

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

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11 **Abstract**

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

33 **Keywords**

34 DOC, carbon cycling, broadleaf woodland, soil, management

35 **1. Introduction**

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

44 Dissolved organic carbon (DOC) is produced during the decomposition of organic material and is
45 transported between carbon pools through hydrological processes such as leaching from the forest
46 floor to the mineral soil (Kolka et al., 2008). An estimated 17% of the annual C input from litter
47 leaches into mineral soils as DOC (Michalzik et al., 2001). The composition of DOC depends on the
48 composition of organic material, which impacts its turnover time and therefore the soils ability to
49 sequester carbon in the long-term (Aitkenhead & McDowell, 2000). The forest floor, woody debris
50 and ground vegetation are considered to be important sources of DOC and contain various
51 substrates which contribute differing amounts of DOC of varying complexity. Park et al. (2002)
52 investigated the impact of resource availability on DOC production over 98 days and determined
53 that leaf litter was the most important source of DOC in deciduous woodlands followed by fresh
54 wood litter (<1 year old). Other studies have found the amount of DOC released from litter to
55 decrease significantly over time, indicating a large labile pool of DOC that can be consumed as a
56 substrate for biological activity (Don & Kalbitz, 2005; Moore & Dalva, 2001). Over the course of a
57 year, deadwood has been found to produce 10x as much DOC as litter (Hafner et al., 2005), and
58 between 3-20x as much DOC as throughfall (Bantle et al., 2014; Hafner et al., 2005). Overall, these
59 studies show that the production of DOC beneath deadwood could be significant in relation to other

60 forest floor materials but the relative magnitude of the contributions of deadwood, forest ground
61 vegetation, and forest floors as sources of DOC-derived carbon fluxes into soils are not always in
62 agreement between studies and therefore require further characterization.

63 Deadwood is defined as the non-living woody biomass not contained in litter and can be either
64 standing, lying on the ground, or in the soil (FAO, 2010). It has many functions within the forest, it is
65 a key indicator of forest biodiversity (Humphrey & Bailey, 2012; MCPFE Liaison Unit & UNECE/FAO,
66 2003); it influences stand dynamics (Hodge & Peterken, 1998); it has a protective role in stabilizing
67 slopes (Stevens, 1997); and is also an important carbon pool (FAO, 2020a; Morison et al., 2012; Pan
68 et al., 2011). However, it is one of the least studied carbon pools and is often not included in forest
69 carbon models or inventories despite being a potentially significant store of carbon. Deadwood is
70 often classified as coarse woody debris (CWD) with a diameter greater than 10 cm; fine woody
71 debris (FWD) with a diameter less than 10 cm or as snags or stumps (Working Group on Forest
72 Biodiversity, 2004). It may be further classified according to stage of decay following the
73 classification by Hunter (1990). Under this classification, decay classes range from class 1 (least
74 decomposed; intact texture with bark present) to class 5 (largely decomposed, bark is absent,
75 powdery texture). The degree to which deadwood has decomposed will determine the biomass of
76 the deadwood and thus the amount of carbon available for leaching. It has been determined that
77 wood at a later stage of decay releases more DOC but over a longer period of time (Bantle et al.,
78 2014). Therefore, forest management that decreases the amount of deadwood within a forest could
79 reduce the amount of DOC within the soil. The aim of this work is to test the hypothesis that
80 management practices, particularly forest thinning and the removal of woody debris created during
81 harvesting, reduce the DOC fluxes into soil water. Our specific objectives are to: (1) determine
82 whether management has altered DOC concentrations in long-term monitoring data; (2) determine
83 the impact of management on the carbon stocks of forest material; (3) evaluate the dominant
84 sources of DOC between different forest materials.

85 2. Materials and methods

86 2.1. Site information

87 Alice Holt Forest is a semi-natural ancient woodland located on the Surrey-Hampshire border, UK
88 (51° 9' N, 0° 52' W). Plots under different management within Alice Holt Forest were used: an
89 environmental change network (ECN) plot and a Forest Level II Intensive Monitoring Network (FLII)
90 plot (fig. 1). Both of these have undergone regular monitoring, that includes soil chemistry and
91 atmospheric pollution, since the mid-1990s. The ECN and FLII sites are dominated by 75 year old oak
92 (*Quercus robur*) with occasional ash (*Fraxinus excelsior*) occurring on Gault Clay overlain by poorly
93 draining surface-water gleys. Soil properties (Ah Horizon) for the ECN and FLII sites, respectively, are
94 as follows: organic carbon content (5.6% and 2.7%); pH_{water} (4.4 and 5.4); sand (%): silt (%): clay (%)
95 (~9:50:40 and ~4:44:52) (Benham et al., 2012; Vanguelova (unpublished results)). Site elevation
96 ranges from 110-125m and the climate is temperate with a mean annual temperature of 10.8°C and
97 mean annual precipitation of 833mm. The forest has historically been thinned at intervals of 20-25
98 years; however, the ECN site has been unmanaged since 1992. Woody debris, created by self-
99 thinning of subdominant or diseased trees which die and fall, are not removed from the site. By
100 contrast, the FLII site is still managed with practices which include tree thinning and scrub layer
101 removal. Harvesting material is removed from the plot by management i.e., the main trunk and lop
102 and top along with any dead trees as part of the thinning process, however deadwood which falls
103 from the canopy to the forest floor (mainly, but not exclusively, fine material) is left *in situ*.
104 Management that took place at the FLII site during the long-term monitoring (section 2.2) and
105 sampling (section 2.3) campaigns was as follows: thinning of oak (2005) and scrub removal (2010),
106 where hazel bushes were cut down and debris removed. Sampling took place two years before the
107 next management for scrub removal (in 2017).



108

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

111 **2.2. Long-term monitoring**

112 The initial ECN measurement protocols were developed by an expert group in the late 1980s
113 (Morecroft et al., 2009) and a detailed series of protocols (Sykes & Lane, 1996) were published.
114 Some protocols have been revised in light of experience, but most methods remain essentially
115 unchanged, allowing robust comparisons across time. The assessment of forest condition under the
116 United Nations Economic Commission for Europe (UNECE) and EU Level I and Level II long-term
117 forest monitoring programs constitutes one of the world's largest bio-monitoring networks
118 (Vanguelova et al., 2007). Plot establishment and instrumentation follow standardised monitoring
119 protocols, as created by the International Co-operative Programme on Assessment and Monitoring
120 of Air Pollution Effects on Forests (ICP; ICP, 2006). In this study, we use the long-term soil water
121 monitoring data collected every two weeks at both sites between 2002 and 2010. Long-term soil
122 water monitoring at the ECN site stopped in 2010 due to funding restrictions. Both networks use the
123 same type of tension samplers (PRENART SuperQuartz soil water samplers, Prenart Equipment Aps,

124 Denmark) and measure soil water chemistry at two similar depths with 6 replicate samplers at each
125 depth. At Alice Holt, the ECN shallow and deep soil solution samplers are located in the Ah and Btg
126 horizons. The FLII shallow and deep soil solution samplers are located in the Ah and Bcg horizons.
127 Shallow and deep samplers are located at 10 and 50 cm depth, respectively. Soil water was sampled
128 at two different locations within the FLII plot to better capture the site variability. Measurements
129 from the ECN shallow plots and FLII deep plots were only available from 2004 – 2010. Soil water
130 samples were filtered through a 0.45 µm membrane filter and analysed for dissolved organic carbon
131 (DOC) by Thermal Catalytic Oxidation using a Thermalox™ Analyzer (Analytical Sciences UK,
132 Cambridge, UK; pH < 5.5, therefore Total Dissolved C = Total DOC).

133 **2.3. Sampling for deadwood, vegetation, forest floor and soil**

134 Deadwood sampling was carried out using the BioSoil (2004) protocols. This was carried out in
135 November 2015, during peak litter fall and the autumn seasonal peak in DOC concentrations. Three
136 circular plots with an area of 400 m² were randomly selected to survey deadwood at both the ECN
137 and FLII sites. Within each 400 m² area, all deadwood debris found were recorded, including stumps
138 and lying coarse and fine woody debris. The length (cm) and diameter (cm) of each deadwood piece
139 were recorded along with decay class 1-5 following the guidelines presented by Hunter (1990) to
140 enable the deadwood biomass and carbon stock to be estimated.

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

148 sample on the same spatial scale for both deadwood and forest floor materials due to the irregular
149 coverage of deadwood and large quantities of forest materials.

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

$$153 \quad \text{Biomass} = \text{Density} \times \text{Volume}$$

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

155 Subsequently carbon stocks were calculated as follows:

$$156 \quad \text{Carbon stock} = \text{Biomass} \times \text{carbon fraction}$$

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

159

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

165 **2.4. Dissolved organic carbon**

166 A water extract was taken from all samples (deadwood in each decay class 1-5, vegetation, litter, F
167 layer, Ah horizon) of the spatial survey using a ratio of 1:10 as 10 g wet sample to 100 mL deionised
168 water. Material from each of the plots per site (n=3) was homogenised and cut in to ~1cm pieces
169 prior to sub-sampling for extraction. Samples were placed on a rotary shaker for 24 hours at 180 rpm

170 before centrifuging at 3500 rpm for ten minutes and pre-filtering through Whatman GF/A filter
171 papers using vacuum filtration. Samples were centrifuged at 1300 rpm for a further 15 minutes
172 before filtering through 0.45 µm cellulose nitrate filter paper.

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

176 **2.5. Statistical analysis**

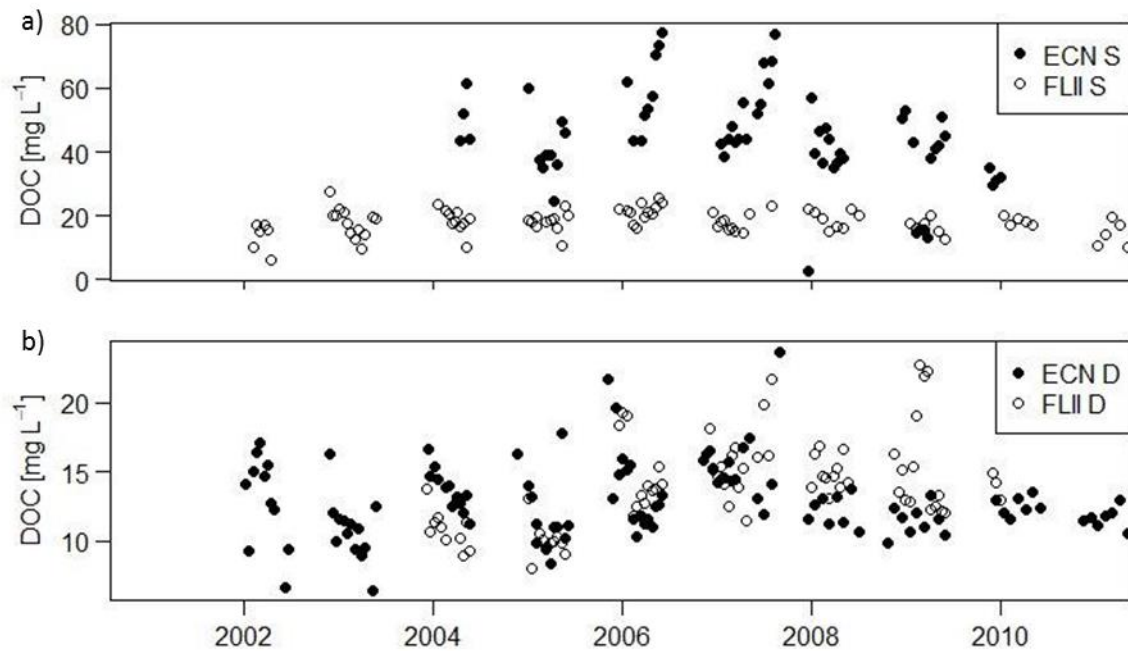
177 Long-term trends in DOC were analysed using the statistical environment R v. 2.13.2 to 3.1.2. The
178 data were tested for normality using Shapiro-Wilk and homogeneity of variances using Flinger-
179 Killeen. Where these were not met, data was analysed using the non-parametric Kruskal-Wallis
180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

181 Statistical analysis of data from the forest material survey was mainly carried out using the
182 Statsmodels module in Python (Seabold & Perktold, 2010). Data were tested for normality of
183 residuals using the Jarque-Bera test and for heteroscedasticity using the Breusch-Pagan test. Raw
184 (non-transformed) data failed to meet either normality or equality of variances or both, likely due to
185 the large range in the size of the actual mean values and variances. We therefore performed Robust
186 (to unequal variance) type III Two-Way ANOVA to identify if site (ECN, FLII) or forest material type
187 (deadwood, fresh vegetation, leaf litter, fermentation layer, Ah soil horizon) affected C stocks and
188 DOC flux results. Data were Box-Cox transformed: $(Y^\lambda - 1)/\lambda$ where λ was chosen so as to minimise the
189 p-value testing normality of residuals (using Jarque-Bera). Significant differences were accepted at
190 $p < 0.05$. Where the Two-Way ANOVA identified a significant main effect, post-hoc comparisons were
191 made using the Games-Howell Method and 95% Confidence in Minitab 18. In the case of a
192 significant site \times forest material type interaction, paired t-tests (Minitab 18; equal variances not
193 assumed) were used to examine the effect of site within each forest material type.

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

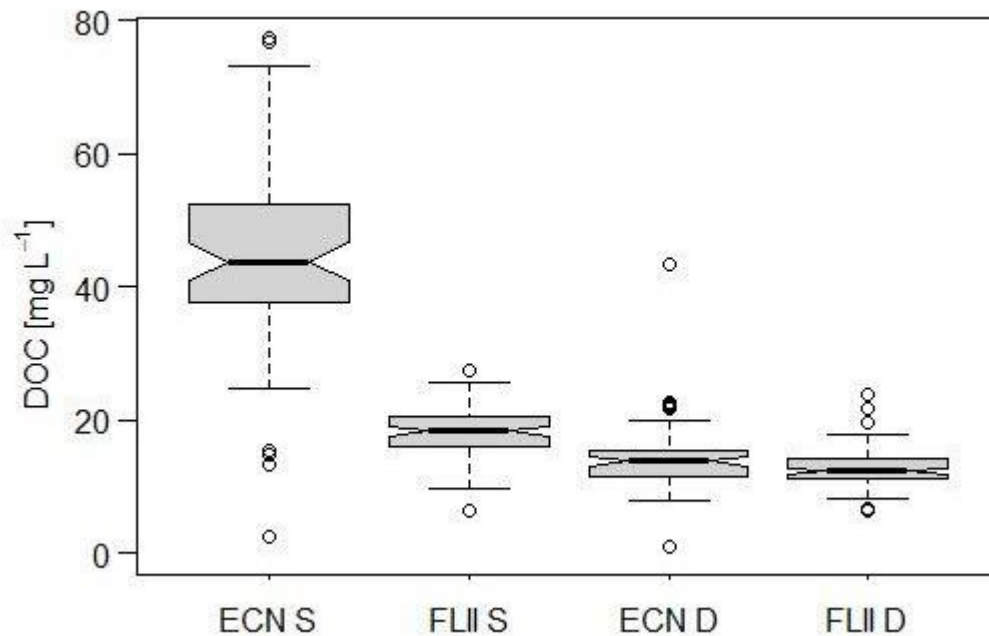
196 3. Results

197 3.1. Long-term trends in soil water DOC at ECN and FLII sites



198
199 Figure 2 - ECN and FLII time series of soil water DOC concentrations from (a)* shallow (S) samplers in
200 the upper plot and (b) deep (D) samplers in the lower plot. Solid dots represent the ECN data and
201 hollow dots represent the FLII data.

202 Long-term soil water monitoring data shows consistently higher DOC concentrations within the ECN
203 plot compared to the FLII plot, which was particularly evident at shallow depths (fig. 2a). From 2002
204 to 2010, median DOC concentrations in the ECN plot were 2.4 times higher than FLII ($p < 0.00001$) in
205 the shallow samplers, with concentrations of 43.8 mg L^{-1} and 18.4 mg L^{-1} , respectively (fig. 3). ECN
206 shallow samplers also displayed a greater range in values from $2.67 - 77.3 \text{ mg L}^{-1}$, compared to $6.42 -$
207 27.6 mg L^{-1} in FLII samplers. Median values in the deep samplers were also significantly higher in ECN
208 than FLII (13.8 mg L^{-1} and 12.4 mg L^{-1} , respectively, $p < 0.01$), although the difference was less (1.1
209 times higher) (fig. 3). Gaps in the time series for both monitoring programmes exist during the
210 summer months in each year due to low soil moisture restricting sample collection.



211

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

216 **3.2. Survey of mass, C stocks and DOC production for forest floor materials**

217 **3.2.1. Deadwood, vegetation, litter, F layer and Ah horizon**

218 Examining the effect of forest material type and site on the mass (kg m^{-2}) of forest materials using
 219 two-way ANOVA revealed that mass differed significantly between material types (d.f. = 4; $F = 129.2$;
 220 $p < 0.001$), with the greatest mass associated with the Ah soil layer followed by the F layer (Table 1).

221 With vegetation, deadwood contributed lower mass than all other materials. Whilst mass of forest
 222 materials did not differ overall between management sites (d.f. = 1; $F = 0.298$; $p = 0.591$), there was
 223 a significant interaction with material type (d.f. = 4; $F = 10.56$; $p < 0.001$) such that a larger density of
 224 the Ah soil horizon and deadwood was found in the ECN plot whilst a greater mass of vegetation and
 225 F layer was present at the FLII plot (Table 1).

226 Two-way ANOVA revealed that total carbon stocks (Mg C ha^{-1}) held in forest material did not differ
 227 between the sites ($F = 1.56$; $p = 0.226$) but depended on material type ($F = 38.56$; $p < 0.001$) and the

228 interaction between material type and site ($F = 19.13$; $p < 0.001$). Overall, deadwood and the Ah
 229 horizon held greater carbon stocks in the unmanaged ECN site than the managed FLII site. In
 230 contrast, the F layer and vegetation held significantly greater stocks in the managed FLII than
 231 unmanaged ECN site (Table 1). Notably, deadwood stocks are over four times lower in the managed
 232 FLII plot than the unmanaged ECN plots, while vegetation stocks are over three times larger.

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

Material type	Mass (kg m^{-2})		Games-Howell group	Carbon stock (Mg C ha^{-1})		Games-Howell group
	ECN	FLII		ECN	FLII	
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	

238 3.2.2. Inventory of deadwood by decay class

239 According to the survey of deadwood volumes within the 400 m² plots, a larger volume of deadwood
 240 was found at the ECN site with the average total, when scaled to a per hectare basis, of $21.2 \pm 6.3 \text{ m}^3$
 241 ha^{-1} and $4.1 \pm 1.6 \text{ m}^3 \text{ ha}^{-1}$ for the ECN and FLII sites, respectively. Robust ANOVA on Box-Cox-
 242 transformed data revealed that decay class significantly affected deadwood biomass (d.f. = 4; $F =$
 243 3.68 ; $p = 0.022$) and deadwood C stocks ($F = 3.68$; $p = 0.022$). The largest quantities of deadwood per
 244 m² were found in decay classes 3 and 4 for both plots (Table 2), with a maximum of $0.242 \pm 0.171 \text{ kg}$
 245 m⁻² for the ECN site (decay class 4) and a maximum of $0.0501 \pm 0.0242 \text{ kg m}^{-2}$ for the FLII site (decay
 246 class 3). There was no overall significant effect of site on deadwood biomass (d.f. = 1; $F = 1.49$; $p =$

247 0.237) or C stock ($F = 1.44$; $p = 0.245$) and no significant site * decay class interaction (d.f. = 4; $F =$
 248 0.105; $p = 0.980$ for both biomass and C stock).

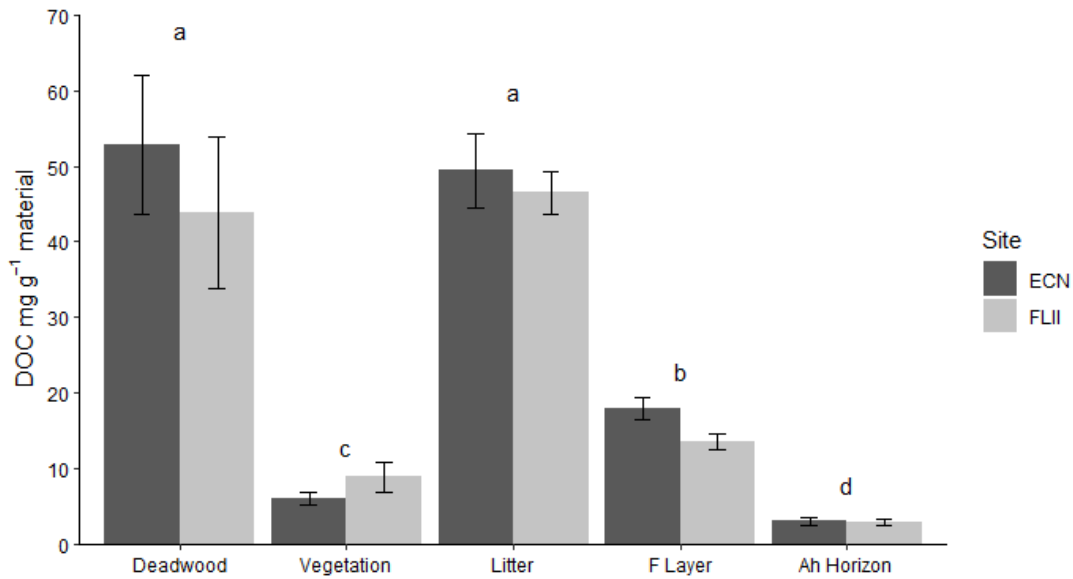
249 Table 2 – Mean biomass \pm SE (kg m^{-2}) and carbon stocks (Mg C ha^{-1}) of each deadwood decay class at
 250 the ECN and FLII plots, $n=3$ per group. Games Howell groups that do not share a letter are
 251 significantly different ($p<0.05$). Values in parenthesis are the coefficient of variation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

Deadwood decay class	Biomass (kg m^{-2})		Games-Howell group	Carbon stock (Mg C ha^{-1})		Games-Howell group
	ECN	FLII		ECN	FLII	
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

252 **3.2.3. Forest floor materials as sources of DOC**

253 Analysis indicated that stage of deadwood decay did not significantly affect the production of DOC (p
 254 = 0.096). Therefore, for the subsequent analysis, all decay classes have been pooled into one class,
 255 'deadwood', and robust two-way ANOVA used to analyse the effect of forest material: deadwood,
 256 fresh vegetation, leaf litter, F layer, Ah horizon, and site: ECN and FLII.

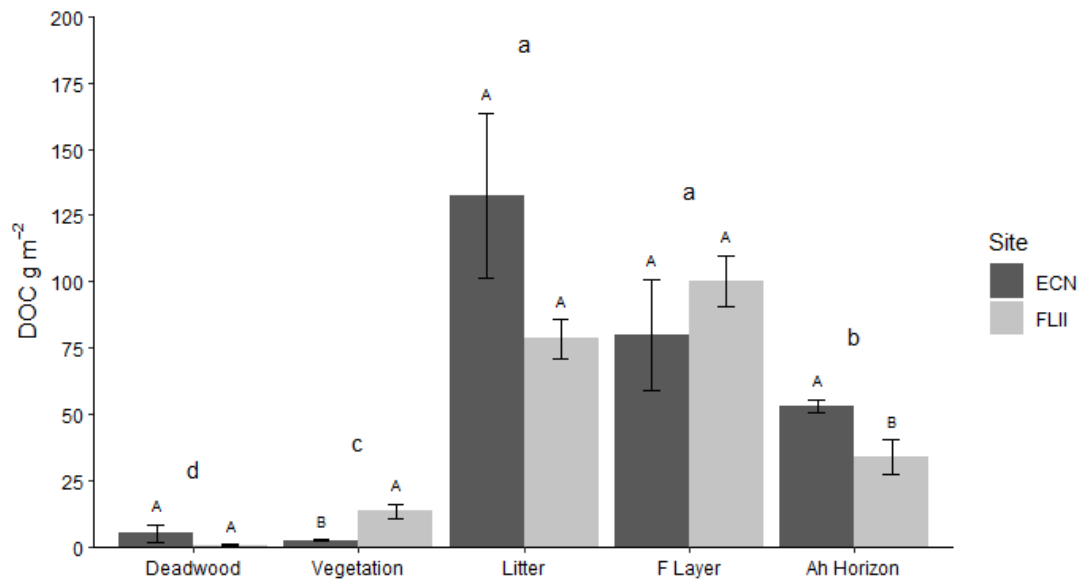
257 The mean amount of DOC released from each source ranged from 2.92-52.78 mg g^{-1} , with the lowest
 258 concentrations in the FLII Ah horizon and highest in the ECN deadwood, respectively (fig. 4). Two-
 259 way ANOVA found that significant differences occurred between forest material sources of DOC ($F =$
 260 95.11; $p<0.001$) but not sites ($F = 0.22$; $p = 0.643$). Deadwood and litter produced significantly
 261 ($p<0.05$) more DOC mg g^{-1} than the vegetation, F layer and Ah horizon (fig. 4). No significant
 262 interaction was found between site and source ($F = 1.10$; $p = 0.368$).



263

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

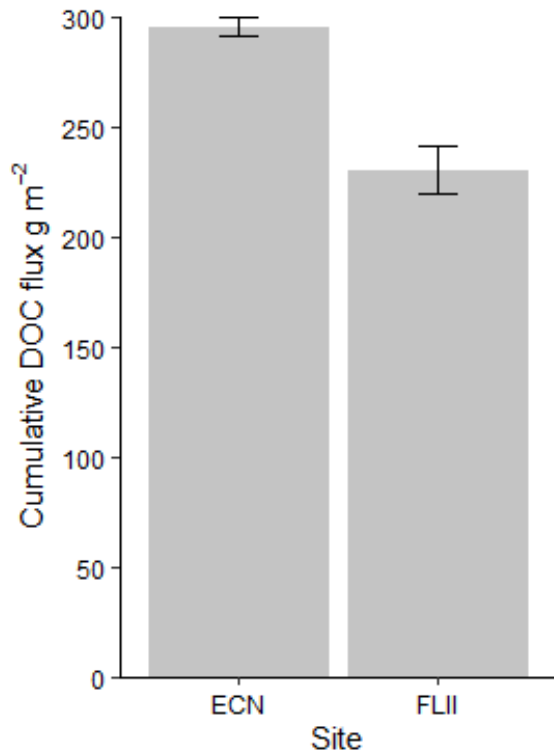
267 The largest DOC flux per unit area (132.6 ± 31.0 g m⁻²) was found in the ECN litter samples whilst the
 268 least was found in deadwood at the FLII plot (0.763 ± 0.297 g m⁻²) (fig. 5). By contrast to the DOC
 269 produced per unit mass (mg g⁻¹), the DOC produced per area (g m⁻²) was lower from deadwood
 270 sources because of the lower volume on the forest floor (fig. 5). Two-way ANOVA found no overall
 271 significant effect of site on DOC g m⁻² (F = 0.24; p = 0.627) but a significant effect of material type (F =
 272 98.89; p<0.001) and a significant interaction between site and source (F = 14.21; p<0.001), such that
 273 vegetation contributed more DOC g m⁻² in FLII plots but the Ah horizon contributed more in the ECN
 274 plots.



275

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

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



283

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

287 **4. Discussion**

288 The long-term monitoring data revealed that forestry management practices may have a large
 289 impact on DOC concentrations and export. We found larger quantities of DOC in shallow soil at the
 290 unmanaged ECN site, whereby the annual median was twice that of the managed FLII site. The larger
 291 quantity of DOC found in the shallow soils than in deep soils is consistent with other research that
 292 has found DOC quantities reduce with depth (Kaiser & Kalbitz, 2012; Lv & Liang, 2012; Michalzik et
 293 al., 2001; Wu et al., 2010). DOC is largely produced in the upper, organic soil layers and associated
 294 litter. DOC that leaches into deeper, mineral soil layers is more susceptible to removal by adsorption
 295 or decomposition (Michalzik et al., 2001) and given the high clay content of the mineral soils under
 296 both sites, adsorption of DOC to soil mineral particles is very likely. The difference in DOC quantity
 297 between the ECN and FLII sites might be attributed to management effects on the quantity of forest
 298 materials as sources of DOC, as further discussed below. It is also possible that management effects

299 on the water balance, for example, tree thinning (causing less canopy interception of rainfall and
300 reduced evapotranspiration) enhanced leaching losses of DOC at the FLII site leading to reduced DOC
301 concentrations in pore water.

302 **4.1. Impact of management on the quantity of forest material**

303 A greater mass of litter, F layer and Ah horizon per unit area was seen than deadwood and
304 vegetation. This would be expected as both leaf litter and organic and mineral soil horizons have a
305 larger spatial extent in comparison to deadwood and ground cover vegetation due to almost
306 continuous, rather than patchy, ground coverage. Differing management may also affect the inputs
307 from these sources. Although not significant due to high variability between plots at the ECN site,
308 the unmanaged ECN plots consistently had greater quantities of leaf litter on the forest floor which
309 could be a result of a denser tree cover in comparison to the FLII site which undergoes thinning. The
310 presence of a shrub layer in the ECN plots, which is not periodically removed by management like
311 the FLII plots, may also contribute to the greater amounts of leaf litter. This has been found in other
312 studies, whereby management, specifically thinning, significantly reduced litterfall (Henneron et al.,
313 2018). In addition, the FLII site has more open canopy due to management than the ECN site, so
314 canopy water interception is smaller and thus higher water and light input to the forest floor could
315 speed the decomposition rate of leaf litter. In addition, the greater light input to the forest floor at
316 the FLII site enables the herb layer to establish which is consistent with the finding that all FLII plots
317 had greater vegetative mass.

318 Typical values of fallen deadwood volumes in temperate, unmanaged forests range from $50 \text{ m}^3 \text{ ha}^{-1}$
319 (Hodge & Peterken, 1998) to $165 \text{ m}^3 \text{ ha}^{-1}$ (Krueger et al., 2017). By contrast, managed woodlands can
320 exhibit deadwood volumes ranging from as low as $2 \text{ m}^3 \text{ ha}^{-1}$ (Tobin et al., 2007) to $30 \text{ m}^3 \text{ ha}^{-1}$
321 (Krueger et al., 2017), largely due to its removal (Powers et al., 2012). In the managed FLII site,
322 deadwood volumes were low ($4.1 \text{ m}^3 \text{ ha}^{-1}$) but fell within the range cited by other literature.
323 However, in the unmanaged ECN site, deadwood volumes averaged $21.2 \text{ m}^3 \text{ ha}^{-1}$ which would fall

324 below cited volumes in other studies. This may be as a result of the historical management
325 undertaken at the ECN site. As management only ended in 1992 at the ECN site, it may be that the
326 deadwood volumes have not reached a level that would be seen in pristine woodland. The volume
327 of deadwood present in forests is dependent on forest stand dynamics and management practices.
328 As the intensity of forest management increases, the amount of deadwood per hectare decreases
329 (Green & Peterken, 1997; Hodge & Peterken, 1998; Paletto et al., 2014). It is not surprising,
330 therefore, given the management history, that the managed FLII site had a smaller biomass of
331 deadwood than the unmanaged ECN site. Tree thinning carried out in the FLII site will have reduced
332 the rate of tree mortality and so resulted in decreased deadwood production whilst the production
333 of deadwood in the ECN site is more dependent on disturbance events. Instances of thinning will
334 have created pulses of deadwood inputs to the forest floor, leading to certain decay classes being
335 more common. For instance, immediately after thinning, deadwood at a lower stage of decay will be
336 more prevalent than later stages of decay (Thibault & Moreau, 2016).

337 The amounts of vegetation, deadwood and litter at each site will have influenced the formation of
338 the F layer and Ah horizon. The F layer is a mix of organic matter at different stages of
339 decomposition which lies on top of the soil (Trimble & Lull, 1956); the Ah horizon is the surface
340 mineral soil consisting of organic material mixed with parent material. Soil organisms digest and
341 incorporate organic matter from forest floor materials into underlying soil (Boyle & Powers, 2013).
342 There is evidence of high density earthworm populations in Alice Holt forest soils with some even
343 found within the deadwood itself (Ashwood et al., 2019). This will have contributed to the transfer
344 of organic matter from the forest floor materials to the soil. At FLII, the trend for a smaller biomass
345 and therefore C stock of litter might indicate lower total inputs from the thinned canopy, as
346 previously discussed. However, the quantity and distribution of organic material between the litter,
347 F layer and (as measured C) in the Ah horizon will depend not only on quantity of input via litter fall,
348 but also subsequent decomposition and redistribution processes. The reduced C stock in the FLII Ah
349 horizon also reflects a lower soil bulk density at this site (in addition to a lower C concentration). The

350 greater biomass and C for the F layer matching the lower C stock for the Ah horizon at FLII might
351 indicate less soil incorporation of organic material from the F layer, if bioturbation activity is reduced
352 at the managed site. However, quantification of process rates (e.g. litterfall, decomposition,
353 bioturbation activity) is required in order to understand the basis of differences in mass and C stocks
354 of forest floor materials between the two sites.

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

362 **4.2. Dominant sources of DOC between different forest materials and the impacts of management**

363 As expected, the amount of DOC produced per g of material for each source did not vary with
364 management (fig. 4). Both sites were part of the same semi-natural woodland and so the quality (as
365 a DOC source) of material between the sites may not vary substantially, only the quantity. Even
366 though the C content of the Ah horizons differed between sites, this did not result in between-site
367 differences in DOC production when considered on a mg g^{-1} basis (fig. 4). Therefore, the amount of
368 DOC produced per m^2 varied between sources of forest floor material as a result of differences in
369 quantity not quality. While management did not significantly affect DOC amounts per area (g m^{-2})
370 when examined as a main effect across all the individual sources (fig. 5), the cumulative flux of DOC
371 in the ECN was higher than that of the FLII (fig. 6), as also seen by our long-term monitoring (figs. 2 &
372 3). Other research has also found that carbon pools of unmanaged forests are larger than similar,
373 managed forests (Chatterjee et al., 2009; Krug et al., 2012; Schulze et al., 2009). Although vegetation
374 and the Ah horizon did differ as sources of DOC (g m^{-2}) with respect to management, reflecting the

375 differences in their quantities between the sites, the large variability in DOC production per source
376 may have masked management as a main effect in our study. Additionally, long-term management
377 was similar at both sites prior to monitoring, with the ECN plot only being unmanaged over the last
378 20 years. It is likely that the time-span required to evaluate an unmanaged forest is longer than this,
379 and for some studies has been defined as an absence of management for 250 years (Knohl et al.,
380 2003; Wirth, 2009). The use of further long-term monitoring would help to clarify how the time since
381 management effects forest carbon stocks and fluxes.

382 Leaf litter produced a substantial amount of DOC both per gram of material, and per m². The amount
383 of DOC produced from leaf litter is notably higher at the ECN site as a result of larger litter inputs.
384 This is possibly due to management practices resulting in a denser tree canopy in comparison to the
385 FLII site. However, leaf litter will only provide inputs to the soil for a short period of time and will not
386 be present all year round. The rate of leaf litter decomposition has been found to be high at Alice
387 Holt forest with 74% decomposition over a year (Benham et al., 2012). Fresh leaf litter releases the
388 largest amount of DOC with the flux declining as leaf litter decays (Don & Kalbitz, 2005). In contrast
389 to leaf litter, deadwood decays more slowly (Didion et al. 2014) due to the greater content and
390 structure of polymers, such as lignin, found in wood (Zhou et al., 2007). Full decomposition may take
391 3-750 years (Harmon et al., 2020), depending on the size and diameter of individual logs (Currie et
392 al., 2002). Thus, deadwood has the potential to form a long-term source of DOC in comparison to
393 the short, seasonal pulses provided by litter. Deadwood produced less DOC per m² than the Ah
394 horizon, F layer and leaf litter due to its patchy spatial distribution. However, along with litter, it
395 released the most DOC per unit mass. Bantle et al. (2014) considered the patchy distribution of
396 deadwood to cause “hotspots” of DOC input into the forest soil. These hotspots could increase their
397 spatial coverage with time under management practices that enable deadwood accumulation and so
398 provide a greater input of DOC over the long-term (Spears & Lajtha, 2004). DOC production per gram
399 of material indicated that deadwood provides a far larger input of DOC to the soil than either the Ah
400 horizon or vegetation (fig. 4). Similar results were found by Kahl et al. (2012) who identified greater

401 fluxes of DOC from logs than the forest floor. Studies have found that the amount of DOC released
402 from deadwood increased as samples decayed (Bantle et al., 2014; Hafner et al., 2005).

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

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

417 The results of long-term forest monitoring indicate that there is a difference in the DOC production
418 between the two sites under different managements, with the annual median at the unmanaged
419 ECN being twice that of the managed FLII. We examined forest organic materials that are thought to
420 release DOC that is transported into soil waters by leaching. The results of our field study also show
421 that a significantly larger total DOC flux is produced in the ECN site (295.5 g m⁻²) compared to the FLII
422 site (230.3 g m⁻²). Whilst no significant differences were found in the total forest organic material
423 mass or carbon stocks between different managements, significant differences were found between
424 different forest floor materials that were dependent on management. Likewise, with DOC release,
425 the flux depended on forest material and management. Management affects the allocation of

426 carbon between different forest organic materials and DOC fluxes. This study has identified that the
427 quantity and type of material has a great potential to influence the amount of DOC in the soil. Whilst
428 in our study the overall volume of deadwood was fairly low, and thus contribution of deadwood to
429 DOC per m² was lower than for other organic sources, in forests with greater deadwood volumes,
430 substantial amounts of DOC may be produced. Management practices, such as tree thinning and the
431 removal of woody debris created by harvesting, may be influencing the amounts of DOC found in
432 forest soil water. Further studies are required across a range of sites and intensity and longevity of
433 management to confirm whether management is affecting DOC in soil water by influencing the
434 composition of forest materials. More work is needed to understand how litter and deadwood
435 contribute to Ah horizon material and DOC through this indirect pathway.

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