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Management impacts on the dissolved organic carbon release from deadwood, ground vegetation and the forest floor in a temperate Oak woodland

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Abstract

The forest floor is often considered the most important source of dissolved organic carbon (DOC) in forest soils, yet little is known about the relative contribution from different forest floor layers, understorey vegetation and deadwood. Here, we determine the carbon stocks and potential DOC production from forest materials: deadwood, ground vegetation, leaf litter, the fermentation layer and top mineral soil (Ah horizon), and further assess the impact of management. Our research is based on long-term monitoring plots in a temperate deciduous woodland, with one set of plots actively managed by thinning, understorey scrub and deadwood removal, and another set that were not managed in 23 years. We examined long-term data and a spatial survey of forest materials to estimate the relative carbon stocks and concentrations and fluxes of DOC released from these different pools. Long-term soil water monitoring revealed a large difference in median DOC concentrations between the unmanaged (43.8 mg L^{-1}) and managed (18.4 mg L^{-1}) sets of plots at 10 cm depth over six years, with the median DOC concentration over twice as high in the unmanaged plots. In our spatial survey, a significantly larger cumulative flux of DOC was released from the unmanaged than the managed site, with 295.5 and 230.3 g m^{-2}, respectively. Whilst deadwood and leaf litter released the greatest amount of DOC per unit mass, when volume of the material was considered, leaf litter contributed most to DOC flux, with deadwood contributing least. Likewise, there were significant differences in the carbon stocks held by different forest materials that were dependent on site. Vegetation and the fermentation layer held more carbon in the managed site than unmanaged, while the opposite occurred in deadwood and the Ah horizon. These findings indicate that management affects the allocation of carbon stored and DOC released between different forest materials.

Keywords

DOC, carbon cycling, broadleaf woodland, soil, management

1. Introduction

The global forest carbon (C) stock is estimated at 861 ± 66 Pg (Pan et al., 2011) (1 Pg = 10^{15} g) of which 119 ± 6 Pg are held in temperate forests and 878 Mt C (1 Mt = 10^{12} g) are found in UK woodlands (Morison et al., 2012). Carbon enters the terrestrial carbon cycle via photosynthesis; it is then cycled through the living biomass which on average accounts for 42-44% of organic C, before being transferred to the soil which contains on average 44-45% of forest C stocks (FAO, 2020b; Pan et al., 2011), while the remaining carbon is held in litter (5-6%) and deadwood (4-8%). However, this partitioning varies nationally, with UK forests holding approximately 5% of their carbon stocks in litter and deadwood, 18% in standing trees, and 76% in soil (Morison et al., 2012).

Dissolved organic carbon (DOC) is produced during the decomposition of organic material and is transported between carbon pools through hydrological processes such as leaching from the forest floor to the mineral soil (Kolka et al., 2008). An estimated 17% of the annual C input from litter leaches into mineral soils as DOC (Michalzik et al., 2001). The composition of DOC depends on the composition of organic material, which impacts its turnover time and therefore the soils ability to sequester carbon in the long-term (Aitkenhead & McDowell, 2000). The forest floor, woody debris and ground vegetation are considered to be important sources of DOC and contain various substrates which contribute differing amounts of DOC of varying complexity. Park et al. (2002) investigated the impact of resource availability on DOC production over 98 days and determined that leaf litter was the most important source of DOC in deciduous woodlands followed by fresh wood litter (<1 year old). Other studies have found the amount of DOC released from litter to decrease significantly over time, indicating a large labile pool of DOC that can be consumed as a substrate for biological activity (Don & Kalbitz, 2005; Moore & Dalva, 2001). Over the course of a year, deadwood has been found to produce 10x as much DOC as litter (Hafner et al., 2005), and between 3-20x as much DOC as throughfall (Bantle et al., 2014; Hafner et al., 2005). Overall, these studies show that the production of DOC beneath deadwood could be significant in relation to other forest floor materials but the relative magnitude of the contributions of deadwood, forest ground vegetation, and forest floors as sources of DOC-derived carbon fluxes into soils are not always in agreement between studies and therefore require further characterization.

Deadwood is defined as the non-living woody biomass not contained in litter and can be either standing, lying on the ground, or in the soil (FAO, 2010). It has many functions within the forest, it is a key indicator of forest biodiversity (Humphrey & Bailey, 2012; MCPFE Liaison Unit & UNECE/FAO, 2003); it influences stand dynamics (Hodge & Peterken, 1998); it has a protective role in stabilizing slopes (Stevens, 1997); and is also an important carbon pool (FAO, 2020a; Morison et al., 2012; Pan et al., 2011). However, it is one of the least studied carbon pools and is often not included in forest carbon models or inventories despite being a potentially significant store of carbon. Deadwood is often classified as coarse woody debris (CWD) with a diameter greater than 10 cm; fine woody debris (FWD) with a diameter less than 10 cm or as snags or stumps (Working Group on Forest Biodiversity, 2004). It may be further classified according to stage of decay following the classification by Hunter (1990). Under this classification , decay classes range from class 1 (least decomposed; intact texture with bark present) to class 5 (largely decomposed, bark is absent, powdery texture). The degree to which deadwood has decomposed will determine the biomass of the deadwood and thus the amount of carbon available for leaching. It has been determined that wood at a later stage of decay releases more DOC but over a longer period of time (Bantle et al., 2014). Therefore, forest management that decreases the amount of deadwood within a forest could reduce the amount of DOC within the soil. The aim of this work is to test the hypothesis that management practices, particularly forest thinning and the removal of woody debris created during harvesting, reduce the DOC fluxes into soil water. Our specific objectives are to: (1) determine whether management has altered DOC concentrations in long-term monitoring data; (2) determine the impact of management on the carbon stocks of forest material; (3) evaluate the dominant sources of DOC between different forest materials.

2. Materials and methods

2.1. Site information

Alice Holt Forest is a semi-natural ancient woodland located on the Surrey-Hampshire border, UK (51° 9′ N, 0° 52′ W). Plots under different management within Alice Holt Forest were used: an environmental change network (ECN) plot and a Forest Level II Intensive Monitoring Network (FLII) plot (fig. 1). Both of these have undergone regular monitoring, that includes soil chemistry and atmospheric pollution, since the mid-1990s. The ECN and FLII sites are dominated by 75 year old oak (*Quercus robur*) with occasional ash (*Fraxinus excelsior*) occurring on Gault Clay overlain by poorly draining surface-water gleys. Soil properties (Ah Horizon) for the ECN and FLII sites, respectively, are as follows: organic carbon content (5.6% and 2.7%); pH_{water} (4.4 and 5.4); sand (%): silt (%): clay (%) (~9:50:40 and ~4:44:52) (Benham et al., 2012; Vanguelova (unpublished results)). Site elevation ranges from 110-125m and the climate is temperate with a mean annual temperature of 10.8°C and mean annual precipitation of 833mm. The forest has historically been thinned at intervals of 20-25 years; however, the ECN site has been unmanaged since 1992. Woody debris, created by self-thinning of subdominant or diseased trees which die and fall, are not removed from the site. By contrast, the FLII site is still managed with practices which include tree thinning and scrub layer removal. Harvesting material is removed from the plot by management i.e., the main trunk and lop and top along with any dead trees as part of the thinning process, however deadwood which falls from the canopy to the forest floor (mainly, but not exclusively, fine material) is left *in situ*. Management that took place at the FLII site during the long-term monitoring (section 2.2) and sampling (section 2.3) campaigns was as follows: thinning of oak (2005) and scrub removal (2010), where hazel bushes were cut down and debris removed. Sampling took place two years before the next management for scrub removal (in 2017).

Figure 1 - The ECN site (left) is presently unmanaged whilst the FLII site (right) still undergoes regular management.

2.2. Long-term monitoring

The initial ECN measurement protocols were developed by an expert group in the late 1980s (Morecroft et al., 2009) and a detailed series of protocols (Sykes & Lane, 1996) were published. Some protocols have been revised in light of experience, but most methods remain essentially unchanged, allowing robust comparisons across time. The assessment of forest condition under the United Nations Economic Commission for Europe (UNECE) and EU Level I and Level II long-term forest monitoring programs constitutes one of the world's largest bio-monitoring networks (Vanguelova et al., 2007). Plot establishment and instrumentation follow standardised monitoring protocols, as created by the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP; ICP, 2006). In this study, we use the long-term soil water monitoring data collected every two weeks at both sites between 2002 and 2010. Long-term soil water monitoring at the ECN site stopped in 2010 due to funding restrictions. Both networks use the same type of tension samplers (PRENART SuperQuartz soil water samplers, Prenart Equipment Aps, Denmark) and measure soil water chemistry at two similar depths with 6 replicate samplers at each depth. At Alice Holt, the ECN shallow and deep soil solution samplers are located in the Ah and Btg horizons. The FLII shallow and deep soil solution samplers are located in the Ah and Bcg horizons. Shallow and deep samplers are located at 10 and 50 cm depth, respectively. Soil water was sampled at two different locations within the FLII plot to better capture the site variability. Measurements from the ECN shallow plots and FLII deep plots were only available from 2004 – 2010. Soil water samples were filtered through a 0.45 µm membrane filter and analysed for dissolved organic carbon (DOC) by Thermal Catalytic Oxidation using a Thermalox™ Analyzer (Analytical Sciences UK, Cambridge, UK; pH < 5.5, therefore Total Dissolved C = Total DOC).

2.3. Sampling for deadwood, vegetation, forest floor and soil

Deadwood sampling was carried out using the BioSoil (2004) protocols. This was carried out in November 2015, during peak litter fall and the autumn seasonal peak in DOC concentrations. Three circular plots with an area of 400 m^2 were randomly selected to survey deadwood at both the ECN and FLII sites. Within each 400 m^2 area, all deadwood debris found were recorded, including stumps and lying coarse and fine woody debris. The length (cm) and diameter (cm) of each deadwood piece were recorded along with decay class 1-5 following the guidelines presented by Hunter (1990) to enable the deadwood biomass and carbon stock to be estimated.

A sample of deadwood from each decay class was collected from each plot for further laboratory analysis, though decay class five was absent from one FLII plot. A total of 15 deadwood samples were collected from the ECN and 14 from the FLII. Within each circular plot, three quadrats measuring 0.25 x 0.25 m were randomly sampled. Fresh ground vegetation, leaf litter (L), fermentation (F) layer and the top 5cm of the Ah mineral soil horizon were collected individually by excavating the quadrats. The three quadrat samples per plot were then pooled to produce a composite sample per plot to estimate the mass of each type of forest material. It was impractical to sample on the same spatial scale for both deadwood and forest floor materials due to the irregular coverage of deadwood and large quantities of forest materials.

Moisture content (%) was determined from subsamples of each collected forest material through the mass lost after oven drying at 105°C overnight. The mass of deadwood per decay class was then calculated using:

$$Biomass = Density\ x\ Volume$$

Using the wood density (g cm^{-3}) values from Vanguelova et al. (2016).

Subsequently carbon stocks were calculated as follows:

$$Carbon\ stock = Biomass\ x\ carbon\ fraction$$

Where carbon fraction is presumed as the standard value of 50%, as per the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (Penman et al., 2003).

Carbon content of ground vegetation, litter and the fermentation layer was determined as 50% of the mass per quadrat (Penman et al., 2003). Organic carbon concentrations of 5.6% (ECN site; Benham et al., 2012) and 2.7% (FLII site, Vanguelova (unpublished results)) as determined by combustion C:N analyser were used for C stock calculations for the Ah horizon. All carbon stock measurements were upscaled to Mg C ha^{-1}.

2.4. Dissolved organic carbon

A water extract was taken from all samples (deadwood in each decay class 1-5, vegetation, litter, F layer, Ah horizon) of the spatial survey using a ratio of 1:10 as 10 g wet sample to 100 mL deionised water. Material from each of the plots per site (n=3) was homogenised and cut in to ~1cm pieces prior to sub-sampling for extraction. Samples were placed on a rotary shaker for 24 hours at 180 rpm before centrifuging at 3500 rpm for ten minutes and pre-filtering through Whatman GF/A filter papers using vacuum filtration. Samples were centrifuged at 1300 rpm for a further 15 minutes before filtering through 0.45 µm cellulose nitrate filter paper.

DOC concentration for these samples was determined using a Shimadzu TOC Analyser. DOC release per unit mass of each source (mg g^{-1}) was scaled up to estimate the potential DOC flux from the forest floor (g m^{-2}).

2.5. Statistical analysis

Long-term trends in DOC were analysed using the statistical environment R v. 2.13.2 to 3.1.2. The data were tested for normality using Shapiro-Wilk and homogeneity of variances using Flinger-Killeen. Where these were not met, data was analysed using the non-parametric Kruskal-Wallis analysis of variance test.

Statistical analysis of data from the forest material survey was mainly carried out using the Statsmodels module in Python (Seabold & Perktold, 2010). Data were tested for normality of residuals using the Jarque-Bera test and for heteroscedasticity using the Breusch-Pagan test. Raw (non-transformed) data failed to meet either normality or equality of variances or both, likely due to the large range in the size of the actual mean values and variances. We therefore performed Robust (to unequal variance) type III Two-Way ANOVA to identify if site (ECN, FLII) or forest material type (deadwood, fresh vegetation, leaf litter, fermentation layer, Ah soil horizon) affected C stocks and DOC flux results. Data were Box-Cox transformed: $(Y^{\lambda}-1)/\lambda$ where λ was chosen so as to minimise the p-value testing normality of residuals (using Jarque-Bera). Significant differences were accepted at $p<0.05$. Where the Two-Way ANOVA identified a significant main effect, post-hoc comparisons were made using the Games-Howell Method and 95% Confidence in Minitab 18. In the case of a significant site × forest material type interaction, paired t-tests (Minitab 18; equal variances not assumed) were used to examine the effect of site within each forest material type.

Cumulative fluxes of DOC were assessed using Welch's two sample t-test assuming unequal variance.

3. Results

3.1. Long-term trends in soil water DOC at ECN and FLII sites

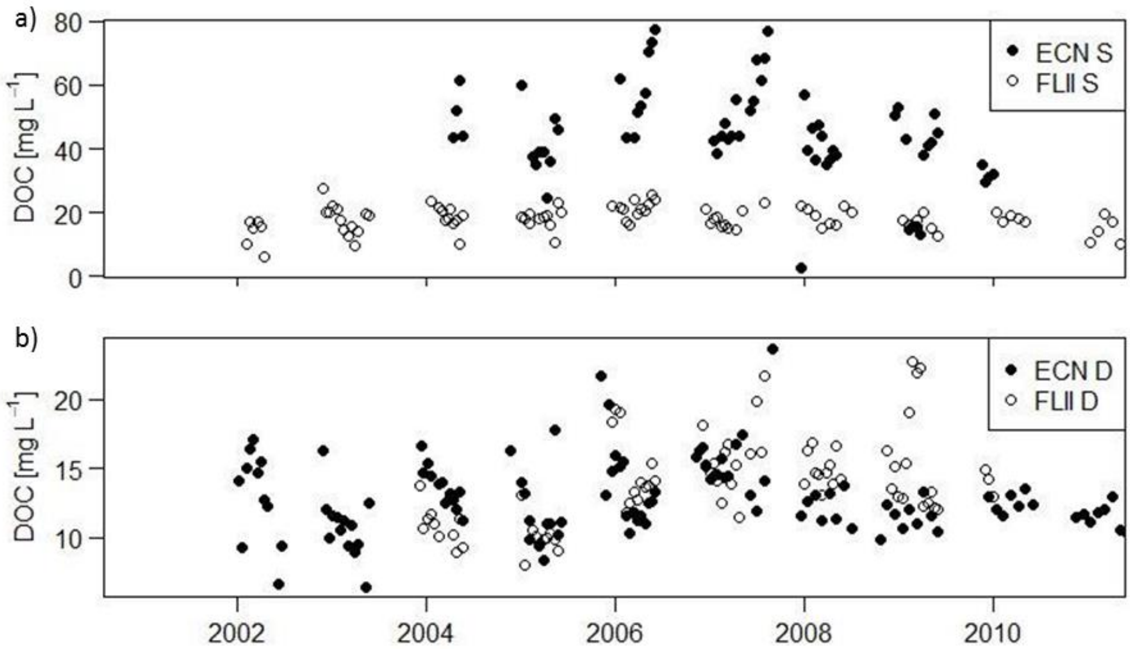

Figure 2 - ECN and FLII time series of soil water DOC concentrations from (a)* shallow (S) samplers in the upper plot and (b) deep (D) samplers in the lower plot. Solid dots represent the ECN data and hollow dots represent the FLII data.

Long-term soil water monitoring data shows consistently higher DOC concentrations within the ECN plot compared to the FLII plot, which was particularly evident at shallow depths (fig. 2a). From 2002 to 2010, median DOC concentrations in the ECN plot were 2.4 times higher than FLII ($p<0.00001$) in the shallow samplers, with concentrations of 43.8 mg L^{-1} and 18.4 mg L^{-1}, respectively (fig. 3). ECN shallow samplers also displayed a greater range in values from 2.67 – 77.3 mg L^{-1}, compared to 6.42-27.6 mg L^{-1} in FLII samplers. Median values in the deep samplers were also significantly higher in ECN than FLII (13.8 mg L^{-1} and 12.4 mg L^{-1}, respectively, $p<0.01$), although the difference was less (1.1 times higher) (fig. 3). Gaps in the time series for both monitoring programmes exist during the summer months in each year due to low soil moisture restricting sample collection.

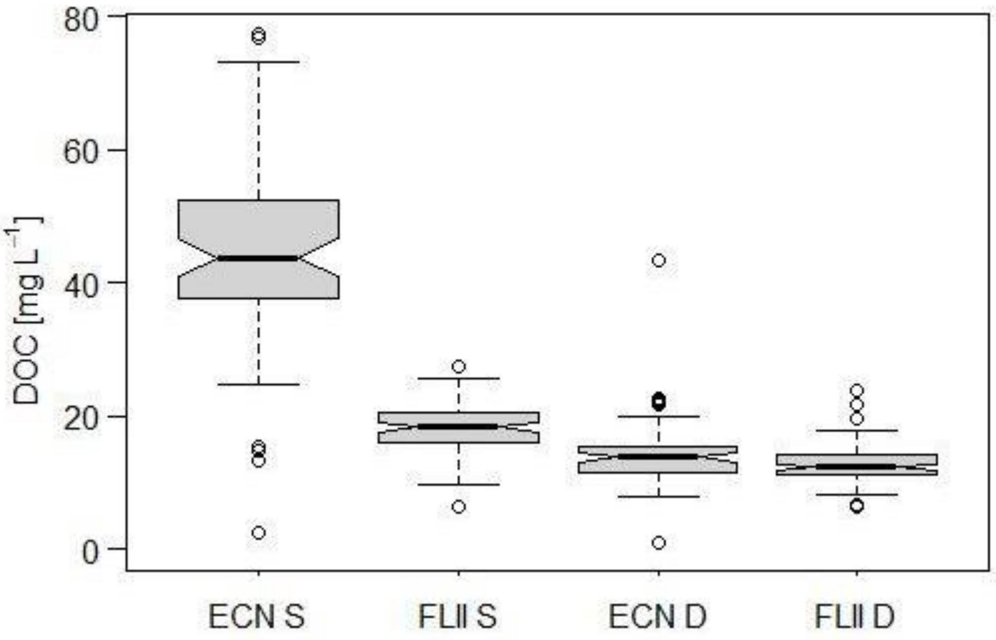

Figure 3 - Comparison of the long term median (2002-2011) of soil water DOC concentrations at ECN and FLII sites. Letters "S" and "D" denote shallow and deep samplers, respectively. Kruskal Wallis-test indicates that shallow soil DOC from the ECN and FLII plots significantly differ ($p<0.00001$). Deep soil DOC was also found to significantly differ between the two plots ($p=0.01$).

3.2. Survey of mass, C stocks and DOC production for forest floor materials

3.2.1. Deadwood, vegetation, litter, F layer and Ah horizon

Examining the effect of forest material type and site on the mass (kg m^{-2}) of forest materials using two-way ANOVA revealed that mass differed significantly between material types (d.f. = 4; F = 129.2; $p<0.001$), with the greatest mass associated with the Ah soil layer followed by the F layer (Table 1). With vegetation, deadwood contributed lower mass than all other materials. Whilst mass of forest materials did not differ overall between management sites (d.f. = 1; F = 0.298; p = 0. 591), there was a significant interaction with material type (d.f. = 4; F = 10.56; $p<0.001$) such that a larger density of the Ah soil horizon and deadwood was found in the ECN plot whilst a greater mass of vegetation and F layer was present at the FLII plot (Table 1).

Two-way ANOVA revealed that total carbon stocks (Mg C ha^{-1}) held in forest material did not differ between the sites (F = 1.56; p = 0.226) but depended on material type (F = 38.56; $p<0.001$) and the interaction between material type and site ($F = 19.13$; $p<0.001$). Overall, deadwood and the Ah horizon held greater carbon stocks in the unmanaged ECN site than the managed FLII site. In contrast, the F layer and vegetation held significantly greater stocks in the managed FLII than unmanaged ECN site (Table 1). Notably, deadwood stocks are over four times lower in the managed FLII plot than the unmanaged ECN plots, while vegetation stocks are over three times larger.

Table 1 – Mean mass ± SE (kg m^{-2}) and carbon stock (Mg C ha^{-1}) for each source material at the ECN and FLII sites (n=3). Total is the cumulative total of all sources. Material types that do not share a lowercase grouping letter are significantly different ($p<0.05$) according to Games-Howell pairwise comparisons. Means within each material type that share an uppercase letter are not significantly different ($p>0.05$; paired t test). Values in parenthesis are the coefficient of variation (%).

Material type	**Mass (kg m^{-2})**			**Carbon stock (Mg C ha^{-1})**		
	ECN	**FLII**	**Games-Howell group**	**ECN**	**FLII**	**Games-Howell group**
Deadwood	0.480 ± 0.129 (46.5)^{A}	0.100 ± 0.040 (68.7)^{B}	d	2.29 ± 0.620 (46.9)^{A}	0.481 ± 0.192 (68.9)^{B}	c
Vegetation	0.489 ± 0.040 (14.2)^{B}	1.67 ± 0.275 (28.4)^{A}	cd	2.26 ± 0.187 (14.4)^{B}	7.86 ± 1.29 (28.4)^{A}	bc
Litter	3.10 ± 1.07 (59.9)^{A}	1.82 ± 0.122 (11.5)^{A}	c	14.3 ± 4.93 (59.5)^{A}	8.45 ± 0.594 (12.2)^{A}	b
F layer	4.61 ± 0.960 (36.1)^{B}	7.86 ± 0.428 (9.4)^{A}	b	21.6 ± 4.58 (36.7)^{B}	37.1 ± 1.92 (9.0)^{A}	a
Ah horizon	18.8 ± 2.58 (23.8)^{A}	11.9 ± 0.633 (9.2)^{B}	a	10.2 ± 1.41 (24.0)^{A}	3.11 ± 0.166 (9.3)^{B}	b
Total	27.43 ± 2.60^{A}	23.37 ± 1.31^{A}		50.68 ± 1.59^{A}	57.02 ± 2.31^{A}	

3.2.2. Inventory of deadwood by decay class

According to the survey of deadwood volumes within the 400 m^2 plots, a larger volume of deadwood was found at the ECN site with the average total, when scaled to a per hectare basis, of 21.2 ± 6.3 m^3 ha^{-1} and 4.1 ± 1.6 m^3 ha^{-1} for the ECN and FLII sites, respectively. Robust ANOVA on Box-Cox-transformed data revealed that decay class significantly affected deadwood biomass (d.f. = 4; $F = 3.68$; $p = 0.022$) and deadwood C stocks ($F = 3.68$; $p = 0.022$). The largest quantities of deadwood per m^2 were found in decay classes 3 and 4 for both plots (Table 2), with a maximum of 0.242 ± 0.171 kg m^{-2} for the ECN site (decay class 4) and a maximum of 0.0501 ± 0.0242 kg m^{-2} for the FLII site (decay class 3). There was no overall significant effect of site on deadwood biomass (d.f. = 1; $F = 1.49$; p =

0.237) or C stock (F = 1.44; p = 0.245) and no significant site * decay class interaction (d.f. = 4; F = 0.105; p = 0.980 for both biomass and C stock).

Table 2 – Mean biomass ± SE (kg m^{-2}) and carbon stocks (Mg C ha^{-1}) of each deadwood decay class at the ECN and FLII plots, n=3 per group. Games Howell groups that do not share a letter are significantly different (p<0.05). Values in parenthesis are the coefficient of variation (%).

Deadwood decay class	Biomass (kg m^{-2})			Carbon stock (Mg C ha^{-1})		
	ECN	FLII	Games-Howell group	ECN	FLII	Games-Howell group
1	0.017 ± 0.015 (151.7)	0.005 ± 0.002 (71.6)	bc	0.080 ± 0.070 (151.5)	0.022 ± 0.009 (71.5)	bc
2	0.018 ± 0.005 (51.7)	0.013 ± 0.009 (113.9)	abc	0.086 ± 0.026 (51.8)	0.064 ± 0.042 (113.7)	abc
3	0.199 ± 0.113 (97.8)	0.050 ± 0.024 (83.8)	a	0.949 ± 0.539 (98.3)	0.242 ± 0.117 (84.1)	a
4	0.242 ± 0.171 (122.3)	0.029 ± 0.011 (63.5)	ab	1.154 ± 0.817 (122.7)	0.142 ± 0.052 (63.6)	ab
5	0.004 ± 0.0002 (9.8)	0.003 ± 0.003 (131.0)	c	0.017 ± 0.001 (10.0)	0.016 ± 0.015 (131.2)	c

3.2.3. Forest floor materials as sources of DOC

Analysis indicated that stage of deadwood decay did not significantly affect the production of DOC (p = 0.096). Therefore, for the subsequent analysis, all decay classes have been pooled into one class, 'deadwood', and robust two-way ANOVA used to analyse the effect of forest material: deadwood, fresh vegetation, leaf litter, F layer, Ah horizon, and site: ECN and FLII.

The mean amount of DOC released from each source ranged from 2.92-52.78 mg g^{-1}, with the lowest concentrations in the FLII Ah horizon and highest in the ECN deadwood, respectively (fig. 4). Two-way ANOVA found that significant differences occurred between forest material sources of DOC (F = 95.11; p<0.001) but not sites (F = 0.22; p = 0.643). Deadwood and litter produced significantly (p<0.05) more DOC mg g^{-1} than the vegetation, F layer and Ah horizon (fig. 4). No significant interaction was found between site and source (F = 1.10; p = 0.368).

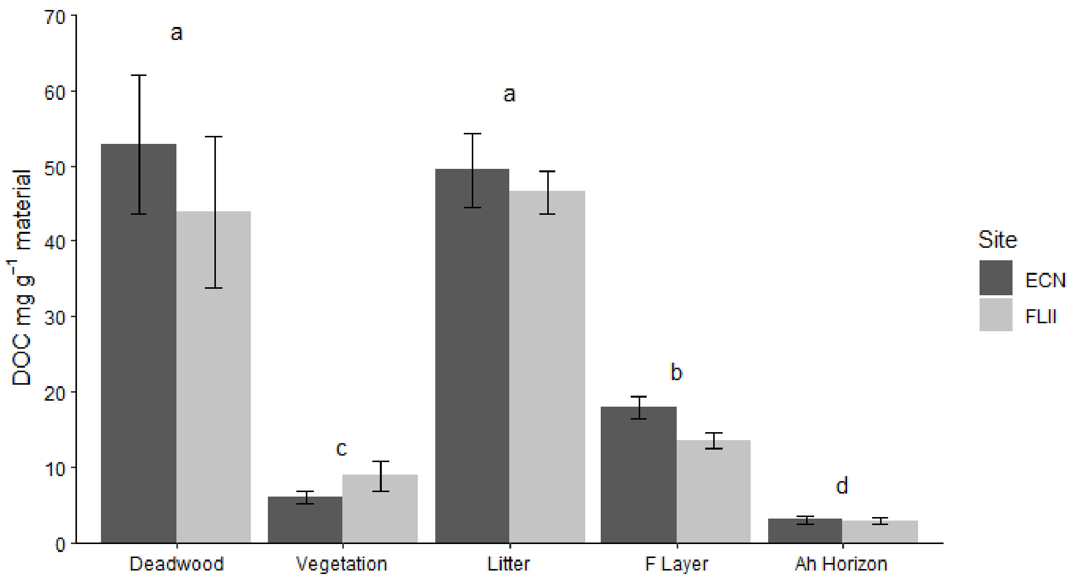

Figure 4 – The influence of site and material type on DOC concentrations (mg g^{-1} material). Data are mean ±1SE (n=3, except deadwood n=15). Material types that do not share a letter are significantly different (p<0.05; Games-Howell method on Box-Cox transformed data).

The largest DOC flux per unit area (132.6 ± 31.0 g m^{-2}) was found in the ECN litter samples whilst the least was found in deadwood at the FLII plot (0.763 ± 0.297 g m^{-2}) (fig. 5). By contrast to the DOC produced per unit mass (mg g^{-1}), the DOC produced per area (g m^{-2}) was lower from deadwood sources because of the lower volume on the forest floor (fig. 5). Two-way ANOVA found no overall significant effect of site on DOC g m^{-2} (F = 0.24; p = 0.627) but a significant effect of material type (F = 98.89; p<0.001) and a significant interaction between site and source (F = 14.21; p<0.001), such that vegetation contributed more DOC g m^{-2} in FLII plots but the Ah horizon contributed more in the ECN plots.

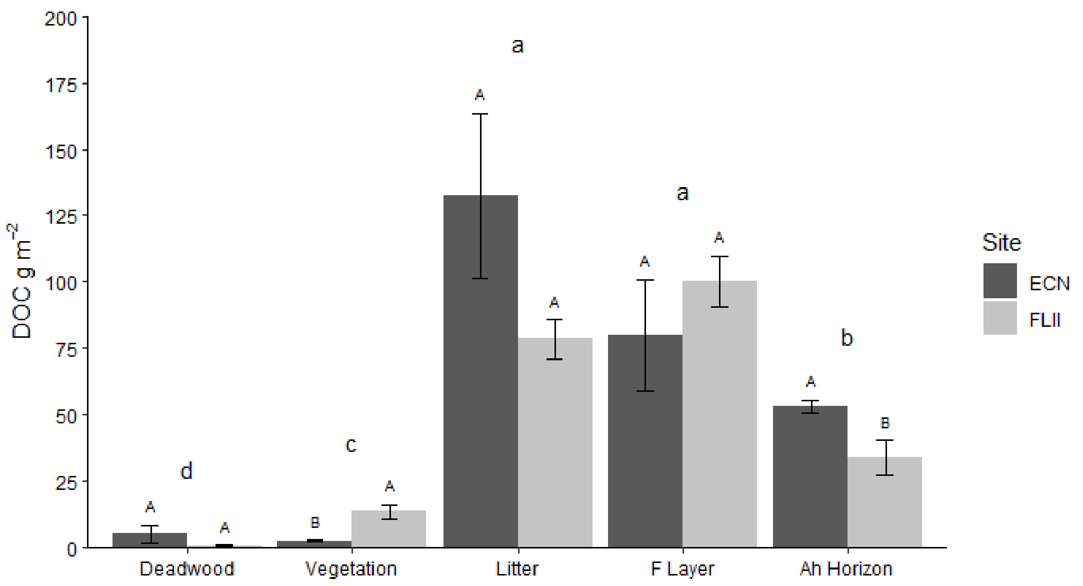

Figure 5 - The influence of site and material type on DOC fluxes (g m^{-2}). Data are mean ±1SE (n=3, except deadwood n=15). Material types across sites that do not share a lower-case letter are significantly different ($p<0.05$; Games-Howell method). Sites within each material type that do not share an upper-case letter differ significantly ($p<0.05$; two sample t-test).

The cumulative DOC flux from all sources was higher in the ECN than the FLII site, measuring 295.5 and 230.3 g m^{-2}, respectively (fig. 6). Results of a Welch two sample t-test found that the flux from the ECN was significantly larger than that of the FLII ($p = 0.02$).

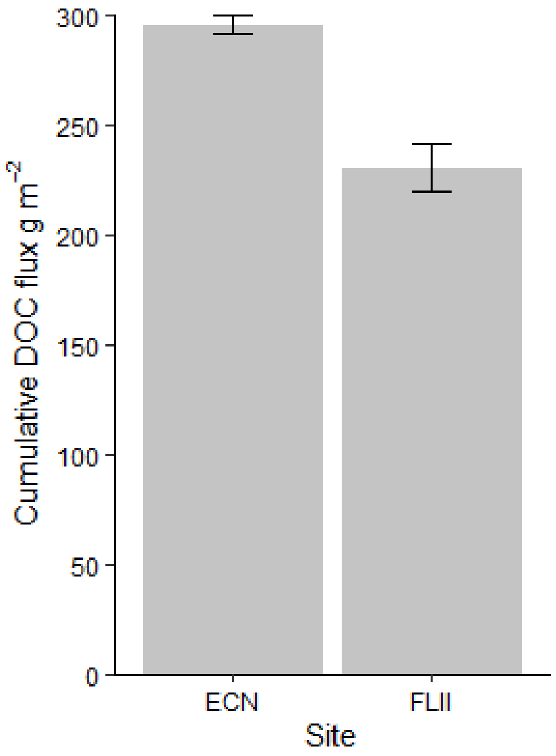

Figure 6 - Cumulative flux of DOC (g m^{-2}) from forest floor materials at sites under different management. The ECN is unmanaged whilst the FLII is managed. Welch two sample t-test found a significant difference between sites (p=0.02)

4. Discussion

The long-term monitoring data revealed that forestry management practices may have a large impact on DOC concentrations and export. We found larger quantities of DOC in shallow soil at the unmanaged ECN site, whereby the annual median was twice that of the managed FLII site. The larger quantity of DOC found in the shallow soils than in deep soils is consistent with other research that has found DOC quantities reduce with depth (Kaiser & Kalbitz, 2012; Lv & Liang, 2012; Michalzik et al., 2001; Wu et al., 2010). DOC is largely produced in the upper, organic soil layers and associated litter. DOC that leaches into deeper, mineral soil layers is more susceptible to removal by adsorption or decomposition (Michalzik et al., 2001) and given the high clay content of the mineral soils under both sites, adsorption of DOC to soil mineral particles is very likely. The difference in DOC quantity between the ECN and FLII sites might be attributed to management effects on the quantity of forest materials as sources of DOC, as further discussed below. It is also possible that management effects on the water balance, for example, tree thinning (causing less canopy interception of rainfall and reduced evapotranspiration) enhanced leaching losses of DOC at the FLII site leading to reduced DOC concentrations in pore water.

4.1. Impact of management on the quantity of forest material

A greater mass of litter, F layer and Ah horizon per unit area was seen than deadwood and vegetation. This would be expected as both leaf litter and organic and mineral soil horizons have a larger spatial extent in comparison to deadwood and ground cover vegetation due to almost continuous, rather than patchy, ground coverage. Differing management may also affect the inputs from these sources. Although not significant due to high variability between plots at the ECN site, the unmanaged ECN plots consistently had greater quantities of leaf litter on the forest floor which could be a result of a denser tree cover in comparison to the FLII site which undergoes thinning. The presence of a shrub layer in the ECN plots, which is not periodically removed by management like the FLII plots, may also contribute to the greater amounts of leaf litter. This has been found in other studies, whereby management, specifically thinning, significantly reduced litterfall (Henneron et al., 2018). In addition, the FLII site has more open canopy due to management than the ECN site, so canopy water interception is smaller and thus higher water and light input to the forest floor could speed the decomposition rate of leaf litter. In addition, the greater light input to the forest floor at the FLII site enables the herb layer to establish which is consistent with the finding that all FLII plots had greater vegetative mass.

Typical values of fallen deadwood volumes in temperate, unmanaged forests range from 50 m^3 ha^{-1} (Hodge & Peterken, 1998) to 165 m^3 ha^{-1} (Krueger et al., 2017). By contrast, managed woodlands can exhibit deadwood volumes ranging from as low as 2 m^3 ha^{-1} (Tobin et al., 2007) to 30 m^3 ha^{-1} (Krueger et al., 2017), largely due to its removal (Powers et al., 2012). In the managed FLII site, deadwood volumes were low (4.1 m^3 ha^{-1}) but fell within the range cited by other literature. However, in the unmanaged ECN site, deadwood volumes averaged 21.2 m^3 ha^{-1} which would fall below cited volumes in other studies. This may be as a result of the historical management undertaken at the ECN site. As management only ended in 1992 at the ECN site, it may be that the deadwood volumes have not reached a level that would be seen in pristine woodland. The volume of deadwood present in forests is dependent on forest stand dynamics and management practices. As the intensity of forest management increases, the amount of deadwood per hectare decreases (Green & Peterken, 1997; Hodge & Peterken, 1998; Paletto et al., 2014). It is not surprising, therefore, given the management history, that the managed FLII site had a smaller biomass of deadwood than the unmanaged ECN site. Tree thinning carried out in the FLII site will have reduced the rate of tree mortality and so resulted in decreased deadwood production whilst the production of deadwood in the ECN site is more dependent on disturbance events. Instances of thinning will have created pulses of deadwood inputs to the forest floor, leading to certain decay classes being more common. For instance, immediately after thinning, deadwood at a lower stage of decay will be more prevalent than later stages of decay (Thibault & Moreau, 2016).

The amounts of vegetation, deadwood and litter at each site will have influenced the formation of the F layer and Ah horizon. The F layer is a mix of organic matter at different stages of decomposition which lies on top of the soil (Trimble & Lull, 1956); the Ah horizon is the surface mineral soil consisting of organic material mixed with parent material. Soil organisms digest and incorporate organic matter from forest floor materials into underlying soil (Boyle & Powers, 2013). There is evidence of high density earthworm populations in Alice Holt forest soils with some even found within the deadwood itself (Ashwood et al., 2019). This will have contributed to the transfer of organic matter from the forest floor materials to the soil. At FLII, the trend for a smaller biomass and therefore C stock of litter might indicate lower total inputs from the thinned canopy, as previously discussed. However, the quantity and distribution of organic material between the litter, F layer and (as measured C) in the Ah horizon will depend not only on quantity of input via litter fall, but also subsequent decomposition and redistribution processes. The reduced C stock in the FLII Ah horizon also reflects a lower soil bulk density at this site (in addition to a lower C concentration). The greater biomass and C for the F layer matching the lower C stock for the Ah horizon at FLII might indicate less soil incorporation of organic material from the F layer, if bioturbation activity is reduced at the managed site. However, quantification of process rates (e.g. litterfall, decomposition, bioturbation activity) is required in order to understand the basis of differences in mass and C stocks of forest floor materials between the two sites.

While total mass was largest at the ECN site, it was not significantly larger than at the FLII site, and the high variability in mass of individual materials (coefficients of variation were large: > 30% for many of the materials and approaching 70% for deadwood at the FLII site) may have masked any effect of management. The high variability seen in our results is common in forest floor material (Cools & De Vos, 2013), and other research has similarly found that management effects were hidden by large variability (Bouriaud et al., 2019). Larger scale sampling may help to clarify this effect.

4.2. Dominant sources of DOC between different forest materials and the impacts of management

As expected, the amount of DOC produced per g of material for each source did not vary with management (fig. 4). Both sites were part of the same semi-natural woodland and so the quality (as a DOC source) of material between the sites may not vary substantially, only the quantity. Even though the C content of the Ah horizons differed between sites, this did not result in between-site differences in DOC production when considered on a mg g^{-1} basis (fig. 4). Therefore, the amount of DOC produced per m^2 varied between sources of forest floor material as a result of differences in quantity not quality. While management did not significantly affect DOC amounts per area (g m^{-2}) when examined as a main effect across all the individual sources (fig. 5), the cumulative flux of DOC in the ECN was higher than that of the FLII (fig. 6), as also seen by our long-term monitoring (figs. 2 & 3). Other research has also found that carbon pools of unmanaged forests are larger than similar, managed forests (Chatterjee et al., 2009; Krug et al., 2012; Schulze et al., 2009). Although vegetation and the Ah horizon did differ as sources of DOC (g m^{-2}) with respect to management, reflecting the differences in their quantities between the sites, the large variability in DOC production per source may have masked management as a main effect in our study. Additionally, long-term management was similar at both sites prior to monitoring, with the ECN plot only being unmanaged over the last 20 years. It is likely that the time-span required to evaluate an unmanaged forest is longer than this, and for some studies has been defined as an absence of management for 250 years (Knohl et al., 2003; Wirth, 2009). The use of further long-term monitoring would help to clarify how the time since management effects forest carbon stocks and fluxes.

Leaf litter produced a substantial amount of DOC both per gram of material, and per m^2. The amount of DOC produced from leaf litter is notably higher at the ECN site as a result of larger litter inputs. This is possibly due to management practices resulting in a denser tree canopy in comparison to the FLII site. However, leaf litter will only provide inputs to the soil for a short period of time and will not be present all year round. The rate of leaf litter decomposition has been found to be high at Alice Holt forest with 74% decomposition over a year (Benham et al., 2012). Fresh leaf litter releases the largest amount of DOC with the flux declining as leaf litter decays (Don & Kalbitz, 2005). In contrast to leaf litter, deadwood decays more slowly (Didion et al. 2014) due to the greater content and structure of polymers, such as lignin, found in wood (Zhou et al., 2007). Full decomposition may take 3-750 years (Harmon et al., 2020), depending on the size and diameter of individual logs (Currie et al., 2002). Thus, deadwood has the potential to form a long-term source of DOC in comparison to the short, seasonal pulses provided by litter. Deadwood produced less DOC per m^2 than the Ah horizon, F layer and leaf litter due to its patchy spatial distribution. However, along with litter, it released the most DOC per unit mass. Bantle et al. (2014) considered the patchy distribution of deadwood to cause “hotspots” of DOC input into the forest soil. These hotspots could increase their spatial coverage with time under management practices that enable deadwood accumulation and so provide a greater input of DOC over the long-term (Spears & Lajtha, 2004). DOC production per gram of material indicated that deadwood provides a far larger input of DOC to the soil than either the Ah horizon or vegetation (fig. 4). Similar results were found by Kahl et al. (2012) who identified greater fluxes of DOC from logs than the forest floor. Studies have found that the amount of DOC released from deadwood increased as samples decayed (Bantle et al., 2014; Hafner et al., 2005).

The DOC released from forest floor materials and upper, organic soil layers during decomposition can translocate into deeper, mineral soil horizons (Michalzik et al., 2001). The quantity of DOC found in the Ah horizon has been found to be largely due to amounts leaching from litter rather than in-situ production (Peichl et al., 2007). Our results broadly show this pattern (fig. 5), with litter producing 2.3-2.5 x more DOC g m^{-2} than the Ah horizon in the FLII and ECN, respectively. Where there were greater quantities of DOC produced by litter in the ECN site, we also found larger quantities in the Ah horizon than in the FLII. Long term repeated soil sampling has determined an accumulation of C within the topsoil mineral Ah horizon in the ECN site (Benham et al., 2012) which also confirms the continuous input of carbon from the forest floor layer to top mineral soil and the capacity of clay rich mineral topsoil to capture C. Here we have considered forest floor materials as sources of DOC production for translocation to underlying soil but also acknowledge that the activities of living woody and herbaceous vegetation (e.g. root exudation and turnover) might also contribute to DOC concentrations differentially, depending on management.

5. Conclusions: has management altered the flux of DOC into soil waters?

The results of long-term forest monitoring indicate that there is a difference in the DOC production between the two sites under different managements, with the annual median at the unmanaged ECN being twice that of the managed FLII. We examined forest organic materials that are thought to release DOC that is transported into soil waters by leaching. The results of our field study also show that a significantly larger total DOC flux is produced in the ECN site (295.5 g m^{-2}) compared to the FLII site (230.3 g m^{-2}). Whilst no significant differences were found in the total forest organic material mass or carbon stocks between different managements, significant differences were found between different forest floor materials that were dependent on management. Likewise, with DOC release, the flux depended on forest material and management. Management affects the allocation of carbon between different forest organic materials and DOC fluxes. This study has identified that the quantity and type of material has a great potential to influence the amount of DOC in the soil. Whilst in our study the overall volume of deadwood was fairly low, and thus contribution of deadwood to DOC per m^2 was lower than for other organic sources, in forests with greater deadwood volumes, substantial amounts of DOC may be produced. Management practices, such as tree thinning and the removal of woody debris created by harvesting, may be influencing the amounts of DOC found in forest soil water. Further studies are required across a range of sites and intensity and longevity of management to confirm whether management is affecting DOC in soil water by influencing the composition of forest materials. More work is needed to understand how litter and deadwood contribute to Ah horizon material and DOC through this indirect pathway.

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