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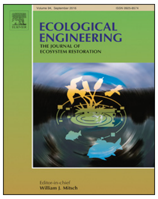

Relationship between groundwater levels and oxygen availability in fen peat soils

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ABSTRACT

Groundwater levels (GWL) are a major controlling factor for aeration and organic matter turnover in wetland soils but little is known about this relationship under field conditions. This study tested how the O_2 availability in fen peat soils is related to groundwater levels. The study encompassed five sites over a wide range of land use intensity. Ground water levels and soil oxygen saturation in 5 cm and 20 cm depth were measured biweekly in three replicates per site over periods of 2–3 years.

The O_2 levels were not linearly proportional to the GWL, but changed sharply from anoxic to nearly atmospheric levels depending on the positions of water table. Binary logistic regression analyses (LRA) were calculated for the individual sites in order to predict the threshold GWL for defined probabilities of hypoxic or oxic conditions in 5 cm depth. The GWLs for 95% probability of oxic conditions were markedly lower for the managed grasslands (−116 cm and −89 cm to surface level, respectively) than for the unmanaged pasture and the sedge fen (−60 cm and −38 cm). Hypoxic conditions required GWLs close to the surface (7 cm and −2 cm for the pasture and the restored site, respectively) while in 5 cm soil depth managed grasslands remained hypoxic even at GWLs of −8 cm and −28 cm. In 20 cm soil depth, full oxygen saturation never occurred even at GWL as low as 80 cm. Threshold GWL required for 95% probability of oxic conditions was higher with increasing porosity and rooting density. The offset between GWL and oxic conditions can be used for hydrological wetland management, especially for restoration efforts.

1. Introduction

Low availability of O_2 is crucial for the development and persistence of organic soils. Oxygen limitation in wetland soils impedes the microbial mineralization of organic substrates (D'Angelo and Reddy, 1999; Moore and Dalva, 1997). Hydrologically intact peatlands feature water levels near the surface, which maintain permanent anoxic conditions already in few centimeters depth. However, the predicted more frequent and more severe summer droughts in Central Europe (Kovats et al., 2014) may cause marked drops in water levels and hence increase the oxygen availability also in greater soil depths.

As the peat consists of tightly-bound organic carbon, aeration of formerly anoxic peat layers promotes the activity of O_2-dependent enzymes which catalyze the oxidative breakdown of phenolic compounds, the phenol oxidases. Hence, the concentration of phenolic compounds decreases upon aeration. This will in turn offset the phenolics' suppressive effect on the activity of hydrolytic enzymes, which conduct the breakdown of a large variety of organic compounds (Freeman et al., 2001, 2004). In this way, O_2 releases an 'enzymatic latch' on peat decomposition, and temporary oxygenation can propel the decomposition of soil organic carbon in peatlands even if the oxygen is no more present (Brouns et al., 2014). Therefore, constrained soil aeration is a crucial requirement for sustained carbon storage in peatlands.

Organic soils distinguish from mineral ones by their low density, heterogeneous pore structure, high water holding capacity and a marked swelling ability. These properties, which are attributable to the particulate organic material, promote the binding of residual water and result in a specific response of gas diffusivity to changes in soil moisture (Grover and Baldock, 2013; Iiyama et al., 2012; Oleszczuk and Brandyk, 2008; Weiss et al., 1998).

Soil oxygen is mainly provided diffusively through the pores in the unsaturated zone. The diffusion of gases in soils depends on the

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Abbreviations: BD, Bulk density – w/v of soil samples; C_{org}, total organic carbon – organic carbon content of soil w/w; GWL, groundwater level – groundwater level relative to surface (negative values depict water tables below ground); LRA, logistic regression analysis; NH_4-N, ammonium nitrogen; POR, porosity → Eq. (3); RBM, root biomass; RLD, mean root length density – cm roots/cm^3 soil volume; SED, sediment density → Eq. (2); WHC, volumetric water holding capacity → Eq. (1)

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proportion of the air-filled pore space and is negatively related to the water content (Refsgaard et al., 1991). Besides the fraction of water bound within the soil pores, also the unbound water moving freely in the matrix can affect the overall oxygen balance. Surface water which is saturated with O_2, e.g. run-off rain water or water from fast-running streams, presents a convective oxygen input to adjacent soil regions. In turn, O_2-depleted surface water, e.g. in slowly running drainage ditches within peatlands, may attenuate O_2 concentrations and expel oxygen from the soil (Reddy and DeLaune, 2008, pp. 199–200).

Within the ground water level, all soil pores are entirely filled by water. Above the water table extends a nearly saturated zone where the water is held in pores or associated to soil particles. This layer is predominately anoxic and can exhibit variable thickness (Fenton et al., 2006), depending on the hydro-physical properties of the soil matrix. Water retention there is linked to bulk density, porosity and pore structure as well as organic matter content and composition (da Rocha Campos et al., 2011; Iiyama et al., 2012; Walczak and Rovdan, 2002; Weiss et al., 1998).

The O_2 saturation in the peat soil layer above the water table does not decrease gradually with depth, but declines sharply from nearly atmospheric to almost anoxic levels within few millimeters of vertical distance (Askaer et al., 2010). This sharp decrease resembles the steep oxygen gradient which is commonly observed in inundated or saturated soils and sediments (Lloyd et al., 1998; Lüdemann et al., 2000; Rahalkar et al., 2009). The thin transition layer between hypoxic and oxic soil zones marks the lower margin of the surface peat layer that is particularly vulnerable to aerobic degradation.

External factors modulate the water retention and the gas exchange characteristics of soils. Plant rooting was shown to enhance soil water retention (Głab and Szewczyk, 2014; Leung et al., 2015), but on the other hand root growth loosens the peat structure and thus enhances gas diffusivity (Cannavo and Michel, 2013). Furthermore, radial oxygen loss from roots of wetland plants (Armstrong et al., 1992; Inoue and Tsuchiya, 2008) can also contribute to better oxygen supply in wetland soils.

Land use can affect the structure and texture of peat soils and hence alter their gas diffusivity. Tillage and drainage promote the disintegration of organic particles and the compaction of the soil (Głab and Szewczyk, 2014; Huang et al., 2006). A higher decomposition state of the peat with a more amorphous structure and smaller pores was shown to raise the capacity for residual moisture at unsaturated conditions but also to decrease the saturated water content (Gnatowski et al., 2010; Grover and Baldock, 2013). Consequently, the interplay of rooting and peat decomposition should modulate the extension of the hypoxic layer above the groundwater table.

The goal of this field study was to clarify the relation between groundwater levels and oxygen availability in fen peat soils under different land use. For this purpose, O_2 was measured in 5 cm and 20 cm depth on five different sites within the same peatland over periods of two or three years. It was hypothesized that with a given offset, peat oxygen availability is directly linked to the position of groundwater table. In connection to this, the critical groundwater level for the shift between hypoxic and oxic conditions differs between sites depending on soil properties and land use. This study shall uncover the currently missing link between oxygen availability in peat soils as a function of groundwater levels.

2. Methods

2.1. Study sites

The study was conducted in the Pfrunger-Burgweiler Ried (Baden-Württemberg, Germany, 47°54′ N, 9°24′ E, 610 m ASL), a peatland complex of approximately 2600 ha. Rewetting measures in this area had started in 2002. At the time of this study (2013–2015), an area of 1700 ha surrounding the abandoned core zone was under agricultural use, partitioned in zones of extensive and intensive pasture, grassland and cropping (Kapfer et al., 2005). The peatland largely consists of fens with Fibric, Hemic and Sapric Histosol (Huang et al., 2009) based on lacustrine sediments as sand mud (Zier, 1998). The regional climate (30-year average) is cool-temperate with a mean annual temperature of 7.3 °C and mean annual precipitation of 880 mm (DWD, Offenbach, Germany).

The five experimental sites were situated at two main locations. The first location encompassed a corn field (site I), an intensive (site II) and extensive grassland (site III) with a distance of 30–80 m between the sites. An extensive wet pasture (site IV) and a restored sedge fen (site V) were at the second main location with a distance of 290 m between the sites. All sites had been subjected to intensive land use for several decades. Next to the corn field, a drainage ditch was excavated during October 2013 in order to facilitate land management. This measure accounted for the lower groundwater levels during the winter 2013/14 on the site. Only scarce vegetation was present under the maize plants, so that the soil surface was largely bare. On the maize field mineral fertilizer (ammonium sulphate nitrate; diammonium phosphate) was applied once a year during plowing and sowing in spring. The intensive grassland (site II) was mown and fertilized with manure 2–4 times per year. The most abundant plant species on this site were *Alopecurus pratensis, Poa trivialis*, *Ranunculus repens* and *Taraxacum officinale*. The unfertilized extensive grassland (site III) with one cut per year featured a shallow, decomposed peat layer of approximately 30 cm thickness, as a result of peat extraction in the past. This site was covered by *Ranunculus repens*, accompanied mainly by *Glyceria fluitans* and *Alopecurus pratensis*.

In the context of renaturation, groundwater levels on sites IV and V had been raised during 2010. These two sites consequently showed higher groundwater levels than sites I, II and III throughout 2013 and 2014. The vegetation on the pasture (site IV) was dominated by *Poa trivialis* and *Alopecurus pratensis*, accompanied by several indicator species for wetness, in particular *Typha latifolia*, *Cirsium oleraceum* and *Juncus effusus*. The sedge fen (site V) was dominated by *Carex rostrata*, and furthermore vegetated by *Agrostis canina* and *Epilobium obscurum*.

2.2. Soil oxygen and water level measurements

Soil oxygen levels in 5 cm and 20 cm depth were determined with an optical measuring system (Fibox 3 LCD, PreSens, Regensburg, Germany) and dipping probes of 4 mm diameter (PSt3 and PSt6, PreSens). The method is based on an O_2-sensing fluorescent dye, which exhibits oxygen-related fluorescence quenching and phase-angle shift of the light signal, proportional to the O_2 concentration. The system is suitable for the determination of O_2 both in the gaseous and in the liquid phases.

Three replicate measurements were conducted on each site. The sensors in 20 cm depth were installed permanently, while the sensors in 5 cm depth were inserted at least 30 min prior to the measurements to ensure equilibration after the placement. The temperature was determined near the sensor tip and included in the calculation of actual O_2 levels, in order to account for the temperature effect. The measurements were conducted on all five sites in 2013 and 2014 from April to October biweekly with occasionally longer intervals. Between November and March, measurements were conducted only in case of potentially oxic conditions in the soil (for GWL lower than 10 cm below the surface). In 2015, the measurements were run only on sites IV and V mostly every two weeks from April to December. This measuring frequency was maintained throughout the whole year, because 2015 had a severe summer drought lasting until the early winter and thus showing unusually low water levels, which resulted in high O_2 availability in the soil.

Ground water levels (GWL) were recorded in 30 min-intervals (EM-50 logger, Decagon, Pullman, USA) with manometric sensors (CTD, Decagon) in 0.5 mm-slotted plastic tubes inserted to a maximal depth of