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Multi-scale relationship between peatland vegetation type and dissolved organic carbon concentration

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Abstract

Dissolved organic carbon (DOC) is a key component of the carbon cycle and has significant impacts on aquatic ecosystems and potable water treatment. Upward trends in river and lacaustrine DOC concentrations have been observed and a number of key drivers have been proposed. Here, we present DOC concentration data from plot scale pore waters at one site and surface water from artificial drains sampled within a national survey which demonstrate a significant correlation between peatland vegetation type and DOC concentration. *Calluna* dominance was associated with the highest DOC concentration, *Molinia* and *Sphagnum* dominance with lower concentrations, and sedge dominance with intermediate concentrations. Water sampled from drains dominated by *Calluna* had greater DOC concentrations than water sampled from pore waters in plots dominated by *Calluna*. In contrast DOC concentrations from plots dominated by sedges were greater than those sampled from drains dominated by sedges. We discuss these findings in relation to plant

functional traits and their influence on the physical and biotic conditions that regulate DOC concentrations. Given the known effects of management activities and climate change on peatland vegetation composition there is potential to manage plant community composition to ameliorate the observed rising DOC concentration.

Key words

Moorland; vegetation; plant functional type; dissolved organic carbon; peatland; water quality

1. Introduction

Peatlands are important terrestrial carbon stores, containing 20 to 30% of the global soil carbon stock (Gorham 1991). Aquatic carbon loss is an important component of the peatland carbon cycle, accounting for 30 to 50% of net ecosystem exchange fixed carbon (Dinsmore and others 2010; Nilsson and others 2008; Roulet and others 2007). Peatlands release carbon through sub-surface pathways as DOC and there is mounting evidence in the fluvial and lacustrine literature that DOC concentrations, [DOC], in waters flowing from peatland catchments are increasing in many parts of the northern hemisphere (Evans and others 2005; Skjelkvåle and others 2005; Stoddard and others 2003; Worrall and others 2004), prompting concern that these important terrestrial carbon stores are becoming carbon sources (Freeman and others 2001a; Freeman and others 2004). The increase in [DOC] is a major problem in water supply areas as DOC is strongly linked to water discolouration which has small legal limits and also disinfection of the water results in reactions with the DOC to produce harmful bi-products. Thus [DOC] is very important in water supply areas, and in the UK uplands many water companies receive a large proportion of their supply from peatlands. It is not possible to turn away these peat water supplies as they are critical to the volume of water needed to fulfil water demand requirements and so instead water companies have to deal with the increasing [DOC] and costly problem.

Several global change drivers have been suggested to explain the increases in [DOC], including increased temperatures (Clark and others 2009; Evans and others 2005; Freeman and others 2001a), changes in hydrology (Clark and others 2009; Mitchell and McDonald 1992; Tranvik and Jansson 2002), increased atmospheric carbon dioxide concentrations (Fenner and others 2007a; Freeman and others 2004), and changes in atmospheric deposition (Clark and others 2008a; Evans and others 2008; Evans and others 2006a; Hruska and others 2009; Monteith and others 2007; Stoddard and others 2003; Tipping and Hurley 1988; Vuorenmaa and others 2006). These drivers have the potential to act independently and interactively to influence processes responsible for DOC production and transport in peatlands.

The type of vegetation present within a peatland has been shown to influence peatland conditions and resources that could contribute to the production and release of DOC including effects on (1) the geochemistry of soil water (Clymo 1987; Kuhry and others 1993); (2) the physical properties of the peat (including temperature and water table) (McNamara and others 2008); (3) the biological agents which live within the peat (Artz and others 2007; Artz and others 2008); and (4) the quality and quantity of plant and litter inputs (Moore and Dalva 2001; Wickland and others 2007). Plant species can be characterised by functional traits, which are measureable physiological and morphological characteristics including plant structure, litter quantity and quality and root architecture. These functional traits dictate how they assimilate and process carbon and influence soil properties and processes and provide a useful mechanistic framework to understand the relationship between vegetation type and carbon cycling (De Deyn and others 2008; Dorrepaal 2007). In peatland ecosystems ericoid dwarf-shrubs, graminoids and bryophytes are the three dominant plant functional types and have been shown to correlate with carbon dioxide and methane fluxes from UK ombrotrophic peatlands (McNamara and others 2008; Ward and others 2009).

Both the historic vegetation type, which controls the physical and geochemical characteristics of the peat mass (Ringqvist and Öborn 2002), and the current vegetation type, which controls short-term carbon cycling, could exert control over pore water [DOC]. Evidence from a ^{14}C carbon dating study has shown that between 96% and 100% of DOC originated from surface peat in three different peatland catchments (Tipping 2010). It has also been proven that in blanket peatlands 80% of runoff originates from the top 5 cm of peat (Holden and Burt 2003), litter and roots from the most recent vegetation, and that stream [DOC] is more strongly correlated to soil water at 1 cm and 5 cm depth compared to 20 cm and 50 cm depth (Clark and others 2008b). Also, experiments examining the impact of elevated CO_2 found significant short-term increases in DOC and attributed this to increased root exudation and increased vascular plant cover (Fenner and others 2007b).

In this study we aim to examine the value and variation in [DOC] at the plot and artificial drain scale and the relationship with vegetation type. We hypothesised that vegetation type would correlate with peatland [DOC] at the plot and drain catchment scales. To do this we collected DOC samples (1) from soil water within plots of different vegetation types at a single site, Bingley Moor, and (2) from surface water drains from sites throughout England and Scotland.

2. Materials & methods

2.1 Field sites

a) Plot soil waters

The plot-scale analysis was undertaken at Bingley Moor, Yorkshire, northern England (53°52'N, 1°8'W). The site consists of blanket peat of approximately 1 m in depth and is at an altitude of 300 m. The site is used for sheep grazing and as a grouse moor, and therefore there is a mosaic of prescribed heather patch burning over some of the site. Five vegetation types - burnt *Calluna* (burnt <2 years ago), *Calluna,* sedges (predominantly *Eriophorum angustifolium*), *Sphagnum* and *Molinia* - were selected. Nine one-metre long 22 mm diameter dipwells with perforations along their entire length were installed in each vegetation type on comparable slopes in terms of their angle, aspect, drainage, and peat depth. The exact peat area the dipwells sampled from would vary depending on the peat hydraulic properties and antecedent conditions but we anticipate the sample would be dominanted by pore water from the surrounding 1 m of peat. Samples were taken once per week for three weeks in June and July 2008 (24/06/08, 29/06/08 and 06/07/08) using a piece of plastic tubing attached to a syringe, yielding 135 samples for [DOC] analysis.

b) National survey drain waters

A national survey was undertaken to examine [DOC] in peatland drains (Armstrong and others 2010). Thirty-two blanket bog sites were visited across England and Scotland (Figure 1) between 14/02/06 and 05/12/06 with 180 grab water samples taken from artificial drains and analysed for [DOC]. The drain catchment areas were generally <1 km^2. The drains had a maximum slope of 9°, ranged from 10 cm to 100 cm deep and from 20 to 280 cm wide. Peat depth was greater than 180 cm at 107 sites and at the remaining 73 the minimum depth was 30 cm, the maximum 179 cm with a mean depth of 95 cm. Out of the 180 drains 146 were blocked and 26 were unblocked, 44 had evidence of burning and 107 had evidence of grazing. The vegetation type of each drain catchment was described as either *Calluna*-dominated (n = 22), sedge-dominated (n = 92), or mixed (varying proportions and types of sedges, *Sphagnum,* and dwarf shrubs, n = 66).

2.2 Laboratory analysis

The water samples were filtered through 0.45 μm filters. [DOC] was measured using a Thermalox Total Carbon analyser, which has a precision of ±0.1 mg C l^{-1} and a minimum detection limit of 1 mg C l^{-1}. Prior to analysis, the DOC samples were acidified and sparged with oxygen in order to stabilise the sample and to remove any inorganic carbon and subsequently analysed in duplicate (or triplicate if CV > 1 %), with [DOC] determined from a seven-point calibration determined using potassium hydrogen phthalate (KHP). In addition, regular analysis of KHP standards and a certified reference material (VKI QC WW4a) ensured that the level of error was kept to a minimum. All samples were stored in the dark at 4°C, filtered and analysed within one week of collection.

2.3 Data analysis

The [DOC] data were logarithmically transformed and statistical significance of vegetation type was tested using a one way analysis of variance (ANOVA) followed by a Bonferroni multiple-comparison test for each of the data sets. The statistical differences between the plot and drain scale data were tested using a t-test with unequal variances and the equality of variances assessed using a F-test. All statistical analysis was undertaken using Stata10 (StataCorp 2007) and P values are reported as <0.01, <0.05, and < 0.10.

3. Results

3.1 Plot soil water

[DOC] ranged from 2.2 to 120.9 mg l^{-1} with a mean of 24.2 and a standard deviation of 18.6 mg l^{-1}. The highest mean and median [DOC] were associated with *Calluna*, then sedges > burnt > *Sphagnum* > *Molinia* (Table 1 & Figure 2). However the highest minimum [DOC] were associated with sedges > burnt > *Sphagnum* > *Molinia* > *Calluna* and the highest maximum [DOC] with *Calluna* > *Sphagnum* > sedges > burnt > *Molinia* (Table 1). The differences in the [DOC] between vegetation types were statistically significantly different ($p<0.05$) except between burnt *Calluna* and *Sphagnum,* and sedges and *Sphagnum*. Variability in [DOC] as determined by the CV was greatest for Sphagnum > Molinia > Calluna > burnt > sedges whereas the IQR indicates that the greatest range in [DOC] were associated with *Calluna* > sedges > *Sphagnum* > burnt > *Molinia* (Table 1 & Figure 2). There was a weak significant difference ($p <0.10$) in [DOC] between the first and second sampling days. There was an intense storm prior to the first sampling day: the weather preceding the second and third sample days was dry, although a rainfall event occurred during the third sampling day.

3.2 National survey drain waters

The [DOC] of water sampled from artificial drains within the national survey varied from 4.7 to 114.0 mg l^{-1} with a mean of 33.6 and a standard deviation of 19.7 mg l^{-1}. The highest mean, median, minimum [DOC] were sampled from *Calluna*-dominated catchments, then mixed > sedge-dominated catchments (Table 1 & Figure 3), with statistically significant differences between sedge and *Calluna* ($p < 0.01$) and *Calluna* and mixed ($p < 0.01$). The highest maximum [DOC] were sampled from sedge < *Calluna* < mixed dominated catchments (Table 1). The variability and range, as defined by the CV and IQR, in [DOC] were greatest for sedges>mixed>*Calluna* (Table 1 & Figure 3).

3.3 Comparison of the *Calluna* and sedge data from the two scales

Given that *Calluna* and sedges were common dominant vegetation types in both the plot and drain scale data it is possible to examine the impact of scale on [DOC] and variability. The pore water [DOC] in plots dominated by *Calluna* was less than that of water sampled from drains dominated by *Calluna*, as indicated by the mean, median, and minimum (Table 1), however, the differences were not statistically significant. In contrast the pore water [DOC] in plots dominated by sedges was weakly ($p < 0.10$) higher than that of water sampled from drains dominated by sedges, as indicated by the mean, medium and minimum (Table 1). The CV and IQR of [DOC] were greater in the plot data for *Calluna* and lower in the sedge data in comparison with the national survey data and the F-test indicated the variance was statistically significant greater for the plot data sedge data ($p < 0.01$) but the variances were similar for the *Calluna* data (Table 1).

4. Discussion

Our data, collected at two scales and from sites throughout England and Scotland, indicate that there were significant differences in DOC associated with different vegetation types (Table 1). *Calluna* was consistently associated with the highest [DOC], sedges yielded intermediate [DOC] and *Sphagnum* low [DOC]. To our knowledge only Vestgarden *et al.* (2010) have undertaken a field study directly examining the role of vegetation on [DOC], finding that the relative [DOC] of soil water under *Sphagnum*¸ *Molinia* and *Calluna* patches varied with depth and season. Given differences in methodologies these results cannot be directly compared to those of our study, although it is interesting to note that *Calluna* is associated with the higher [DOC] in both, except at depth. Although not examining the effect of vegetation type on [DOC] directly, Fenner and others (2007b) attributed an increase in [DOC] during an elevated carbon dioxide experiment to a change from predominantly

Sphagnum to *Juncus effusus* vegetation cover; this is in agreement with the findings of our study.

The differences in [DOC] of *Calluna* and sedges sampled at the two scales contrast: *Calluna* was associated with higher values at the drain scale and sedges with higher [DOC] at the plot scale. The variability in [DOC] was greatest for *Calluna* at the plot scale and for sedges at the drain scale. Explanations for these differences cannot be resolved in this study but may relate to the sampling windows (June to July 2008 for the plot data and February to December 2006 for the drain data), processing of the DOC between the pore water and drainage channels related to differences in the DOC character, the exact vegetation community in the plots and drain catchments, and the connectivity of the pore water to drainage channels.

Although to our knowledge only Vestgarden *et al.* (2010) have reported a relationship between [DOC] and vegetation type in the field the importance of vegetation type in controlling [DOC] has been shown in soil cores (Neff and Hooper 2002; Vestgarden and Austnes 2009) and indirectly through the use gradients, such as ground wetness (Wickland and others 2007), by changing the amount of litter (Lajtha and others 2005) or by considering different peatland types (Chanton and others 2008). Both Neff and Hooper (2002) and Vestgarden and Austnes (2009) concluded that vegetation cover and composition was at least as important as climatic conditions, which provides evidence that vegetation management may provide a means of ameliorating against the increasing trend in DOC, depending on the success of manipulation and sufficient response times. Furthermore, given that land management activities have a substantial impact on peatland vegetation coverage, both the extent and the species composition, the changes in [DOC] observed in association with land management (Armstrong and others 2010; Clay and others 2009; Evans and others 2006b;

Worrall and others 2007a; Worrall and others 2007b; Yallop and Clutterbuck 2009) may be attributable to the effect of vegetation.

Effect of vegetation type on physical environment conditions

Vegetation controls the physical environmental conditions by effecting the water table depth and temperature. Lower water tables are associated with higher DOC production given the increased aerobic zone (Clark and others 2009; Clymo 1987). It is commonly accepted that water table influences the vegetation type (Heathwaite and others 1993) and that blanket peatland topography may also impact the local water tables (Holden 2005a), but different physiological characteristics of different plant functional types can cause differences in water table depths in the same hydrological setting by effecting hydraulic conductivities (Holden 2005b; Holden 2009; Holden and others 2001) and evapotranspiration. Vegetation primarily impacts the water table depth by affecting the evapotranspiration rate as different plant functional types have different transpiration rates, intercept varying amounts of water which then evaporates, and afford different surface cover and therefore influence evaporation direct from the peatland surface (Gilman 1994; Lafleur and others 2005; Schouwenaars 1993). While difficult to isolate (Kim and Verma 1996; Schouwenaars 1993), the differences in interception losses between vegetation types are likely to dominate over differences in evaporation and transpiration given ground cover is often high and transpiration losses are limited over the short-growing season in upland areas (Wright and Harding 1993). This reasoning suggests that lower water table depths will be associated with shrubs and sedges (as found by McNamara (2008)), and therefore high [DOC] would be expected in soil water under shrubs and low [DOC] from soil water sampled from under *Sphagnum*, as was found in our data (Figure 2).

The other physical control of vegetation on DOC is soil temperature with significantly different temperatures measured under different vegetation types (McNamara and others 2008). Higher soil temperatures, up to a threshold, are associated with higher decomposition rates (Cole and others 2002; Davidsons and Janssens 2006; Dioumaeva and others 2003), increased exudation of DOC from roots (Uselman and others 2004), and evapotranspiration. However our data show the highest [DOC] were associated with *Calluna* (Figure 2), whereas McNamara (2008) recorded the lowest temperatures under Calluna, thus we hypothesise that temperature is not a causal mechanism of the association between vegetation and [DOC]. This is in agreement with larger scale studies examining the role of temperature on [DOC] (Freeman and others 2001a; Pastor and others 2003).

Effect of vegetation on biotic conditions

There are a range of mechanisms by which the biotic conditions influence [DOC]. Different rates and quality of root exudates (Yan and others 2008) contribute to [DOC] directly but also stimulate microbial activity (Freeman and others 2004), are a potential biological control on [DOC]. However, given the limited data on the amount and quality of root exudates and the consumption of DOC during microbial respiration it is not possible to assess the relationship between root exudation and pore water and channel [DOC].

Differences in [DOC] and composition between different litters have been determined in the laboratory (Cleveland and others 2004; Moore and Dalva 2001) and thus is an established mechanism by which vegetation type may influence [DOC]. The differences in [DOC] leached from different litters can be attributed to the chemical controls of vegetation over [DOC] due to litter and root exudation, including those associated with pH (Kuhry et al 1993;

Clymo, 1987), compounds which inhibit decomposition (Turetsky 2003; Freeman and others 2001b), and nutrient concentrations (Aerts and others 1999; Coulson and Butterfield 1978).

Finally, microbial assemblages and soil fauna populations have been found to vary with vegetation type (Artz and others 2007; Artz and others 2008; Coulson and Butterfield 1978; Standen and Latter 1977). As both microbe and soil fauna decompose organic matter their numbers and types will influence [DOC]. Quantification of DOC produced by organisms is difficult to obtain (Møller and others 1999) given the dependencies, however, higher numbers of soil fauna have been associated with *Calluna* (Coulson and Butterfield 1978; Standen and Latter 1977) which was characterised by high [DOC] in our study. Consequently, we suggest that the numbers and type of microbes and fauna are an important driver in the [DOC]-vegetation type relationship.

5. Conclusion

We conclude that there is a correlative relationship, which was apparent in soil water sampled from plots and in water sampled from drains within a national survey, between vegetation type and [DOC]. Higher [DOC] were associated with *Calluna* and lower concentrations with sedges and *Sphagnum*. Potential mechanisms of causality, based on the different physical and biotic conditions associated with different plant functional types, were identified in the literature, including water table depth, temperature, microbial assemblages, root exudates and litter quantity and quality. We recognise that there are topographic and hydrological controls that determine where different plant types grow within a peatland, but these plants in turn impact local water tables, peat growth and local topography. Further research effort is required to elucidate the dominant causal drivers between plant functional traits and DOC production and transport. Furthermore, these results from the two scales raise the possibility of managing vegetation to control [DOC] to reduce carbon losses from peatlands and to reduce water treatment costs for potable supplies. Such management might include actively spreading *Sphagnum* to encourage its propagation and raising water tables to encourage *Sphagnum* regeneration at the expense of more shrubby vegetation such as *Calluna.* Once *Sphagnum* establishes, species like *Calluna* may be reduced by overgrowth with *Sphagnum* and by the wetter surface conditions within the peatland. These management strategies would be in line with those undertaken in many peatland restoration projects and may be cost-effective in the long-term for organisations such as water companies to buy into as both capital and operational treatment costs for DOC and water discolouration at water treatment works are high. The data we present also has important implications for paired catchment studies which examine the impact of treatments, such as grazing, burning, or restoration activity, and highlights the necessity to assess vegetation cover in addition to the standard morphological and hydrological variables.

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Figure 1. Map of national survey sampling sites.

Figure 2. [DOC] of soil water samples taken from different vegetaton plots.

Figure 3. [DOC] of water sampled from surface drains dominated by *Calluna*, mixed vegetation and sedges within a national survey.

9. References

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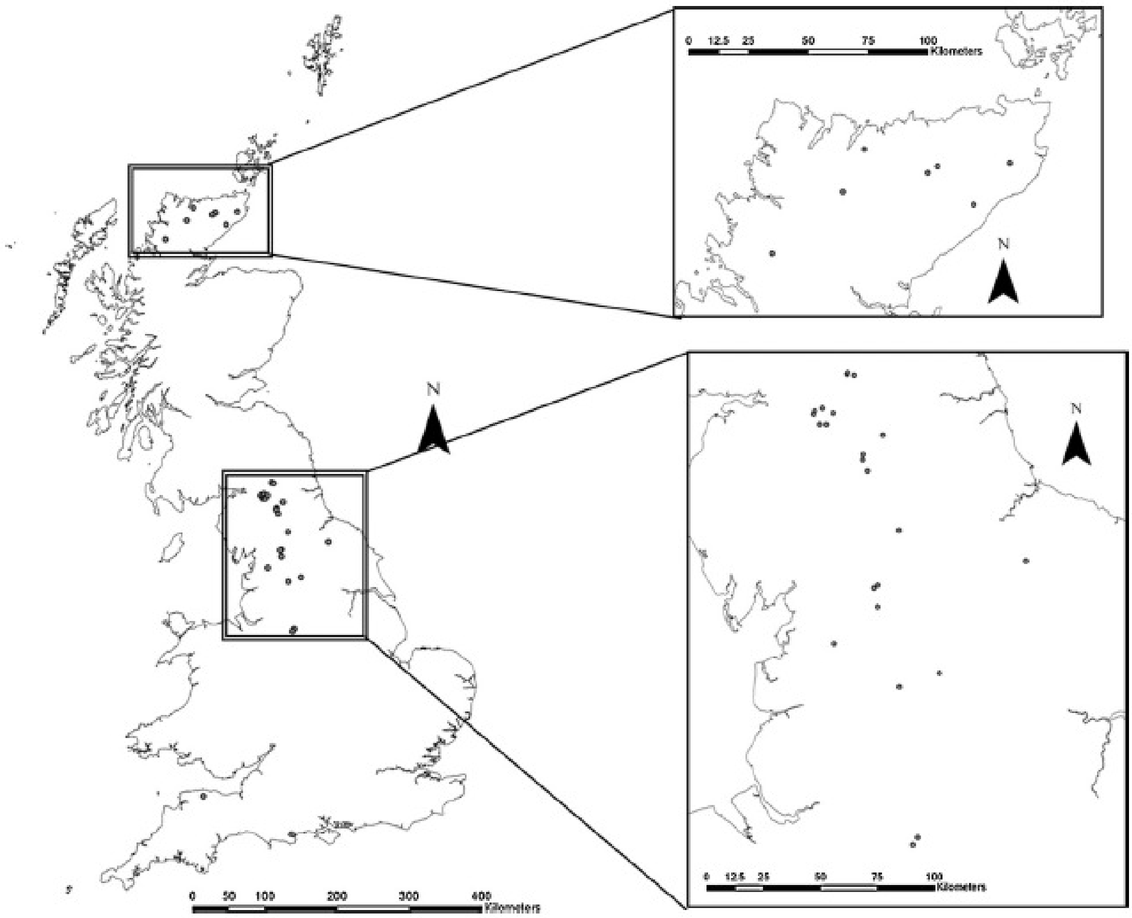
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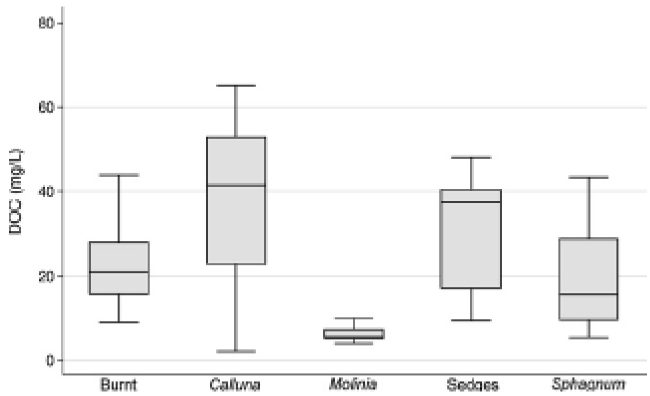
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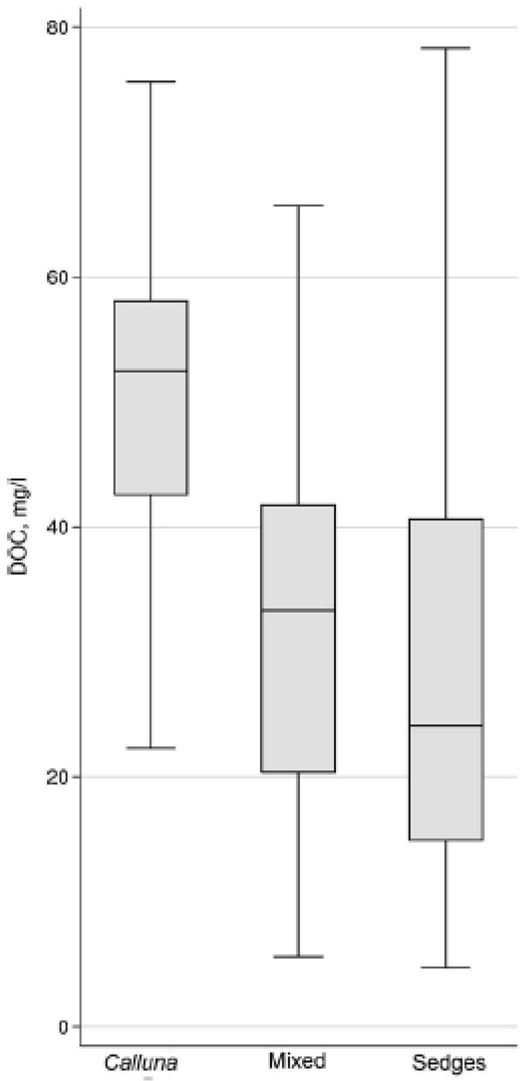
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