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Dissolved organic carbon concentrations vary with season and land use – investigations from two fens in Northeastern Germany over two years

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Abstract

The rising export of dissolved organic carbon (DOC) from peatlands during the last 20 years is of great environmental concern, as DOC harms drinking water quality and diminishes the carbon storage of peatlands. Lack of knowledge particularly exists for fens. The aim of our study was to determine DOC concentrations at an agriculturally used fen and a rewetted fen throughout the year. We measured DOC concentrations in ditch water of these fens in 2011 and 2012. Furthermore, discharge measurements were condcucted to detect DOC export. Overall DOC concentrations at our agriculturally used site and at our rewetted site were 35 $mg\,L^{-1}$ and 26 $mg\,L^{-1}$ (median), respectively. The maximum DOC concentration at our agriculturally used site was twice as high as at the rewetted site (134 $mg\,L^{-1}$ vs. 61 $mg\,L^{-1}$). Annual DOC export was calculated for the rewetted site, amounting to 200 $kg\,C\,ha^{-1}$ on average. Our results suggest that rewetting of degraded fens reduces DOC export in the long-term, while agricultural use of fens leads to enhanced decomposition and thus, elevates DOC export.

1 Introduction

Recently, much attention has been paid to the storage of carbon in soils. Peaty soils are in the focus of climate research since ongoing cultivation transforms such soils from carbon sinks to sources. Pristine peatlands accumulate organic carbon since decomposition rates are very low due to a lack of oxygen. The storage of organic carbon in peatlands can exceed 2800 tons per hectare (Zeitz et al., 2008; Roßkopf and Zeitz, 2009) and peatlands contain about 30 % of the entire terrestrial soil carbon (Parish et al., 2008; Post et al., 1982). After the transformation of peatlands to agricultural land, net carbon release predominantly occurs both via carbon dioxide (CO_2) and aquatic pathways. Disturbance of the natural biogeochemical cycles has serious consequences: in Germany, for instance, drained peatlands account for 30 % of green house gas (GHG) emissions from the entire farming sector, although they cover only approximately 8 % of farm land (Drösler, 2010).

Besides CO_2, soil carbon is also released as dissolved organic carbon (DOC), which is defined by molecule sizes smaller than 0.45 µm (Thurman, 1985). DOC is a natural part of soil solution and fresh water. It serves several biogeochemical functions, such as nutrient cycling, electron donating under anoxic conditions, regulation of lake stratification and acidity as well as transport of metals, to mention only a few (Marschner and Bredow, 2002; Gorham et al., 1986; Fee et al., 1996; Chapelle, 2000; Chin et. al., 1998; Helmer et al., 1990; Discroll et al., 1988; Dawson et al., 1978). At the same time, DOC export from peatlands harms drinking water quality (Chow et al., 2003; Krasner, 1999) and represents a loss of long-term stored atmospheric carbon that will be mineralized to CO_2 sooner or later. Thereby, a high proportion of carbon export can occur as DOC. According to Dawson et al. (2002, 2004), carbon losses in stream water were dominated by DOC, while other forms of aquatic carbon (dissolved inorganic carbon, particulate organic carbon, dissolved CO_2) were negligible. Strack et al. (2008) reported that DOC losses accounted for 17 % of the total carbon exchange after drainage. The IPCC recently stated: "It is therefore good practice to include DOC in flux-based carbon estimation methods to avoid under-estimation of soil C losses" (Balin et al., 2013, p. 3.7). The export of DOC varies between 1 and 50 $g\,C\,m^{-2}\,a^{-1}$ (Moore, 1998; Schwalm and Zeitz, 2010) and contributes significantly to carbon balances of peatlands.

The extent of DOC export is strongly influenced by hydrology, as increased surface runoff is usually associated with increased DOC losses. Drainage of peatlands raises runoff and thus, facilitates DOC losses (Van Seters and Price, 2002). Hydrological events, such as storms or snowmelt, also cause a DOC flush due to elevated runoff (Wilson et al., 2013; Hagedorn et al., 2000). Besides hydrology, DOC export is determined by the DOC concentration in ditch water. This in turn is regulated by several factors such as DOC production, consumption and adsorption in the soil. Therefore, high production of DOC does not necessitate high DOC concentrations, since consumption or adsorption reactions can be high as well. Peatlands generally have a very low ca-

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pacity for adsorption of DOC (Kaiser et al., 1996; Kaiser and Zech, 1997) and they possess an enormous pool of potential DOC due to their high content of organic carbon (Dalva and Moore, 1991). Under near natural conditions, concentrations of DOC in peatlands are approximately 30 mg L^{-1} (Thurman, 1985). However, pristine peatlands are scarce in Central Europe; in Germany 99 % of these soils are disturbed (Succow and Joosten, 2001). Many studies detected elevated DOC concentrations in peatlands after drainage or other disturbances (Gandois et al., 2013; Grieve and Gilvear, 2008; Strack et al., 2008; Banas and Gos, 2004; Glatzel et al., 2003). On the other hand, a drop in the water table is considered to be a factor for declining DOC concentrations due to acidification (Clark et al., 2012) or as a result of aerobic microbial degradation of organic material, thereby producing CO_2 rather than DOC (Freeman, 2004; Mulholland et al., 1990). After drainage, peatlands undergo rapid peat decomposition. Some studies found that highly decomposed peat enhances net DOC production due to the presence of decomposable organic matter or as a result of the more favourable geochemical conditions (Frank et al., 2013; Zak, 2007). In contrast, other studies reported that peat decomposition leads to a lower organic carbon content and thus, to lower DOC concentrations (Kalbitz and Geyer, 2002). However, rewetting of drained peatlands certainly induces a DOC flush (Clark et al., 2012; Zak and Gelbrecht, 2007; Kalbitz et al., 2000; Lundquist et al., 1999). In the long term, rewetting of degraded peatlands has been shown to decrease DOC concentrations to those of near natural levels (Frank et al., 2013; Höll et al., 2009; Wallage et al., 2006). However, since the DOC concentration does not always decrease after rewetting of a peatland, this strategy is still under debate. Seasonal variations of DOC concentrations were shown in most studies. Concentrations were higher during summer and/or autumn as compared to winter (Wilson et al., 2013; Höll et al., 2009; Dawson et al., 2008; Tipping et al., 1999; Scott et al., 1998; Dalva and Moore, 1991), which results from higher temperatures and organic matter turnover during the growing season as well as from litterfall. In contrast, Tiemeyer and Kahle (2012) did not find any seasonal or annual variation of DOC for peatlands in Northeastern Germany.

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Extensive research has been conducted to identify the main causes of DOC concentration changes in peatlands. There seems to be a contradiction in the literature discussing the impact of land use (i.e. water table draw down) on DOC concentrations and DOC seasonality. This may be a result of the variability in study sites, which have different genesis (minerotrophic fen, ombrotrophic bog) and climatic conditions (continental, oceanic etc.). Most of the studies took place in bogs or upland peatlands (e.g. Frank et al., 2013; Armstrong et al., 2012; Dawson et al., 2008; Wallage et al., 2006; Bengtson and Törneman, 2004; Aitkenhead et al., 1999). Only limited research has been undertaken in agriculturally used fens (mentioned in the IPCC 2013 supplement to the 2006 guidelines: wetlands) and knowledge from other investigations cannot be easily applied to such sites. Furthermore, rewetting of agriculturally used fens is associated with elevated DOC concentrations in the short term and the observation of long-term effects is necessary to assess its success. In addition, little information is available to quantify DOC export after rewetting of agriculturally used fens (to our knowledge, only Kiekbusch, 2003 reported exports).

Our study aims to detect variability of DOC concentrations over time and between an intensively used fen and a rewetted fen in lowlands of Northeastern Germany. Measurements of DOC were undertaken for about two years. Our agriculturally used site was chosen due to its long-lasting land use and drainage history, which started at the beginning of the 18th century. A second site was chosen, that is as similar as possible to the first in terms of site characteristics, land use history and climatic conditions. In contrast to the agriculturally used site, this fen has been rewetted for a long period of 10 years. In this study, we make the following assumptions: (1) agricultural use of fens elevates their DOC concentrations since peat decomposition is enhanced. Rewetting of agriculturally used and degraded fens results in decreasing, near-natural DOC concentrations in the long term. (2) Concentrations of DOC undergo seasonality; i.e. low DOC concentrations occur during winter and high concentrations during the growing season and/or after litterfall. (3) DOC export contributes significantly to the carbon balance of fens.

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2 Materials and methods

2.1 Study site

The study was conducted at two sites located in Northeastern Germany. Site AU (= agriculturally used) is located in the area of *Havelländisches Luch*, a fen-rich lowland in the federal state of Brandenburg. Peat and calcareous gyttja cover Pleistocene sands. The predominant hydrogenetic mire type of this landscape is water rise mire. Site AU has a catchment area of 650 ha, which is characterized by intensive farming (grassland and little *Zea mays* (L.)). The mean annual temperature is 8.9 °C and the mean annual precipitation is 515 mm (own weather station *Forschungsstation Paulinenaue*). Since the beginning of the 18th century, this site has been drained (see Fig. 1) and has been agriculturally used. After this long period of agricultural use, the peat is strongly degraded or even amorphous, the peat layer has shrunk considerably and the soil carbon content has decreased (Schmidt et al., 1973; Beuthner, 2012). Current peat layer thickness is 2 to 12 dm (see Table 1 for further details).

Site RE (= rewetted) is located in the region of *Mecklenburgisch-Brandenburgische Seenplatte* (federal state of Mecklenburg–Western Pomerania), which is the largest lake district of Central Europe. Similar to Site AU, peat soils and calcareous gyttja cover Pleistocene sands. Site RE has a catchment area of 50 ha, which has previously been intensively used as grassland and was rewetted in 2003. The mean annual temperature is 8.9 °C and the mean annual precipitation is 591 mm (weather station *Waren/Müritz*, German Weather Service). Regarding vegetation, mainly peatland specific plants occur as well as a little swamp forest. Former ditches have been blocked or modified to reduce water discharge (see Fig. 2). No inflow exists from surface waters, but one artificial outflow can be found.

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2.2 Water sampling, chemical analysis and discharge records

At the agriculturally used site (Site AU), water samples were taken from three ditches for DOC analysis. Two of these sampling points were located in the central catchment area. The third sampling point was chosen at the main outflow of the catchment into the drainage channel. At this location, discharge and pH measurements were conducted, too. At the rewetted site (Site RE), water sampling as well as discharge measurements were carried out at the only outflow of the catchment area.

Water samples were collected biweekly from January 2011 to December 2012, unless water was frozen. Samples were immediately refrigerated, treated with hydrochloric acid ($pH < 4$) and stored at $-18\,^{\circ}C$, if immediate analysis was not possible. After filtration with a 0.45 µm membrane filter (Minisart RC 25, Sartorius, Göttingen, Germany), samples were analysed by high temperature oxidation with LiquiTOC (Elementar Analysesysteme, Hanau, Germany). Additionally, soil water samples were collected from wells at Site AU in October 2012.

At both study sites, ditch water levels were recorded every 15 min with Mini-Divers (Schlumberger Water Services, Delft, the Netherlands). At Site AU, water levels are available from January 2011 to December 2012, whereas at Site RE water levels are only recorded from April 2011 to December 2012.

Discharge measurements were intended to take place biweekly with an electromagnetic flow sensor (Nautilus by Ott Hydromet GmbH, Kempten, Germany). Unfortunately it was difficult to implement this interval since summer drought, winter frost or (at Site AU) closed weirs impeded discharge.

At Site RE, the correlation between water discharge and water level was used to generate continuous run off data with interpolation. This could not be carried out at Site AU since drainage via pumps made it difficult to correlate water discharge with water levels.

The R package 3.0.2 (R Core Team, 2013) was used for statistical analysis.

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3 Results and discussion

3.1 Climatic driver variables during the study period

Interestingly, strong climatic differences were recorded between both study years (2011 and 2012). The year 2011 was not only warmer and wetter than 2012, but also than the long-term average recorded for the respective stations.

The agriculturally used site (Site AU) had a mean annual temperature of 9.8 °C in 2011 and 9.3 °C in 2012 (the average of period 1961–1990 is 8.1 °C, all weather data in this section was provided by German Weather Service, 2013). 2011 was associated with a smaller range in mean daytime temperatures than 2012 (–8–25.5 °C vs. −17.3–25 °C) because of the very low temperatures prevailing at the beginning of 2012. Mean annual temperature of the rewetted site (Site RE) was 9.9 °C in 2011 and 9.3 °C in 2012 (average of period 1961–1990 is 8.9 °C). The range in mean daytime temperature was again smaller in 2011 as in 2012 (–8.2–24.3 °C and −15.5–23.9 °C, respectively).

Both study years were relatively warm, but the year 2011 was climatically unordinary: as mentioned above, the mean annual temperature of 2011 was not only higher than the one of 2012, but also much higher than the average of 1981–2010 and much higher than the average of 1961–1990 (see Table 2). Mean annual temperature and annual precipitation during the study period compared to the long-term average (1961–1990 and 1981–2010). Data for the agriculturally used site was obtained from a local weather station, data for the rewetted site was provided by the weather station Waren (German Weather Service). Even though 2011 was an outstandingly warm year, the temperature, in general, has a positive trend at both sites. This is in line with the latest IPCC report: "Each of the last three decades has been successively warmer [. . .] since 1850. [. . .] 1983–2012 was likely the warmest 30 year period of the last 1400 years (medium confidence)." (Stocker et al., 2014, p. 3). Specifically the springtime months (March, April) were exceptionally warm at both study sites and during both years. This finding corresponds to the seasonal climate shift observed in Germany, as the present phenological spring starts earlier than 50 years ago (German Weather Service, 2013).

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Beside extraordinary temperatures, 2011 was also a very wet year. High annual precipitation of 642 mm and 676 mm occurred at the Site AU and RE, respectively, which is in both cases around 100 mm more than the reported long-term average (521 mm for Site AU and 574 mm for Site RE, German Weather Service, 2013). This is mainly caused by intensive rainfalls in July and December. High winter precipitation and extreme rainfall events as observed in summer 2011 are in accordance with prognoses of climatic changes due to global warming (Solomon et al. (IPCC), 2007). However, no consistent long-term trend in annual precipitation can be identified.

3.2 DOC concentrations: differences between sites

At the rewetted site, DOC concentrations were lower and showed a smaller range as compared to the results of the agriculturally used site (see Fig. 3). The median ditch water DOC concentration of Site RE was 26.3 mg L^{-1} (±13.4), whereas Site AU had a median of 34.5 mg L^{-1} (±23.0). The maximum DOC concentration at the agricultural area was twice as high as at the rewetted site (133.6 mg L^{-1} vs. 60.8 mg L^{-1}). Höll et al. (2009) and Fiedler et al. (2008) both found lower DOC concentrations at rewetted fens as compared to drained fens. In contrast, Zak and Gelbrecht (2007) and Glatzel et al. (2003) report higher DOC concentrations after rewetting of drained fens.

Additional information is given for Site AU, where soil water DOC was measured in October 2012. These concentrations were considerably higher than those of the simultaneous ditch water sampling (65.0–135.28 mg L^{-1} vs. 19.2–28.68 mg L^{-1}). Riedel et al. (2013) and Zak et al. (2004) reported a decrease of DOC concentration from soil to ditch, too. According to them, this results from aeration of anoxic water and it can account for a DOC decline of 58 % to 85 %. Even though the DOC concentration decreased rapidly from soil to ditch, our ditch concentrations exceed most soil DOC concentrations reported in the literature. Comparable fens mostly have soil DOC concentrations of up to 50 mg L^{-1} and are seldom higher than 100 mg L^{-1} (Fiedler et al., 2008; Kalbitz and Geyer, 2002; Strack et al., 2008; Moore, 1987; Zak, 2001). With respect to rewetted, degraded fens, values reported in literature, however, vary remarkably. While some authors mentioned medium soil water DOC concentrations (round 40 to 60 $mg L^{-1}$ by Höll et al., 2007; Fiedler, 2008; Zak, 2007), other reported very high concentrations (up to 130 $mg L^{-1}$ by Kiekbusch, 2003 and up to 205 $mg L^{-1}$ by Zak, 2007). Our DOC measurements from the rewetted site tended to be lower than those found in literature. This is again due to differences in sampling as our samples were collected from ditch water, while soil water was sampled in the studies mentioned above. To our knowledge, only Strack et al. (2008) conducted ditch water sampling comparable to our study. They present DOC concentrations of 16.2 $mg L^{-1}$ (±4.78) and 22.4 $mg L^{-1}$ (±6.1) at two near natural, undrained fens. It therefore appears that our DOC concentrations measured at Site RE are only marginally elevated as compared to near natural conditions. Further evidence for the successful restoration at Site RE is given by the decline of DOC concentrations since 2006/2007 (compare with Zauft and Zeitz, 2011).

In our opinion, the hydrological conditions account for the differences in DOC concentrations between the agriculturally used and the rewetted site. Site AU had high and extremely fluctuating DOC concentrations during the whole year due to water table draw down for the last 300 years and highly dynamic water table depths (see Fig. 4 for water levels). Aeration of the former anoxic soil has resulted in strongly decomposed peat, which provides large amounts of DOC (Frank et al., 2013; Zak and Gelbrecht, 2007). A rise in water table (after strong precipitation or rewetting) is accompanied by a flush of DOC-rich water from soil to ditches as a result of the following: (1) accumulated DOC is mobilized, (2) death and decomposition of microbial biomass is enhanced (Lundquist et al., 1999; Kalbitz et al., 2000) and (3) redox-sensitive bound organic carbon is dissolved (Zak and Gelbrecht, 2007). As compared to Site AU, we found significantly lower DOC concentrations with a smaller range at the rewetted site. The restoration of Site RE in 2003 has led to a perennial near-surface water table (Fig. 5), which slowed down DOC production (Frank et al., 2013; Höll et al., 2009; Wallage et al., 2006). Ten years of rewetting were possibly sufficient to replenish our study site with phenolic compounds, whereby peat decomposition slows down (according to the enzymytic “latch” mechanism, Freeman et al., 2001).

In contrast to our findings, Kalbitz and Geyer (2002) reported higher DOC concentrations in intact peatlands than in degraded ones. In addition, Freeman et al. (2004) could not show that dry-wet cycles elevate DOC concentrations. Instead they found increasing net primary production and root exudation to boost DOC concentrations. This concept may, to a certain extent, explain the high concentration of DOC at Site AU because vegetation differs between our study sites (mainly *Lolium* sp. at Site AU vs. *Carex* sp., *Phragmites* sp., *Juncus* sp. and mosses at Site RE). However, if vegetation type plays a major role in determining DOC net production, higher DOC concentrations should be measured in summer than in winter, which is not the case (see Sect. 3.3 for seasonal influences).

To summarize, our findings support the hypothesis that land use of fens increases DOC concentrations, whereas rewetting contributes to lower, near natural DOC concentrations in the long term.

3.3 DOC concentrations: seasonal and annual variation

No strict seasonality of DOC concentrations could be reported during the two study years. Nevertheless, DOC concentrations in ditch water were dynamic in time, especially at the agriculturally used site. At this site, we found DOC peaks in spring 2011, in winter 2011/2012 and in June 2012 (see Fig. 4). DOC concentration changed by a factor of 2 within short periods. At the rewetted site, changes in DOC concentrations were different. Highest concentrations were observed in October 2011, in January/February 2012 and in April 2012. Overall, DOC concentration changes with time were smoother at the rewetted site than at Site AU (see Fig. 5).

Höll et al. (2009) also found DOC peaks in winter, which matches our results. In their study, higher concentrations were generally detected in summer than in winter, a finding that was already noted by many other authors (Tipping et al., 1999; Scott and Woof, 1998; Dalva and Moore, 1991). This appears plausible since microbes are more active

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and root exudation is more pronounced during the growing season. Yet, our summer DOC concentrations were equal or only marginally lower than the winter concentrations. This mainly results from the high DOC concentrations in winter 2011/2012 (see for Site AU and for Site RE). Further studies not finding any seasonality were conducted by Tiemeyer and Kahle (2012) and Dosskey and Bertsch (1994). Interestingly, our agricultural site (Site AU) showed 40 % higher DOC concentrations in the wetter year 2011 as compared to 2012, whereas DOC concentrations of Site RE were slightly lower in 2011. Other publications on fens in Southern Germany report the same (Höll et al., 2009; Fiedler et al., 2008).

We assume that high precipitation at drained peatlands acts as interim rewetting and thus, led to the increased DOC concentration at Site AU in 2011 (see Sect. 3.2). With respect to the rewetted site, the opposite effect took place. Here we report the dilution of DOC concentrations since the area is water saturated throughout the year and no drastic hydrological changes are induced by rainfall. Extraordinary high DOC concentrations were recorded for both study sites in winter 2011/2012 and could be connected to the higher-than-average temperatures. Though other seasons in our study were also warmer than average, the higher temperature in winter could account for an extra production of DOC as temperature specifically limits microbial activity during this part of the year.

A positive correlation between temperature and DOC production was observed both in laboratory and field studies (e.g. Clark et al., 2009; Tipping et al., 1999) and could also explain variations in DOC concentrations. Indeed, the year 2011 was not only wetter, but also warmer than 2012 and our agricultural site showed elevated DOC concentrations. On the other hand Site RE showed slightly lower concentrations in the warmer year, so that temperature cannot explain our DOC data. Similar to our study, results by Fiedler et al. (2008) did not find a correlation between DOC concentration and temperature or precipitation or groundwater level. Results regarding the effect of temperature on DOC concentration are often inconsistent, as temperature interacts

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with many other factors, especially in field studies (see review of Kalbitz et al., 2000; Schwalm and Zeitz, 2010).

Overall, our hypothesis that concentrations of DOC underlie seasonality must be rejected. The course of DOC concentrations throughout the year is entirely different at both study sites.

3.4 DOC export

Export of DOC from our rewetted site averaged 200 $kg\,C\,ha^{-1}\,a^{-1}$ (see Table 3 for monthly average). The DOC export peaked during times of high discharge (see Fig. 8). As compared to data from 2006/2007 (Zauft and Zeitz, 2011), the DOC losses decreased considerably at Site RE since discharge and DOC concentration were much lower. Therefore, the restoration process at Site RE can be considered successful. DOC export from our agriculturally used site could only be calculated for single days and varied between 0.01 and 2.3 $kg\,ha^{-1}\,d^{-1}$ (that means 4 to 840 $kg\,C\,ha^{-1}\,a^{-1}$ extrapolated for one year). The amount of carbon loss strongly depends on whether the pumps are active or not. In summary, DOC concentrations and discharge are elevated at the agricultural compared to the rewetted site, implying a higher total carbon loss. When related to the catchment size, AU probably has slightly lower DOC export per hectare than Site RE (since the catchment area is much larger).

DOC export data for rewetted, degraded fens comparable to Site RE was published by Kiekbusch (2003), however, these losses accounted only for 30 to 40 $kg\,C\,ha^{-1}\,a^{-1}$. DOC losses of similar magnitude than ours were reported for upland bogs or poor fens (Worrall et al., 2008; Strack et al., 2008; Billet et al., 2004; Urban et al., 1989).

Billet et al. (2004) has shown that organic carbon losses in drainage water can compensate net carbon accumulation and make peatlands, commonly considered carbon sinks, to become neutral or even a carbon source. Therefore, DOC has to be included when determining the carbon budget of peatlands. Average carbon accumulation rates in peatlands are estimated to be 230 $kg\,C\,ha^{-1}\,a^{-1}$ (Billet et al., 2004; Höper, 2007), even though this accumulation rate is thought to be overestimated by some authors

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(Moore et al., 1998). In any case, the amount of DOC losses is of great importance to the carbon budget.

Currently, much effort is undertaken to revitalise drained, degraded peatlands. In the German federal state of Mecklenburg-Western Pomerania, more than 14 000 ha of peatland have been rewetted over the last years with the aim to restore their function as carbon sinks. Referring to the data of our rewetted site, this undertaking will only be successful if DOC losses can be minimised. Agriculturally used fens do not act as carbon sinks and a high DOC export even increases their carbon emissions.

In conclusion, our initial assumption regarding the role of DOC in carbon balancing can be confirmed. Especially in the restoration process of peatlands, it is essential to include hydrological carbon losses in order to evaluate its success.

Our calculation of DOC export has some uncertainty. While the DOC concentrations can be seen as reliable (an estimated error of $< 5\%$ from repeated measurements), the discharge measurement has at least an error of $\pm 10\%$ (Devito et al., 1989). Further uncertainty is given by the water level–discharge relationship (rating curve) and its interpolation. The runoff at Site RE was very low and not always detectable due to the summer drought and winter frost. At Site AU, the weirs were predominantly closed and no discharge occurred. Due to the drainage of Site AU via pumping systems, a rating curve could not be used for discharge interpolation.

4 Conclusions

Our results show a high temporal variability of DOC concentrations, providing evidence for the importance of long-term observations of DOC concentrations, especially when monitoring the success of fen rewetting. All seasons need to be taken into account, as the highest DOC concentrations occurred during winter and not, as often reported, during growing season. Furthermore, land use management of peatlands influences DOC losses. Our results suggest that rewetting decreases DOC concentrations as well as discharge, and water table draw down increases both concentration and discharge.

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Hydrological carbon exports account for large amounts of the total carbon loss and those DOC exports need to be considered in carbon balancing. To restore the function of peatlands as carbon sinks, DOC losses should be minimized.

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Table 1. Description of the study sites, mean annual climatic conditions (1961–1990) were provided by German Weather Service.

	Agriculturally used site (Site AU)	Rewetted site (Site RE)
Position of water sampling	52°40′53″ N 12°43′31″ E	53°21′47″ N 12°54′35″ E
Mean annual climatic conditions	8.6 °C and 521 mm	8.1 °C and 574 mm
Catchment area	650 ha	50 ha
Percentage peatland	65 %	95 %
Hyrogenetic mire type	mainly water rise mire, also terrestrialisation mire	percolation mire and terrestrialisation mire
Trophy conditions	eutrophic	eutrophic
Degree of decomposition	sapric	hemic
Peat layer thickness	3–12 dm	10–30 dm
Type of peat	*Carex* and *Phragmites*	*Phragmites* and *Carex*
pH (water)	6.2–8.6	6.4–7.2

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Table 2. Mean annual temperature and annual precipitation during the study period compared to the long-term average (1961–1990 and 1981–2010). Data for the agriculturally used site were obtainded from a local weather station, data for the rewetted site were provided by the weather station *Waren* (German Weather Service).

	Agriculturally used site		Rewetted site	
1961–1990	8.6 °C	521 mm	8.1 °C	574 mm
1981–2010	8.9 °C	591 mm	8.9 °C	515 mm
2011	9.8 °C	642 mm	9.9 °C	676 mm
2012	9.3 °C	529 mm	9.3 °C	532 mm

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Table 3. Discharge, DOC concentrations and DOC export by month at the rewetted site.

	ø discharge (± sd) [$L s^{-1}$]	Number of measurements and interpolations	∑ discharge [m^3]	ø DOC concentration [$mg L^{-1}$]	∑ DOC [$kg ha^{-1}$]
2011				20.7	209
Feb	32.5 (±0)	1	84 240	21.78	36.69
Mar	3.2 (±0)	1	8268	30.51	3.60
Apr	21.8 (±12.3)	18	56 411	29.85	24.05
May	0.9 (±2.0)	31	2396	37.13	1.27
Jun	6.0 (±3.2)	30	15 491	34.39	7.61
Jul	30.8 (±6.7)	31	79 710	41.17	46.89
Aug	31.6 (±3.8)	31	81 945	28.46	33.32
Sep	12.9 (±10.1)	30	33 311	35.91	17.09
Oct	7.4 (±0.9)	31	19 170	16.75	4.59
Nov	7.9 (±1.0)	30	20 472	16.23	4.75
Dec	30.1 (±6.6)	31	77 971	26.27	29.26
2012				19.2	201
Jan	28.6 (±9.1)	31	74 010	37.03	39.15
Feb	19.5 (±12.6)	29	50 418	59.06	42.54
Mar	19.3 (±13.0)	31	50 115	14.93	10.69
Apr	32.5 (±0)	30	84 240	48.36	58.20
May	27.6 (±10.1)	31	71 407	9.39	9.57
Jun	1.9 (±2.9)	30	4965	19.25	1.37
Jul	5.0 (±9.4)	31	12 847	30.35	5.57
Aug	13.5 (±13.4)	31	34 963	25.60	12.79
Sep	1.4 (±2.8)	30	3548	28.93	1.47
Oct	8.1 (±7.8)	31	20 854	24.48	7.29
Nov	18.2 (±12.9)	25	47 140	18.77	12.64

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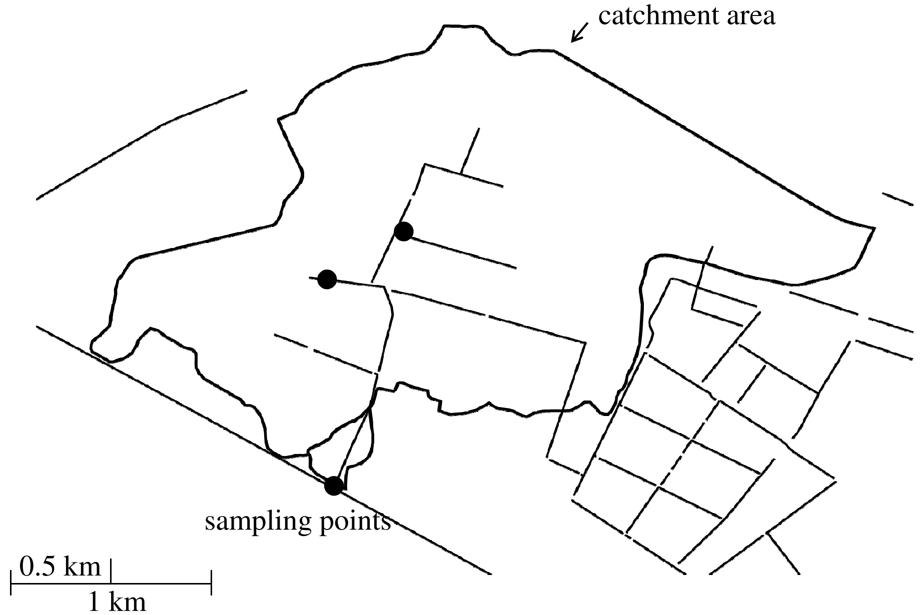

Fig. 1. Catchment area of Site AU.

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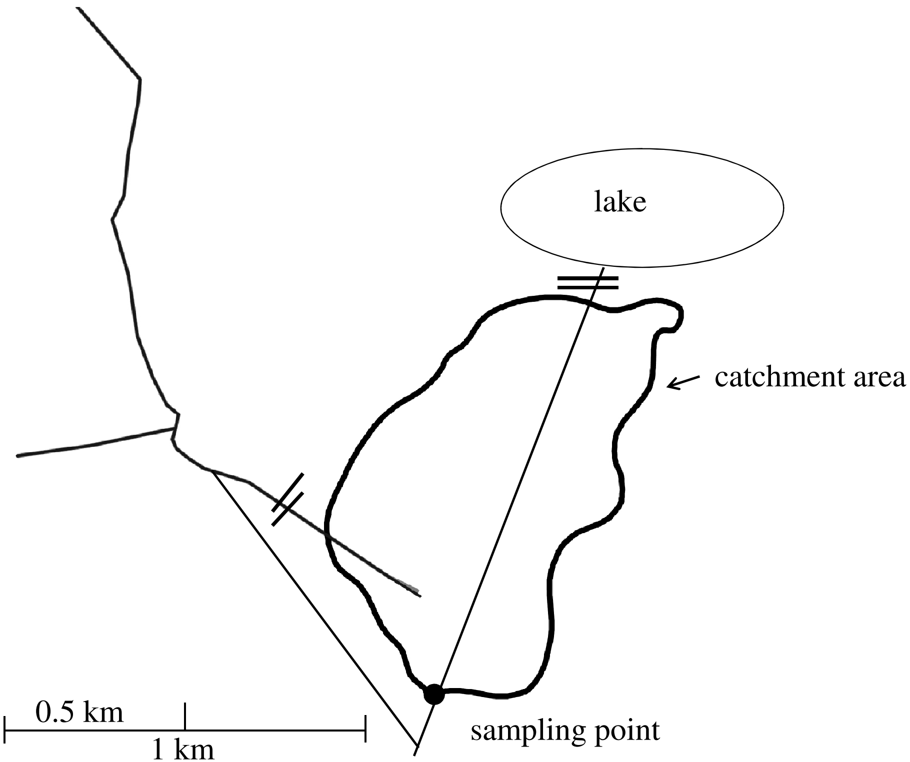

Fig. 2. Catchment area of Site RE.

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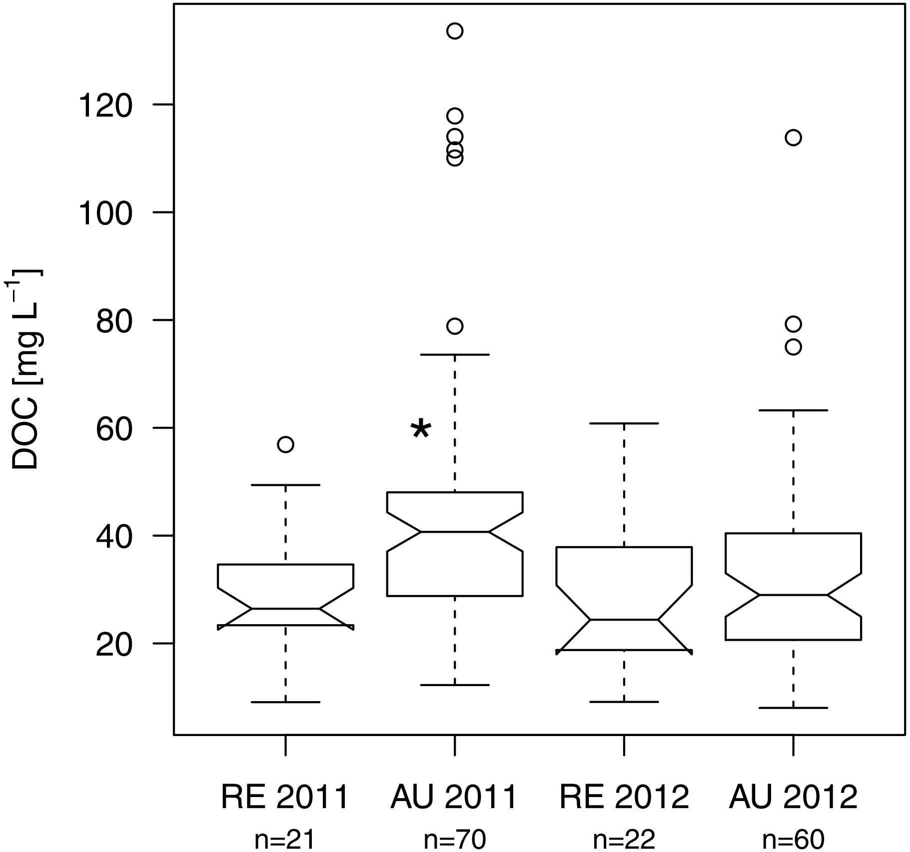

Fig. 3. Boxplot of DOC concentrations in ditches of both sites during two years (RE = rewetted, AU = agriculturally used). The horizontal line is representing the median, the box shows the lower and upper quartile, points are extreme values, significance is denoted by asterisks.

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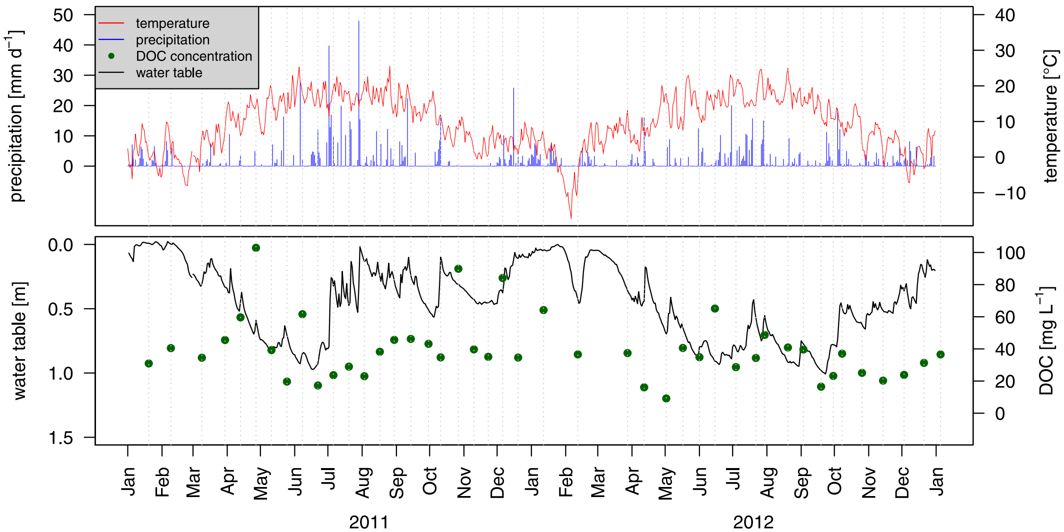

Fig. 4. Agriculturally used site: temperature, precipitation, water table depth and DOC concentration during the study period (monthly average).

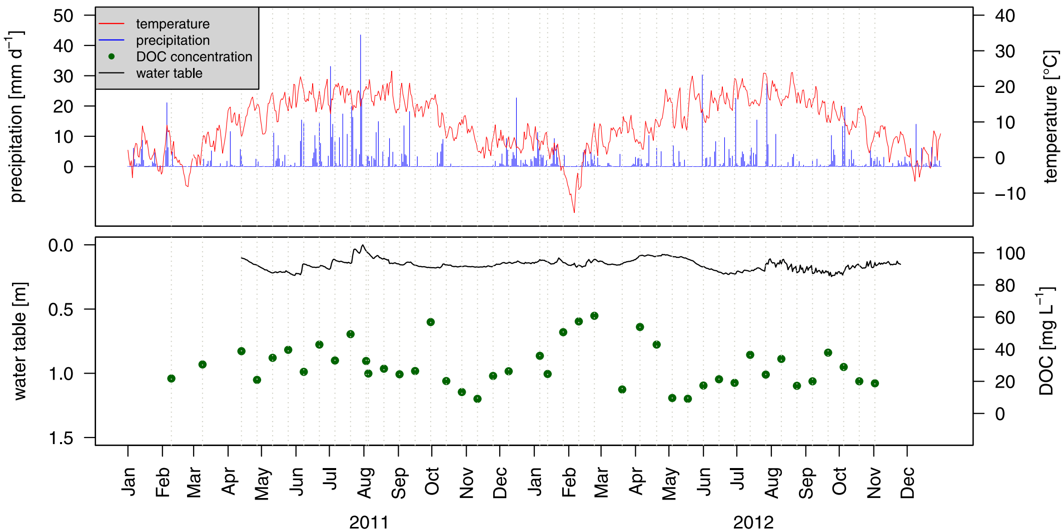

Fig. 5. Rewetted site: temperature, precipitation, water table depth and DOC concentration during the study period (monthly average).

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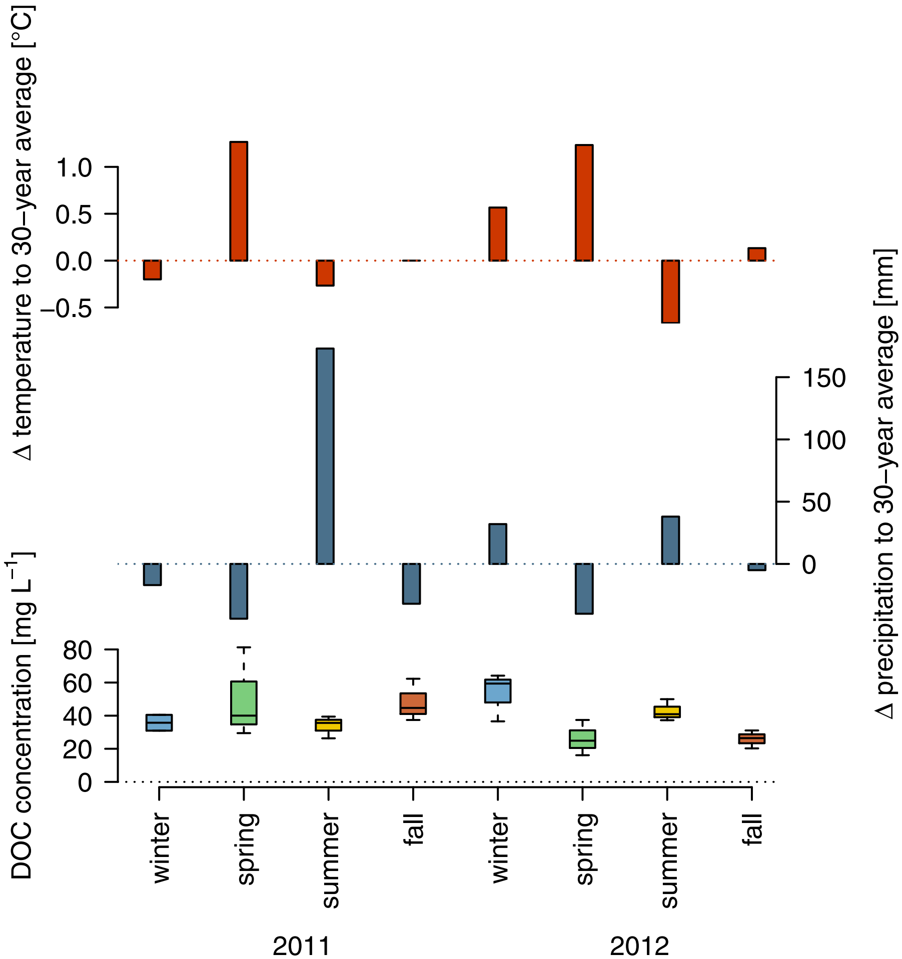

Fig. 6. DOC concentration by season and difference of temperature/precipitation to long-term average at Site AU (winter = DJF, spring = MAM, summer = JJA, fall = SON).

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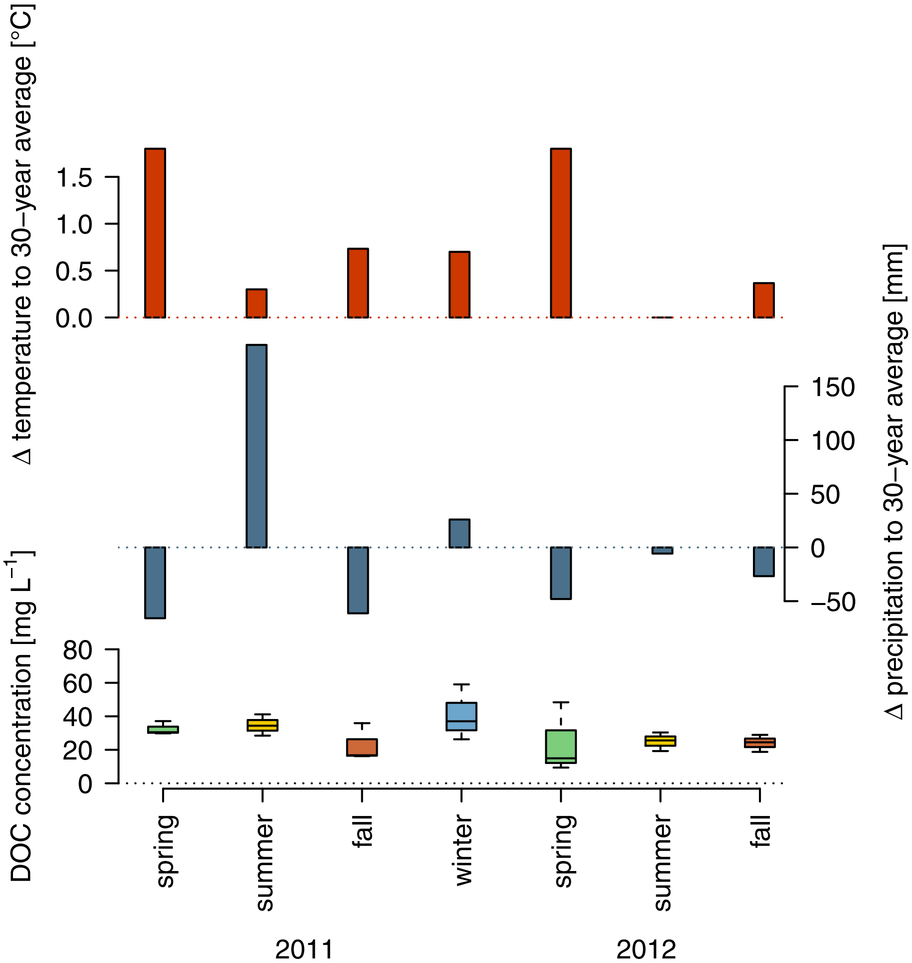

Fig. 7. DOC concentration by season and difference of temperature/precipitation to long-term average at Site RE (winter = DJF, spring = MAM, summer = JJA, fall = SON).

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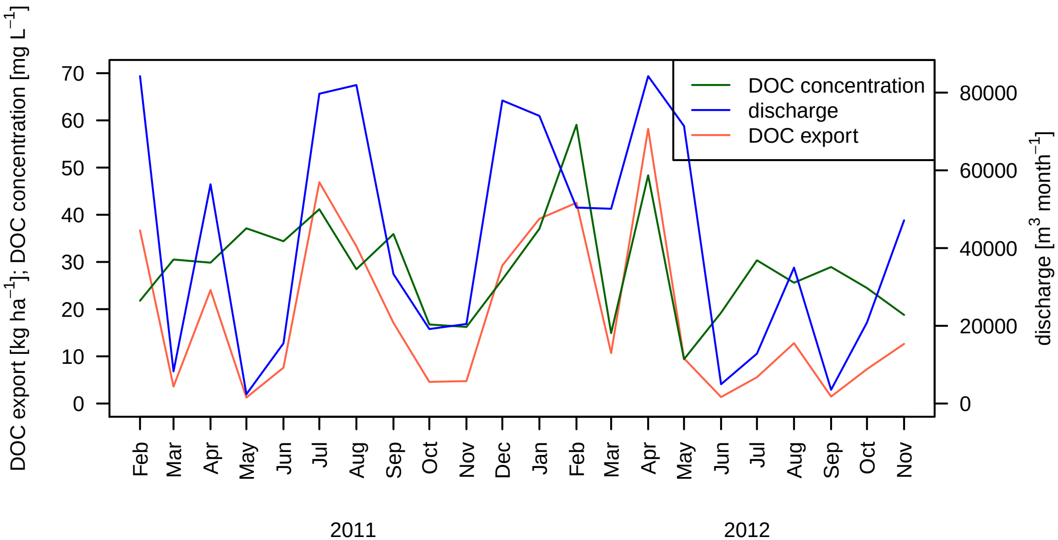

Fig. 8. Monthly averaged DOC concentration, discharge and DOC export at the rewetted site.

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