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

1. Introduction

36 The global forest carbon (C) stock is estimated at 861 ± 66 Pg (Pan et al., 2011) (1 Pg = 10^{15} g) of

37 which 119 ± 6 Pg are held in temperate forests and 878 Mt C (1 Mt = 10^{12} 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.

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,

6

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 m^2 were randomly selected to survey deadwood at both the ECN

137   and FLII sites. Within each 400 m^2 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 $$Biomass = Density \; x \; Volume$$

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

155   Subsequently carbon stocks were calculated as follows:

156 $$Carbon \; stock = Biomass \; x \; carbon \; fraction$$

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}.

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 × 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.

3. Results

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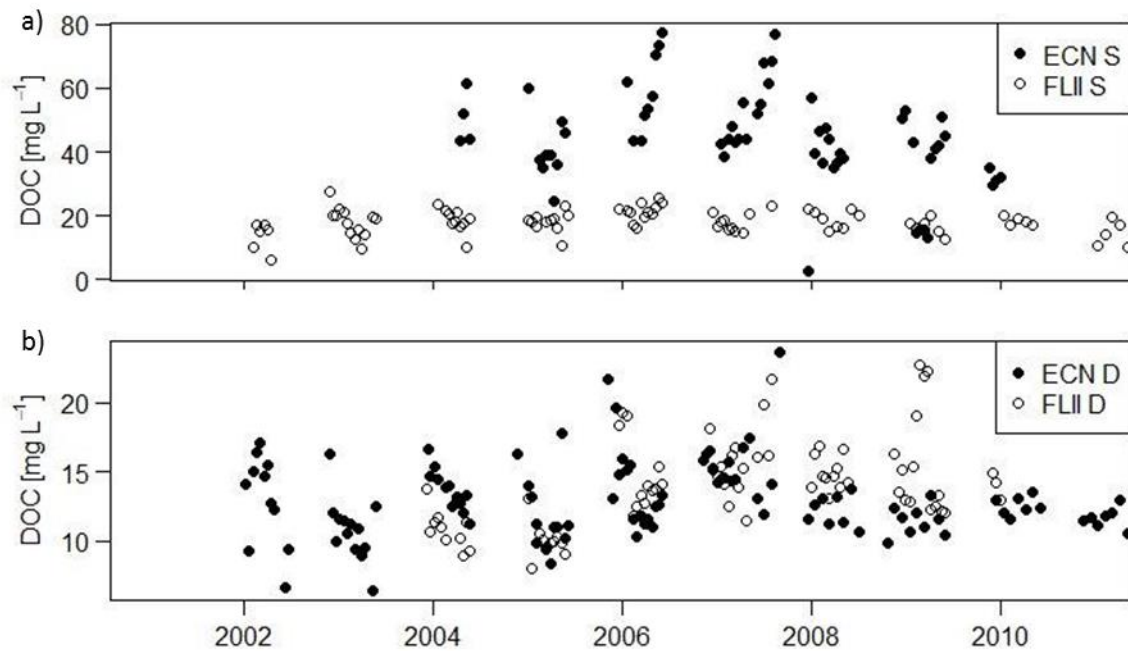

198
199   Figure 2 - ECN and FLII time series of soil water DOC concentrations from (a)* shallow (S) samplers in
200   the upper plot and (b) deep (D) samplers in the lower plot. Solid dots represent the ECN data and
201   hollow dots represent the FLII data.

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 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.
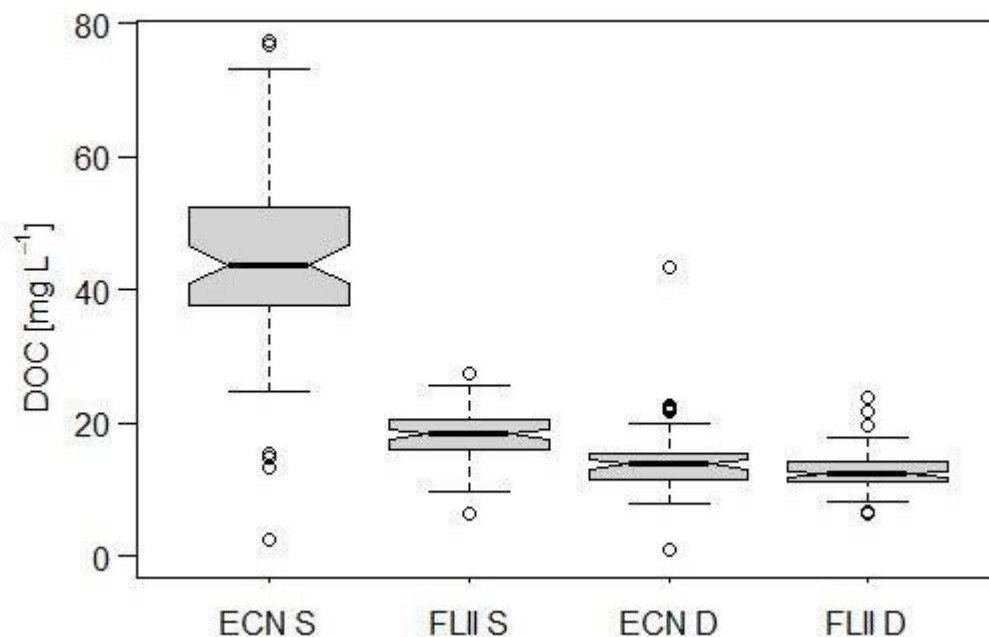
211

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

11

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 ± 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})			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	

238　**3.2.2. Inventory of deadwood by decay class**

239　According to the survey of deadwood volumes within the 400 m^2 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 ± 6.3 m^3

241　ha^{-1} and 4.1 ± 1.6 m^3 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　m^2 were found in decay classes 3 and 4 for both plots (Table 2), with a maximum of 0.242 ± 0.171 kg

245　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

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 ± 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})			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

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

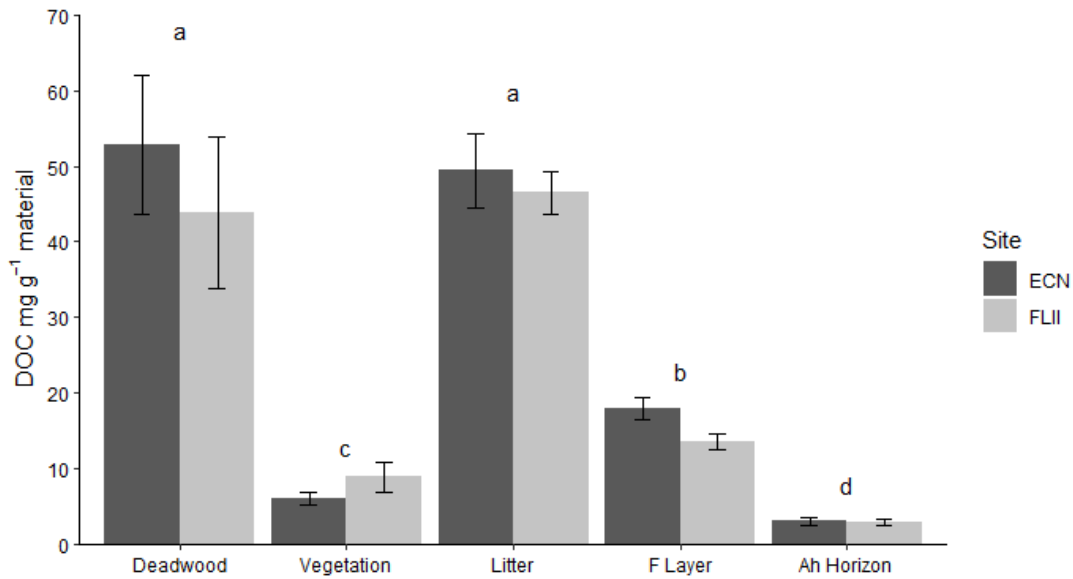262   interaction was found between site and source (F = 1.10; p = 0.368).

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
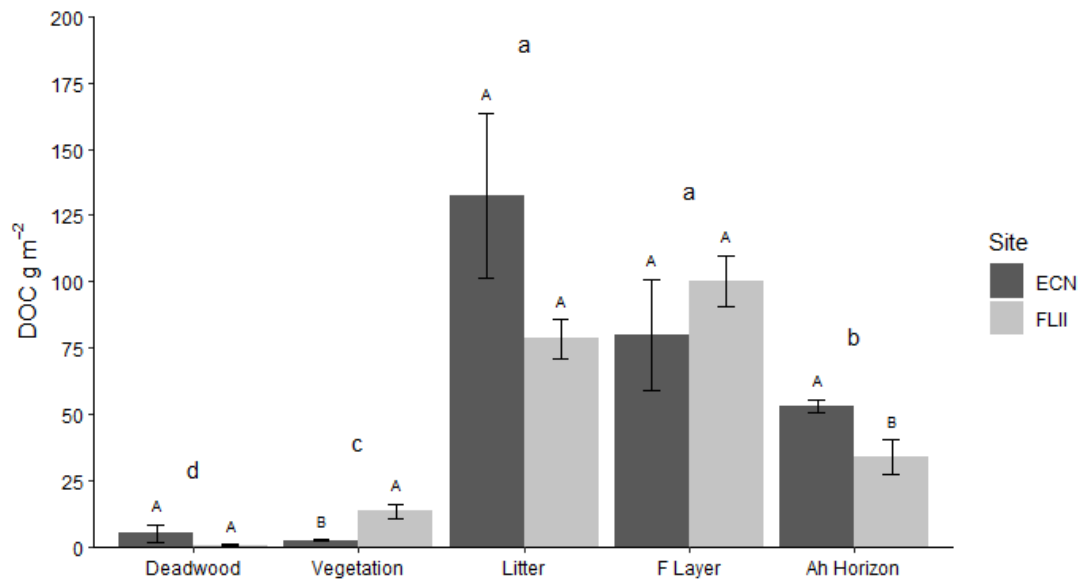
274 plots.

275

276   Figure 5 - The influence of site and material type on DOC fluxes (g m^{-2}). Data are mean ±1SE (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

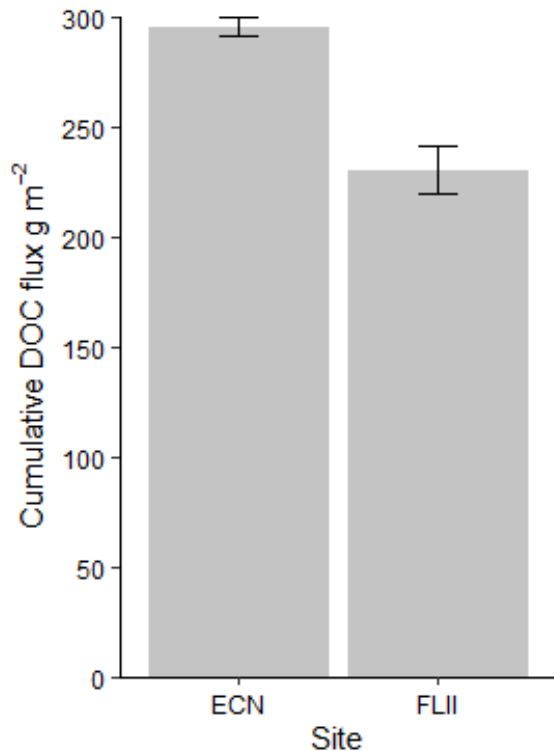282   the ECN was significantly larger than that of the FLII (p = 0.02).

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

16

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.

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 m^3 ha^{-1}

319   (Hodge & Peterken, 1998) to 165 m^3 ha^{-1} (Krueger et al., 2017). By contrast, managed woodlands can

320   exhibit deadwood volumes ranging from as low as 2 m^3 ha^{-1} (Tobin et al., 2007) to 30 m^3 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 m^3 ha^{-1}) but fell within the range cited by other literature.

323   However, in the unmanaged ECN site, deadwood volumes averaged 21.2 m^3 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 m^2. 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 m^2 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 m^2 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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