zones, which exchange solutes with the mobile zone by diffusion. Surprisingly, however, the effects of this dual porosity on DOC transport have not yet been explored. This study investigated the physicochemical controls on DOC concentrations in a peat-sand mixture by means of a saturated column experiment with undisturbed columns. The soil came from a former bog in northern Germany where peat layers remaining after peat extraction were mixed with the underlying mineral soil by ploughing. Three pumping rates and two levels of electrical conductivity (EC) were applied. The transport properties of the soil were obtained by analysing breakthrough curves of potassium bromide using the transport model STANMOD, which is based on the two-region non-equilibrium concept. The results of the column study were compared to DOC concentrations measured bi-weekly for two years at the field site from where the columns were taken. Despite a similar texture and soil organic carbon (SOC) content, the fraction of the mobile zone in the columns varied between 51% and 100% of total porosity. Thus even heavily degraded organic soils mixed with sand still showed a dual porosity comparable to degraded peat soils. Percolating the columns with the high EC solution caused low pH values, probably due to ion exchange and cation bridging. The combination of high EC and low pH greatly decreased DOC concentrations at the outlet of the columns. DOC concentrations decreased and fluxes increased as the pumping rates increased. Taking pore water velocity in the mobile zone into account could help to explain the differences between the columns. Overall, transport of DOC did not seem to be limited by production of DOC, but by rate-limited exchange processes. In contrast to the column experiment, field concentrations of DOC were much higher and were not related to pH, but increased with higher electrical conductivity. These higher concentrations could be explained by low pore water velocities and the slightly higher SOC content in the field. This first experiment on DOC transport in peat-sand mixtures taking the dual-porosity nature of organic soils into account clearly demonstrated the importance of pore water velocity and thus the residence time for DOC concentrations. While hydrochemical conditions are frequently addressed in laboratory studies, there is a need for improved understanding of their interaction with hydrology and soil-physical properties, especially when attempting to interpret DOC data on different spatial and temporal scales.

1. Introduction

Organic soils are the most important source of dissolved organic carbon (DOC) in surface water (Aitkenhead et al., 1999). Most studies investigating the release of DOC from organic soils have focused on natural and re-wetted peat soils (Clark et al., 2005; Evans et al., 2012; Koehler et al., 2009; Wallage et al., 2006), but the majority of organic soils in central Europe are drained for agriculture or forestry use (Lappalainen, 1996). While there have been a few studies on DOC

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concentrations in agricultural peatlands (Frank et al., 2014; Schwalm and Zeitz, 2015) and natural organo-mineral soils (Clark et al., 2011; Stutter et al., 2007a), there is very little information on DOC concentrations in organic soils that have been disturbed by being mixed with sand. There is only one single laboratory study on the effects on water quality of mixing peat with mineral soil, suggesting that the concentrations of several solutes, including DOC, increase as the remaining peat aggregates decrease in size (Ross and Malcolm, 1988). Measures such as deep ploughing or sand addition followed by normal ploughing have frequently been practised to improve trafficability, and have resulted in topsoil horizons consisting of a peat-sand mixture. For example, in north-western Germany, at least 17% of the organic soils used agriculturally have been subjected to sand mixing or application (Schulz and Waldeck, 2015). Similar measures have been implemented in Scandinavia (Sognnes et al., 2006) and The Netherlands (de Bakker, 1978). Biogeochemical data on such soils are scarce. Results on greenhouse gas emissions suggest drained peat-sand mixtures are still strong sources of carbon dioxide (Leiber-Sauheitl et al., 2014). Field data at the same study site showed high DOC concentrations irrespective of the soil organic carbon (SOC) content and the pH (Frank et al., 2017). However, to the best of the authors' knowledge, no attempts have been made besides the study by Ross and Malcolm (1988) to explain the effects of sand mixing on water quality.

After peat extraction, former bogs are frequently re-wetted to initiate new peat formation (Andersen et al., 2016; Gorham and Rochefort, 2003; Poschlod et al., 2007). Depending on the extraction depth, the local geohydrology, and the re-wetting method, formerly rain-fed sites may become influenced by groundwater or allochthonous surface water with higher nutrient contents and ionic strength (Graf and Rochefort, 2008; Malloy and Price, 2014). The effects of re-wetting on the peatland's biogeochemistry (e.g. Frank et al., 2014; Strack and Zuback, 2013) and biodiversity (e.g. Poschlod et al., 2007) need to be evaluated to define appropriate restoration goals, taking into account changes in hydrology and hydrochemistry compared to the pre-extraction conditions (Graf and Rochefort, 2008; Malloy and Price, 2014).

Ionic strength has frequently been suggested as an important driver of DOC concentrations in surface waters (Hruška et al., 2009), since a high ionic strength reduces the solubility of DOC (Kalbitz et al., 2000; Tipping and Hurley, 1988). However in field studies it is difficult to differentiate potential drivers of DOC concentrations such as water table depth (WTD) (Frank et al., 2014; Wallage et al., 2006), temperature (Koehler et al., 2009), ionic strength (Clark et al., 2011) and pH (Evans et al., 2012) because these factors may interact. For instance, high temperatures may cause lower WTD, which in turn induces lower pH and higher ionic strength due to sulphate formation (Clark et al., 2005). Moreover, different processes operate on different spatial and temporal scales and with different lag times, thus complicating the causal interpretation of DOC data (Clark et al., 2010).

Laboratory studies on DOC in organic soils are frequently run without percolation and/or with disturbed soil samples (Clark et al., 2011; Grybos et al., 2009; Münch et al., 2002). Therefore, the majority of studies do not address effects of flow velocity or non-equilibrium flow on DOC or other solutes. Non-equilibrium flow and transport can be caused by mobile and immobile zones within the soil (Jarvis, 2007). According to the concept of dual porosity, water only moves within the mobile zone while water in the immobile zone is stagnant, and solute exchange between the two domains only happens via diffusion (van Genuchten and Wierenga, 1976). In the context of DOC studies, Kalbitz et al. (2000) have already pointed out the discrepancies between laboratory and field results due to preferential flow being neglected in laboratory studies. There is little data on peat soils, but Forsmann and Kjaergaard (2014) showed that release rates of phosphorus under preferential flow conditions are less than those obtained in batch studies.

Based on scanning electron microscopic imaging and theoretical considerations, Loxham (1980) recognised early on the importance of immobile zones in peat for solute transport. Despite growing interest in DOC and nutrient release from organic soils, there have only been a few studies on the transport properties of organic soils. These studies have shown that pristine (Hoag and Price, 1997), moderately decomposed (Ours et al., 1997; Rezanezhad et al., 2012) and strongly degraded (Kleimeier et al., 2014) peat soils feature immobile zones. Some of these studies (Kleimeier et al., 2014; Rezanezhad et al., 2012) used re-packed peat material, which complicates the interpretation of results. No study has focused on the solute transport characteristics of peat-sand mixtures. To the best of the authors' knowledge, there has also been no study on the dual porosity of organic soils in conjunction with DOC transport, although it has been suggested that mean residence time, which is greatly affected by the extent of immobile zones, controls DOC concentrations (Limpens et al., 2008).

Here, we aim to improve our understanding of DOC dynamics in peat-sand mixtures using both laboratory and field data. By quantifying the transport properties of undisturbed columns collected at the field site with a bromide tracer test in the laboratory, we wish to take into account effects of the dual porosity nature of organic soils on DOC concentrations and fluxes. Furthermore, we want to test the impact of pore water velocity and ionic strength on DOC concentrations in these columns to improve the understanding of the dynamics of the DOC concentrations in the field. It was hypothesized that:

(1) due to the peat-derived organic material, peat-sand mixtures exhibit a dual porosity nature,
(2) higher pore water velocities, either induced by experimental boundary conditions or by a larger share of immobile regions, cause decreasing DOC concentrations,
(3) high ionic strength, i.e. high electrical conductivity, causes lower DOC release than low electrical conductivity,
(4) and experiments under controlled laboratory conditions provide reasonable estimates of DOC mobilisation under field conditions.

2. Material and methods

2.1. Study area

The “Großes Moor” study area is a former bog in north-western Germany. Mean annual precipitation and temperature are 663 mm and 8.5 °C respectively. At the study site, shallow peat (≈30 cm) remained after peat extraction. In parts of the study area, the remaining peat was mixed with the underlying sand by ploughing (≈30 cm), leading to a very heterogeneous soil. After several years of more intensive agricultural use, the study site became a nature conservation area in

Table 1
Basic soil properties of the soil columns and the upper horizon (0–30 cm) of the field sites (SOC, soil organic carbon; C/N ratio, carbon to nitrogen ratio; n.d. not determined). Sand, silt and clay fractions refer to the fine soil. Pore volume is only a useful parameter for samples of a defined volume. $C_{low}W_{29}$: sampling site with a low SOC content and a mean water table depth of 29 cm; $C_{low}W_{14}$: low SOC content and mean water table depth of 14 cm (Leiber-Sauheitl et al., 2014).

		Columns				Field	
Parameter	Unit	C1	C2	C3	C4	$C_{low}W_{29}$	$C_{low}W_{14}$
SOC	(g kg^{-1})	46.9	48.6	57.9	47.7	113.0	93.0
pH ($CaCl_2$)	–	n. d.	n. d.	n. d.	n. d.	4.5	4.5
C/N ratio	–	20	21	25	20	27	24
Bulk density	(g cm^{-3})	1.31	1.33	1.31	1.30	1.06	0.97
SOC stock (kg m^{-2} m^{-1})	55	59	65	56	107	81	
Porosity	–	0.45	0.47	0.47	0.47	0.59	0.59
Pore volume	ml	673	710	704	708	–	–
Coarse material	(g kg^{-1})	100	86	140	98	n. d.	n. d.
Sand	(g kg^{-1})	848	835	838	839	717	856
Silt	(g kg^{-1})	106	119	116	116	212	102
Clay	(g kg^{-1})	47	46	46	46	72	42