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Controls on dissolved organic carbon export through surface runoff from loamy agricultural soils

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ABSTRACT

Dissolved organic carbon (DOC) is one of the most active and mobile carbon pools, and thus an important component of the global carbon cycle. Previous research on DOC transport in the soil and on factors controlling DOC export towards the river system focused mainly on forest and wetland areas, with only limited information available from agricultural soils. We carried out rainfall simulations on agricultural field sites to identify the effect of soil properties, field characteristics and hydrological conditions on DOC export by surface runoff from loamy agricultural soils. Furthermore, the temporal evolution of DOC concentrations and specific UV absorbance (SUVA) values in runoff water during a rainfall event was monitored. Additional rainfall simulations in the lab allowed to investigate the effects of drop impact, crop residue incorporation and drying–rewetting of the soil on DOC concentrations and SUVA values in both runoff and percolation water.

DOC concentrations were the highest and SUVA values the lowest at the start of a rainfall event, both in runoff and percolation water. Afterwards, DOC concentrations diminished and SUVA values rose to steady values towards the end of the experiments. Overall, rainfall conditions prior to the experiment showed to be a major control on DOC concentrations and quality in runoff water from agricultural fields. Smaller rainfall depths before the experiment and lower initial soil moisture content led to high concentrations of low aromatic DOC in the runoff water. This drying–rewetting effect on DOC concentrations and quality was also observed in the lab for percolation water. For the range of considered soil types, only a limited effect of soil and field characteristics on DOC concentrations and quality in runoff was observed. The effect of reduced tillage on DOC concentrations in surface runoff was ambiguous, with effects differing between experimental field sites.

1. Introduction

Dissolved organic carbon (DOC) is one of the most active and mobile carbon pools and consequently plays an important role in the global carbon cycle (Jardine et al., 2006). Due to its high mobility and reactivity, it plays a significant role in the cycling and distribution of nutrients and carbon both within and between ecosystems. Dissolved organic matter provides energy and nutrients to biota, but can also increase the bioavailability of trace metals or organic pollutants (Kalbitz et al., 2000). In drinking water production, it can lead to the formation of unwanted disinfection by-products, such as trihalomethanes (Liang and Singer, 2003). The yearly flux of DOC from land to the oceans was estimated to be ± 0.4 Pg C year^{-1} (Aitkenhead and Mcdowell, 2000), about half the current net terrestrial uptake of ± 0.9 Pg C year^{-1} (Regnier et al., 2013).

Over the last decades, increasing DOC concentrations have been reported in the surface waters of agricultural areas. The causal factors remain unclear (Evans et al., 2005; Freeman et al., 2004; Gruau and Jardé, 2005) as most research on DOC transport in soils and on factors controlling DOC export towards the river system focused on forests and wetland areas. Results from agricultural sites remain scarce. Although DOC concentrations in the soil typically decrease with land use from forest soils over grassland soils to arable soils (Chantigny, 2003), agricultural systems deserve our increased attention. In agricultural catchments, the proportion of low molecular weight DOC is larger than in natural or forested catchments (Cronan et al., 1999). As a strong relationship exists between DOC flux and soil C/N on a catchment scale (Aitkenhead and Mcdowell, 2000), the transition from a natural system to an agricultural system with typically lower C/N, will likely alter the DOC dynamics.

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De Troyer (2011) has studied the vertical flux of DOC in agricultural land, and the soil characteristics controlling this export. Examining pore waters of different agricultural soils, it was found that soil properties can only weakly explain DOC concentrations in the soil solution. Likewise, data from her field study indicated a limited effect of environmental conditions and land management practices on DOC concentrations in vertical transport. Instead, vertical DOC transport was mainly controlled by the water flux. This confirmed the findings of Mertens et al. (2007) and Don and Schulze (2008), who showed the DOC export from agricultural and grassland soils to be primarily determined by the hydrological regime, rather than by the factors thought to control the production of DOC.

However, agricultural land use does not only lead to changes in DOC dynamics within the soil, but also leads to significant surface runoff and thereby enables a new pathway for DOC transfer from terrestrial to aquatic systems. At present, limited information is available on DOC transport by surface runoff. Rainfall experiments with undisturbed soil samples in the lab showed significantly lower DOC concentrations in runoff than in percolating water (Bajracharya et al., 1998), indicating that a shift in hydrological pathways could alter DOC delivery to streams. DOC concentrations in both runoff and percolation water peaked at the onset of the experiments and diminished toward the end of the event. This suggests that accumulated soluble organic C is rapidly flushed upon rewetting of the soil, both by percolation and runoff water.

Agricultural land is subject to several land management strategies which are successfully applied to increase crop yield and prevent soil degradation, but might also affect the DOC transport. For example, reduced tillage (RT) is being increasingly used as a means to protect soils from erosion and compaction, to conserve soil moisture and to reduce production costs (Holland, 2004). Its effectiveness compared to conventional tillage (CT) in the form of classic mouldboard ploughing for runoff and soil loss reduction in the Belgian Loam Belt has been demonstrated by Leys et al. (2007, 2010). In terms of soil properties, several studies have shown that the impact of the tillage technique on total soil organic carbon (SOC) content is often limited (Hermle et al., 2008; Van den Putte et al., 2012; VandenBygaart et al., 2003). The vertical distribution of SOC however can differ significantly, with higher SOC content near the soil surface at RT sites compared to more evenly distributed SOC at CT sites (Christopher et al., 2009; Hermle et al., 2008; VandenBygaart et al., 2003). The higher SOC contents in the top few centimeters of the soil at RT sites are explained by low mobilization and accumulation of crop residues at the surface (Bertol et al., 2004, 2007). The labile DOC fraction is even more sensitive to tillage disturbance than total SOC (Roper et al., 2010). Cookson et al. (2008) reported higher DOC levels in no-till and conventional-till in comparison to rotary-tilled soils, both within and across soil depths. On grassland, lower DOC concentrations were found in the surface soil after ploughing, compared to neighboring undisturbed grass strips (Don and Schulze, 2008). In addition, lower specific UV absorbance (SUVA) values, indicating lower aromaticity of DOC in the ploughed areas, showed that not only DOC concentrations but also DOC quality shifted upon ploughing.

Whether this enrichment in both SOC and DOC in the top layer of RT fields affects the DOC in runoff, is not clear. Bertol et al. (2004 & 2007) found particulate organic carbon enrichment in the runoff sediments of RT compared to CT systems. This can be explained by preferential mobilization of the lighter fractions during low-intensity erosion events (Wang et al., 2013). The dynamics of the dissolved fraction of organic matter is also likely to be affected by the tillage technique (Chantigny, 2003). However, to the best of our knowledge, there are no reports on the export of DOC through runoff from fields under different tillage systems.

Consequently, the controls on the transport of DOC through surface runoff from agricultural fields are largely unknown. It is not clear whether DOC concentrations in runoff water from agricultural field are mainly determined by the hydrological regime (as is the case for vertical fluxes), and in what way they are affected by soil properties or management strategies. The effect of these hydrologic, soil and management properties on DOC quality measures such as SUVA is also of major environmental interest, since DOC linked transport of e.g. heavy metals not only depends on concentrations but also on quality of DOC (Amery et al., 2008).

This study aims to define the factors controlling DOC export by surface runoff from loamy agricultural soils and to gain knowledge on the processes releasing DOC into the surface runoff during a rainfall event at the interrill plot scale. The relative importance of different controls is investigated by studying the effect of soil properties (e.g. SOC, texture, bulk density and gravimetric water content), hydrological boundary conditions (e.g. rain intensity) and field characteristics (e.g. crop cover, tillage technique) on DOC concentrations and quality in surface runoff from simulated rainfall experiments in the field. As we hypothesize antecedent soil moisture conditions, raindrop impact and addition of crop residues to be important controlling factors for the release of DOC in the surface runoff, the effect of these controls was studied in more detail using controlled lab experiments.

2. Materials & methods

2.1. Study area

Rainfall experiments were conducted on 6 different arable field sites in the Belgian loam belt (central Belgium). The area receives a mean annual precipitation of ca. 800 mm and has a mean annual air temperature of ca. 9.7 °C. Soils in the study area are mainly loess-derived Luvisols, which are highly susceptible to erosion processes such as rill and interrill erosion. The fertile loess-derived soils are well suited for arable cropping. The main cultivated crops are sugar beet (*Beta vulgaris* L.), maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and potatoes (*Solanum tuberosum* L.). Field sites selected for the rainfall experiments were split into 2 parts under different management. On one part conventional tillage (CT) was applied, which consists of classic mouldboard inversion ploughing; on the other part reduced tillage (RT) was used. Reduced tillage comprised various techniques such as deep non-inversion tillage, shallow non-inversion tillage and direct drilling. On average, RT had been applied on the trial fields for 6 years.

2.2. Field rainfall experiments

Fifty-six field rainfall experiments were conducted in 2010 (Table 1). The majority (45) thereof was done from April to June, shortly after crop emergence. Cultivated crops were winter wheat, barley, sugar beet and maize. On two field sites, experiments were repeated in fall, right after harvest, when soil was bare or planted with a green manure (white mustard, *Sinapis alba* L.). On each field site, three representative locations were selected per tillage technique. Wheel tracks and boundaries were avoided. At these locations, runoff plots of circa 0.85 m by 0.85 m were delineated, by installing metal plot boundaries and a runoff collection gutter (Fig. 1).

For all rainfall experiments, a nozzle-type field rainfall simulator was used (Lechler full-cone nozzle, type 460.788, for more details see Poesen et al., 1990) suspended at 3 m height. At its design intensity of 45 mm h^{-1}, the kinetic energy of the simulated rainfall equals ca. 15 J m^{-2} mm^{-1}, which is ca. 65% of the kinetic energy of natural rainfall occurring at the same intensity (Poesen et al., 1990). Due to variation in wind speed and direction however, the actual rainfall intensity varied and averaged 59 $\pm$ 11 mm h^{-1} ($n = 56$). Raindrop-size distribution and hence rainfall kinetic energy can be expected not to be strongly affected by the actual rainfall intensity as the same nozzle and water pressure were used throughout all experiments. The experiments were done using demineralized water, as advised by Borselli et al.