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Fluxes of dissolved organic carbon in stand throughfall and percolation water in 12 boreal coniferous stands on mineral soils in Finland

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The magnitude and variation in DOC fluxes in bulk deposition (BD), stand throughfall (TF) and percolation water (PW) were determined on seven Scots pine and five Norway spruce plots in Finland during 1998–2004. Water fluxes for PW were calculated using an anion budget method. The relationships between the DOC fluxes and climatic and stand parameters were also investigated. The mean DOC flux in TF varied between 2 and 6 g C m^{-2} a^{-1} and between 3 and 8 g C m^{-2} a^{-1} on the pine and spruce plots, respectively. The output flux of DOC in PW at the 40-cm depth varied between 1 and 10 g C m^{-2} a^{-1} on all the plots. The DOC fluxes in TF and net TF correlated positively with the effective temperature sum and growing season length on the pine and spruce plots, i.e. the highest DOC fluxes were recorded in southern Finland and the fluxes decreased towards the north. The TF and net TF DOC fluxes correlated positively with the amount of precipitation on the pine plots, and the net TF DOC fluxes with the stem volume on the spruce plots.

Introduction

The fluxes of dissolved organic carbon (DOC) in bulk deposition, which is wet deposition and in part dry deposition falling on the tree canopies, in stand thoughfall, and in soil water percolating down the soil profile play an important role in the C budget and balance of boreal coniferous forest ecosystems. The annual DOC fluxes in bulk deposition, stand throughfall and soil water in upland forested sites are relatively small as compared with the other fluxes and stocks in boreal forests in Finland (Ilvesniemi *et al*. 2002, Piirainen 2002, Starr and Ukonmaanaho 2004). For example, the C flux in tree litterfall can be more than ten times higher than the C input to the forest floor in stand throughfall (Piirainen *et al*. 2002, Finer *et al*. 2003). Similarly, the C flux from the soil in soil respiration has been reported to be considerably greater than the corresponding fluxes in stand throughfall and soil water (Ilvesniemi *et al*. 2002). Although the annual amount of C entering and leaving the soil in water fluxes can be relatively small as compared with the other C fluxes, the C fluxes in stand throughfall and soil water fluxes play an important long-term role in a number of processes. Dissolved organic matter (DOM) carried down the soil profile in percolation water accumulates on soil particles especially in the B horizon, thereby contributing to the podzolisation process (e.g. Qualls and Haines 1992, Kaiser and Zech 1998, Lundström *et al*. 2000). DOM in soil water forms complexes with metals (e.g. Fe and Al) and affects the acidity and ion balance of the soil solution (e.g. Lundström 1993, Lindroos *et al*. 1995). An important process is also the affinity of DOM to bind Hg, and the DOM fluxes in soil water therefore play a key role in Hg cycling (Driscoll *et al*. 1995, Krabbenhoft *et al*. 1995, Scherbatskoy *et al*. 1998). Changes in the C stocks and factors affecting C cycling may also be reflected in the amount of DOC in the individual fluxes. Surface waters receive large amounts of DOC through leaching from forest ecosystems, and the possible effects of climate change have been studied and discussed in relation to the changes in DOC in surface waters (Kortelainen and Saukkonen 1998, Freeman *et al*. 2001, Skjelkvåle *et al*. 2001).

Although some information is already available about the C fluxes in water passing down through the tree canopies and soil in forest stands growing on mineral soils in Finland, relatively little is still known about the magnitude and especially the variation in these fluxes under different conditions (e.g. Starr and Ukonmaanaho 2004). Intensive, continuous sampling and analysis are required throughout the year in order to determine the DOC fluxes in stand throughfall and soil water, and therefore the number of sites where detailed fluxes have been estimated in Finland is currently not very large.

Climatic factors such as the amount of precipitation, and the occurrence of precipitation in the form of snow, are considered to be important factors regulating the DOC fluxes in stand throughfall (Starr and Ukonmaanaho 2004). For instance, in areas where the winter period is short and growing season long, precipitation has a higher potential for leaching than in areas where a relatively high proportion of the precipitation falls as snow.

An important factor determining the DOC flux in soil water is the amount of water percolating down through the soil. The water flux can be estimated directly on the basis of the amount of water collected in e.g. zero-tension lysimeters or indirectly using hydrological models (e.g. WATBAL, Starr 1999). Water fluxes can also be estimated using the conservative anion (e.g. Cl, SO_4) budget method (Nilsson *et al*. 1998). Starr and Ukonmaanaho (2004) calculated the DOC fluxes for soil water at the depth of 40 cm using the WATBAL model, while Piirainen *et al*. (2002) successfully performed their calculations using the amount of water collected by zero-tension lysimeters. Direct measurement of the amount of water collected by zero-tension lysimeters is considered in some studies to give underestimates of the soil water fluxes (e.g. Giesler *et al*. 1996). This has led to the use of models and budget methods. The usefulness of some models is, however, restricted by the fact that detailed input data are needed for calculations. Furthermore, it is clear that there is no method that gives an absolutely correct measure of the water fluxes.

The aim of this study was to determine the magnitude and variation in the DOC fluxes in bulk deposition, stand throughfall and percolation water in 12 coniferous stands located on mineral soil sites in different parts of Finland. We hypothesised that the DOC fluxes are related to climatic factors such as precipitation and length of the growing season, as well as to certain stand factors. The information obtained about these fluxes will be used in making detailed calculations and models of the C budgets of forest ecosystems.

Material and methods

The bulk deposition (BD), stand throughfall (TF) and percolation water (PW) data were collected during 1998–2004 from five Norway spruce (*Picea abies*) and seven Scots pine (*Pinus sylvestris*) stands located in different parts of Finland (Fig. 1). These stands belong to the network of intensively monitored sample plots of the

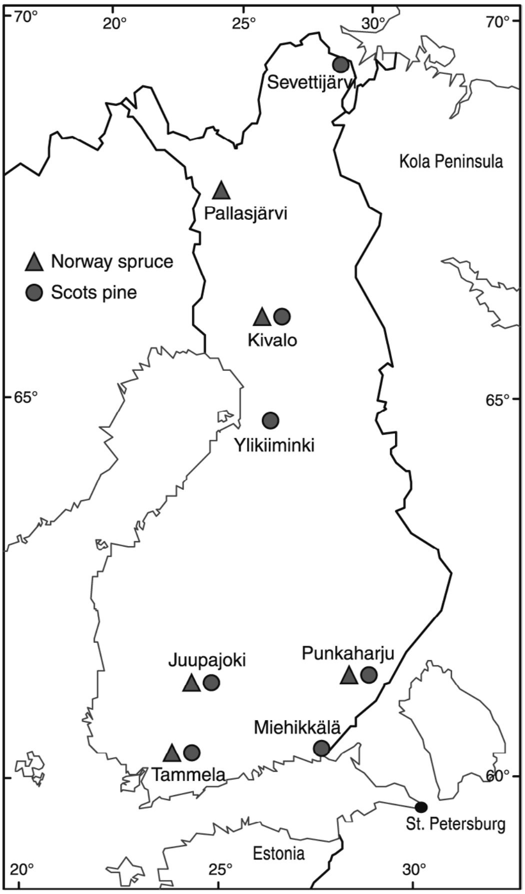

Fig. 1. Location of the seven Scots pine plots and five Norway spruce plots in Finland.

EU Forest Focus and UN/ECE ICP Forests programmes. The spruce stands were located on herb-rich and moist site types, and the pine sites on less fertile dryish and dry sites (Derome *et al.* 2007). Soil texture on the spruce plots was till and on the pine plots sorted glaciofluvial material, and the soil type podzol. Stand, climatic and soil characteristics of the plots are presented in Table 1.

TF samples were collected inside the stand using 20 rainfall (funnel-shaped collector, diameter 20 cm) and 6–10 snow collectors (top opening, diameter 36 cm) located systematically on the 30 × 30 m plot. The samples were collected at 2–4 week intervals throughout the year. BD samples were collected using the same type of collectors and sampling interval as for TF in an open area close to the stand, but the numbers of rainfall and snow collectors were three and two, respectively. PW samples were collected using zero-tension lysimeters (funnel-shaped, diameter 20 cm) located at the depths of 5, 20 and 40 cm below the ground surface. For details about the construction and installation of the lysimeters, *see* Derome *et al.* (1991). There were five lysimeters per depth on each of the plots. The PW samples were collected at four-week intervals during the snow-free period. It was not possible to collect PW samples during the winter due to the relatively thick snow cover on the plots as well as to freezing of the sampling tubes leading down to the lysimeters.

The amount (weight) of BD, TF and PW was measured in the field or, in the case of snow samples, in the laboratory after melting. In addition to the measurements, the annual flux of percolation water was also calculated by the so-called conservative anion budget method using SO_4 as a conservative anion (e.g. Nilsson *et al.* 1998). SO_4 was selected instead of Cl because Cl concentrations were extremely low and did not consistently increase with increasing depth, while SO_4 concentrations on all the plots exhibited a logical, consistent increasing trend with increasing depth. In the calculation, the following formula was used:

$$WF_x = SO4_{TF} \times WF_{TF}/SO4_x \quad (1)$$

where WF_x = water flux (mm) at x cm depth (x = 5, 20 or 40 cm below the ground surface), $SO4_{TF}$ = TF sulphate concentration (mg l^{-1}), WF_{TF} = water flux (mm) in TF, and $SO4_x$ = sulphate concentration (mg l^{-1}) in percolation water at x cm depth. It was assumed that the magnitude of the SO_4 input into the soil was in equilibrium (steady state) with the output in percolation water, as successfully applied on similar plots in southern Sweden (Nilsson *et al.* 1998). The values obtained by the anion budget method and those measured directly from the zero-tension lysimeters were compared during the period 1998–2000.

The BD, TF and PW samples were filtered (0.45 μm membrane filter) and the DOC concentration determined by pyrolysis and IR detection of the evolved CO_2 on a TOC analyser (NPOC determination, Shimadzu TOC5000). In

Table 1. Stand, climatic and soil characteristics of the sample plots. SP = Scots pine, NS = Norway spruce.

Plot, code	Latitude °N	Tree species	Mean precipitation ($mm\ a^{-1}$) in 1998–2004	Mean growing season length (days) 1998–2004	Mean effective temperature sum (degree days) in 1998–2004	Basal area with bark ($m^2\ ha^{-1}$) in 2004*	Stem number per ha in 2004*	Mean diameter (weighted with basal area) (cm) in 2004*	Mean (arithmetical) heigth (m) in 2004*	Stem volume with bark ($m^3\ ha^{-1}$) in 2004*	Stand age (years) in 2004*	Soil type	Soil texture
Sevettijärvi, 1	69	SP	432	106**	698**	13.3	350	24.7	11.5	76.4	205	Podzol	sorted
Kivalo, 6	66	SP	622	136	912	24.8	1755	14.4	13.3	167.3	60	Podzol	sorted
Ylikiiminki, 9	64	SP	569	156	1125	14.1	548	19.3	14.3	100.1	95	Podzol	sorted
Juupajoki, 10	61	SP	636	170	1333	20.1	378	27.2	22.4	210.6	85	Podzol	sorted
Punkaharju, 16	61	SP	564	176	1454	33.2	959	22.1	22.8	358.6	85	Podzol	sorted
Tammela, 13	60	SP	645	177	1367	25.6	604	24.0	21.1	254.5	65	Podzol	sorted
Miehikkälä, 18	60	SP	637	174	1451	18.6	415	24.9	20.2	177.8	125	Podzol	sorted
Pallasjärvi, 3	67	NS	572	133	764	13.9	1104	17.6	11	72.8	145	Podzol	till
Kivalo, 5	66	NS	619	136	912	23.2	1663	15.3	11.6	133.3	75	Podzol	till
Juupajoki, 11	61	NS	636	169	1287	35.8	852	25.2	21.9	375.5	85	Podzol	till
Punkaharju, 17	61	NS	564	176	1454	31.1	374	33.1	27.1	386.7	75	Podzol	till
Tammela, 12	60	NS	639	177	1367	30.1	663	25.2	21.6	309.4	65	Podzol	till

*Derome *et al*. 2007, **year 2006.

this method, DOC was determined as NPOC in accordance with standard BS EN 1484: 1997. The annual DOC fluxes were calculated using the DOC concentrations and the amount of BD, TF or PW. The relationships (Pearsons correlations) between the DOC fluxes in BD, TF and the leaching flux from the tree canopies (i.e. TF-BD), as well as in PW at different depths in the soil, and several climatic and stand parameters were also investigated. The climatic and stand parameters studied are presented in Table 1. Annual precipitation and the DOC fluxes in BD and TF for the individual years (1998–2004) have earlier been published in Lindroos *et al.* (2000, 2001, 2002, 2007). The annual monitoring surveys provide basic information about the deposition and percolation water chemistry. In this study, the results for the individual monitoring years were combined and related to several climatic and stand parameters in order to study the processes controlling the DOC fluxes.

Tree species, diameter (at 1.3 m above ground level), tree height and crown length were determined for all the trees on the 30 × 30 m plots. The individual tree measurements were converted into stand level characteristics (stem number per hectare, basal area, cubic volume, mean diameter and height). Taper curve functions (Laasasenaho 1982) were used for estimating the stem volume for each tree. The calculations were performed using the KPL software (Heinonen 1994), developed originally for generalizing sample tree information into tree populations for which less detailed measurements are available.

Estimates of stem, branch and needle biomasses were calculated using the functions of Marklund (1987, 1988). The functions describe the biomass components of individual trees as a function of species, diameter and tree height. In some cases crown length and the latitudinal coordinate are also included as explanatory variables.

The crown width of each tree was measured along four radii, oriented north, east, south and west from the stem. The coordinates of each tree were also determined using a tachymeter. The projection of the crown perimeter of each stem was estimated using a stiff cubic spline (IMSL Fortran Numerical Library, Visual Numerics Inc., Houston, Texas), which was forced through the four crown projection points. The total combined area of the forest floor covered by the vertical projection of the tree crowns was calculated using the Arcinfo GIS system (ESRI, Redlands, California), and divided by the plot size in order to obtain the percentage canopy cover.

The annual amount of precipitation was calculated from the four-week BD measurements. Temperature was measured at one-minute intervals using FW-5k sensors, located just above the canopy of the stands on towers erected on the plots, and converted into the daily mean temperature. The effective temperature sum is the sum of the differences between the daily mean temperature on individual days during the growing season and a threshold value of +5 °C. The growing season starts in the spring when the 5 °C threshold is exceeded for at least five consecutive days, and ends in autumn when the temperature remains below the threshold on at least five consecutive days. In Punkaharju and Tammela, the meteorological parameters were measured only in the spruce plots. As the pine plots at these locations are situated close to the spruce plots, the temperatures measured above the spruce stands were used for both plots.

Results

Water fluxes

The water flux ($l\ m^{-2}\ a^{-1} = mm\ a^{-1}$) determined directly from the amount of water collected by the zero-tension lysimeters during 1998–2000 on the 12 plots was clearly lower than the flux obtained by the SO_4 budget method (Fig. 2). Although the water fluxes determined by the SO_4 budget method are most likely overestimates, this method was considered to give more realistic results than direct measurements made using the lysimeters (*see* Discussion). The SO_4 budget method was therefore used in the subsequent calculations of the DOC fluxes in PW in the soil.

Overall, the mean water fluxes (1998–2004) determined by the SO_4 budget method for the pine and spruce sites decreased as precipitation passed through the canopy layer and down the soil profile on all the plots (Fig. 3). The mean annual BD varied between 432 and 645 mm on

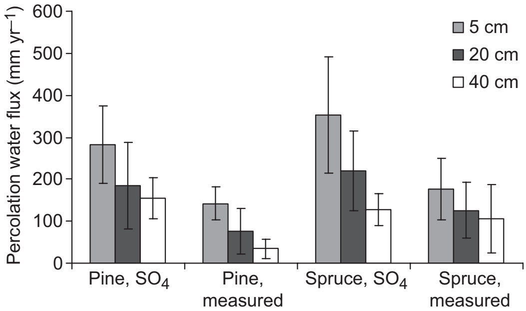

Fig. 2. Percolation water fluxes (mean ± S.D.) during 1998–2000 for the Scots pine and Norway spruce plots calculated by the anion budget (SO_4) method and by direct measurements (measured) with zero-tension lysimeters. 5 cm, 20 cm and 40 cm = percolation water collected at depths of 5, 20 and 40 cm below the ground surface.

the pine plots (Table 1 and Fig. 3a). Annual BD on plot No. 13 (Tammela) in southern Finland was the highest, and the lowest on plot No. 1 (Sevettijärvi) located in northernmost Finland. The variation in the mean annual BD in the spruce stands was 564–639 mm (Table 1 and Fig. 3b). The mean output water flux at the depth of 40 cm in the soil was below 200 mm on all the pine and spruce plots, except on one of the pine plots (No. 6, Kivalo) in northern Finland (Fig. 3).

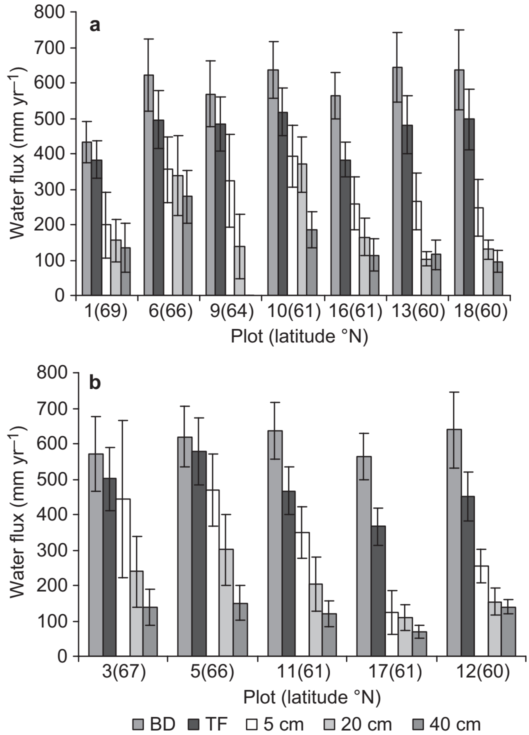

Fig. 3. Annual water fluxes (mean ± S.D., 1998–2004, SO_4 budget method) for (**a**) the Scots pine and (**b**) Norway spruce plots. The plots are arranged from left to right running from northern to southern Finland (latitude of the plot in parentheses). BD = bulk deposition, TF = stand throughfall, 5, 20, 40 cm = flux at corresponding depths.

DOC concentrations and fluxes

The mean DOC concentration (mg l^{-1}) clearly increased on all the pine and spruce plots as water passed down through the canopy layer and the organic layer of the soil to the depth of 5 cm (Fig. 4). The DOC concentration in TF was generally higher on the plots located in southern than in northern Finland. The DOC concentration was at its highest on all the pine and spruce plots in PW collected immediately below the organic layer (5-cm depth). The DOC concentration in PW decreased on all but two of the plots as water percolated down to the depth of 40 cm. On the two pine plots located in northern Finland (No. 1 and 6), the lowest DOC concentration was measured at the depth of 20 cm, but on plot No. 1 the concentrations were at almost the same level at the depths of 20 and 40 cm.

The DOC flux (g C m^{-2} a^{-1}) increased on all the plots as precipitation passed through the canopy layer (i.e. TF > BD) (Fig. 5). The TF fluxes on the plots in southern Finland were higher than those in the north. In general, the DOC flux increased on passing down through the organic layer to the depth of 5 cm. In contrast, the DOC flux in PW decreased on moving to the depths of 20 and 40 cm, and the lowest values generally occurred at the depth of 40 cm. The output flux of DOC at the depth of 40 cm was, in general, at the same level as the input flux in BD or TF.

There were no clear temporal trends in the DOC fluxes (e.g. in TF and PW at the depth of 40 cm) during the period 1998–2004 on the pine and spruce plots (Fig. 6). The pine plot in northern Finland (No. 6) was, however, a clear exception. A strongly increasing trend occurred in the DOC output flux at the depths of 20 and 40 cm during 1998–2004.

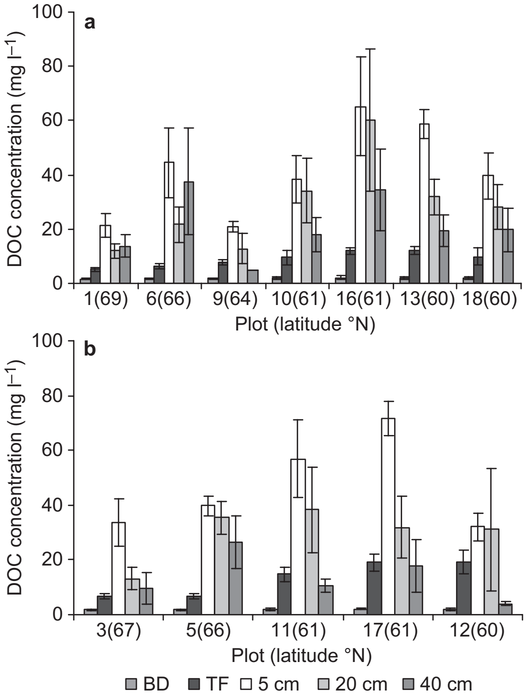

Fig. 4. The DOC concentration (mean ± S.D., 1998–2004) in (**a**) the Scots pine and (**b**) Norway spruce plots. The plots are arranged from left to right running from northern to southern Finland (latitude of the plot in parentheses). BD = bulk deposition, TF = stand throughfall, 5, 20, 40 cm = flux at corresponding depths.

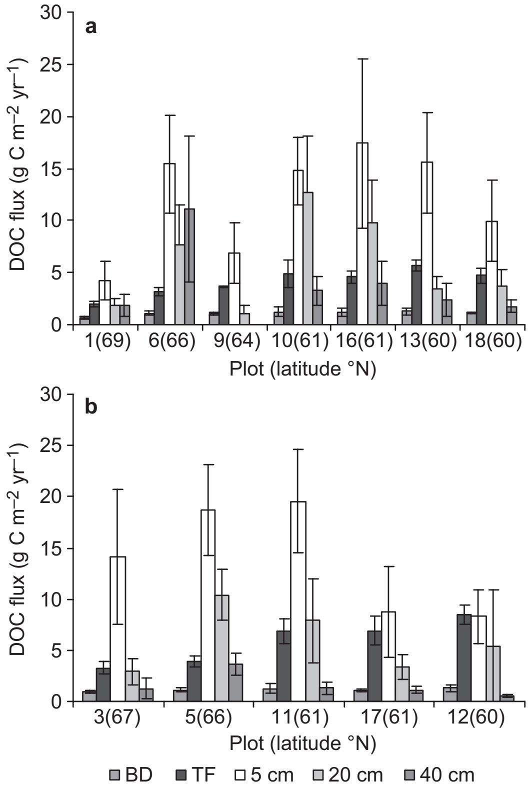

Fig. 5. Annual DOC fluxes (mean ± S.D., 1998–2004) in (**a**) the Scots pine and (**b**) Norway spruce plots. The plots are arranged from left to right running from northern to southern Finland (latitude of the plot in parentheses). BD = bulk deposition, TF = stand throughfall, 5, 20, 40 cm = flux at corresponding depths.

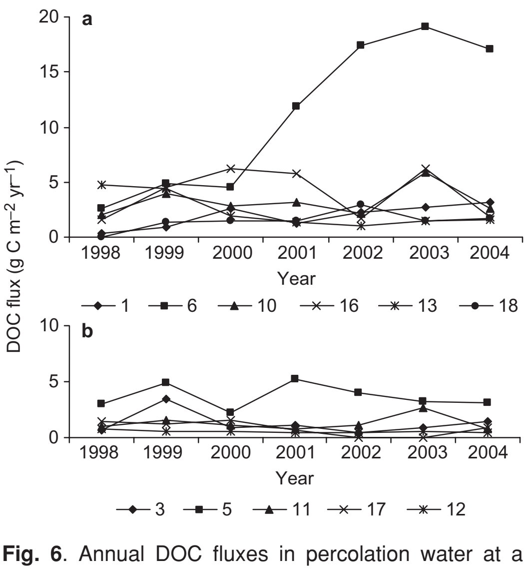

Fig. 6. Annual DOC fluxes in percolation water at a depth of 40 cm below the ground surface on (**a**) the Scots pine and (**b**) Norway spruce plots during 1998–2004. The plot number is indicated in the legend.

DOC fluxes and their relationship with climatic parameters and stand characteristics

The DOC fluxes in TF and net throughfall (net TF = TF – BD) correlated positively ($p < 0.05$) with the amount of precipitation in BD on the pine plots (Table 2 and Fig. 7a). There were also significant positive correlations between the DOC fluxes in TF, net TF and the climatic factors: length of the growing season and effective temperature sum (ETS) on the pine plots (Fig. 7b and c). The DOC fluxes in TF and net TF also correlated positively ($p < 0.05$) with the mean height of the trees in the pine stands. All the above-mentioned parameters correlated negatively ($p < 0.05$) with the latitude of the pine plots, i.e. the highest DOC fluxes, ETS, length of the growing season and mean height of the trees occurred on the pine plots in southern Finland. The DOC fluxes in PW at the depths of 20 and 40 cm correlated positively ($p < 0.05$) with the water flux on the pine plots.

The DOC flux in TF and net TF correlated positively ($p < 0.05$) with the length of the growing season and ETS in the spruce stands (Table 3 and Fig. 8a, b). There was a significant positive correlation between the DOC flux in net TF and the stem volume of the spruce stands. The other stand parameters (e.g. stand basal area, mean diameter, mean height, canopy coverage, biomass parameters) also correlated relatively strongly, although not significantly, with the DOC flux in TF and net TF in the spruce stands. No significant correlations were found between the DOC flux in PW at different depths and the climatic and stand characteristics. The DOC fluxes in TF and net TF, as well as climatic factors (length of the growing season, ETS) and several stand characteristics, correlated negatively ($p < 0.05$) with the latitude of the spruce stands, i.e. the highest values occurred in southern Finland.

There was no significant correlation between the input flux of DOC in TF or net TF and the output flux in PW at any of the soil depths on the pine and spruce plots (Tables 2 and 3).

Discussion

Correct estimation of the amount of water passing down through the soil is of crucial importance when calculating the output fluxes of elements

Table 2. Correlations between DOC fluxes (mean 1998–2004) in bulk deposition (BD), throughfall (TF) and percolation water (PW) at the depths of 5, 20 and 40 cm in the soil and several stand and climatic characteristics on the pine plots. Statistically significant correlations ($p < 0.05$, $n = 7$) are set in boldface.

	Latitude	BD-DOC	TF-DOC	(TF-BD)-DOC	$PW_{5\ cm}$-DOC	$PW_{20\ cm}$-DOC	$PW_{40\ cm}$-DOC
Latitude	1						
BD-DOC (g C m^{-2} a^{-1})	**–0.88**	1					
TF-DOC (g C m^{-2} a^{-1})	**–0.97**	**0.90**	1				
(TF-BD)-DOC (g C m^{-2} a^{-1})	**–0.96**	**0.85**	**1.00**	1			
$PW_{5\ cm}$-DOC (g C m^{-2} a^{-1})	–0.60	**0.83**	0.66	0.61	1		
$PW_{20\ cm}$-DOC (g C m^{-2} a^{-1})	–0.34	0.51	0.34	0.30	0.74	1	
$PW_{40\ cm}$-DOC (g C m^{-2} a^{-1})	0.26	0.17	–0.21	–0.28	0.51	0.43	1
BD (mm)	**–0.78**	**0.91**	**0.80**	**0.76**	0.67	0.39	0.25
TF (mm)	–0.40	0.54	0.44	0.41	0.20	0.15	0.16
$PW_{5\ cm}$ (mm)	–0.18	0.51	0.23	0.17	0.43	0.60	0.44
$PW_{20\ cm}$ (mm)	0.14	0.17	–0.10	–0.15	0.38	**0.76**	0.65
$PW_{40\ cm}$ (mm)	0.43	0.02	–0.34	–0.41	0.27	0.40	**0.88**
Mean growing season length (days) in 1998–2004	**–0.98**	**0.91**	**0.95**	**0.94**	0.63	0.36	–0.22
Mean ETS in 1998–2004*	**–0.98**	**0.84**	**0.92**	**0.91**	0.58	0.37	–0.29
Basal area (m^2 ha^{-1}) 2004	–0.48	0.65	0.51	0.47	**0.91**	0.57	0.44
Stem number per ha in 2004	0.21	0.23	–0.17	–0.24	0.52	0.28	**0.94**
Mean diameter (cm) in 2004	–0.39	–0.02	0.37	0.43	–0.13	0.13	–0.72
Mean height (m) in 2004	**–0.92**	**0.79**	**0.90**	**0.90**	0.68	0.58	–0.23
Stem volume (m^3 ha^{-1}) in 2004	–0.69	0.72	0.69	0.67	**0.86**	0.60	0.13
Stand age (years) in 2004	0.57	**–0.89**	–0.65	–0.59	**–0.82**	–0.45	–0.46
Canopy coverage (%) in 1999**	–0.21	0.65	0.29	0.22	0.86	0.39	0.82
Biomass:							
Stem (kg ha^{-1}) in 2004	–0.71	0.71	0.69	0.67	**0.84**	0.63	0.11
1. Living branches (kg ha^{-1}) in 2004	0.43	–0.50	–0.41	–0.38	0.00	0.12	0.16
2. Dead branches (kg ha^{-1}) in 2004	–0.54	0.70	0.54	0.49	**0.91**	0.62	0.45
3. Needles (kg ha^{-1}) in 2004	0.18	0.18	–0.14	–0.20	0.56	0.26	**0.87**
1 + 2 + 3 (kg ha^{-1}) in 2004	0.21	–0.11	–0.18	–0.19	0.42	0.34	0.49

* ETS = effective temperature sum, **$n = 5$.

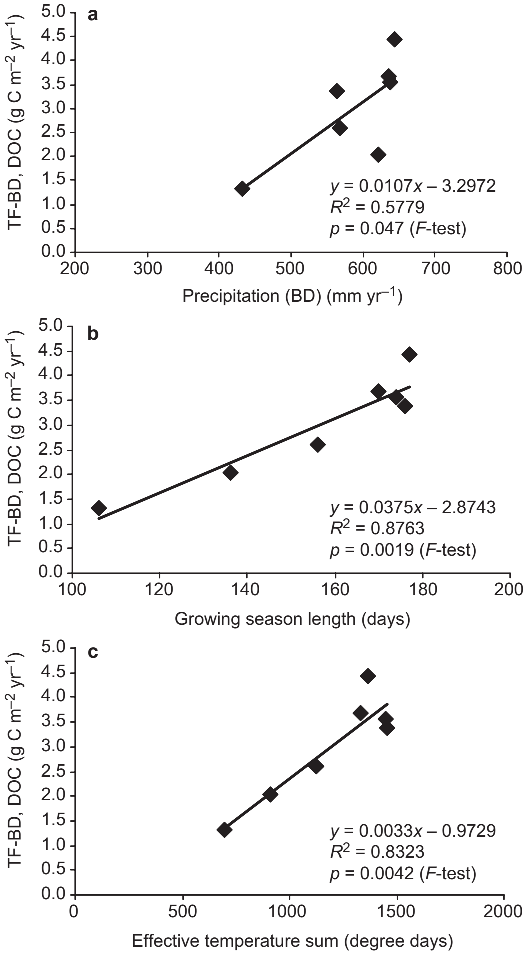

Fig. 7. Relationships between the annual DOC flux in net throughfall (net TF = TF – BD) and (**a**) annual precipitation, (**b**) length of the growing season, and (**c**) effective temperature sum for the Scots pine plots. The values are means for the period 1998–2004 (for the plot No. 1, length of the growing season and ETS for the year 2006, *see* Table 1).

from the surface soil. In Finland, the amount of water collected directly by zero-tension lysimeters has been extensively used in a number of studies (e.g., Derome and Nieminen 1998, Lindroos *et al*. 2000b, Piirainen *et al*. 2002b). However, it is clear that the water fluxes estimated directly from the amount of water collected by zero-tension lysimeters are strongly affected by many factors related to the spatial heterogeneity of the forest soil and installation of the lysimeters (e.g. Piirainen *et al*. 2002b). For instance, Giesler *et al*. (1996) reported that the water fluxes determined in their studies using zero-tension lysimeters were underestimates. The installation of zero-tension lysimeters clearly causes changes in the hydrological conditions in the soil (e.g. Joffe 1932) due to the unavoidable cutting of roots and disturbances in soil texture and structure. Furthermore, zero-tension lysimeters underestimate the annual output water flux because, during snow-melt in the spring, the amount of water flowing down the soil profile is usually much larger than the capacity of the water sample collectors connected to the underside of the lysimeters. The number of replicate lysimeters is also much too small to obtain a reliable estimate of the water flux on the whole 30 × 30 m plot: the number of precipitation collectors required to obtain a reliable estimate of throughfall is at least 20, and the spatial variation in percolation water is obviously many times greater. We compared the water fluxes determined directly using zero-tension lysimeters and the water flux estimations calculated with the SO_4 budget method. The anion budget method using SO_4 anions has been used successfully in Sweden to calculate nitrogen output fluxes (Nilsson *et al*. 1998). However, if SO_4 anions are taken up by plants or adsorbed by hydroxides enriched in the B horizon of these podzolic soils (Gustafsson 1994, Karltun 1995), then the SO_4 concentrations will in actual fact be lower than we assumed and thus slightly overestimate the water flux in the soil. Although, the SO_4 budget method may give an overestimation of the water output flux, we considered that it would give a more correct picture of the annual water flux than direct measurement with lysimeters. The water fluxes determined directly from the zero-tension lysimeters were lower than the water fluxes estimated using the SO_4 budget method and, because we could not collect all the water percolating down the soil profile (e.g. during early and late winter), it is obvious that direct measurements are not true values but clear underestimates. Our DOC output fluxes (calculated by the anion budget method) were also very comparable with those reported by Starr and Ukonmaanaho (2004) using the WATBAL model on plots in eastern Finland.

During our study, the mean DOC flux in TF varied between 2 and 6 g C m^{-2} a^{-1} and between 3 and 8 g C m^{-2} a^{-1} on the pine and spruce plots,

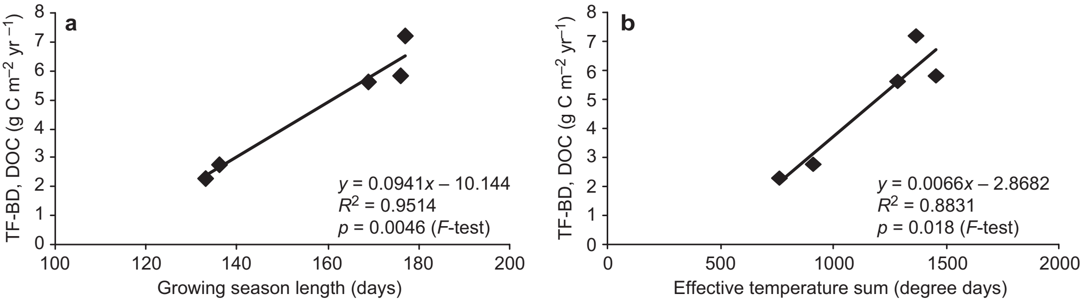

Fig. 8. Relationships between the annual DOC flux in net throughfall (net TF = TF – BD) and (**a**) length of the growing season, and (**b**) effective temperature sum for the Norway spruce plots. The values are means for the period 1998–2004.

respectively. The measured DOC input to the forest floor was very similar to that reported for pine stands in a forested catchment in eastern Finland (average 4 g C m^{-2} a^{-1}, Starr and Ukonmaanaho 2004). Our plots are located in managed forest stands, while those studied by Starr and Ukonmaanaho (2004) are in unmanaged forest. The DOC flux in TF on our plot

Table 3. Correlations between the DOC fluxes (mean 1998–2004) in bulk deposition (BD), throughfall (TF) and percolation water (PW) at the depths of 5, 20 and 40 cm in the soil and several stand and climatic characteristics on the spruce plots. Statistically significant correlations ($p < 0.05$, $n = 5$) are set in boldface.

	Latitude	BD-DOC	TF-DOC	(TF-BD)-DOC	$PW_{5\ cm}$-DOC	$PW_{20\ cm}$-DOC	$PW_{40\ cm}$-DOC
Latitude	1						
BD-DOC (g C m^{-2} a^{-1})	–0.81	1					
TF-DOC (g C m^{-2} a^{-1})	**–0.98**	0.85	1				
(TF-BD)-DOC (g C m^{-2} a^{-1})	**–0.99**	0.83	**1.00**	1			
$PW_{5\ cm}$-DOC (g C m^{-2} a^{-1})	0.45	–0.11	–0.52	–0.54	1		
$PW_{20\ cm}$-DOC (g C m^{-2} a^{-1})	0.10	0.38	–0.12	–0.15	0.72	1	
$PW_{40\ cm}$-DOC (g C m^{-2} a^{-1})	0.62	–0.26	–0.64	–0.65	0.64	0.75	1
BD (mm)	–0.38	0.83	0.43	0.40	0.33	0.69	0.08
TF (mm)	0.72	–0.19	–0.67	–0.69	0.70	0.68	0.76
$PW_{5\ cm}$ (mm)	0.80	–0.35	–0.77	–0.78	0.75	0.50	0.61
$PW_{20\ cm}$ (mm)	0.80	–0.33	–0.78	–0.80	0.78	0.64	0.81
$PW_{40\ cm}$ (mm)	0.51	0.05	–0.40	–0.42	0.44	0.48	0.39
Mean growing season length (days) in 1998–2004	**–0.99**	0.73	**0.97**	**0.98**	–0.53	–0.21	–0.66
Mean ETS in 1998–2004*	**–0.97**	0.70	**0.94**	**0.94**	–0.50	–0.14	–0.54
Basal area (m^2 ha^{-1}) 2004	**–0.90**	0.81	0.83	0.82	–0.05	0.26	–0.28
Stem number per ha in 2004	0.78	–0.30	–0.76	–0.78	0.72	0.68	0.86
Mean diameter (cm) in 2004	–0.83	0.36	0.77	0.78	–0.60	–0.46	–0.64
Mean height (m) in 2004	**–0.92**	0.54	0.86	0.87	–0.51	–0.29	–0.59
Stem volume (m^3 ha^{-1}) in 2004	**–0.94**	0.67	0.87	**0.88**	–0.30	–0.07	–0.50
Stand age (years) in 2004	0.70	–0.80	–0.70	–0.69	0.19	–0.47	–0.09
Canopy coverage (%) in 1999	–0.75	0.64	0.67	0.67	–0.03	0.34	–0.02
Biomass:							
Stem (kg ha^{-1}) in 2004	–0.87	0.50	0.78	0.79	–0.34	–0.18	–0.49
1. Living branches (kg ha^{-1}) in 2004	–0.81	0.63	0.71	0.71	0.01	0.19	–0.23
2. Dead branches (kg ha^{-1}) in 2004	–0.87	0.52	0.78	0.79	–0.31	–0.14	–0.47
3. Needles (kg ha^{-1}) in 2004	–0.62	0.64	0.55	0.54	0.08	0.54	0.22
1 + 2 + 3 (kg ha^{-1}) in 2004	–0.82	0.63	0.72	0.72	–0.03	0.19	–0.22

* ETS = effective temperature sum.

network was also very similar to that reported by Piirainen (2002) and Piirainen *et al*. (2002) for a spruce-dominated, mixed forest in eastern Finland. The mean DOC flux in net TF varied between 1.3 and 4.5 g C m^{-2} a^{-1} and 2 and 7 g C m^{-2} a^{-1} on the pine and spruce plots, respectively. The magnitude of the DOC fluxes is also comparable with the results reported for a mature, northern hardwood forest at Hubbard Brook, USA (Fahey *et al*. 2005).

The output flux of DOC in percolation water at the depth of 40 cm varied between 1 and 4 g C m^{-2} a^{-1} (except for plot No. 6, ca. 10 g C m^{-2} a^{-1}) on our plots in both the spruce and pine stands. Starr and Ukonmaanaho (2004) reported an average output flux of 3.7 g C m^{-2} a^{-1} at the depth of 35 cm in a pine stand in eastern Finland while, according to Piirainen (2002) and Piirainen *et al*. (2002), the output DOC flux below the B horizon of a podzolic soil in a spruce-dominated, mixed forest in eastern Finland was about 0.3 g C m^{-2} a^{-1}. Despite the obvious differences in forest structure and soil properties, the magnitude of the DOC fluxes on these mineral soil sites seems to relatively similar. Furthermore, the water flux was estimated using different methods in the above-mentioned studies: Starr and Ukonmaanaho (2004) used a hydrological model (Starr 1999), and Piirainen *et al*. (2002) direct measurement using zero-tension lysimeters. Our values are also in relatively good agreement with those reported in the Hubbard Brook Experimental Forest, USA (Johnson *et al*. 2000, Fahey *et al*. 2005).

Litterfall is an important pathway through which C is returned to the forest soil. The C flux in above-ground tree litterfall on the pine plots in our network ranged from about 60 to 170 g C m^{-2} a^{-1}, and on the spruce plots from 30 to 250 g C m^{-2} a^{-1} during 1996–2003 (Derome *et al*. 2006, Ukonmaanaho 2007). This means that the C input to the forest floor in above-ground tree litterfall was about 10–30 times greater than the C input in TF. This finding is very close to the value reported by Piirainen (2002).

The magnitude of the DOC output flux below the rooting zone (40-cm depth) was at the same level or lower than the DOC input in TF. This clearly demonstrates that only a relatively small amount of carbon is leached from the uppermost soil layers, and subsequently into the groundwater. The output fluxes of DOC in percolation water (1–4 g C m^{-2} a^{-1}, except for plot No. 6, ca. 10 g C m^{-2} a^{-1}) on our plots were also very small as compared with the reported annual CO_2 effluxes from forest soil in Finland (e.g. 520 g C m^{-2} a^{-1}, Ilvesniemi *et al*. 2002).

The highest output fluxes of DOC in PW occurred on pine plot No. 6, in northern Finland. There was also an increasing trend in the output DOC flux on this plot during 1998–2004, but not on the other plots. The reason for the high DOC output flux, as well as the increasing temporal trend, is most probably the high natural mortality rate of small trees in the stand due to self-thinning during the study period, and subsequent extra C input to the forest floor. The mortality was a natural result of the high stand density (1755 stems ha^{-1}). The diameter of most of the dead trees was < 5.0 cm, which is the threshold used in measuring trees for the EU Forest Focus and UN/ECE ICP Forests Programmes, and these trees had therefore not been included in the stand parameters.

The DOC concentration and flux increased as precipitation passed down through the stand canopy and organic layer of the forest soil. The DOC flux below the organic layer was clearly lower than the litterfall C input to the forest floor, but higher than that in TF. The DOC flux decreased with increasing depth down the podzolic soil profile. This reduction could be partly due to biological degradation processes. In mineral soils in Finland, however, the DOC in percolation water below the organic layer consists mainly of large molecular weight, hydrophobic and hydrophilic acids (Lindroos *et al*. 2003) and, because the biodegradability of these compounds is known to be relatively low (Qualls and Haines 1992), microbial degradation is probably only marginal. Chemical processes, such as the precipitation and accumulation of organic matter in the illuvial horizon together with Fe, Al and Si (Lundström *et al*. 2000), are important in the development of podzolic soils, and this will lead to lower DOC fluxes in percolation water with increasing soil depth.

The DOC fluxes in TF and net TF correlated positively with the ETS and length of the growing season in both the pine and spruce stands, i.e. the highest DOC fluxes were recorded on the plots in southern Finland and the fluxes decreased northwards. A similar latitudinal pattern has also been reported by Starr and Ukonmaanaho (2004) for unmanaged boreal forest ecosystems in Finland. Higher temperatures and a longer growing season in the south favour the leaching of DOC from the canopy layer, since the leaching efficiency of snow is extremely low and there is a longer period with snow in the winter in the northern parts of the country (Starr and Ukonmaanaho 2004). The throughfall and net throughfall DOC fluxes also correlated with the amount of precipitation on the pine sites, because water is the main driving force causing the leaching of DOC from tree canopies.

The net throughfall DOC flux correlated positively with the stem volume of the spruce stands. According to Starr and Ukonmaanaho (2004), a low stand volume could be related to less interaction between the canopy layer and rainfall than in the case of higher stand volumes, which clearly suggests that higher DOC fluxes in throughfall would be related to the stand volume. Also many other stand parameters correlated relatively strongly, although not significantly, with the throughfall and net througfall DOC fluxes in the spruce stands. However, climatic factors may also have an effect on these relationships because the highest values for many stand parameters occurred on the plots in southern Finland.

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