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Efforts to increase our understanding of the terrestrial carbon balance have resulted in a dense global network of eddy covariance towers, which are able to measure the net ecosystem exchange of CO_2, H_2O and energy between ecosystems and the atmosphere. However, the typical set-up on an eddy covariance tower does not monitor lateral CO_2- and carbon fluxes such as dissolved organic carbon (DOC). By ignoring DOC fluxes eddy covariance-based CO_2 balances overestimate the carbon sink of ecosystems as part of the DOC drains into the inland waters and get respired outside the footprint of the eddy covariance tower. In this study we quantify 7 years (2000–2006) of DOC fluxes from a temperate Scots pine forest in Belgium and analyse its inter-annual variability. On average, 10 gC m^{-2} $year^{-1}$ is leached from the pine forest as DOC. If the DOC fluxes are considered relative to the gross ecosystem carbon fluxes we see that DOC fluxes are small: $0.8 \pm 0.2\%$ relative to gross primary productivity, $1.0 \pm 0.3\%$ relative to ecosystem respiration, and ($2.4 \pm 0.4\%$) relative to soil respiration. However, when compared to net fluxes such as net ecosystem productivity and net biome productivity the DOC flux is no longer negligible ($11 \pm 7\%$ and 17%, respectively), especially because the DOC losses constitute a systematic bias and not a random error. The inter-annual variability of the DOC fluxes followed that of annual water drainage. Hence, drainage drives DOC leaching at both short and long time scales. Finally, it is noted that part of the carbon that is leached from the ecosystem as DOC is respired or sequestered elsewhere, so the physical boundaries of accounting should always be reported together with the carbon budget.

1. Introduction

The effort to increase our understanding of the carbon balance has resulted in a global network of eddy covariance towers (2000; Baldocchi, 2008; Baldocchi and Meyers, 1998). These towers continuously measure the exchange of CO_2 and H_2O between the ecosystem and the atmosphere and as such, monitor the net ecosystem productivity (i.e. the net balance between CO_2 uptake and release) of these ecosystems. In recent years, it was realized that the functional link between terrestrial and aquatic ecosystems occurs in the form of lateral fluxes of organic carbon. Despite their modest magnitude, these fluxes could be of disproportionate importance to the global carbon cycle (Battin et al., 2009) because they export carbon from terrestrial ecosystems to aquatic ecosystems that are globally appreciable carbon pools because of their often very high carbon density and long residence times (Cole et al., 2007; Downing et al., 2009; Mulholland and Elwood, 1982).

Given that the dissolved organic carbon (DOC) export occurs at the soil–water interface, carbon losses from the ecosystem through DOC leaching are thus not detected by the eddy covariance methodology (EC). Failing to account for DOC fluxes overestimates the carbon sink of terrestrial ecosystems when this estimate relies solely on eddy covariance measurements. Siemens (2003) suggested omission of DOC fluxes as a possible explanation for the gap between atmosphere-based and land-based estimates of the continental carbon balance of Europe (Janssens et al., 2003). Indeed, the gap decreased when the European carbon balance accounted for DOC losses (Schulze et al., 2009). Also, most global land surface models do not simulate DOC leaching but rely on measured eddy covariance data for their validation. Consequently, these models will overestimate ecosystem carbon uptake when they reproduce the eddy covariance data, however, it should be noted that other model deficiencies, such as the lack of forest management, may be more important.

Many studies have reported DOC concentrations and fluxes from forested ecosystems (see review by Michalzik et al. (2001)). Unfortunately, many of these studies are only short-term and thus give no insight in the long-term drivers of this flux. Such insights are essen-

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Table 1
Depth, pH, texture analysis, bulk density, C-concentration, C storage to a depth of 1 m in all soil horizons at the forest.

Horizon	Depth (cm)	pH (H_2O)	pH ($CaCl_2$)	Clay (%)	Loam (%)	Sand (%)	Bulk density ($g\,cm^{-3}$)	%C (wt.%)	Total C (t ha)
Litter	−6–0	3.9	3.3						
Al/Ap	0–34	3.8	3.3	4.2	6.9	88.9	1.36	1.12	48.9
A/E	34–50	4.1	3.7	2.1	9.2	88.8	1.54	0.75	18.5
Cg	50–90	4.1	3.8	1.1	0.8	98.1	1.54	0.33	20.7
2CBhg	90–100	4.1	3.8				1.55	0.31	4.8

tial because process understanding is the basis of developing land surface models, which are becoming increasingly powerful tools in studying earth system interactions and global biogeochemical cycling.

The objectives of this study are twofold: one is that we would like to quantify the importance of DOC leaching for the carbon balance of a temperate forest based on a 7-year dataset, and two is that we would like to test whether or not the hydrological regime is indeed the main driver of DOC leaching, both on intra-annual and inter-annual timescale.

2. Materials and methods

2.1. Plot description

The experimental forest "De Inslag" is located in Brasschaat, 20 km NE of Antwerp in the Belgian Campine region (51°18′N, 4°31′E). The study site consists of a 2.0 ha, 80-year-old even aged Scots pine stand situated within a 150 ha mixed coniferous/deciduous forest. The stand is part of the ICP Forests level II and Fluxnet/CarboEurope-IP networks. The forest surrounding the site consists of several broadleaf species, some native, such as *Betula pendula* Roth., *Sorbus aucuparia* L. and, *Quercus robur* L. and some – for this region – alien species such as *Quercus rubra* L. and *Castanea sativa* Mill. The understorey, which was comprised of, mainly, *Prunus serotina* Ehrh., another alien species in the region, was removed in 1993. Since then, a small but steady colonisation of the shrub layer by *Betula* species and *Sorbus aucuparia* L. occurred. Following the understorey removal, *Molinea caerulea* L. Moench. emerged along with *Rubus* species and *Dryopteris* ferns.

The site has a temperate maritime climate, with a long-term mean annual temperature of 11 °C. The long-term mean temperatures of the coldest and warmest months are 3 and 19 °C, respectively, and mean annual precipitation is 830 mm. The study site is subject to an atmospheric nitrogen deposition of on average 48 kg N ha^{-1} as described in detail by Neirynck et al. (2008). The site has a flat topography (slope: 0.3%) with an elevation of 16 m a.s.l.

The soil is covered with an organic surface layer of 6 cm depth. A deep (1.20–2.25 m) Aeolian sand layer (Dryas III) rests on a substratum of Clay of the Campine (40% of clay) (Tiglian) at a depth varying mainly between 1.2 and 2.5 m and more in places (Baeyens et al., 1993). The soil is moist, but rarely saturated, because of rapid hydraulic conductivity in the upper horizons. According to the World Reference Base for Soil Resources version, 2006 (WRB I.W.G., 2006), the soil is classified as an Albic Hypoluvic Arenosol. A description of the topsoil profile with texture analysis and pH for all horizons is given in Table 1. Most fine (<1 mm) and medium roots (1–5 mm) are found in the top 60 cm of the soil profile (Janssens et al., 1999). Detailed information on course roots distribution is not available but after a wind throw uprooted trees showed that coarse roots are mostly limited to the upper meter of the soil profile. A detailed report of the physical and chemical properties of the topsoil is presented by Roskams et al. (1997) and Janssens et al. (1999).

In 1995 tree density was 538 trees ha^{-1}. In the winter of 1999 163 trees ha^{-1} were harvested which decreased tree density to 375 stems ha^{-1} (Xiao et al., 2003). In terms of the carbon balance, this harvest was equivalent to a removal of 18.3 tC ha^{-1}. Stand inventories in 2001 and 2003 indicated that no further reduction in tree density has occurred during the study period (Curiel Yuste et al., 2005). The next thinning is planned for 2012 which results in an effective rotation cycle of 13 years for carbon sink calculations. Frequent and intense thinning is the result of the long-term management planning that envisions an accelerated conversion of needle-leaved to broadleaved tree species.

2.2. Meteorological measurements

Half-hourly air temperature and relative humidity (Didcot Instrument Co. Ltd., Abingdon, United Kingdom DTS-5A) are recorded at the top of the tower and soil temperature is measured at 2 cm below soil surface with temperature probes (Didcot DPS-404, UK). All meteorological variables were measured at 0.1 Hz and half-hourly means were stored on a data logger (Campbell CR10, UK). Precipitation was measured with a rain gauge (Didcot DRG-51). Missing data for air temperature, relative humidity and precipitation were obtained from a nearby weather station from the Flemish Environmental Agency (VMM) at Luchtbal, which is within 10 km from the research site. Volumetric soil water content (SWC) was measured using two series of TDR sensors (Time Domain Reflectometry), at two places within the experimental plot. Measurements were conducted twice a week from 2000 to 2003 and twice a month during the remaining 3 years. At each of the two sample points SWC was measured every 25 cm until a depth of 175 cm.

2.3. Eddy covariance

The vertical flux of CO_2 and H_2O above the canopy was measured using the eddy covariance technique (Baldocchi and Meyers, 1998). The eddy covariance system consists of a sonic anemometer (Model SOLENT 1012R2, Gill Instruments, Lymington, UK) for wind speed and an infrared gas analyser (IRGA) (Model LI-6262, LI-COR Inc., Lincoln, NE, USA) to measure the CO_2 and H_2O concentrations. The measurements are conducted at the top of the tower at a height of 41 m, circa 18 m above canopy. Detailed description of the experimental setup can be found in Carrara et al. (2004, 2003). Half-hourly net ecosystem exchange fluxes (NEP) were calculated from quality controlled and gapfilled time series following the recommendations of the Euroflux network (Aubinet et al., 2000; Papale et al., 2006; Reichstein et al., 2005). Gap-filling and separation of NEP into ecosystem respiration (Reco) and gross ecosystem production (GPP) were based on extrapolating the nighttime relationship between temperature and respiration to the daytime as described by Reichstein et al. (2005). Latent heat fluxes were corrected for the energy balance closure as described by Barr et al. (1994) and Blanken et al. (1997). This adjustment is sometimes referred to as "Bowen ratio closure" because it is based on the assumption that the Bowen ratio is correctly measured (Twine et al., 2000). The energy balance closure for the site is on average 86%, and is described in detail by Gielen et al. (2010). Due to instrument failure no eddy covariance measurements were recorded during 2003.

The carbon sink or carbon effectively sequestered in the forest ecosystem (net biome production [NBP]) was calculated as the sum of total NEP over 6 years (2000–2006, omitting 2003) minus the carbon-export (harvest) over 6 years, calculated as the 18.8 tC ha^{-1} that was harvested in 2000 spread over the rotation period (13 years), times the length of the study period (6 years).

2.4. Water balance

Water drainage was calculated as the unknown in the water balance equation using evapotranspiration (ET), as measured by eddy covariance, and observed precipitation and changes in soil water content (SWC). A detailed description of the water balance of the study site is presented in Gielen et al. (2010). Due to instrument failure no eddy covariance measurements were made during 2003. Therefore, the ET for 2003 was simulated by means of the process based model ORCHIDEE (Krinner et al., 2005). The simulations were thoroughly validated using 7 years of EC measurements and were found to well reproduce the monthly EC fluxes for C and water (r^2 = 0.86; Gielen et al., 2010).

2.5. DOC-measurements

Soil water was sampled fortnightly using lysimeter candles equipped with ceramic cups installed in the Al/Ap-horizon (±10 cm), the A/E-horizon (±30–40 cm) and the Cg-horizon (±70–80 cm). The lysimeters were operated at a transient vacuum during 2 days before sampling, using an initial tension of about −60 cbar. Afterwards, samples were collected and pooled into one composite sample per layer for analysis. Sampling of soil water took place at three locations where for each depth two lysimeter candles were collocated.

Before analysis, all samples were filtered through 0.45 μm nylon syringe filters (Rotilab®, Carl Roth GmbH, Karlsruhe, Germany) and kept in cool boxes until analysis. All samples were analysed for DOC-concentration on a Shimadzu 15 TOC-V CPN-analyser (Shimadzu Corp., Tokyo, Japan) with IR detection following thermal oxidation.

DOC-leaching of the Cg-horizon (gC m^{-2} month^{-1}) was calculated as the product of the mean monthly DOC-concentration measured below the root zone (Cg-horizon) (mg l^{-1}) and the estimates of monthly water drainage (l m^{-2}). For this analysis the Cg-horizon is considered as the ecosystem boundary. The total DOC pool for each horizon was calculated as the product of the monthly DOC-concentration and monthly mean SWC for each horizon, taking into account the thickness of the layer (Table 1). In addition, a normalized DOC pool for each horizon was estimated by dividing each layer by its thickness (Table 1).

2.6. Soil respiration

Soil respiration was modelled on half-hourly basis throughout the full study period (2000–2006) with a model combining the soil respiration response to temperature and SWC (Curiel Yuste et al. 2003). The latter SWC response was introduced to account for drought when SWC at 25 cm below soil surface dropped below 0.123 m^3 m^{-3}. However Curiel Yuste et al. (2003) noticed an increase in soil respiration when the litter layer was rewetted after a short rain event and therefore introduced an index (I_w) which above a threshold of 0.3 resumed the temperature response function.

Measurements to parameterised the model were performed by a closed dynamic system (IRGA: CIRAS-1 soil chamber: SRC-1, both PP-Systems, Hitchin, UK) periodically throughout 2001 on 10 PVC collars that were randomly installed throughout the plot. The dataset was then subdivided into three subsets, each representing a different period of the year (winter/early spring, late spring/summer and fall). Each subset was used to obtain specific values for the parameters of the temperature function (Table 2). Curiel Yuste et al. (2003) reproduced the measurements very well with their model (r^2 = 0.95).

Table 2
Q_{10} and SR_{10} parameters for each period of the year used for the temperature response function to simulated soil respiration for the entire study period.

Season	DOY	Q_{10}	SR_{10}
Winter/early spring	1–120	2.74	1.02
Growing season	121–274	1.98	1.23
Fall	274–365	3.21	1.15

The general function to calculate soil respiration (SR) is

$$SR = f(T)f(\mathrm{SWC}) \tag{1}$$

where SR is soil respiration, $f(T)$ is a temperature function and $f(\mathrm{SWC})$ is a linear function which is introduced when SWC drops below 0.123 m^3 m^{-3}. The temperature function is

$$f(T) = SR_{10}Q_{10}{}^{(T-10)/10} \tag{2}$$

where SR_{10} is soil respiration at 10 °C, Q_{10} is the temperature sensitivity parameter and T is soil temperature at 2 cm depth. Specific values for these parameters can be found in Table 2. The SWC function which reduces SR when SWC at 25 cm is below 0.123 m^3 m^{-3} is

$$f(\mathrm{SWC}) = a \times \mathrm{SWC} + b \tag{3}$$

where SWC is soil water content at 25 cm (m^3 m^{-3}) and a and b are constant, 5.2 and −0.05, respectively (Curiel Yuste et al., 2003).

The rewetting index (I_w) which, when above 0.3, is used as an indicator to resume temperature response function after a short rain event is calculated as follows:

$$I_w = \alpha + \log\frac{R^{0.5}}{(\mathrm{VPD}_a \times t^2)} \tag{4}$$

where α is a constant (2.5) (Curiel Yuste et al., 2003), R represents the amount of precipitation during the last rainfall event (mm), t the time since the last rain event (h) and VPD_a is the mean vapour pressure deficit of the atmosphere at 2 m above the forest floor averaged over the last 24 h (kPa).

3. Results

3.1. Meteorological measurements

Rainfall varied considerably during the course of this study (Fig. 1). Within the 7 years of observations, the driest year was 2003, which exhibited a total rainfall of 676 mm; in contrast, the wettest year was 2002, with a total of 1041 mm. Mean annual temperature was lowest in 2002 (10.3 °C) and highest in 2006 (11.9 °C). The lowest average monthly temperature was measured in January 2001, with mean monthly temperature of 3.1 °C. The warmest month was July 2006, with a mean monthly temperature of 22.4 °C (Fig. 1).

3.2. DOC concentrations and pools

DOC concentrations in the upper Al/Ap-horizon show a distinct seasonal pattern with a mean maximum of 46 mg l^{-1} in August and a mean minimum of 22 mg l^{-1} in March (Fig. 2c). This pattern shows good agreement with the pattern of soil temperature at 2 cm depth (Fig. 2a) which preserved the seasonal pattern but is slightly dampened and lagged compared to the air temperature. The average DOC concentration in the A/E-horizon peaks in July with 35 mg l^{-1} and is lowest in March with 22 mg l^{-1}. Thus, DOC concentrations in the A/E-horizon are lower than in the

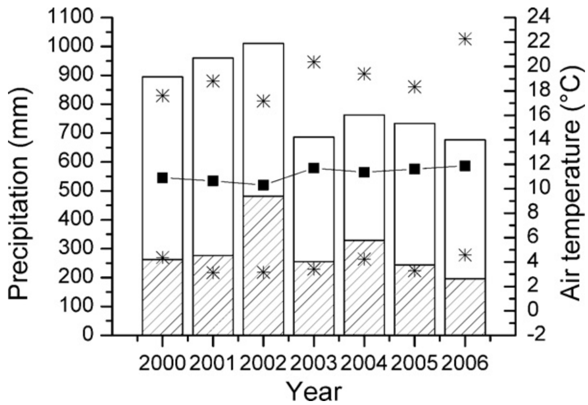

Fig. 1. Meteorological conditions at 'De Inslag', Brasschaat, Belgium during the study period (2000–2006). The bar graph shows the annual precipitation (left ordinate) which is divided into growing season (open bars) and dormant season (dashed bars). Filled squares show mean annual air temperature (right ordinate) and the upper and lower asterisk show highest and lowest mean monthly temperature for that specific year.

Al/Ap-horizon during the growing season, however, the reverse is true during winter. Finally DOC concentrations in the Cg-horizon decrease to an average of 19 mg l^{-1} without a distinct seasonal pattern. In addition to the concentrations, also the inter-annual variability in DOC concentrations decreases with increasing soil depth (data not shown).

The amount of organic carbon that is dissolved in soil water (i.e. the DOC pool) was estimated separately for each horizon, by multiplying the average monthly SWC in the horizon under study (Fig. 2b) by the monthly DOC concentration that horizon. The Cg-horizon had the largest DOC pool, about 2 gC m^{-2}, which is twice the content of the A/E-horizon (Fig. 2e).

When normalizing the DOC pool for the thickness of each horizon, the normalized DOC pool of the Al/Ap-horizon shows a similar seasonal pattern as the DOC concentration, with a minimum of 0.04 gC m^{-2} cm^{-1} in April and a maximum of 0.07 gC m^{-2} cm^{-1} in October. Due to the higher SWC in the A/E and Cg-horizons the normalized DOC pool increases slightly with soil depth. The seasonal pattern of the normalized pool in the A/E-horizon shows a maximum of 0.07 gC m^{-2} cm^{-1} during the dormant season in February and a minimum of 0.05 gC m^{-2} cm^{-1} in June. In the deepest horizon (i.e. the Cg-horizon) the normalized DOC pool shows very little seasonal variation (Fig. 2e).

3.3. *Water drainage and DOC fluxes*

The monthly water drainage from below the Cg horizon at the study site varied between 0 and 130 mm $month^{-1}$ (Fig. 3a). Several peaks of more than 100 mm occured during the 7-year study period. These peaks were observed mostly during the dormant season when ecosystem water demand is low. Mostly, drainage decreased during the growing season when evapotranspiration was higher, however, intense summer rains occasionally resulted in larger peaks in drainage fluxes (e.g. 2001 and 2005). The time series of 7 years of monthly DOC leaching out of the Cg-horizon (Fig. 3b) showed large variability, ranging from no leaching during the dry summers of 2003 and 2006 to peaks of 2.7 gC m^{-2} per month in October 2001. DOC-leaching fluxes were typically highest during fall and winter season.

3.4. *Carbon fluxes*

The mean and standard deviation of 7 years of DOC leaching is 10 ± 2 gC m^{-2} $year^{-1}$ (Table 3). From the eddy covariance data a GPP with a mean and standard deviation of -1170 ± 100 gC m^{-2} $year^{-1}$ was estimated, Reco was on average 1060 ± 240 gC m^{-2} $year^{-1}$ and NEP was -80 ± 150 gC m^{-2} $year^{-1}$. Finally, SR fluxes for the 7-year study period amounted to 410 ± 30 gC m^{-2} $year^{-1}$ (Table 3).

When the DOC fluxes below the root zone are considered relative to the other ecosystem fluxes (Table 3), we see that DOC fluxes are negligible compared to the gross ecosystem CO_2 fluxes such as GPP ($0.8 \pm 0.2\%$), Reco ($1.0 \pm 0.3\%$), or even SR ($2.4 \pm 0.4\%$). However, comparing to the net ecosystem CO_2 exchange (NEP) the DOC flux becomes equivalent to a substantial part of the net annual ecosystem CO_2 exchange ($11 \pm 7\%$). Not accounting for DOC in the annual carbon balance would thus result in a systematic overestimation of the carbon uptake of roughly 10% (Table 4).

The cumulated NEP over the 6 years of measurements was -480 gC m^{-2}, however when estimating the actual carbon sink (NBP) by accounting for the harvest, the ecosystem was a source of 387 gC m^{-2} (Fig. 4). Thus, with an average NEP of -80 gC m^{-2} $year^{-1}$ it requires a rotation cycle of at least 24 years before carbon losses due to wood harvest would be compensated for by regrowth (thus cumulative NBP over 24 years equals zero). An extra three years are needed if in addition to harvest, carbon loss as DOC is also accounted for. DOC fluxes out of the Cg-horizon show a mean monthly maximum of 1.2 gC m^{-2} in January and decrease in summer to a mean monthly minimum of 0.5 gC m^{-2} in July (Fig. 5). This pattern is mainly determined by the water drainage fluxes, which are decreasing in summer months due to higher water consumption by the ecosystem. However, due to a very irregular precipitation pattern with irregular but intense summer rains, the observed mean DOC leaching never reaches zero at monthly timescale. Contrary to DOC leaching, the other ecosystem fluxes show a more regular seasonal pattern, with GPP reaching a mean monthly maximum uptake of -200 gC m^{-2} $month^{-1}$ during the peak of the growing season in July. Also Reco reaches a maximum of 140 gC m^{-2} during the same month. The sum of Reco and GPP fluxes results in a mean monthly maximum CO_2 uptake of -70 gC m^{-2} in June. Because SR is strongly affected by drought stress in the upper soil layers which occurs mostly in summer and because soil temperature lags air temperature, the mean monthly

Table 3
Measured values for yearly ecosystem fluxes of dissolved organic carbon (DOC), net ecosystem exchange (NEP), ecosystem respiration (Reco), gross ecosystem productivity (GPP) and soil respiration (SR), all expressed in gC m^{-2} year. Values between brackets are the DOC fluxes relative to the respective ecosystem flux, expressed in percentage. Note that there are no EC measurements available for 2003.

Year	DOC (gC m^{-2} $year^{-1}$)	NEP (gC m^{-2} $year^{-1}$) (%)	Reco (gC m^{-2} $year^{-1}$) (%)	GPP (gC m^{-2} $year^{-1}$) (%)	SR (gC m^{-2} $year^{-1}$) (%)
2000	12	130 (9.2)	1450 (0.8)	1320 (0.9)	450 (2.7)
2001	13	−200 (6.0)	900 (1.3)	1100 (1.1)	420 (2.9)
2002	10	−60 (20.0)	1030 (1.2)	1090 (1.1)	430 (2.8)
2003	8	–	–	–	350 (3.4)
2004	9	−50 (24.0)	1090 (1.1)	1140 (1.1)	400 (3.0)
2005	7	−360 (3.3)	780 (1.5)	1140 (1.1)	390 (3.1)
2006	9	−80 (15.0)	1170 (1.0)	1250 (1.0)	440 (2.7)

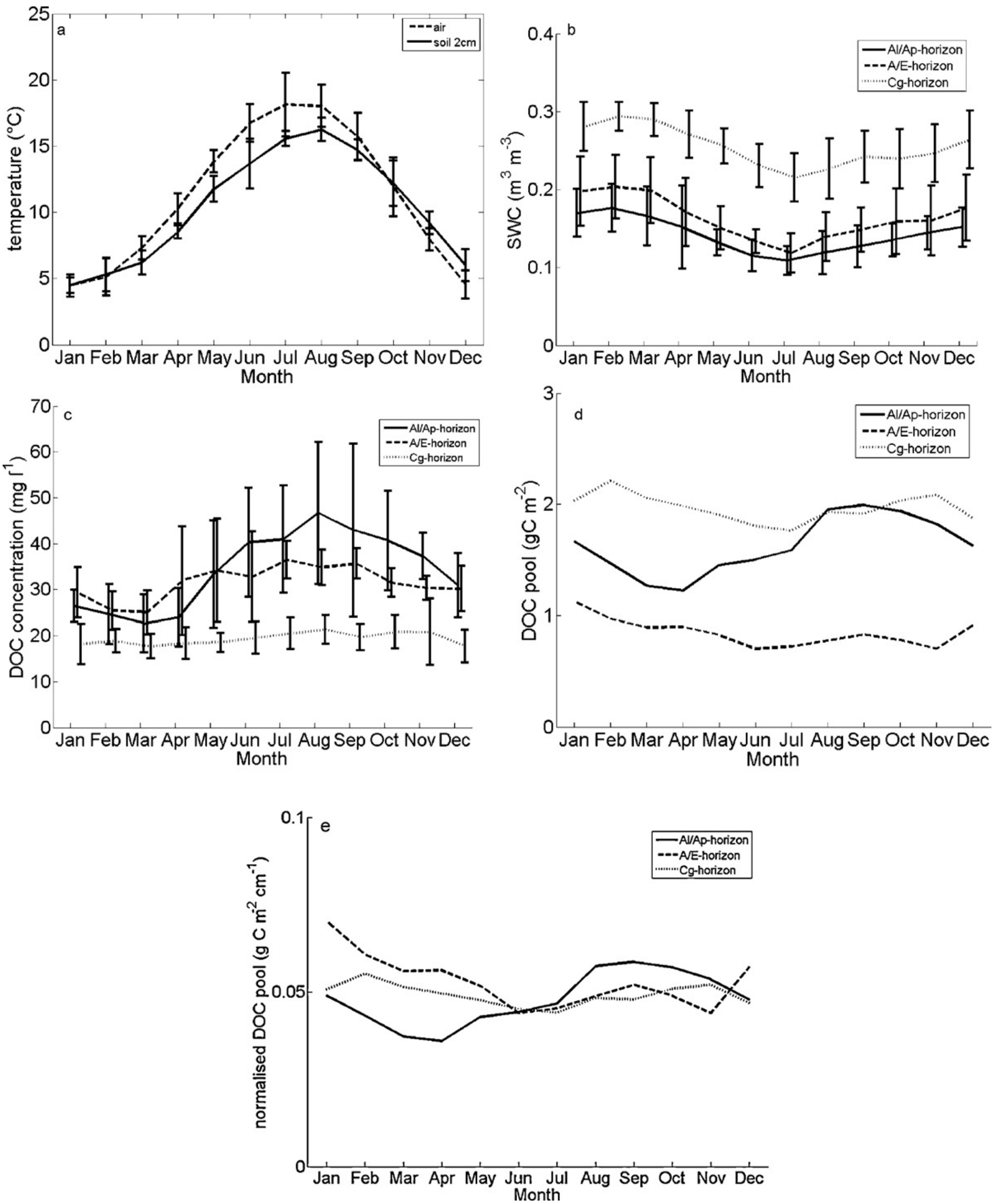

Fig. 2. Seasonal patterns of air temperature (°C) and soil temperature at 2 cm below soil surface (°C) (panel a); SWC ($m^2\ m^{-3}$) measured in the different soil horizons Al/Ap, A/E and Cg (panel b); DOC concentrations ($mg\ l^{-1}$) in the different soil horizons Al/Ap, A/E and Cg (panel c) and DOC pool ($gC\ m^{-2}$), calculated as the product of DOC concentration and SWC at the three soil horizons (panel d). A normalized pool ($gC\ m^{-2}\ cm^{-1}$) for each horizon was calculated by dividing the pools by their depth (panel e). In each panel, data are mean monthly averaged over the 7-year period.

maximum of 40 $gC\ m^{-2}$ is reached in October and thus well after summer.

3.5. Drivers

Regression analysis showed a significant relation between DOC leaching and water drainage both on annual (Fig. 6a, Table 4) and on monthly basis (Fig. 6b, Table 4). Further regression analysis with other variables (soil temperature, air temperature, precipitation and the ecosystem carbon fluxes [GPP, Reco, NEP, SR]) on both monthly and annual time scale showed that only precipitation on monthly time scale correlated significantly with DOC leaching. Partial correlation with drainage as a fixed factor indicated that the residuals where only significantly related to SR on yearly temporal scale, albeit with very low explanatory power ($r^2 = 0.08$) Furthermore, regression analysis showed a significant relation between the soil temperature at 2 cm below soil surface and DOC concentration in the different horizons (Fig. 6c). However, the slope of the relationship decreased with increasing soil depth (Table 5).

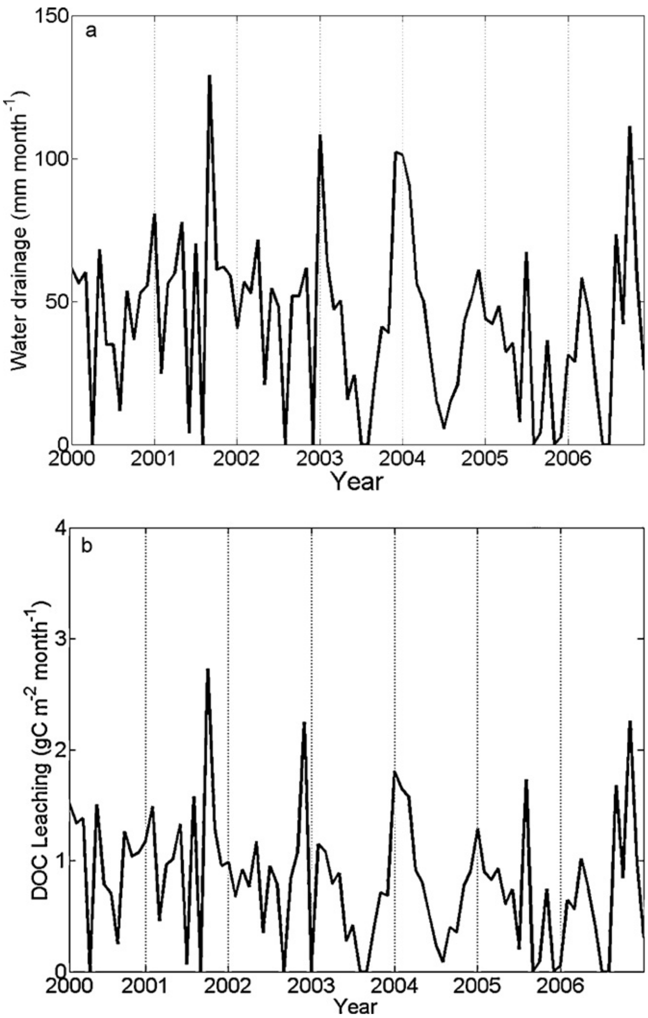

Fig. 3. Monthly water drainage (mm month^{-1}) averaged over the full study period (2000–2006) (panel a). Monthly DOC-leaching (gC m^{-2} month^{-1}) for the full study period (2000–2006), as calculated the product of monthly DOC concentration measured at Cg horizon and water drainage (panel b).

4. Discussion

4.1. Patterns and drivers of DOC fluxes

The importance of DOC in the global carbon cycle lies in its role of being able to transport carbon between different pools in

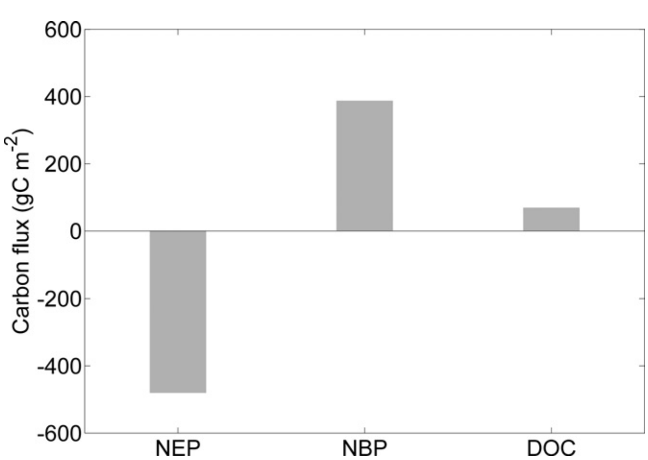

Fig. 4. Mean NEP, NBP and DOC over a 6-year period (2000–2006, omitting 2003 due to lack of NEP data), all expressed in (gC m^{-2}).

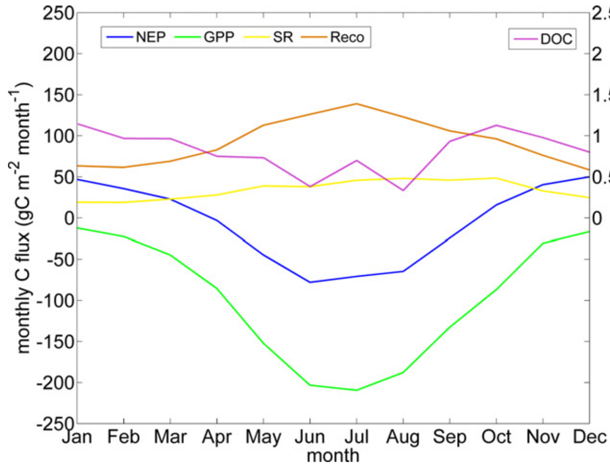

Fig. 5. Mean seasonal pattern over the entire study period for GPP, Reco, NEP and SR (in gC m^{-2} month^{-1}) on the left ordinate and DOC fluxes on the right ordinate (gC m^{-2} month^{-1}). Scale differs in both *Y*-axis.

the ecosystem or even outside the ecosystem through soil water drainage. In forest ecosystems, the forest floor has been identified as a primary source for DOC (Cronan and Aiken, 1985; Currie et al., 1996; Qualls and Haines, 1991). Microbial degradation of soil organic matter followed by desorption of organic substances from soil solids and leaching of organic substances from fresh litter are thought to be the most important processes causing the release of DOC (Kalbitz et al., 2000). In addition, a recent study by Weintraub et al. (2007) highlighted the importance of rhyzodeposition as a source of DOC. In line with the above, it was reported for boreal and temperate forests that the DOC flux from the upper horizon increases with the carbon stock in the upper horizon (Currie and Aber, 1997; Froberg et al., 2006). DOC fluxes from the organic soil layer may well increase with the size of the C stock in the upper horizon owing to longer contact time of soil water with the organic substrates. Moreover, the largest DOC flux occurs out of the upper horizon, as part of the DOC is getting respired or adsorbed on its way through the soil. The internal topsoil fluxes of DOC within the ecosystem are thus in general higher than the net loss of DOC to ground water and surface waters. Furthermore, it should be noted that total organic carbon (TOC) that is leached from terrestrial ecosystems consists not only of DOC but also of particulate organic carbon (POC). Sand-Jensen and Pedersen (2005) reported 4.6 times larger DOC concentrations than POC concentrations in a forested catchment in Denmark. However, across Northern Europe, Ciais et al. (2008) estimate that POC represent only 8% of TOC. Thus, by only estimating the DOC fluxes we might have slightly underestimated the total organic carbon losses from the ecosystem.

The DOC concentrations at our site are well within the ranges reported in the review by Michalzik et al. (2001). In their review, Michalzik and co-workers reported DOC concentration for temperature coniferous forests between 20 and 90 mg l^{-1} for the upper soil and between 2 and 35 mg l^{-1} for the lower soil horizons. In our study, the DOC concentrations in the upper Al/Ap-horizon showed a significant relation with soil temperature, which was not apparent in the lower soil horizons. In temperate forests, the concentrations of DOC in the upper soil horizon solution likely follow the seasonal pattern in soil temperature because of enhanced microbial activity with higher soil temperatures (Guggenberger and Zech, 1993).

When looking at the DOC-pools (and thus normalizing the DOC concentrations for SWC-content), this relation with soil temperature was no longer present, although, the highest DOC pools were still observed in summer. This suggests that soil drying may result in higher DOC concentrations through accumulation of microbial products (Kalbitz et al., 2000).

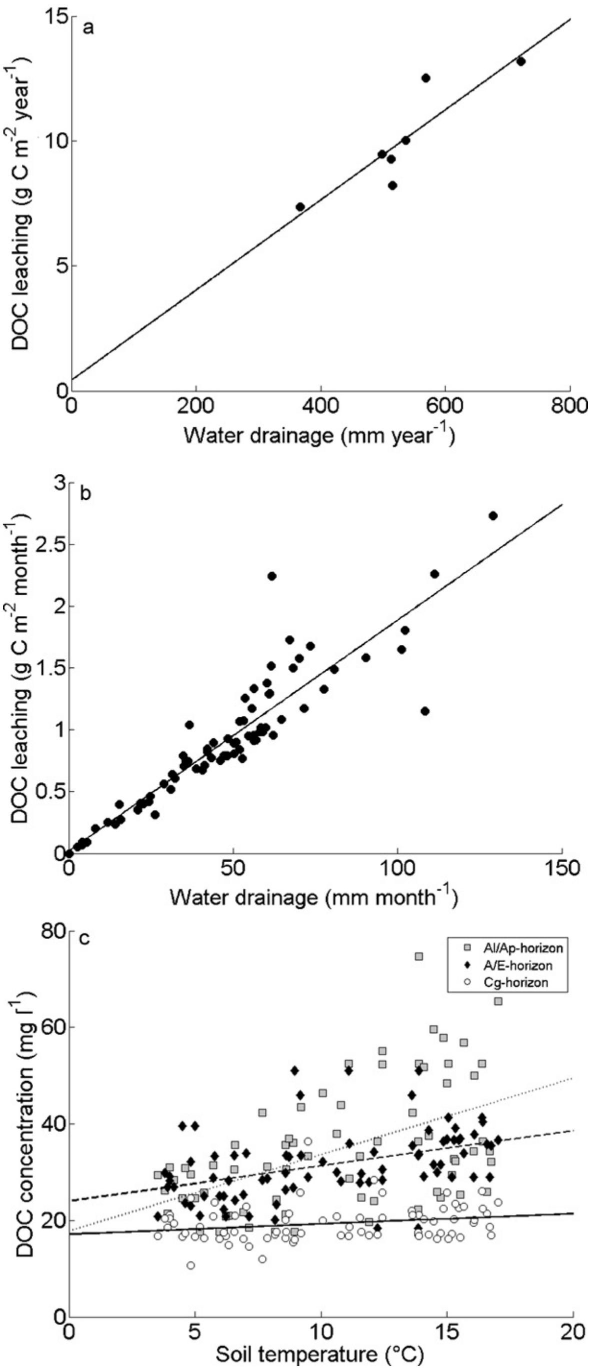

Fig. 6. The relation between annual DOC leaching (gC m^{-2} month^{-1}) on the ordinate and the annual water drainage (mm year^{-1}) on the abscissa (panel a). The relation between monthly DOC leaching (gC m^{-2} month^{-1}) on the ordinate and the monthly water drainage (mm month^{-1}) on the abscissa (panel b). The relation between monthly DOC concentration (mg l^{-1}) for the three soil horizons (Al/Ap, A/E and Cg) on the ordinate and mean monthly soil temperature measured at 2 cm depth (°C) on the abiscissa (panel c).

Table 4
Coefficients for the linear regression analyses between water drainage and DOC leaching for the monthly and yearly timescale. Included in the table are estimates of the coefficient of determination (r^2) and the p-values for each regression analysis. In all cases the model used was: $y(x) = a \times x + b$.

Timescale	a	b	r^2	p
Yearly	0.02	0.42	0.78	<0.01
Monthly	0.02	0.02	0.87	<0.01

Table 5
Coefficients for the linear regression analyses between soil temperature (°C) and DOC concentration (mg l^{-1}) for the different soil horizons (Al/Ap, A/E and Cg). Included in the table are estimates of the coefficient of determination (r^2) and the p-values for each regression analysis. In all cases the model used was: $y(x) = a \times x + b$.

Horizon	a	b	r^2	p
Al/Ap	1.58	17	0.27	$p < 0.01$
A/E	0.73	24	0.18	$p < 0.01$
Cg	0.21	17	0.06	$p < 0.05$

The decrease in DOC concentration with soil depth could be due either to microbial consumption or to abiotic storage via sorption to minerals or precipitation (Kalbitz and Kaiser, 2008). Based on our results we cannot specify how much each of these processes contributes to the reduction in total DOC-concentration. However, it is generally assumed that adsorption is far more important than decomposition in reducing DOC concentration in mineral soils (Kalbitz and Kaiser, 2008). The different seasonal patterns in DOC concentration between the Al/Ap and A/E and Cg-horizons suggest differences in the relative importance of microbial activities, adsorption and lateral flow in controlling DOC concentrations in each of soil horizons.

Also the DOC fluxes leaching from the Cg-horizon of our study site were observed to be within the reported range of 1–20 gC m^{-2} year^{-1} (Michalzik et al., 2001). Seasonal and inter-annual variability in DOC concentration observed in the Cg-horizon was very low. Consequently, total monthly and annual DOC fluxes in the Cg-horizon were found to be significantly correlated with respectively, monthly and annual water drainage fluxes. In a field experiment Tipping et al. (1999) observed a significant increase in the export of DOC with increasing water input. Also Don and Schulze (2008) found a strong relation between DOC export and water drainage from two grassland sites in Germany.

Additional regression analysis showed that annual precipitation sum was also significantly correlated to annual DOC leaching, although the explanatory power ($r^2 = 0.10$) was much lower with precipitation than with drainage ($r^2 = 0.85$). In addition, a partial correlation analysis performed with yearly drainage as a fixed factor indicated that the residuals between the predicted DOC-fluxes and the estimated DOC fluxes were significantly related only to SR, albeit with very little explained variance ($r^2 = 0.08$). Thus, our data show that the DOC fluxes leaving the ecosystem are limited by precipitation (and drainage) rather than by site productivity. Our results thus suggest that drainage is the main driver of DOC leaching at inter-annual scale in addition to its earlier reported role at intra-annual scales (Kalbitz et al., 2000; Michalzik et al., 2001; Neff and Asner, 2001).

4.2. *Gross, net and lateral carbon fluxes*

The observed ecosystem carbon fluxes are within previously reported ranges. Luyssaert et al. (2007) reported, based on a global database analysis, a range between −1390 and −2130 gC m^{-2} year^{-1} for GPP and from 1200 to 1440 gC m^{-2} year^{-1} for Reco for temperate evergreen forest. Our values are at the lower end of range for both GPP and Reco. The low GPP values are most probably due to the rather low LAI, for which a maximum of 1.5 was estimated using hemispherical pictures (Op de Beeck et al., 2010). Furthermore, the observed SR was at the lower end of the range of 760 ± 340 gC m^{-2} year^{-1} reported for the European forest (Janssens et al., 2001). This rather low SR values has been attributed to the refractory and acidic nature of the pine litter at the study site (Curiel Yuste et al., 2005). Nonetheless, the contribution of SR to Reco is well within the range of previously reported values (Janssens et al., 2001).

NEP values are also at the lower end of the reported range for temperate evergreen forest between −200 and −510 gC m^{-2} year^{-1} (Luyssaert et al., 2007). The low NEP at our forest may be attributed to limited nutrient availability due in the acid sandy soil (Curiel Yuste et al., 2005). Positive NEP during 2000 (a carbon source to the atmosphere) may be due to drastic thinning that year, thus temporary further reducing the LAI, or alternatively, to the shorter growing season relative to the other years (Carrara et al., 2003). Overall, our data suggests that our study site has a rather low productivity compared to other temperate forests.

The total amount of carbon that leaches out of the ecosystem as DOC is small compared to the gross ecosystem fluxes like GPP, Reco and SR. However, when compared against the net ecosystem productivity it is a substantial part of the carbon balance of a forest ecosystem. Our results show that on average the equivalent of 11% of net ecosystem productivity is lost as DOC. This is important as it could lead to a systematic overestimation of the net carbon uptake of the ecosystem. To our knowledge, no other data on site level are available on the amount of carbon leached with respect to other measured ecosystem carbon fluxes.

Luyssaert et al. (2010) reported in their European forest carbon balance an average DOC leaching of 10 gC m^{-2} year^{-1} for all terrestrial ecosystems including forests. Their calculations are based on upscaling of the chemical composition of surface water and river flow measurements across Europe (Meybeck and Ragu, 1997). This estimate was similar to the previous estimate of 9 gC m^{-2} year^{-1} which was reported by Siemens (2003). Additionally, Luyssaert et al. (2010) reported an average NEP of −200 gC m^{-2} year^{-1}, which means that on average 5% of the net carbon uptake is lost as DOC across Europe.

Furthermore, net biome production (NBP), which indicates how much carbon is actually taken up and stored in the ecosystem, can be calculated for our site by subtracting the wood export (harvest) from the cumulated NEP over the study period. Because of the rather large amount of carbon that was removed through the harvest we observe that the ecosystem lost 65 gC m^{-2} year^{-1}, without accounting for the DOC. This would add another 12 gC m^{-2} year^{-1}, or 17% to the NBP. With an average NEP of −80 gC m^{-2} year^{-1} it requires a rotation cycle of at least 24 years before carbon losses due to wood harvest would be compensated for by regrowth (thus cumulative NBP over 24 years equals zero). An extra three years are needed if cumulated DOC losses are also accounted for. The observed carbon source and apparently irrational thinning frequency and intensity are the result of the management plan that envisions an accelerated conversion from a conifer to deciduous forest while maintaining continuous forest cover. Schulze et al. (2009) reported for European forests an average NBP of −75 gC m^{-2} year^{-1}, in addition to an average 7 gC m^{-2} year^{-1} lost as DOC. Finally, it should be stated that part of the carbon that gets leached as DOC from the ecosystem will be respired or sequestered elsewhere. Thus, carbon balances should preferably be assessed on larger scale than ecosystem level.

5. Conclusion

This study presents seven years of DOC concentrations and fluxes at a temperate Scots pine forest in Belgium. DOC concentrations decrease with increasing soil depth due to a combination of adsorption to the soil matrix and mineralisation. Results show that DOC concentrations and fluxes at our site show a good agreement with literature values. DOC fluxes were observed to be small compared to gross CO_2 fluxes like gross primary productivity, ecosystem respiration and soil respiration. However, relative to the net ecosystem CO_2 fluxes the DOC flux is a substantial part of the net annual ecosystem exchange (11 ± 7%) and the net biome production (17%, no uncertainty due to lack of repetition). Thus, DOC fluxes should be accounted for when assessing site, regional and global carbon balances, especially because the DOC loss constitutes a systematic bias and not a random error. Our analyses further suggest that both at inter- and intra-annual time scales the DOC fluxes leaving the ecosystem are limited by water drainage rather than site productivity.

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