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Detrital controls on soil solution N and dissolved organic matter in soils: a field experiment

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Abstract. We established a long-term field study in an old growth coniferous forest at the H.J. Andrews Experimental Forest, OR, USA, to address how detrital quality and quantity control soil organic matter accumulation and stabilization. The Detritus Input and Removal Treatments (DIRT) plots consist of treatments that double leaf litter, double woody debris inputs, exclude litter inputs, or remove root inputs via trenching. We measured changes in soil solution chemistry with depth, and conducted long-term incubations of bulk soils from different treatments in order to elucidate effects of detrital inputs on the relative amounts and lability of different soil C pools. In the field, the addition of woody debris increased dissolved organic carbon (DOC) concentrations in O-horizon leachate and at 30 cm, but not at 100 cm, compared to control plots, suggesting increased rates of DOC retention with added woody debris. DOC concentrations decreased through the soil profile in all plots to a greater degree than did dissolved organic nitrogen (DON), most likely due to preferential sorption of high C:N hydrophobic dissolved organic matter (DOM) in upper horizons; percent hydrophobic DOM decreased significantly with depth, and hydrophilic DOM had a much lower and less variable C:N ratio. Although laboratory extracts of different litter types showed differences in DOM chemistry, percent hydrophobic DOM did not differ among soil solutions from different detrital treatments in the field, suggesting that microbial processing of DOM leachate in the field consumed easily degradable components, thus equalizing leachate chemistry among treatments. Total dissolved N leaching from plots with intact roots was very low (0.17 g m^{-2} $year^{-1}$), slightly less than measured deposition to this very unpolluted forest (~0.2 g m^{-2} $year^{-1}$). Total dissolved N losses showed significant increases in the two treatments without roots whereas concentrations of DOC decreased. In these plots, N losses were less than half of estimated plant uptake, suggesting that other mechanisms, such as increased microbial immobilization of N, accounted for retention of N in deep soils. In long-term laboratory incubations, soils from plots that had both above- and below-ground litter inputs excluded for 5 years showed a trend towards lower DOC loss rates, but not lower respiration rates. Soils from plots with added wood had similar respiration and DOC loss rates as control soils, suggesting that the additional DOC sorption observed in the field in these soils was stabilized in the soil and not readily lost upon incubation.

Introduction

Ecologists have long recognized that the quality and quantity of plant detrital inputs affect soil organic matter (SOM) accumulation and chemistry. However, most studies of litter decay have focused on short-term (usually under 5 years) analyses of litter loss and not on the accumulation and stabilization of the organic products that remain. General patterns have emerged from such litter decomposition studies. For example, high concentrations of lignin and polyphenols in litter can slow decomposition and delay nitrogen (N) release (Melillo et al. 1982, 1989; Palm and Sanchez 1991; Hattenschwiler and Vitousek 2000). Decomposition of labile components, such as cellulose, may be N limited, and thus a high litter N concentration has been shown to increase cellulase activity and decay rates during the early stages of decomposition (Kuperman 1999; Berg 2000; Carreiro et al. 2000). With the disappearance of cellulose and other labile C sources, the concentration of more recalcitrant compounds increase, and high N concentrations may slow further decomposition (Magill and Aber 1998; Berg 2000; Carreiro et al. 2000; Sinsabaugh et al. 2002; Saiya-Cork et al. 2002).

However, fewer studies have addressed the link between litter chemistry and SOM formation and stabilization, particularly in forest soils. Quideau et al. (2001) demonstrated, using ^{13}C-NMR, that soil organic matter chemistry was significantly affected by the species composition of the overlying vegetation. However, it is not known if these chemical differences translated into differences in soil organic matter turnover rates. Dignanc et al. (2002a, 2002b) studied organic matter composition in Oa and A horizons with a wide range of C/N ratios. They noted that with increasing N concentration, concentration of lignin decreased in the Oh horizons but increased in the A horizons. Thus, a negative effect of N on lignin degradation was observed for mineral soils. They noted that while litter N concentration may have a controlling effect on litter biodegradation in the forest floor, stabilization of organic matter in the mineral soil may be more influenced by physical parameters related to soil texture. In contrast, Sjoberg et al. (2004) were not able to show any major C structural changes due to N fertilization in a Norway spruce forest soil.

Similarly, few studies have made a link between litter chemical quality, dissolved organic matter (DOM) production and soil solution chemistry, and stabilization of SOM. In a 90-day incubation experiment with DOM samples produced from different litter sources, Kalbitz et al. (2003) found increases in aromatic compounds, partial degradation of higher-molecular, lignin-derived DOM compounds, and increases in the proportions of lower-molecular degradation products after incubation. They found that carbohydrates were more readily lost via microbial metabolism. After incubation, the composition of highly degradable DOM samples became chemically similar to relatively stable DOM samples. This might suggest that while different litter sources can produce chemically distinct DOM, microbial processes might work to equalize DOM as it passes through the soil.

Other work using litter manipulations has shown that the exclusion of aboveground litter inputs caused no change in the overall leaching losses of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in forest floor leachates (Park and Matzner 2003). In addition, Kalbitz et al. (2004) found that DOC production may not be related to the quality of litter inputs following clear-cutting in forests. These studies, however, have been based on relatively short-term responses, and the long-term influence of changes in detrital contributions to both the amount and chemical fractionation of dissolved organic matter in soils is less well known.

More studies have examined interactions among DOC and N production and availability, although results are mixed. In both field and laboratory studies of a forest with high chronic N deposition, Park and Matzner (2001) and Park et al. (2002) demonstrated that enhanced C inputs to soils reduced N leaching due to increased microbial immobilization, and they hypothesized that C limitation in forest floors exposed to chronic N deposition leads to an enhanced N leaching. Park et al. (2002) also reported that fertilization with N reduced DOC release but enhanced both DON and DIN release. In contrast, McDowell et al. (2004) found that concentrations of DOC were unchanged by N fertilization in both hardwood and pine stands of a moderately N-enriched forest in Massachusetts. It is not clear if C additions to an unpolluted forest such as the H.J. Andrews site would show the same pattern of lowering N export as observed by Park and Matzner (2001), as Andrews soils should be significantly more C rich and N poor than in these previously studied N-rich forests.

Inspired by a project started in 1957 in forest and grassland ecosystems at the University of Wisconsin Arboretum (Nielson and Hole 1963), we established a long-term field study in an old growth coniferous forest at the H.J. Andrews Experimental Forest, OR, USA, to address how detrital quality and quantity control soil organic matter accumulation and stabilization. The Detritus Input and Removal Treatments (DIRT) plots consist of treatments that double leaf litter inputs, double woody debris inputs, exclude litter inputs, or remove root inputs via trenching. The central goal of the DIRT project is to assess how rates and sources of plant litter inputs control the accumulation and dynamics of organic matter and nutrients in forest soils over decadal time scales. DIRT plots were also established in an oak forest at the Harvard Forest, MA, USA in 1990 and in a black cherry/sugar maple-dominated forest in the Bousson Experimental Forest, PA, USA in 1991.

In contrast to bulk soil properties, which are typically slow to respond to a chronic stress, soil solution chemistry may provide an early indication of the long-term changes in soils associated with an experimental manipulation (McDowell et al. 2004). Thus we focused on changes in soil solution chemistry here, as well as to responses to laboratory incubation. We hypothesized that differences in detrital quality delivered to the forest floor would translate to differences in the chemical quality of DOC that leached through the soil profile as well as differences in the amount of C lost via respiration. However, we

hypothesized that soils receiving high DOC inputs would effectively stabilize this added C, which would not be readily lost via respiration upon incubation. We also hypothesized that changes in DOC would affect N dynamics as well, with treatments producing greater quantities of DOC resulting in lower nitrate and DON leaching.

Methods

Study site

Plant litter inputs have been manipulated at the DIRT plots in the H.J. Andrews Experimental Forest in Oregon (44°13′ N, 122°13′ W, 531 m elevation) since 1997. Mean annual temperature at the headquarters site at the Andrews is 8.7 °C (average from 1973–2002) and mean annual precipitation is 2370 mm $year^{-1}$, mostly as rain. Over 70% of the precipitation occurs during a ''wet season'' between November and March (Sollins et al. 1980). Nitrogen deposition to this area is ~0.2 g N m^{-2} $year^{-1}$ (Vanderbilt et al. 2003). The DIRT site was established in an undisturbed old-growth western hemlock (*Tsuga heterophylla* (Rafinesque) Sargent) – Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand. Other significant tree species at the site include vine maple (*Acer circinatum* Pursh.) and western red cedar (*Thuja plicata* D. Don). Soils are derived from volcanic parent materials and have been classified as coarse loamy mixed mesic Typic Hapludands. The soils have strong andic properties: high amorphous Al hydroxide and aluminosilicate concentrations (oxalate-extractable Al = 1.1%) and a pH in 1 N NaF near 11 (Yano et al. 2005; Spears and Lajtha 2004; Table 1).

Table 1. Soil characteristics of the H.J. Andrews DIRT site. Bulk soil characteristics are from 14 pits described to at least 60 cm (mean ± 1 SE).

Taxonomic subgroup	Typic Hapludands[a]
Depth (cm)	90 + cm
O horizon depth (control plots)	1.5 ± 0.3 cm
O horizon depth (double needle plots)	1.9 ± 0.3 cm
pH of mineral surface horizon[b]	5.4
C:N (0–5 cm)	34.6 ± 3.3
C:N (5–10 cm)	18.6 ± 0.4
C:N (10–20 cm)	16.3 ± 1.4.
Bulk density mineral surface horizon (Mg/ha)[b]	0.82
Texture[b]	Loam
%clay[b]	9–20% (mean = 13%)
Mean annual soil temperature at 5 cm (°C), 2001–2003	9.5
Mean annual soil moisture at 10 cm (%), 2001–2003	29

[a]Small areas of Andic Dystrudepts and Vitrandic Dystrudepts also underlie the treatment plots. Differences between O horizon depths are not significant.
[b]Data from Dixon (2003).

Table 2. DIRT plot treatments at the H.J. Andrews LTER site, Oregon.

Treatment	Method
CONTROL	*Normal litter inputs are allowed.*
NO LITTER	*Aboveground inputs are excluded from plots.*
DOUBLE LITTER	*Aboveground leaf/needle inputs are doubled by adding litter removed from* NO LITTER *plots.*
DOUBLE WOOD	*Aboveground wood inputs are doubled by adding large shredded wood pieces based on measured input rates of woody debris fall.*
NO ROOTS	*Roots are excluded with impenetrable barriers extending from the soil surface to the top of the C horizon.*
NO INPUTS	*Aboveground inputs are prevented as in* NO LITTER *plots; Belowground inputs are prevented as in* NO ROOTS *plots.*

Each treatment is replicated three times.

Six litter input/exclusion treatments, replicated three times, were randomly assigned to the plots (Table 2). Plots are typically 10 m × 15 m and include trees, although there is a small range in plot sizes due to available space and obstacles. To double needle and fine litter inputs, the litter on No Litter plots was excluded with 1 mm-mesh screens and was transferred to Double Litter plots 4–5 times per year: at the end of the dry season, twice or more during the wet season (November–March), and at the beginning of the dry season. Any large branches and stems or lichen/moss masses that fell on screens were discarded. While a certain amount of DOM will pass through the screens between screen cleaning events, the vast majority of litter C inputs to the plots will be excluded through this screening technique. Water balance can also be affected by the screens; screens may impede deposition (although no ponding or lateral flow has been observed) and reduce evaporation from the soil. Measures of soil water potential (see below) in all plots suggest that water potentials are slightly elevated in spring and fall in screened plots, but are not significantly different during the season of significant water flux. However, these differences are taken into account when calculating respiration fluxes (below).

To double the mass of woody debris in the forest floor of Double Wood plots, a mix of decomposed woody debris (class 4 log material as defined by Triska and Cromack 1979)) and shredded chips (5–20 cm in length) of Douglas-fir wood with a ratio of decomposed woody debris to intact woody debris of 4:1, are added every other year. Logs were obtained from a local mill and were chipped by Rexius of Eugene, Oregon. To date (over six years), a total of 107,650 g C m^{-2} of litter has been added to the double needle plots; a total of 345,600 g C m^{-2} of wood debris has been added to the double wood plots.

Soil water collection and treatment

Five Prenart Superquartz tension lysimeters, three at 30 cm and two at 100 cm, were installed in each plot in 1997 at a 30° angle according to the method

described by Lajtha et al. (1999). Solutions collected during the first year were discarded in order to allow the lysimeters time to equilibrate. Soil water was collected approximately monthly during the first few wet seasons, and several times per season in subsequent years, except when access was blocked by snow. In summer 2000, one zero-tension lysimeter (20 cm × 20 cm plastic containers) was installed at the bottom of the O horizon in Control, Double Wood, and Double Needle plots to collect O-horizon leachate, and soil water was collected three times at 2–3 month intervals during the 2000–2001 wet season. Treatments where litter was excluded and thus had minimal O-horizons were not instrumented. An area of about 30 cm × 30 cm of the O horizon was carefully cut out and removed, lysimeters were installed, then the piece of O horizon was gently put back on the lysimeter. Because there was no disturbance of mineral soil, we did not discard initial samples. To minimize biological and chemical alteration of solution, all samples were retrieved within 72 h after the application of tension (for tension lysimeters) or after the beginning of water collection (for zero-tension lysimeters). All samples were transferred on ice to Oregon State University and stored frozen until analysis for dissolved organic carbon and nitrogen (DOC and DON), dissolved inorganic nitrogen (DIN, nitrate and ammonium), and chemical fractionation. Initial experiments with filtering soil solutions demonstrated that tension lysimeter samples did not need to be filtered, but O-horizon leachates were filtered through Whatman GF/F glass fiber filters (0.7 μm nominal pore size) before being stored.

Annual net fluxes of elements were calculated following Yano et al. (2005) for one water year, which is defined as September 30–September 29 in this region. We used precipitation and stream discharge measurements for a nearby monitored watershed and assumed that water flux from 100 cm was equal to annual stream discharge. We partitioned annual water fluxes from other horizons following Sollins et al. (1979) who used a hydrologic simulation model that was calibrated against daily data for precipitation and streamwater discharge, throughfall, and litter and soil moisture content, measured between 1973 and 1975. We assumed that the contribution of different soil layers to total transpiration paralleled the distribution of fine root in the soil column; e.g., 45% of total fine root mass is found in the top 10 cm soil layer, thus this layer contributes to 45% of total transpiration. Fluxes from different soil depths were then corrected for water loss via transpiration estimated from fine root distribution (Yano et al. 2005).

Soil and litter collection

O-horizon material for laboratory analysis of water extractable organic carbon (WEOC) was collected in August of 1999 from three mature Douglas-fir stands in the Andrews Experimental Forest that had thick (~4 cm) organic horizons that could be separated into Oi, Oe, and Oa horizons with a knife. The Oi horizon is composed of freshly fallen intact needles with minimal decay, the Oe

horizon contains partially decomposed needles, and the Oa horizon is composed of well-decomposed material whose origin is unrecognizable. Wood was collected from three newly fallen (Class 1) and three well decomposed (Class 5) Douglas-fir logs from the McDonald–Dunn Research Forest located about 90 km northwest of the Andrews Experimental Forest. Root material was collected from Douglas-fir seedlings that were grown on a mixture of mineral soil from the study site and commercial silica sand (soil: silica sand = 1:1) and harvested by gently washing in deionized water. All roots harvested were pooled into a single sample because of low total mass. Subsamples of all litter were air-dried and ground to pass a 0.6 mm screen and extracted in deionized water with a tissue-to-water ratio of 1:40, 1:25, and 1:25 for needle, wood, and root litter, respectively. The extraction was conducted in a shaker at 100 rpm at 22 °C for 48–68 h followed by centrifugation at 7000 rpm for 15 min. The supernatant of each extract was filtered (Whatman GF/F glass fiber filters) and stored frozen.

Fractionation of DOC and DON

Dissolved organic matter in soil solution was characterized by fractionation with Amberlite XAD-8 resin (Leenheer 1981; Qualls and Haines 1991). Soil solution was fractionated on an approximately monthly basis during November 2001 through May 2002 on a total of 5 dates. The water was filtered, acidified to pH 2 with sulfuric acid, and passed through columns containing XAD-8 resin, which retains hydrophobic acids, neutrals, and bases (Leenheer 1981). The hydrophobic fraction was then eluted with 0.1 N NaOH. Concentrations of C and N were measured in the fractions as DOC and DON (described below) and they were reported as hydrophilic and hydrophobic DOC and DON (Kaiser and Zech 2000; McDowell et al. 2004).

Laboratory incubations

Soils for long-term incubations were collected in June 2002 at six random sampling points within each treatment plot. At each point, the O-layer was removed and a hand trowel was used to remove the top 0–5 cm of the A-horizon soil from approximately a 5 × 5 cm area. Soil collected at each sampling point was composited within plots, sieved (< 2 mm), and stored moist at 4 °C sealed tightly in storage bags for several weeks. 150 ml bench top filtration units (Falcon Filter, Becton Dickinson Labware) were modified according to Nadelhoffer (1990) to create microlysimeter chambers that allowed measurement of respiratory C losses as well as water-soluble C and N losses over time. Soils were mixed with an equivalent amount of acid-washed sand in order to minimize anoxic conditions once the soils were re-wet (Nadelhoffer 1990;

Swanston et al. 2002). Because soils were stored and manipulated before the incubation, the first re-wetting of soils in chambers was done with inoculum that contained live microbes from the native soil. The inoculum was prepared by shaking fresh soil from a control plot in distilled water for ten minutes (1:10 soil to water ratio) and settling for one hour. The supernatant was used as the inoculum. Substrates were placed in the upper chambers of the microlysimeters, inoculated, and then incubated for 365 days.

At days 1, 5, 35, 101, 151, 267, and 361 of the incubation, water-soluble leachates (total dissolved nitrogen (TDN), DOC, NO_3^-, NH_4^+) were measured in soil solution leached from each chamber. 100 ml of distilled water was added to the upper chamber of the microlysimeter and allowed to equilibrate with the soil for one hour. At the end of an hour, the solution was drawn through the soil and filtered through a pre-combusted Whatman GF/F filter. Soil solution samples were kept at 4 °C until analysis if within 48 h, otherwise were frozen at −20 °C. Any soil that was inadvertently removed with the soil solution was added back to the chambers following centrifugation.

CO_2 efflux from the substrates was measured for each chamber on days 3, 5, 8, 12, 17, 26, 53, 151, 267, and 361, by syringe sampling of the headspace through a septum placed over an opening in the filter lid. Before sealing the incubation chamber, the headspace was purged with CO_2-free air for approximately 2 min so that a baseline concentration of 0 ppm CO_2 was reached. CO_2 was measured at 0 and 240 min to determine the rate of CO_2 efflux from the substrate. A 500 μl-calibrated syringe was used to mix the headspace gas several times before extracting a sample, which was immediately injected into a 5700A Hewlett Packard gas chromatograph fitted with a Poropak R 80/100 column and thermal conductivity detector. A sub-set of chambers was also sampled at 480 min to assure linearity of the increase in CO_2 concentration over time.

Chemical analysis

DOC analysis was by Pt-catalyzed high-temperature combustion (Shimadzu TOC-5000A or TOC-V CSH analyzer). Nitrate-N was measured using the hydrazine sulfate reduction method and NH_4-N was determined by the Berthelot reaction method with an Orion Scientific AC 100 continuous flow auto-analyzer (Westco Scientific Instruments, Inc., Danbury, CT). Total dissolved N (TDN) was measured using persulfate digestion followed by NO_3^- analysis (Ameel et al. 1993) or by high-temperature combustion (Shimadzu TOC-V CSH analyzer with TN unit). DON was calculated as the difference between TDN and DIN (nitrate + ammonium); because DON was calculated by difference, values were sometimes slightly negative due to the detection limits of the analyzers, in which case a value of 0 mg l^{-1} was assigned.

Soil CO_2 flux

Soil flux measurements in the DIRT plots were recorded every other week (June-Sept.) to once a month (remainder of the year) using a LI-6200-09 soil respiration chamber in conjunction with a LI-6200 portable photosynthesis analyzer (LI-COR, Lincoln, Nebraska). There are five permanently installed PVC collars inserted 2 cm into the soil in each plot. Four co-located soil moisture measurements at 12 cm depth were made using time domain reflectometry at the time of each respiration measurement (Hydrosense probe, Decagon Devices, Pullman Washington). These data, as well as continuous soil moisture at 10 cm depth from a nearby meterological station, were used to model daily soil respiration by fitting a quadratic function with continuous soil temperature data from the same met station. Daily rates were then summed to create an annual value (complete methods given in Sulzman et al. 2005).

Statistical analyses

All replicate soil solution samples from lysimeters within individual plots were averaged on each sampling date prior to statistical analysis, leading to a total n of 3 for each treatment per date. Analyses of extracts and lysimeter fluxes were made using ANOVA in a completely randomized design with 6 detrital treatments and 3 replicates per treatment (PROC MIXED, SAS v.9.1). *A priori* comparisons between treatments were made with Tukey's adjusted values ($\alpha = 0.05$). All adjusted p values for pairwise comparisons were $p < 0.05$ unless otherwise noted.

For cumulative C losses via both respiration and DOC in the laboratory incubations, data were analyzed using a completely randomized design with repeated measures model. Before accepting the results of the statistical model, the model residuals were examined for constant variance. Log transformations for both cumulative C loss through respiration and DOC were used to homogenize variance. When a p-value from repeated measures ANOVA was significant, all possible comparisons of detrital treatments were generated using the Tukey–Kramer HSD method. Significance for the contrasts was set at $p = 0.05$; however, p-values up to 0.10 were also discussed. Most calculations and all statistical analysis were completed using SAS v. 9.1 (SAS institute, Inc.).

Results

Soil solution chemistry

Concentration of DOC in O-horizon leachate was significantly higher in Double Wood plots than in Control or Double Litter plots during the one water year that it was measured following 4 years of litter manipulation

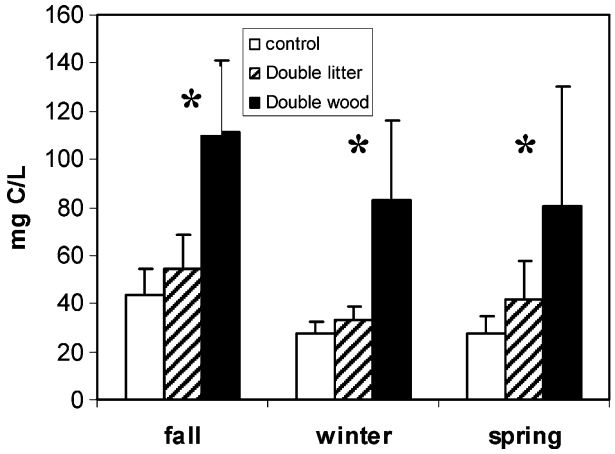

Figure 1. DOC concentration in zero-tension lysimeters below the O-horizon measured in November (fall), January (winter), and May (spring) of 2000–2001 in the H.J. Andrews DIRT plots (mean ± 1 SE of 3 replicates in each season). * indicates mean is significantly different from other treatments within a season.

(Figure 1). In every season measured, the mean DOC concentration of Double Litter O-horizon leachate also appeared higher than for Control plots; however, this difference was not statistically significant.

Within 2 years of wood additions, concentration of DOC from tension lysimeters at 30 cm in Double Wood plots increased significantly relative to all other plots (Figure 2), and calculated fluxes during water year 2002 were significantly greater in Double Wood plots than in all other treatment pots ($p = 0.02$) except Control plots, where the increase was not significant. In contrast, DOC at 30 cm did not increase in Double Litter plots compared to Control plots as was true for O-horizon leachate (Figure 1), and appeared to be slightly (but not significantly) lower. DOC concentrations at 30 cm appeared to be lower in the two treatments without roots (No Inputs and No Roots) but this was not significant, perhaps due to high seasonal variability; mean DOC concentrations in No Roots plots were about 1/3 of concentrations in Control plots, and No Input plots were less than half of Control DOC values. At 100 cm DOC concentrations were very low (generally < 5 mg C l^{-1}) in all plots, and no significant differences in concentrations were observed among treatments ($p = 0.39$), although mean concentrations of DOC in plots without roots were lower than in Control plots.

In Control plots, much larger decreases in absolute DOC flux were seen between 0 and 30 cm than between 30 and 100 cm (Table 3). Between the O-horizon and 30 cm, concentrations of DOC were reduced about 6-fold, but were reduced less than 3-fold between 30 and 100 cm. DON was reduced by about 6-fold between the O horizon and 30 cm, yet was reduced by less than 2-fold between 30 cm and 100 cm.

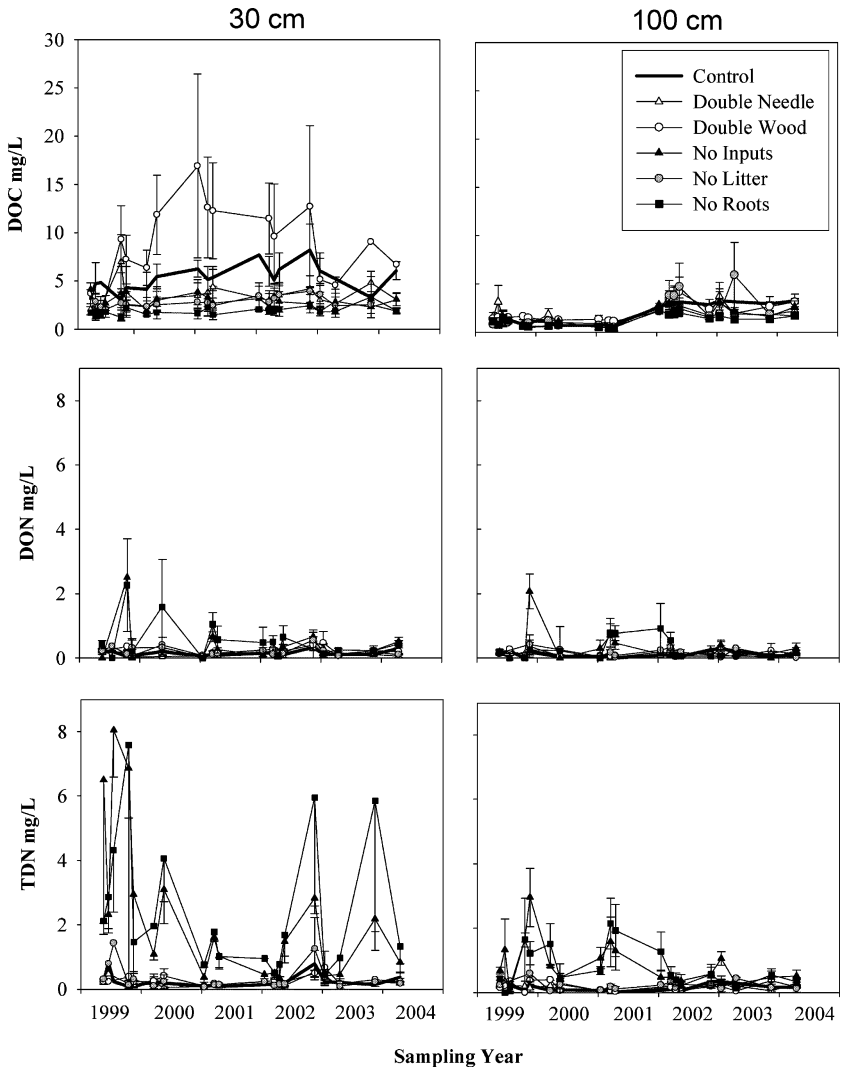

Figure 2. Concentrations of DOC, DON, and Total Dissolved N (TDN) in lysimeters at 30 and 100 cm in all DIRT treatments plots (mean of 3 plot replicates ±1 SE at each date; lysimeters within plots are averaged to produce one value at each date).

TDN concentrations were low at all horizons (annual means < 2 mg N l^{-1}) in treatments that were not trenched to exclude roots. Similarly, NO_3-N concentrations were extremely low (annual means < 0.1 mg N l^{-1}) in these treatments (data not shown). However, the two treatments without live plant roots had significant spikes in NO_3-N for two full years after the trenching treatment was installed, either as a trenching disturbance effect or due to decomposition of severed fine roots. TDN was similarly elevated, but only

Table 3. Comparison of C fluxes from soil via respiration and DOC leaching, and total dissolved N (TDN) and nitrate losses via leaching, water year 2002 (mean ± 1 SE).

	C flux (g C m^{-2} $year^{-1}$)	TDN flux (g N m^{-2} $year^{-1}$)	NO_3-N flux (g N m^{-2} $year^{-1}$)
Respiration (Control plot)	788 (73)		
Respiration (root-free)	601 (94)		
Control plots			
O horizon	57.6	1.30	
30 cm h	9.4 (1.1)	0.41 (0.05)	0.05 (0.03)
100 cm	3.2 (0.04)	0.17 (0.03)	0.01 (0.002)
No roots plots			
30 cm	3.2 (0.5)	2.80 (0.760)	0.89 (0.17)
100 cm	2.0 (0.1)	1.43 (0.26)	0.66 (0.07)
Litter addition plots			
Double needle			
30 cm	6.0 (1.1)	0.30 (0.05)	0.01 (0.005)
100 cm	2.8 (0.3)	0.13 (0.02)	0.02 (0.002)
Double wood			
30 cm	19.0 (4.0)	0.40 (0.02)	0.03 (0.005)
100 cm	3.8 (0.7)	0.14 (0.02)	0.02 (0.003)

Root free, or heterotrophic estimates of respiration are from No Root plots. O-horizon concentrations were measured only during the 2001 water year and were assumed to be representative of the 2002 water year.

the No Root treatment was significantly greater than the treatments with intact roots at both 30 cm ($p < 0.02$) and at 100 cm ($p < 0.01$). Nitrate-N remained significantly higher in the two trenched treatment plots compared to the other treatment plots at 30 cm even 7 years after trenching ($p < 0.001$). Nitrate was higher in the treatment plots without roots at 100 cm as well, but this effect was significant only for the No Input plots ($p < 0.02$). There were no other differences among treatments.

TDN loss from below 100 cm from Control plots was calculated as about 0.17 g m^{-2} $year^{-1}$, close to measured total N deposition inputs at the Andrews Experimental Forest of 0.16–0.20 g m^{-2} $year^{-1}$ and higher than streamwater losses of about 0.1 g m^{-2} $year^{-1}$ (Vanderbilt et al. 2003). Both total dissolved N and NO_3-N flux from below No Roots plots were an order of magnitude greater than from Control plots (Table 3).

The DOC:DON ratio of soil water was significantly affected by the litter input treatments. Double Wood treatments had elevated DOC without a corresponding increase in DON at 30 cm, and No Input and No Root treatments had elevated DON with a slight decrease in DOC. DOC:DON ratios narrowed considerably by 100 cm. Generally, DOC:DON mass ratio decreased with increasing soil depth in Control plots from 0 to 30 to 100 cm (DOC:DON = 54, 41, and 29, respectively).

Fluxes of C as DOC were significantly lower than fluxes as CO_2 from soil due to respiration (Table 3). DOC leaching from the O horizon was about 10% of heterotrophic respiration losses (as measured by respiration in No Root

plots). Absolute DOC leaching from the system (or DOC flux at 100 cm) was less than 0.5% of respiration losses.

Composition of detrital extracts and lysimeter solutions

In laboratory extracts, there were differences in chemical fractions of water extractable organic C among the different detrital types (needles, wood, roots) as well as along decay gradients within litter types (Figure 3a). For both wood and O-horizon litter, percent hydrophobic DOC increased with increasing degree of decay: the most recent litter (Oi horizon material) was significantly less hydrophobic than the oldest litter (Oa horizon material) ($p < 0.05$), and young wood was less hydrophobic than old wood ($p < 0.001$).

In contrast to patterns observed for laboratory leachates from different litter sources, there were no statistical differences in the composition of leachates at any given horizon from different treatments in the field (Figure 3b). The proportion of hydrophobic DOC, however, generally decreased with depth for every treatment. Hydrophobic DOC constituted approximately 60–67% of DOC in

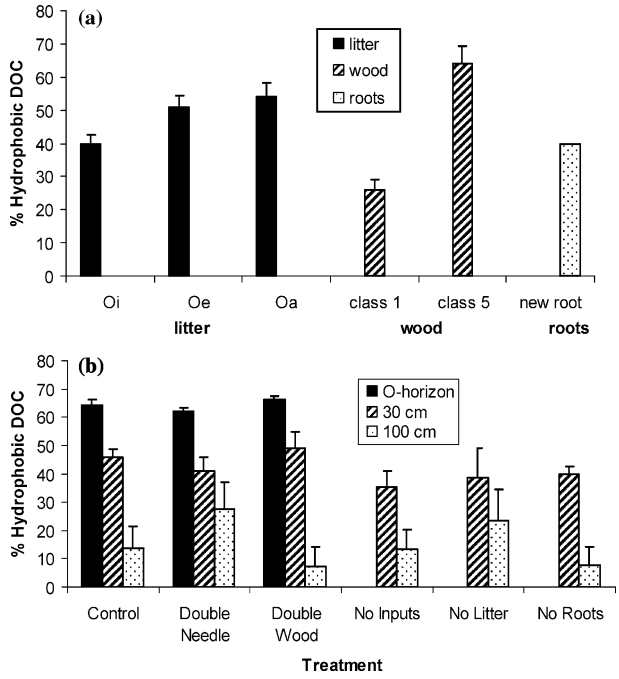

Figure 3. (a) Percent hydrophobic DOC in laboratory water extracts from different litter sources (mean ± 1 SE; $n = 3$ for needle litter and wood sources, $n = 1$ for roots). (b) Percent hydrophobic DOC in soil water from O horizon zero-tension lysimeters and from 30 and 100 cm tension lysimeters in the DIRT plots (mean ± 1 SE of 3 replicates).

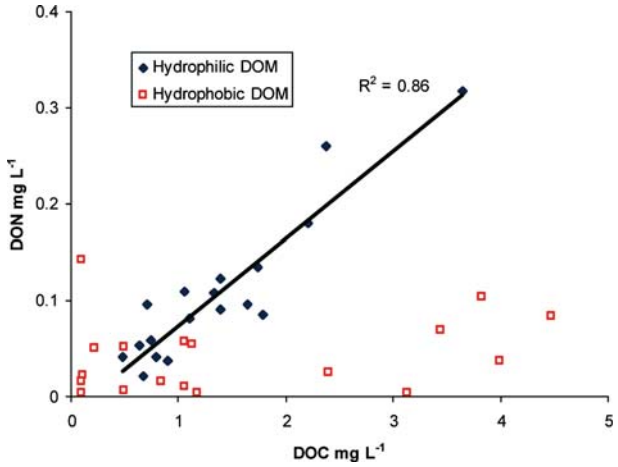

Figure 4. Relationships between DOC and DON in hydrophobic and hydrophilic fractions in soil ater collected from tension lysimeters across all DIRT treatments and both (30, 100 cm) depths.

O-horizon leachate, 35–50% of DOC leached at 30 cm, and approximately 5–25% of DOC leached at 100 cm. Hydrophobic DON constituted approximately 15–40% of the DON leached from the plots (data not shown). Concentrations of hydrophilic DOC and DON were related at both 30 and 100 cm across all treatments (Figure 4), but hydrophobic DOC and DON were not.

Laboratory incubations

When soils from the treatments were placed in long-term incubations, respiratory C losses were always greater than DOC losses, with approximately 3-times more C loss via microbial respiration compared to via DOC in leachates (Figure 5). This relationship differs slightly from field flux measurements, where there was approximately a 10-fold difference in C flux through soil respiration and DOC leaching from the O horizon (Table 3). Although cumulative respiration was slightly lower in No Input plots than in the other soils, this effect was not significant ($p = 0.11$). Similarly, No Input plots had lower DOC loss than other plots but this was not significant at the 0.05 level ($p = 0.07$). There were no significant differences between Double Wood soils and Control soils for either respiration or DOC loss.

Discussion

In this study, the decrease in DOC in lysimeter leachates from Control plots through the profile was greater than the decrease in DON or nitrate. This

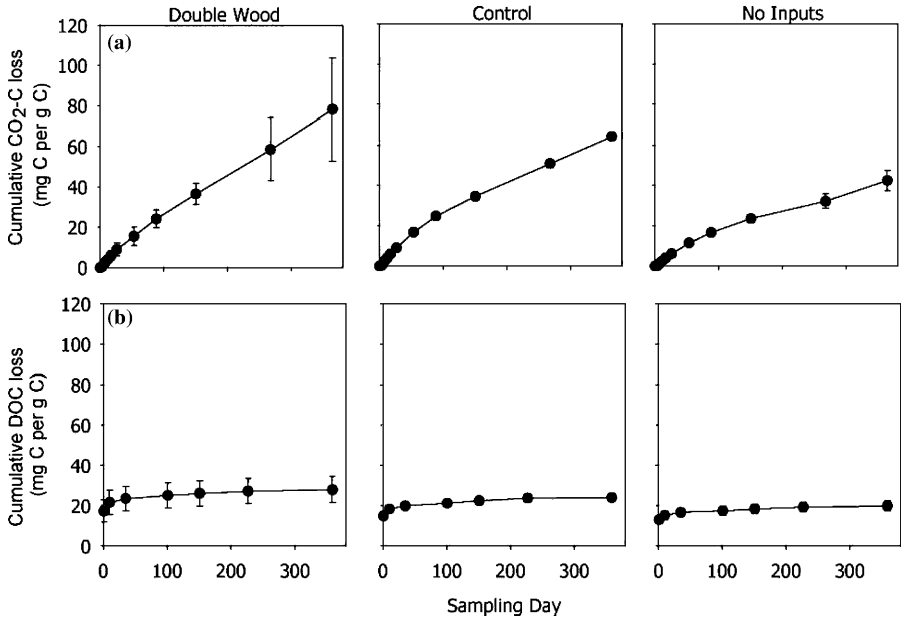

Figure 5. (a) Cumulative respiration and (b) cumulative DOC losses from long-term laboratory incubations of soils from three DIRT treatments at the H.J. Andrews Forest (mean ± 1 SE; $n = 3$ for each treatment).

pattern has been observed in other forest soil profiles, and is generally attributed to sorption of hydrophobic DOC with a high C:N ratio. Hydrophilic DOC tends to be more N-rich (Kaiser and Zech 2000) with lower retention in the soil profile. Indeed, the percentage of total DOC that was hydrophobic decreased through the soil profile, leaving a more N-rich, hydrophilic leachate at 100 cm. There was a greater decrease in DOC between the O-horizon and 30 cm than between 30 and 100 cm. This is most likely due to strong sorption of hydrophobic DOC in upper soil horizons with less efficient sorption of hydrophilic components in the lower profile. Although some studies have suggested that microbial consumption of DOC might be as high as 50% in upper soil profiles (McCracken et al. 2002), other authors have suggested that the labile C fraction of soil solution (assumed to be mainly carbohydrates) is too small to explain the large reduction in DOC with depth. McDowell and Likens (1988) reported labile C as 3–6% of total DOC, similar to estimates of Qualls and Haines (1992) of 6–19% and Yano et al. (2000) of $< 2\%$. It also appears that these soils have a high capacity for DOC sorption; although concentrations of DOC in the O-horizon and at 30 cm of the Double Wood treatment were significantly elevated compared to other treatments, this difference disappeared by 100 cm. This also suggests that plots with increased wood additions are retaining more DOC, presumably stabilized onto mineral surfaces. Compared to Control plots, Double Wood plots release an additional

10,770 g C m^{-2} $year^{-1}$ of DOC from the O-horizon, approximately 1% of typical soil C pools in this region (Smithwick et al. 2003). However, it might take decades or centuries to detect this additional C as new SOM against the high spatial variability of existing SOM pools in old-growth coniferous forests. Laboratory incubations suggested that Double Wood soils, per unit C, do not have higher respiration rates than Control soils, suggesting that the added C has the same lability as background SOM from Control plots. Spears et al. (2003) calculated that only 5% of the C in coarse woody debris that fell naturally to the ground was released as DOC while 95% was respired, again suggesting that effects of added woody litter on the amount and chemistry of SOM might take centuries to detect.

We hypothesized that there would be very little N leaching from Control plots due to a strong N limitation of the microbial community caused by the high C:N ratio of the forest floor (~45), as well as the low N deposition input to this very unpolluted forest. In an analysis of data from 139 European forest ecosystems, Dise et al. (1998) found that dissolved inorganic N (DIN) leaching losses were very low when forest floor C:N ratios were greater than 30. Gundersen (1995) also found very low rates of nitrification and DIN leaching in sites with N deposition levels below 10 kg ha^{-1} $year^{-1}$. Indeed, our calculated flux of 0.17 g N m^{-2} $year^{-1}$ (or 1.7 kg ha^{-1} $year^{-1}$) from Control plots is very low. However, DIN losses were significantly elevated in the two treatments without roots at both 30 and at 100 cm. Certainly this could partially be due to the elimination of plant N uptake, which as been estimated as about 4 g Nm^{-2} $year^{-1}$ in this system (Sollins et al. 1980). Estimated fluxes of N from the trenched plots were significantly lower than this estimate of plant uptake. Similarly, many studies of leaching losses of N after clearcutting have shown lower N loss than estimated plant uptake in the intact forest (Sollins and McCorrison 1981). Schimel and Bennett (2004) have suggested mechanisms whereby N turnover in the absence of plant activity would decrease; indeed, net N mineralization rates have often been shown to be significantly below estimated uptake of N by vegetation. They suggested that plants are often good competitors with microbes for N, and thus plants might take up a portion of the N that would otherwise be immobilized by microbes. They also pointed out that mycorrhizae have a direct role in decomposition; thus when plant roots are present, mycorrhizae may allow the plant partner to be a more effective competitor against saprophytic microbes for N.

The increase in DIN flux in plots without roots may also be due to lower DOC production and availability. Microbially available C within the soil-litter system is critical for immobilization, and Aber (1992) suggested that the ability of most forests to retain moderate additions of N implies that there is an excess of available carbon in soils that can be tapped when N additions occur. Nitrifiers should only be able to effectively compete with heterotrophs when labile C is limiting; nitrification rates are generally low when heterotrophs can immobilize N. Labile C introduced belowground by root turnover, root exudates, and/or mycorrhizal turnover may be more critical to N

immobilization than is bulk SOM. Indeed, Yano et al. (2005) showed that root leachates produce high quantities of hydrophilic neutral DOC, a fraction that is rich in sugars and thus potentially highly available to microbes.

In plots where both the overstory and understory were treated with herbicide, Sollins et al. (1981) found increases in nitrate compared to untreated plots even though DOC levels also increased, suggesting that DOC alone is not an adequate measure of available C. They suggested that the increased DOC from treated plots was less easily metabolized than DOC from intact forest stands, possibly due to the loss of rhizosphere-derived DOC. Similarly, Hart (1999) showed that even though C:N of decayed tree boles was much higher than that of mineral soil in an old-growth stand near our study site in the Andrews forest, N mineralization rates in the tree boles and mineral soils were similar. The low microbial respiration rate of the boles suggested that readily oxidizable C availability was low per mass of total C, again suggesting that C:N ratio alone is a poor predictor of DIN release.

Much effort has been devoted to comparing the cycling and transport of DOC with DON and also understanding the high variability of DOC:DON in soil solution (McDowell 2003). Previous work has shown that N fertilization (Currie et al. 1996), differences in vegetative cover (Currie et al. 1996), and site history (Neff et al. 2000) can influence DOC:DON in soil water. The factors regulating production (Michalzik and Matzner 1999; McDowell 2003), transport (Kaushal and Lewis 2003), and metabolism (Wiegner and Seitzinger 2001) of DOC and DON may be different. In this study, the dynamics of soil solution DOC, DON, and nitrate appeared to be affected differently by the litter treatments. While Double Wood plots exhibited increased DOC, this was not followed by a corresponding increase in DON. Similarly, plots without roots showed elevated nitrate and DON relative to other plots but showed the lowest concentrations of DOC. This suggests that roots are the source of large amounts of DOC in the soil profile, and clearly not all DOC from roots is highly labile. Previous work has shown that DOM with varying C:N can originate from different chemical fractions (Kaushal and Lewis 2003), and therefore be influenced by different physical and biotic processes (McDowell 2003). C:N of DOM was also affected by differential sorption through the soil profile; with preferential sorption of hydrophobic DOM with higher C:N ratios. The hydrophilic DOM that passed through the soil profile had both less variable and lower C:N ratios.

We originally hypothesized that differences in detrital quality delivered to the forest floor would translate to differences in the chemical quality of DOC that leached through the soil profile. Roots, wood, and litter may ultimately contribute dissolved organic matter to soil solution, and our results showed that these different sources produced DOC of different chemical composition in laboratory extractions. Our results also suggest that DOM from these sources underwent substantial transformation as it traveled through the soil profile. Although O-horizon DOC concentrations increased in response to increased woody debris inputs, chemical quality of leachates were very similar among

plots, perhaps due to microbial processing and equalization of DOC chemistry. Indeed, Christ and David (1994) showed that lysimeter solutions were more similar chemically to incubated soil extracts than to fresh extracts. O-horizon leachates were significantly more hydrophobic than needle, root, or young wood extracts, suggesting that microbial consumption of labile, hydrophilic DOC might occur relatively rapidly during decomposition of litter. DOC concentrations also decreased through the soil profile in all plots to a greater degree than did dissolved organic nitrogen (DON), most likely due to preferential sorption of high C:N hydrophobic DOM in upper horizons.

The long-term incubations of soils from different treatments were intended to elucidate effects of detrital inputs on the relative amounts and lability of soil C. Although respiration in the No Input soils was slightly lower than in other treatments, there were no significant differences in cumulative respiration among the different litter treatments in the laboratory incubations. These results are similar to those of Hart and Sollins (1998) who did not find changes in C pools or microbial respiration in nearby plots that had roots excluded for 13 years. Although we expected stronger differences among treatments after 7 years of detrital additions, our results suggest that it might take several decades to see significant differences in soil C lability due to plant litter manipulations.

Our field lysimetry showed high concentrations of DOC in upper soil horizons in Double Wood plots that decreased dramatically by 100 cm, and because the labile C fraction of soil solutions has been shown to be quite low in this and other forests (McDowell and Likens 1988; Qualls and Haines 1992; Yano et al. 2005), it is most likely that abiotic sorption, rather than microbial uptake, is responsible for the majority of DOC removal in the soil profile. We hypothesized that this sorbed DOC would be lost upon incubation and would not be highly stable. However, the lack of increased respiration from Double Wood soils in the incubation study, coupled with the field observations of DOC removal, suggests that the added DOC to these soils was not highly labile, and thus can potentially serve as a source of stabilized SOM.

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