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Carbon, nitrogen, and phosphorus accumulation in novel ecosystems: Shallow lakes in degraded fen areas

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ABSTRACT

Draining fen areas seriously impairs ecosystem services as carbon (C), nitrogen (N), and phosphorus (P) accumulation. Fen restoration has become central in management efforts to recover these ecosystem services in the face of global climate change and water eutrophication challenges. However, restoration has resulted in the creation of shallow lakes, rather than former pristine fen conditions. A new sediment layer, where C, N, and P accumulate, forms at these novel ecosystems, and differs from peat accumulation occurring in natural fens. We performed an initial estimate of C, N, and P accumulation in water inundated fens, and their potential as C, N and P sinks within the temperate area is discussed. Furthermore, the roles of topsoil removal and ecosystem age were considered. A set of abandoned peat extraction sites ($n = 6$), and rewetted fens ($n = 6$) were selected. The effects of topsoil removal prior to restoration are represented by the former sites, which were created 20–86 years ago; and the absence of topsoil removal was represented by the latter, which were established 7–20 years ago. Sediment cores were obtained, and OC, N, and P accumulation rates estimated. Fossil diatoms in the sediment layer–peat interface were evaluated to ascertain trophic conditions in the initial lake formation stages. Surface water quality was analysed to describe current trophic conditions. Our results determined C, N, and P accumulation rates at inundated fens ($133.89 \pm 7.23\ g\ C\ m^{-2}\ y^{-1}$; $9.60 \pm 0.57\ g\ N\ m^{-2}\ y^{-1}$; $0.88 \pm 0.08\ g\ P\ m^{-2}\ y^{-1}$) were within the range of natural fens, and other temperate aquatic ecosystems. Topsoil removal prevented eutrophication, and decreased C, N, and P accumulation ($P < 0.01$), although it remains questionable how rewetted sites lacking topsoil removal will function in the long-term. Results demonstrated OM mineralisation has been an ongoing process in the new sediment layer for several decades, what does not occur in water saturated peat at undisturbed pristine fens.

1. Introduction

Peatlands occupy ~3% of the Earth's terrestrial surface, and under natural conditions have accumulated deep organic soils, providing important carbon (C), nitrogen (N), and phosphorus (P) reserves (Joosten and Clarke, 2002; Mitsch and Gosselink, 2007), and so important ecosystem services. The importance of peatlands in the global carbon cycle greatly exceeds the extent of their geographic distribution, as these ecosystems accumulate a substantial amount of the world's soil carbon reserves, i.e. 20–30% for northern peatlands (Gorham, 1991). In addition, undisturbed peatlands serve to buffer water catchment-scale fluxes (Fisher and Acreman, 2004; Hoffmann et al., 2006; Smolders et al., 2010), and accumulate N and P in the long term as stable refractory organic matter (Craft and Richardson, 1998; Graham et al., 2005; Succow and Joosten, 2001), which provide a vital role in preventing eutrophication of adjacent aquatic ecosystems. However, C, N, and P accumulation in peatlands has been notably impaired due to site draining for agricultural and horticultural purposes, forestry, and peat extraction for its high-energy properties (Kalbitz and Geyer, 2002; Lamers et al., 2002; Van Diggelen et al., 2006). Alternatively, simultaneous C and N export to the atmosphere, and C, N, and P transfer to adjacent aquatic ecosystems have increased (Craft and Richardson, 1998; Freeman et al., 2001; Gorham, 1991; Mitsch and Gosselink, 2007; Reddy et al., 1999; Richardson and Marshall, 1986). Groundwater-fed peatlands, known as fens, are most threatened by conversion into agricultural fields (Van Diggelen et al., 2006). Fens are converted to agricultural fields by large-scale draining of the area, and by groundwater diversion for irrigation, which can irreversibly alter fen hydrological dynamics, even when performed at large distances from the fen (Van Loon et al., 2009).

Fen restoration has become a crucial issue in light of global environmental problems, including climate change and eutrophication of water bodies (e.g. wetlands, lakes, and estuaries) (Hoeper et al.,

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2008; Verhoeven et al., 2006; Zak et al., 2011). Fen restoration is based on raising water levels to the soil surface to restore peat forming conditions, i.e. re-colonisation by peat-forming plants, and creation of anaerobic conditions, which slows peat decomposition. Complete fen hydrology restoration is often impossible due to non-reversible physical changes of peat characteristics in the upper soil layer (Grootjans and Van Diggelen, 1996; Lamers et al., 2002; Van Loon et al., 2009). However, flooding is performed as an alternative, despite the low potential to rehabilitate pristine fen conditions (Van Bodegom et al., 2006; Van Dijk et al., 2007). Several previous studies reported increased oxygen availability due to draining, which subsequently altered the degree of peat decomposition in the upper soil layer (∼0–50 cm), decreasing hydraulic conductivity, and concurrently increasing mobile nutrient pool size (Aldous et al., 2005; Cabezas et al., 2012; Litaor et al., 2004; Schindler et al., 2003; Zak et al., 2008). As a consequence, fen rewetting by flooding resulted in the origin of shallow eutrophic lakes (Hahn-Schofl et al., 2011; Trepel and Palmeri, 2002). The grassland vegetation occupying the drained fen died back, and a new sediment layer was formed of fresh plant litter. Subsequently, litter from aquatic primary production, and submerged macrophytes and helophytes provided fresh organic matter (OM) to the new sediment layer. Zak et al. (2010) and Zak and Gelbrecht (2007) demonstrated removal of the highly decomposed peat layer prior to flooding decreased nutrient release from the underlying peat because the remaining peat is more recalcitrant, and so are the size of the nutrient mobile pools much smaller. Anyway, permanently flooded conditions remained at restored fens cannot be avoided.

Consequently, in the short term ($<10^2$ y) flooding degraded fen areas resulted in the development of novel ecosystems, rather than restoring fens to pre-disturbance conditions. To our knowledge, no studies have evaluated the effect of flooding over the long-term ($>10^2$ y). Novel ecosystems are areas supporting species composition and/or ecological function exceeding the historical range of variation resulting from human modification of the "wild" conditions, or abandonment of previously managed systems (Hobbs et al., 2006). Restoration efforts are unlikely to return such novel ecosystems to less modified conditions due to the existence of biotic, abiotic, financial, pragmatic, or cultural barriers (Hobbs et al., 2009). However, restoration can reach resilient and self-sustainable systems characterised by desirable communities that provide ecosystem services (Hobbs and Harris, 2001; Seastedt et al., 2008). Therefore, efforts at degraded fen areas should focus on achieving the latter as primary restoration goals (Pfadenhauer and Grootjans, 1999; Prach et al., 2007; Klimkowska et al., 2010; Zedler, 2003). However, ecosystem services as C, N, and P accumulation in restored fen substrates are poorly understood, i.e. the role of sediment accumulation versus peat formation remains unclear.

In this study, a primary estimation of C, N, and P accumulation in the newly established sediment layer of flooded fens was evaluated. The potential importance of flooded fens as C, N, and P sinks at the global scale was further evaluated by comparing nutrient accumulation rates with values reported in the literature for natural fens, and aquatic ecosystems in other temperate regions worldwide. In addition, we contributed valuable insights to restoration ecology by ascertaining topsoil removal and soil age affects on fen ecology, i.e. influence of time following restoration on C, N, and P accumulation rates.

2. Materials and methods

2.1. Sediment sampling

The study sites ($n = 12$, Table 1) are located in NE Germany (Fig. 1). All the study sites are located in carbonate buffered percolating mires dominated by groundwater flow (Joosten and Clarke, 2002). According to our field experience, external sediment inputs are negligible at those study sites. However, autochthonous OM input occurred from dense populations of submerged, floating, and emersed aquatic plants. A substantial amount of aquatic plant biomass was observed within the water bodies during several years of fieldwork, which was of major importance (Schulz et al., 2011). The study sites were subsequently characterised as two distinct types:

(a) RF-HD: rewetted fens – highly decomposed peat layer. Degraded fen areas where natural rewetting has been performed by cessation of water pumping activities in the surrounding area. A rewetting date was recorded for each fen, which ranges from 7 to 20 years (i.e. fen ages) for RF-HD fens. The upper peat layer was highly decomposed at the time of rewetting, when the system was converted from a degraded fen to a shallow lake (<1 m water depth). Groundwater–surface water exchange is though to be reduced at these sites by the low hydraulic conductivity of the highly decomposed peat layer (Schindler et al., 2003). P release potential from the peat was considered as high for those sites and dependent on the Fe:P peat ratio (Geurts et al., 2008; Zak et al., 2004). Former field studies showed the dominant vegetation was comprised of Typha sp. and Ceratophyllum sp., the latter an submerged aquatic plant, which grows very well under high nutrient conditions. Peat-forming plants, including Phragmites australis and Carex sp. were respectively absent or in very low frequency. Littoral zone plant biomass was considered negligible relative to aquatic plant biomass.

(b) PH-SD: peat holes – slightly decomposed peat layer. Abandoned peat extraction sites at fen areas with varying degrees of degradation. Records of peat excavation termination dates were maintained, therefore age since abandonment was known, which ranged from 20 to 86 years. In contrast to RF-HD sites, the upper peat layer at the ponds was only slightly decomposed. Groundwater–surface water exchange was assumed to be markedly higher than at RF-HD because the peat layer retains its physical structure due to a lower degradation (Schindler et al., 2003). Furthermore, P release from slightly decomposed peat has been demonstrated to be low (Zak and Gelbrecht, 2007). We assumed the sites represented an example of the effects of topsoil removal prior to rewetting. P. australis, a peat forming grass specie, and/or a different species of submerged aquatic plats dominated the vegetation (Table 1). As found for RF-HD sites, littoral zone plant biomass was considered negligible relative to aquatic plant biomass.

Sediment cores ($n = 16$–20; Ø = 6 cm) were collected at each study site ($n = 12$) from November 2010 to March 2011. A grid sampling strategy was selected, performing 3–5 transects depending on site heterogeneity and size. Sediment cores were obtained from a boat or from the frozen upper water layer. This approach assured disturbance of the upper sediment layer and resuspension during sampling to be avoided. Open water was the dominant cover type at PH-SD and RF-HD; therefore core samples were obtained from these areas. We confirmed that the new sediment layer, and underlying peat were collected in every core. Core specimens were transported to the lab, and processed within 24 h.

The sample cores were visually examined, and the new sediment layer was readily identifiable; its depth was measured before extruding the sediments from the sampling cores. The identification was reliable in all samples, because the loose new sediment layer was easily differentiated from the more compact material that composed the underlying peat layer. In addition, differences