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The relevance of particulate organic carbon (POC) for carbon composition in the pore water of drained and rewetted fens of the "Donauried" (South-Germany)

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Abstract

Numerous studies have dealt with carbon (C) concentrations in Histosols, but there are no studies quantifying the relative importance of all individual C components in pore waters. For this study, measurements were made of all the carbon components (i.e., particulate organic carbon, POC; dissolved organic carbon, DOC; dissolved inorganic carbon, DIC; dissolved methane, CH_4) in the soil pore water of a calcareous fen under three different water management regimes (re-wetted, deeply and moderately drained). Pore water was collected weekly or biweekly (April 2004 to April 2006) at depths between 10 and 150 cm.

The main results obtained were: (1) DIC (94–280 mg C l^{-1}) was the main C-component. (2) POC and DOC concentrations in the pore water (14–125 mg C l^{-1} vs. 41–95 mg C l^{-1}) were pari passu. (3) Dissolved CH_4 was the smallest C component (0.005–0.9 mg C l^{-1}). Interestingly, about 30% of the POM particles were colonized by microbes indicating that they are active in the internal C transfer in the soil profile ("C-Shuttles"). Consequently, it was concluded that POC is at least as important as DOC for internal soil C turnover. There is no reason to assume significant biochemical differences between POC and DOC as they only differ in size. Therefore, both POC and DOC fractions are essential components of C budgets of peatlands. Furthermore dissolved CO_2 in all forms of DIC apparently is an important part of peatland C-balances.

1 Introduction

The carbon (C) storage in ecosystems and the C balance between the atmosphere and terrestrial ecosystems is vulnerable to changes in environmental conditions (global change). Soils hold the largest C pool of terrestrial ecosystems (IPCC, 2007). To fully understand soil C dynamics and potential feedbacks with the atmosphere, greater insight into the soil internal C dynamics (turnover and pathways) is needed.

Space for internal C dynamics is given in the pore system and the medium is pre-

dominately water. Total carbon (TC) in pore water is composed of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC=CO_2 in all dissociation species), dissolved methane (CH_4), and particulate organic carbon (POC). Organic matter (OM) in pore water is differentiated by size: Particulate organic matter (POM), and in parallel POC, is defined as organic matter in water samples larger than 0.45 μm and dissolved organic matter (DOM), linked to DOC, is defined as organic matter in water samples smaller than 0.45 μm (Zsolnay, 2003).

Most studies on carbon concentrations in Histosols concentrated on DOM and DIC (Billett et al., 2004; Worrall et al., 2005; Fiedler et al., 2006) and POM seems to be the forgotten component. Therefore, the importance of POM is potentially underestimated but there is no study that allowed an estimation of the relative importance of the individual C components in the soil pore water of Histosols. Wet ecosystems can lose a significant fraction of the net carbon uptake via leaching (Neal and Hill, 1994; Waddington and Roulet, 1997; Pastor et al., 2003; Worrall et al., 2003) but it is unknown how much C may be lost via leaching of POC. However, studies about POC in aquatic systems highlight peatlands as a major POC source to the flanking aquatic systems (Bouchard, 2007; Dawson et al., 2004; Laudon et al., 2004). It can be assumed that POC is an important component of the pore waters of Histosols, since it must originate from there, i.e. moving from the peat to the pore water and then to the stream water. Consequently, the objective of this study was to evaluate the temporal and spatial patterns of the individual C components (POC, DOC, DIC and dissolved CH_4) in the pore water profiles of a fen throughout the year along a gradient of water management to achieve first insights into the relative importance of POM compared to the other C fractions.

2 Material and Methods

2.1 Environmental settings

The study site is located in the Donauried fen area near Ulm, Germany (Table 1). The Donauried area extends over 472 km^2 and includes the largest coherent peatland area (30 km^2) in southern Germany. The peatland is fed by productive karst springs (1100–8800 $l\,s^{-1}$) originating from the flanking Swabian Alb (Geyer and Gwinner, 1986). The mean annual air temperature of the study area is 7.7°C, and the mean annual precipitation is 744 mm.

The historical peat layer, which was approximately 7 m thick, has gradually diminished due to anthropogenic interventions over the last 200 years, i.e. lowering of the groundwater level and direct peat removal. Between 1951 and 1990, the average loss of peat was 7.2 mm a^{-1}, (Flinsbach et al., 1997) which is equivalent to 5.67 t C ha^{-1} a^{-1}. In 1966, certain areas within the peatland were protected. Since 1984, an area of approximately 0.5 km^2 has been flooded by regulating water inflow and outflow (11–24 $l\,s^{-1}$). For this study, three anthropogenically affected peatlands (previously used as peat cuts) were investigated (Table 1):

1. a deeply drained fen site (48°29′7.48″ N, 10°11′29.03″ E) with a mean groundwater level (GWL) of −99±37 cm,
2. a moderately drained fen site (48°28′59.63″ N, 10°12′19.50″ E) with a mean GWL of −22±16 cm, and
3. a long-term re-wetted fen site (48°28′59.15″ N, 10°11′51.92″ E), rewetted for ∼20 years, with a mean GWL of −5±12 cm (Höll, 2007).

The areas can be differentiated by their predominant plant communities resulting from the long-term differences in water supply of the peatland. While mainly *Thypha spec.*,

Carex spec. and *Equisetum spec.* were found on the re-wetted fen, the plant community of the deeply and moderately drained areas were characterised as meadow species (*Lolium perenne* L, *Poa pratensis* and *Festuca ovina*, *Bromus erectus*).

2.2 Sampling

Sampling of freely drained pore water was carried out at weekly (DOC, DIC, CH_4) and biweekly (POC) intervals between April 2004 and April 2006. Samples were collected at different depths (from 10 to 150 cm, Table 1) at the respective sites using slotted PVC wells (3 replicates per depth). Whenever the given soil depth was below the groundwater level, pore water could be collected. The PVC well (10 cm long, outer diameter of 2.5 cm; Stockmann, Warendorf, Germany) was sealed at both ends and coated with filter gauze (32–60 PP, Eijkelkamp, Giesbeek, Netherlands) in order to prevent coarse particles (>2 mm) from entering. A stainless steel capillary (3×0.5 mm; Hero, Berlin, Germany) was inserted from the top of the centre of the tube. The end of the capillary was closed using a three-way stop-cock (Fleischhacker, Schwerte, Germany).

The pore-water samplers were inserted to pre-defined depths using a stab drill. The hollow space above the well was filled with a mixture of peat and coarse sand. In order to determine DIC and dissolved CH_4, the samples were introduced through the three-way stop-cock using evacuated N_2- rinsed vacutainer (22.5 ml; Altmann-Analysentechnik, Holzkirchen, Germany). This technique is specific for the sampling of freely drained pore water under water-saturated conditions. The carbonates were converted to CO_2 by the injection of 0.5 ml H_2SO_4 (10%) into the vacutainer being half filled with sample solution. Pore water was subsequently removed with a syringe (Omnifix, 50 ml; VWR, Bruchsal, Germany) in order to determine TOC and DOC. On return to the laboratory all samples were shaken and half of these samples were filtered (0.45 μm pore size, PET45/25; Macherey-Nagel, Düren, Germany) to determine DOC. Samples for DOC and TOC analysis were stored at 4°C and analysed the next day. POC was calculated as the difference between TOC and DOC. Total carbon (TC) in the pore water was calculated as sum of POC, DOC, DIC, and CH_4.

Water samples for straining POC particles were taken twice in autumn at the moderately drained fen at 20, 40 and 60 cm depth.

Additionally samples were collected for analysis of size distribution of POM (July, August and November 2006) at the moderately drained fen and re-wetted fen at depths between 10 and 60 cm.

The samples for the $\delta^{13}C_{DIC}$ were collected in April 2005. The $\delta^{13}C$ of CO_2 in the unsaturated soil pores was collected in evacuated vacutainers (more details see Höll, 2007). The DIC was converted to CO_2 by acidification with 85% H_3PO_4 and stored under N_2. For sampling groundwater and water from the karst aquifer we could kindly use the deep wells of the local water supply company (Zweckverband Landeswasserversorgung). The $\delta^{13}C_{DIC}$ was determined in the same way as $\delta^{13}C$ of CO_2.

2.3 Analyses

CH_4 and DIC as CO_2 were analysed in the headspace of the vacutainers by gas chromatography (CH_4: FID, CO_2: ECD and FID with methanizer; PE Autosystem XL Gas Chromatograph, Perkin Elmer, Wellesky, MA, USA). External standards for CH_4 and CO_2 were used to calibrate the system at 1, 101, 1024 ppm CH_4; 293, 14890, 2983 ppm CO_2. The volume-related back calculation (mg l^{-1}) was made using the Bunsen solubility coefficient (Clever and Young, 1986, for more details see Fiedler et al., 2006).

Organic carbon of pore water (with and without filtration) was analysed using a DIMATOC 100 (Dimatec, Essen, Germany). All samples were continuously homogenised by a magnetic stirrer during the measurement. Two external standards for TOC were used to calibrate the system.

The size distribution (0.45 μm to 2000 μm) was measured using a laser diffractometer (Coulter LS200; Fa. Beckmann, Krefeld, Germany). The sum frequency distribution was made on the assumption that all particles were spherical (Coulter Software, Vers. 3.01).

The water samples for straining POC particles were filtered using a 2 μm nylon membrane (Millipore, Germany). Standard fixation and dehydration procedures (Amann et

al., 1990) were slightly modified, according to Assmus et al. (1995). Filters were transferred to a fixation buffer (4% paraformaldehyde in PBS) and fixed for 2 h at 28°C. The samples were washed and dehydrated in 50, 80, and 96% ethanol (5 min each). Filters were stained with the DNA-specific dye DAPI (Sigma, Germany). DAPI was stored in a 0.35 mg ml^{-1} aqueous stock solution at 4°C. For staining, the stock solution was diluted 500-fold in distilled water and 20 ml of the working solution was applied to each filter. After incubation for 10 min at room temperature, the filters were rinsed with distilled water and air dried. Afterwards the filters were transferred to slides and mounted in antifading solution (Johnson et al., 1981). Epifluorescence microscopy was performed with an Axioplan microscope (Zeiss, Germany) supplying an excitation wavelength at 365 nm.

For isotope measurements, samples were injected in gas tight flasks (volume 1 ml). The δ^{13}C-ratios were determined on a continuous flow isotope ratio mass spectrometer (IRMS), (DELTAplus XP, Thermo Finnigan, Bremen, Germany) which was equipped with a GasBench II for automatically analysing dissolved inorganic carbon (DIC) and gases at the Max-Planck Institute for Biogeochemistry (Jena, Germany).

2.4 Statistical Analyses

Non-parametric analyses were used since the data were not normally distributed (Sharpo-Wilks' W Test) and could not be transformed. The Mann-Whitney (U) Test was used to detect significant (α=1%) differences between individual sites and depths. Analyses were made using Statistica 6.0 (StatSoft Inc., Tulsa, USA).

3 Results

3.1 Distribution of C components

3.1.1 Spatial pattern

The site specific position of the groundwater level did not affect the concentrations of total carbon (TC) (around 300 mg C l^{-1}) in pore waters.

The mean POC concentrations ranged from 14 to 125 mg l^{-1} (Table 1). No statistically significant trends in sites and depths were found, even though concentrations tended to be lower with increasing soil depth (moderately drained and re-wetted fen). The highest concentrations were systematically found at the depth of the site-specific mean groundwater table (deeply drained −150 cm, 125 mg C l^{-1}; moderately drained, between −20 and −40 cm, 67–74 mg C l^{-1}; re-wetted fen −10 cm, 72 mg C l^{-1}). The POC fraction of TC varied between 15 and 30% (Fig. 1). In the re-wetted and moderately drained peatland, the POC proportion was similar to DOC. In the deeply drained fen POC tended to be lower than DOC.

Generally, POC concentrations tended to be lower with increasing distance to the overlying water table.

DOC concentrations decreased with increasing wetness of the site, i.e., DOC concentrations were lowest in the re-wetted fen (around 50 mg C l^{-1}). The mean DOC concentrations in drained areas ranged between 72 and 95 mg C l^{-1} and were irregularly distributed in depth.

At all sites, the most important C component of pore water (up to 280 mg C l^{-1}) was dissolved inorganic carbon. The DIC proportion increased with increasing wetness of the site i.e., deeply drained (50–60%) < moderately drained (up to 70%) < re-wetted fen (75% of TC) and increasing depth (Fig. 1). DIC concentrations significantly increased with soil depth (Table 1), where in some cases DIC concentrations were two-fold higher than in the upper horizon (189 vs. 94 mg C l^{-1} in moderately drained fen).

Dissolved CH_4 had the lowest concentrations of all C components (~0.1% of TC

in pore waters). The mean CH_4 concentrations ranged from 0.005 to 0.006 mg C l^{-1} (deeply drained fen), 0.005 to 0.196 mg C l^{-1} (moderately drained fen), and 0.363 to 0.175 mg C l^{-1} (re-wetted fen), respectively.

3.1.2 Temporal pattern

Neither the total C concentrations nor the POC, DOC, and DIC concentrations revealed a statistically significant dependence on soil temperature, precipitation or groundwater level. Dependence was particularly expected at the upper soil layers. However, groundwater tables tended to be low when air temperatures were high. Consequently, the number of samples and the temporal coverage of the topsoil levels for higher temperatures were significantly lower than for lower temperatures. Additionally, the temperature amplitude in greater depths with constant water saturation was dampened.

Beside irregular seasonal dynamics distinct but non-significant trends between the two years of study were found. In both years, the rainfall was lower than the long-term mean of 744 mm (580 mm from April 2004 to March 2005, and 685 mm from April 2005 to March 2006). The lower precipitation in the first study period led to considerably lower groundwater levels compared to the second year (GWL: re-wetted fen −9, period 2004/2005 vs. 0 cm, period 2005/2006); moderately drained fen −29 vs. −19 cm, deeply drained fen −125 vs. −75 cm). The deeper the drainage, the larger were the differences in mean groundwater tables between the two years.

Relatively high TC concentrations were measured in both years (300 mg C l^{-1}). In the re-wetted fen mean POC concentrations were mostly around 50 mg C l^{-1}, with the exception in 10 cm depth where mean concentrations ranged between 75 mg C l^{-1} (wetter period) and 105 mg C l^{-1} (drier period). Lower mean POC concentrations in the wetter period than in the drier period were also found in all depths of the moderately drained fen (37 to 73 mg C l^{-1}, period 2005/2006 vs. 56 to 114 mg C l^{-1}, period 2004/2005). However, in the deeply drained fen higher POC concentrations were found in the drier than in the wetter period (except in 150 cm depth).

The inter-annual variation for DOC concentrations was similar to POC. In the wetter period, higher DOC concentrations were found in the deeply drained fen (except in 150 cm depth), while lower concentration were observed in the moderately drained (66 to 87 mg C l^{-1}, period 2005/2006 vs. 81 to 92 mg C l^{-1}, period 2004/2005) and rewetted fen (37 to 49 mg C l^{-1} vs. 52 to 64 mg C l^{-1}).

In the wetter year, the proportion of DIC of TC in the pore water was higher (51–79%) at all sites and depths than in the drier year (26 to 73%). In the moderately drained fen this trend was more pronounced than in the rewetted and deeply drained fen.

The δ^{13}C values of DIC ranged between −16.7±0.6 and −18.4±0.6, and were lower than those in the aquatic system (karst spring −14.3±0.1, surface water −11.7 to −13.0±0.8), but higher than those of the CO_2 of the gaseous phase in pores (−23.9±1.3 to −26.6±0.4) (Table 2).

3.2 Characterization of POM

3.2.1 Particle size distribution of the POM fraction

The particle size distribution of POM at the re-wetted fen was rather uniform regardless of sampling depth or time (Fig. 2a). In the re-wetted fen, 75–95% of all particles were smaller than 1 μm. The moderately drained fen (Fig. 2b) had larger particles (60–100%>1 μm) than the re-wetted fen. In particular the rewetting of the area after a longer dry period (see Fig. 2b, 20 cm, August) led to very large particles of >20 μm (100%) in the pore waters.

3.2.2 Colonization by microbes

Microbes could be detected on about 30% of the POM particles >1 μm. A rough calculation based on the microscopic images revealed different colonization patterns in relation to the depth of the particles. In tendency more particles from the upper layers were colonized by microbes compared to deeper layers. In contrast the number of microbes

per particle was more related to the size of the particles than to the depth. Smaller particles were colonized by 5–10 microbes, whereas on larger particles (>10μm) more microbes could be localized. Most of the microbes localized on the POM particles were rod shaped and single cells, which formed microcolonies, indicative of bacteria or Archaea. Typical filamentous fungi were not observed. An example of a colonized POM particle is given in Fig. 3.

4 Discussion

4.1 POC and DOC are pari passu

The first simple "take-home-message" of this study is that POC occurs in similar concentrations as DOC in the pore waters. Therefore it is potentially important for internal C turnover. The mean DOC concentrations of the investigated peat sites exhibit concentrations that are in the same range of published data for drained (81 to 129 mg l^{-1}; Moore and Clarkson, 2007) and re-wetted peatlands (70–100 mg C l^{-1}; Glatzel et al., 2003). Therefore, the Donauried study site does not appear to be an exceptional site and POC values could represent common values. Because of a lack of data from other peat pore waters, we can only compare our data with POC data from open aquatic systems for which DOC/POC ratios from 0.4 to 17 have been reported (Zhang et al., 1992; Dawson et al., 2004; Raymond et al., 2004; Guo and MacDonald, 2006; Bouillon et al., 2007). The mean DOC/POC ratios of the present study ranged between 0.4 and 2.8. This appears rather comparable but since samples from open aquatic systems are taken at some distance from the peat source it can be expected that POC is more depleted in rivers than DOC due to the faster sedimentation of larger heavier particles. Consequently, POC concentrations of aquatic systems reported in the literature were mainly 10 to 1000 times lower (Richey and Victoria, 1993; Hope et al., 1997; Dawson et al., 2002) than the POC concentrations determined in the pore water of our peatland (40 and 125 mg C l^{-1}, Table 1). Comparable high POC concentrations have been found

only in estuaries (134 mg C l^{-1}, Zhang et al., 1992) and in rivers during floods (up to 75 mg C l^{-1}, Meybeck and Helmer, 1989).

4.1.1 Definition of POC

For future investigations we suggest a global agreement on defining DOM <0.45 μm and POM >0.45 μm (Zsolnay, 2003) which would guarantee a direct comparison of the data between DOC studies. Past studies sometimes defined POC as particles >0.7 μm (Hope et al., 1997; Billett et al., 2004; Dawson et al., 2004; Kardjilov et al., 2006) or >0.8 μm (Raymond et al., 2004). The use of 0.7 μm filter pore size for this study would have reduced the results for POC concentrations by 20 to 85%.

Other studies also defined an upper limit for the size of POC, e.g. Chow et al. (2005) proposed 1.2 μm and Michalzik and Stadler (2005) used 2 mm as an upper limit. Our study demonstrated that flooding of soil horizons releases large particles and that particle sizes may vary over a wide range. Therefore, we propose that no upper size limit of POC is defined since an important mobile C fraction would be missed in the pore water dynamics of peat. For instance, 10 to 100% of the POC in our study was too large to fit in the definition range of Chow et al. (2005).

4.1.2 Origin and biochemical composition of POM and DOM

Both DOM and POM are composed of aggregated colloids, organic filaments, cell fragments, microbial biomass (e.g., algae and bacteria) (Ranville and Schmiermund, 1998). POM may form from aggregation of DOM (Kerner et al., 2003). Consequently, there is no reason to assume that DOM and POM differ substantially in their biochemical composition. The preferential presence of large particles (>20 μm) after re-wetting and generally higher POC concentrations in the zone of intensive dry / wet cycles suggest that POM of this study mainly originated from mechanical ablation of the peat. However, high and relatively constant POC concentrations in the permanently water-saturated areas suggest further mechanisms for the formation of POM. Microbes may

play an important role in POM dynamics. Polysaccharide producing microbes can lead to the formation of particles >2 μm. According to Petry (2004), this can lead to a POC increase of 8–72% in waters. Using a DAPI stain it was possible to detect microbes on the particles. Interestingly, only one third of the particles was colonized by microbes, suggesting differences in substrate quality of the POM. However, DAPI staining does not differentiate between active, inactive or dead cells. It is therefore still unclear if the microbes detected on the POM particles were actively metabolizing and functionally important for POM turnover. Therefore, the activity status of microbes colonizing POM particles and consequently the significance of bacteria fungi and Archaea for the stability of POM has to be investigated in further experiments using molecular tools. Nevertheless our results suggest that POM may function as an important internal shuttle for C and associated organisms.

4.2 Sources of DIC – the largest component of TC

DIC was the largest C component of the investigated pore waters. The high DIC concentrations resulted from a surplus of CO_2 derived from the feeding karst waters (geogenic carbon) and the accumulation of biogenic CO_2. The distribution of $\delta^{13}C$ values shows the expected distinct variations among the samples. The $\delta^{13}C$ values determined for CO_2 in the gaseous phase (from −23.0 to −25.1) in the Histosols were close to the isotopic signature of decomposed C-3 vegetation in soils (−25) (Deines, 1980). Signatures of the different samples of the aquatic systems were comparable to those reported from other aquatic systems, including streams (−13.9), springs (−14.2), groundwater (−13.7), and soil water (−16.3) (Pan et al., 2002; Marfia et al., 2004). The $\delta^{13}C$ values for DIC of the pore waters (−16.7 to −18.4) were lower than values of aquatic system and higher than CO_2 of the gaseous phase of pore space (up to −26.6±0.4). This reveals that the DIC of the pore waters in our site does not exclusively originate from accumulated CO_2 of in situ microbial activity but also from the karst water feeding the fen. Unfortunately, it is not possible to separate this mixed

signal into the two sources, since we neither know the production rates of CO_2 in the soils nor could we determine the proportion of the karst water that really reaches the measurement plots.

The mean DIC concentrations (94–280 mg C l^{-1}) of the pore waters investigated were higher than concentrations found in soil solutions of other studies (30–113 mg C l^{-1}, Marfia et al., 2004; Sigfusson et al., 2006) or aquatic systems (<15 mg C l^{-1}, Hoffer-French and Hermann, 1989; Huttunen et al., 2002, Billett et al., 2004; Dawson et al., 2004). In this study, the highest DIC concentrations were observed in the re-wetted fen in the permanently water-saturated horizons. We attribute a significant share of the DIC to the use of DIC-rich karst water for re-wetting because DIC in the re-wetted fen showed the highest δ^{13}C values (−16.7±0.6).

4.3 CH_4 – the smallest and most dynamic component

Dissolved CH_4 exhibited the lowest concentrations of all C components varying around 0.1% of TC in pore waters. Nevertheless, the values represent super-saturation of CH_4 of up to 100 000 fold compared to atmospheric equilibrium concentration. Methane amounts might not be important for sub-surface C-budgets, but CH_4 concentrations are highly variable in time and space. Fiedler et al. (2005) reported CH_4 concentrations in pore water of hydric soils of up to 1.8 mg C l^{-1}. Consequently, CH_4 must be considered for the understanding of C turnover in peat soils. Small CH_4 pools in the soil solution measured synchronously to net CH_4 emissions at the soil surface (data not shown) also point to fast escape from the production zone to the atmosphere or indicate high turnover rates.

5 Conclusions

There is a sharp discrepancy in the attention that is brought about to DOC as compared to POC that was hardly considered. This study exhibited that POC and DOC were at

least equally relevant for the carbon composition in the pore water of the studied Histosols. Independent of water management the POC fraction reached means of up to 30% of TC while DOC had means of up to 35% of TC in pore waters. Our results furthermore suggest that DOC and POC represent a size continuum of the same organic matter and need to be studied together to understand their ecological function in the ecosystem. From both a quantitative and qualitative point of view, results suggest that POC is an essential C fraction for internal soil C turnover. However, the POC fraction is a black box up to now. It is only certain that POM particles were colonized by microbes and therefore it is highly likely that it is part of the more labile active carbon pool that is essential for rapid carbon turnover. For this study, it was impossible to derive a mechanistic model explaining POM concentration dynamics because neither spatial nor temporal patterns were significantly correlated with environmental parameters such groundwater level, soil temperature or precipitation. Given the importance of POM within the C budget of peatlands, more data sets over a longer period than two years are needed. The ultimate fate of POM in pore waters of Histosols demands greater consideration when calculating C budgets, particularly the extent to which POM is exported to aquatic systems, or undergoes degradation and returns to the atmospheric C pool.

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Table 1. Descriptive statistics of C components in pore water and characteristics of the Histosols of the Donauried study site. The sampling period was 1 April 2004 to 31 March 2006. Means, standard deviations (SD) and sample numbers (n) of all measured values are shown; statistically significant differences between sites and depth for each carbon component are indicated by different letters (p<1%), n.d.=not defined.

Depth [cm]	BD	H	$CaCO_3$	C_{org}	N_t	Time with water saturation	TOC (DOC+POC) mean±SD(n)	POC mean±SD (n)	DOC mean±SD (n)	DIC mean±SD (n)
	[g cm^{-3}]		[g kg^{-1}]			[%]	[mg C l^{-1}]			
Deeply drained fen (Foli-Calcic Histosol); extensive grassland since about 25 years										
−10	0.31	H10	69	407	28	0	n.d.	n.d.	n.d.	n.d.
−20	0.29	H9-10	84	397	26	0	n.d.	n.d.	n.d.	n.d.
−40*	0.22	–	820	189	2.5	5	90±23 (9)^{b,d,h}	14±14 (9)^{A,B}	86±34 (17)^{A,B}	126±76 (21)^{h,k}
−60	0.18	H6	70	451	25	16	101±39 (26)^{c,d,e}	30±39 (26)^{A,B}	81±27 (49)^{A,C}	152±77 (91)^{g,h}
−80**	0.39	–	22	86	5.0	33	132±40 (44)^{g,h}	45±36 (44)^{A}	95±25 (68)^{A}	176±71 (74)^{e,f}
−150***	–	–	–	–	–	87	130±74 (61)^{d,f,h}	125±166 (61)^{A}	72±30 (97)^{A}	280±111 (212)^{a}
Moderately drained fen, (Calcari-Fibric Histosol); extensive sheep pasture, nature protection area since 1992										
−10	0.24	H9	62	406	36	29	115±59 (15)^{d,c,h}	55±63 (15)^{A,B}	73±30 (41)^{A,B}	94±46 (78)^{k}
−20	0.21	H6	49	425	27	52	141±94 (52)^{d,h}	74±94 (52)^{A}	79±29 (81)^{B,C}	152±78 (121)^{f,h}
−40	0.13	H5	41	465	24	86	138±122 (56)^{h}	67±121 (56)^{A}	88±33 (104)^{B,C}	173±85 (177)^{f,g}
−60	0.17	H5	29	469	23	97	104±41 (79)^{d,f}	38±36 (79)^{A,B}	76 ± 29 (129)^{B}	189 ± 69 (212)^{e}
Re-wetted fen, (Calcari-Sapric Histosol); nature protection area since 1972										
−10	0.17	H9	57	398	31	91	107±89 (53)^{c,b,f}	72±87 (53)^{A}	41±21 (80)^{D}	193±72 (116)^{d,e}
−20	0.20	H9	56	414	33	94	90±53 (65)^{b,e,g}	46±53 (65)^{A,B}	50±24 (121)^{D}	222±88 (201)^{c,d}
−40	0.21	H7	47	407	32	97	81±53 (55)^{a,b}	46±26 (55)^{A,B}	52±34 (117)^{D}	249±79 (188)^{a,b}
−60	0.16	H7	51	498	27	100	73±51 (57)^{a}	37±52 (57)^{B}	55±41 (126)^{D}	231±66 (208)^{b,c}

H humification index (according to von Post), *calcareous horizon (Kalkmudde), **silty horizon (Schluffmudde), ***gravel aquifer

Table 2. Isotopic ratios of dissolved inorganic carbon and CO_2 of gaseous phase (average above all depth, n=sample numbers).

	δ^{13}C-ratios [‰]			
	Deeply drained fen	Moderately drained fen	Re-wetted fen	Hydrosphere
Pore water	−17.9±0.7 (n=10)	−18.4±0.6 (n=10)	−16.7±0.6 (n=10)	
Groundwater				−11.8±0.2 (n=3)
Karst groundwater				−12.4±0.1 (n=3)
Karst spring				−14.3±0.1 (n=3)
Drainage ditch				−16.7±0.6 (n=10)
River (Nau) close to fens				−13.0±0.8 (n=5)
Gaseous phase in pores	−26.2±1.2 (n=13)	−26.6±0.4 (n=14)	−23.9±1.3 (n=14)	

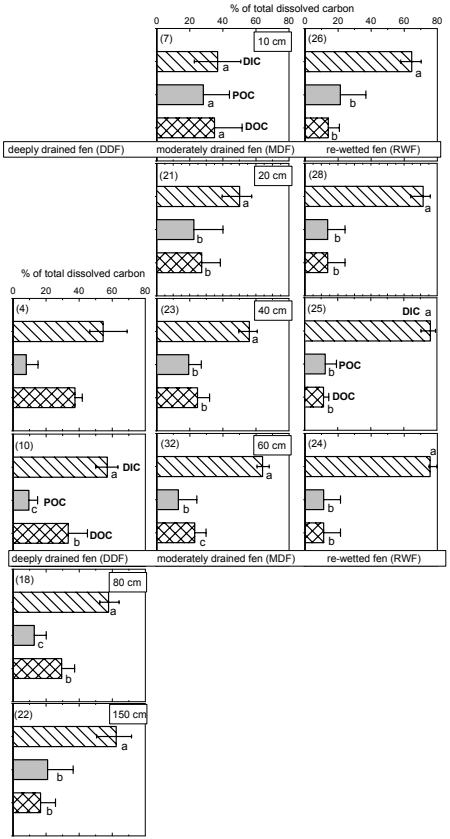

Fig. 1. Relative contribution of each C-component [%] with regard to the overall annual dissolved C content (numbers in brackets are dates of measurements). Statistically significant differences between C-components are indicated by different letters.

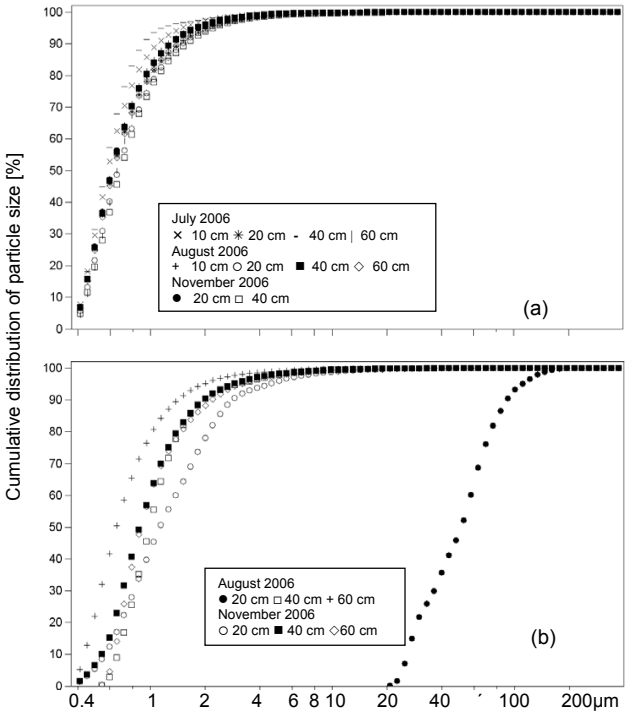

Fig. 2. Sum curves [cumulative %] of particle size in the POM fraction (>0.45 μm) at different managed peatlands of the Donauried (Germany), **(a)** re-wetted fen, **(b)** moderately drained fen at distinct sampling depths and times.

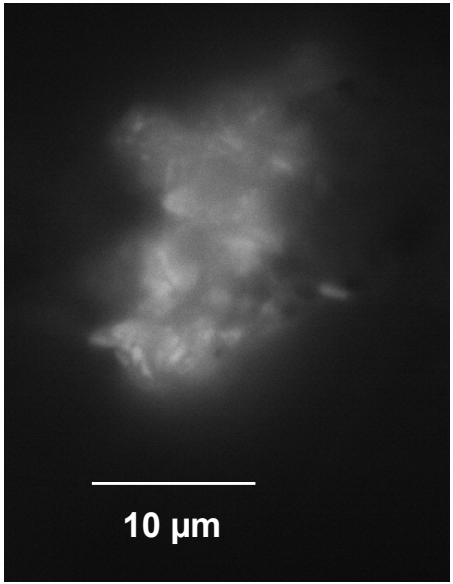

Fig. 3. DAPI staining POC particle (>0.45μm) from water sample collected from moderately drained fen collected in 40 cm below surface. The photo shows a microcolony of about 5–10 cells on particle.