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Sustained production of dissolved organic carbon and nitrogen in forest floors during continuous leaching

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ABSTRACT

The release of dissolved organic matter (DOM) in forest floors is a dynamic component of organic carbon transformations in forest soils. The biogeochemical processes driving the production and release of dissolved organic carbon and nitrogen (DOC and DON) in forest floors are strongly affected by hydroclimatic conditions during rainfall events. We conducted an exhaustive percolation experiment to examine the pool size and sustained production of mobilizable DOC and DON in Oi, Oe and Oa layers of spruce, larch and beech forest floors. The percolation experiment with small reconstructed soil columns was conducted at 5 and 15 °C for 25 days with a percolation volume equal to 36 mm d^{-1}, adding up to a total percolation volume of 900 mm. Percolates were collected at an interval of 5 days and analyzed for DOC and DON. Simultaneously to the periodic analysis of percolates, the CO_2 release was measured. The sustained release of DOM during the last leaching period from day 20 to 25, after 720 mm of percolation, was defined as the *production rate of DOM*. The cumulative release of DOM was large: in case of the 15 °C treatment, the total amount of DOM extracted for 25 days was on average 1.6% and 2.2% of the total C and N stock, respectively. The largest cumulative release of DOM and CO_2 was observed for the beech samples. The ratio of cumulative CO_2/cumulative DOC release ranged from 1 to 3 for Oi and Oe samples but was < 0.2 for spruce Oa. No changes in DOC/DON ratios as a result of percolation amount were detected. The production rates indicated a rapid replenishment of DOM pools after leaching. The Q_{10} values for the DOM production rates ranged from 2 to 4 and were similar to those for CO_2 production. The positive correlation between DOM and CO_2 production rates in Oi and Oe samples highlights the importance of microbial activity for DOM release. The pool of mobilizable DOM in forest floors seems large enough to provide a sustained rate of DOM release throughout precipitation events under field conditions although the actual rate of mobilization may vary in the field, depending on antecedent conditions and the duration and intensity of the rainfall event.

1. Introduction

In forest soils, the forest floor is the primary source of dissolved organic matter (DOM) and forest floor percolates provide substantial carbon inputs into the underlying mineral soil, influencing C stocks and microbial live as an energy source (Borken et al., 2011; Camino-Serrano et al., 2014; Inamdar et al., 2011; Michalzik et al., 2001; Wu et al., 2014). The current fluxes of DOM from forest floors can be seen as the partial mobilization from a relatively large pool of potential DOM, the latter being build up by the decomposition of soil organic matter (SOM) (Park and Matzner, 2003). The release of DOM from SOM is a rather complicated process as it is driven by biological, physicochemical and hydrological processes. Microbial activity (Michel and Matzner, 2002) and root exudation (Giesler et al., 2007) are examples of biological control. Regarding physicochemical drivers, pH and ionic strength of the soil solution determine the surface charge and solubility of SOM (Clark et al., 2005; Deb and Shukla, 2011; Moldan et al., 2012; Naidu et al., 1994). Because of the complexity of the processes involved and their interactions, DOM dynamics have been often neglected in simulation models of SOM. The dynamic modelling of DOM fluxes is also hampered by conceptual deficits and the lack of empirical data describing the pool of potential DOM and its dynamics in terms of depletion and production.

The dynamics of rainfall and soil water fluxes are key drivers for the in situ fluxes of DOM. A strong positive linear correlation between fluxes of DOM from forest floors and water fluxes was reported in many

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field studies (Borken et al., 2011; Michalzik et al., 2001; Neff and Asner, 2001; Schmidt et al., 2010; Wu et al., 2014). In laboratory experiments, frequent leaching also increased DOM release from forest floor samples (Gödde et al., 1996; Judd and Kling, 2002). Hence, field and laboratory studies indicated that the concentration of DOM in forest floor percolates is relatively stable under increasing water fluxes. This calls for either a large pool of potential DOM that is not easily exhausted, or the potential pool is replenished at a high rate. In this sense, the production (replenishment) rate of the potential DOM pool seems rather high. Little is known about the pool size of potential DOM and the production rate of DOM in percolates from forest floors. However, this information is a premise when modelling the temporal dynamics of concentrations and fluxes of DOM from forest floors. The actual pool of DOM is a result of DOM production and mineralization to CO_2 and the turnover time of the DOM pool might be rather short less than a day as suggested by Bengtson and Bengtsson (2007). In contrast, direct measurements of mineralization of DOC from decomposed litter show that DOC in leachates from forest floors is more recalcitrant and has a much longer mean residence time (Don and Kalbitz, 2005).

Whether the production of dissolved organic carbon and nitrogen (DOC and DON) is similar remains another open question. Different source pools, with different turnover rates and solubility (e.g.: C-rich litter/humus vs. N-rich microbial biomass, hydrophilic amino groups vs. hydrophobic aliphatic compounds), might induce different responses of DOC and DON in soils to leaching. In fact, different response of DOC and DON fluxes from forest floors to changes in environmental conditions were reported for forest floor percolates, such as seasonally and annually varying DOC/DON ratios (Solinger et al., 2001) and decreasing ratios with increasing mean annual precipitation (Wu et al., 2010). On the contrary, similar response of DOC and DON from forest floors to precipitation amount was also found (Michalzik et al., 2001; Schmidt et al., 2010).

Tree species influence DOM dynamics in forest soils, as the quality of SOM under different tree species usually differs in lignin content, microbial activity, and C/N ratio. The effect of tree species on DOM fluxes is not conclusive. Higher concentrations and fluxes of DOM in coniferous than in deciduous forest floors were reported (Camino-Serrano et al., 2014; Fröberg et al., 2011; Hansson et al., 2011; Kalbitz et al., 2004b), but opposite findings were published by Smolander and Kitunen (2011) and Trum et al. (2011). Buzek et al. (2009) reported similar DOM production rates in deciduous and coniferous soils.

The release of DOC from soils is temperature dependent as both, microbial processes (depolymerisation of macromolecules) and the physicochemical dissolution of SOM are temperature dependent (Borken et al., 2011; Gödde et al., 1996; Moore et al., 2008; Peichl et al., 2007). Information on Q_{10} values for DOC vs. the release of DON from forest floors is sparse. A range from 1.0 to 6.8 for DOC release was observed, depending on the temperature range (Moore et al., 2008; Gödde et al., 1996).

The objectives of this study were 1) to investigate the size of the mobilizable DOM pool in forest floors, 2) to quantify the apparent continued production rate of DOM by percolation experiments 3) to determine changes in the ratio of DOC/DON during percolation extraction, and 4) to investigate temperature and tree species effects.

2. Material and methods

2.1. Site description

Samples of forest floor were collected under stands of Norway spruce (*Picea abies*, located in the Fichtelgebirge, 50°08′ N, 11°52′ E) and European beech (*Fagus sylvatica*, located in the Steigerwald, 49°52′ N, 10°27′ E) in Germany. Mean annual precipitation and air temperature are 750 mm and 7.5 °C at the beech site and 1160 mm and 5.3 °C at the spruce site (Gerstberger et al., 2004). Forest floor samples were additionally collected in a stand in Seohwa, South Korea (38°12′ N, 128°11′ E), where the dominant tree species are *Larix kaempferi* (Lamb.) Carr. and *Pinus densiflora* Siebold & Zucc. The average annual temperature of the western part of the Gangwon-province is 11 °C and the monthly average temperature ranges from − 5 °C in January to 24 °C in August (Korean meteorological administration, www.kma.go.kr). Annual precipitation ranges from 1200 to 1500 mm (Seo et al., 2011).

Table 1
Properties of forest floors at the study sites.

	Layer	pH ($CaCl_2$)	C	N	C/N	C stock	N stock
			(%)			(kg m^{-2})	(g m^{-2})
Spruce	Oi	3.6[a]	45.8[b]	1.7[b]	27[b]	0.74[b]	27
	Oe	2.9[a]	42.1[b]	1.8[b]	22[b]	1.20[b]	55
	Oa	2.6[a]	21.2[b]	1.1[b]	19[b]	1.42[b]	75
Larch	Oi	4.4	47.9	1.7	28	0.31	14
	Oe + Oa	4.2	38.4	1.9	20	0.54	30
Beech	Oi	4.7[a]	47.2	1.7	28	0.20[a]	7
	Oe + Oa	4.5	26.2	1.0	26	2.49[a,c]	95

[a] From Gerstberger et al. (2004).
[b] From Schulze et al. (2009).
[c] From Schütt et al. (2014b).

2.2. Forest floor properties

The forest floor of the spruce site comprised distinct Oi, Oe and Oa layers. The organic layer of the beech site was characterized by a distinct Oi and Oe layers and a thin Oa layer. The forest floor of the larch site comprised distinct Oi layers and less distinct Oe and Oa layers.

The O-layers were more acidic at the spruce site (pH < 4) than those at the larch and beech sites (pH 4.2–4.7, Table 1). The C content was higher in the Oi layer (45–48%) than in the Oe and the Oa layer (21–42%) at all sites. The C/N ratio was also higher in the Oi layer (27–28) than in the Oe and the Oa layer (19–26) at all sites.

2.3. Experimental design

Samples were collected in August 2014 at the German sites and in October 2014 at the Korean site. Coarse material (e.g. twigs, roots, insects, and gravel) was removed from the forest floor samples and the samples were mixed to ensure homogeneity. Soil dry mass was measured after oven-drying at 60 °C for 48 h. Before percolation started, the samples were incubated at field capacity for 1 week. The litter samples (Oi layer) from the coniferous sites were cut into pieces of about 1 cm and from the beech site into pieces of about 1 cm^2.

For percolation, syringe columns (diameter: 2.9 cm, height: 4–6 cm) were filled with the forest floor samples (1.8 g of dry mass of Oi and 2.8 g of dry mass of Oe + Oa samples) in 3 replicates for each treatment. The samples were continuously percolated with an artificial throughfall for 25 days at a rate of 15 mL d^{-1} (36 mm d^{-1}), using peristaltic pumps. The artificial throughfall had a pH of 4.0, electrical conductivity of 50.0 µS/cm and the following composition (µmol L^{-1}) 1.5 $MnCl_2$, 13 $MgCl_2$, 1.5 K_3PO_4, 0.2 $FeSO_4$, 10.0 $Al(NO_3)_3$, 99.1 $CaSO_4$, 87.1 NH_4NO_3, 20.0 K_2SO_4, and 7.0 Na_2SO_4. The percolated solutions were permanently collected and the cumulative samples analyzed after 5, 10, 15, 20 and 25 days. At day 5, 10, 15, 20 and 25, the soil columns were placed in airtight glass jars, and the soil CO_2 release was measured (see below). To study the effect of temperature, the experiment was conducted in temperature controlled chambers at 5 and 15 °C.

The experimental setup aimed at the depletion of the mobilizable DOM pool in forest floors by extremely high water percolation rates in a short period of time. Permanent leaching should lead to an almost steady state of DOM release driven no longer by the depletion of the existing pool but by the production of DOM. Hence, the remaining DOM release from day 20 to day 25 (following 720 mm of percolation) is here defined as the "*DOM production rate*" which is equal to the

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