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Natural revegetation of bog pools after peatland restoration involving ditch blocking: the influence of pool depth and implications for carbon cycling.

Natural revegetation of bog pools after peatland restoration involving ditch blocking – the influence of pool depth and implications for carbon cycling

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Abstract

Throughout the last two centuries peatlands have been subject to extensive drainage, typically through the digging of ditches. Ecosystem restoration now focuses on damming or infilling these ditches to increase biodiversity and to provide a range of ecosystem services such as carbon sequestration and water provision. We surveyed 60 bog pools created following ditch blocking (alone) on a blanket bog in north Wales. Eighteen months after restoration the mean total pool vegetation cover was 76%. There was a strong negative relationship between pool depth and *Eriophorum* cover (r^2 = 0.74), and a weaker positive relationship between depth and *Sphagnum* cover (r^2 = 0.35). Observations showed that pools had been colonised by various invertebrate species. Pool dissolved organic carbon (DOC) concentrations were not connected to pool vegetation, suggesting that catchment-scale processes drive DOC. Other studies have shown that *Eriophorum* generates large methane fluxes, and that *Sphagnum* can act as a methane sink. Therefore we recommend that pools should be deeper than 0.5 m to give the greatest carbon benefit, whilst noting that this is unlikely to significantly affect DOC fluxes.

Keywords: ditch blocking, vegetation, DOC, bog pool, peatland restoration, greenhouse gas

1. Introduction

Northern peatlands are a vitally important component of the global carbon cycle, storing an estimated stock of 547 Pg of carbon (Yu *et al.*, 2010). Additionally, peatlands are important for biodiversity, as numerous species of invertebrates, birds and bryophytes are restricted to such habitats (Warner & Asada, 2006). On both local and global scales, peatlands have been damaged through drainage and peat extraction, but attempts are now being made to restore them through ecological engineering techniques. Restoration ecology, as a discipline, was outlined by Aber & Jordan (1985) as a tool that could “provide a framework for this systematic study and reconstruction of communities and ecosystems”, “broaden the scope of ecology”, and pave the way for the “generalization and simplification of ecological theory”.

In the United Kingdom (UK) peatland restoration is typically carried out through the blocking of drainage ditches (figure 1), with the aim of raising the water table and encouraging the establishment of peat-forming plant species such as *Sphagnum*. Blocking takes place using dams constructed from a variety of materials including peat, plywood, plastic and heather bales (Armstrong *et al.*, 2009). A more complex method is that of infilling, where dams are constructed and the base of the ditch is compressed by mechanical force to destroy any soil pipes that might flow beneath the ditch. Following restoration pools form behind dams, and in natural peatlands these pools are critical biodiversity hotspots (Mazerolle *et al.*, 2005).

There are few studies of pools and of the effect of ditch blocking on peatlands that have solely been drained, as most of the literature has focussed on cutaway peatlands where drainage and harvesting have both occurred. In an Irish study on an abandoned cutaway peatland, pools of standing water were colonised by *Juncus bulbosus* var. *Fluitans* which spread to provide a substrate for the growth of *Sphagnum cuspidatum* and *Sphagnum auriculatum*. The stabilisation of the water table using a peat bund increased the rate of this re-colonisation, resulting in the spread of these same pool species after two years (Farrell & Doyle, 2003). It has been noted elsewhere that *S. cuspidatum* can act as an aquatic pioneer species by forming a semi-floating raft suitable for further colonisation by other species (Money & Wheeler, 1999). For the restoration of pools in a Canadian cutaway peatland, *Sphagnum* species were taken from a natural site and transferred using the 'moss layer transfer technique'. After three growing seasons *Sphagnum* cover reached 50% along pool margins (Poulin *et al.*, 2011). Another Canadian study found that the stocking of pools with aquatic plants had no effect on vegetation colonisation, and that four years after restoration pH and dominant plant species differed from natural pools. The authors suggested that an increased stocking density might promote vegetation recolonisation (Mazerolle *et al.*, 2005).

Another pioneer plant of peatlands is *Eriophorum vaginatum*. Ditch blocking has been observed to promote the spread of *E. vaginatum* (Komulainen *et al.*, 1998, Lavoie *et al.*, 2005), and it can colonise pool margins (Poulin *et al.*, 2011). It typically colonises bare peat with a lower water table, but can tolerate higher water tables (Kivimäki *et al.*, 2008). The vegetation response to the creation of pools is important from the perspective of the carbon and greenhouse gas budget of a site. Vascular plants can act as 'chimneys' by transporting gas directly to the atmosphere via their aerenchymatous tissue, and they also provide substrates for methanogenesis via root exudation and litter production (Marinier *et al.*, 2004).

As vegetation communities change following peatland restoration, it is possible that an associated change occurs in the fluvial carbon balance. Dissolved organic carbon (DOC) is exported from peatland catchments in drainage waters, and its production is affected by numerous factors, including vegetation (Palmer *et al.*, 2001). For example, Armstrong *et al.* (2012) noted that *Calluna* was associated with high DOC concentrations in both a plot-scale (pore water) and a ditch-scale (surface water). DOC is of interest for various reasons: it is a component of the carbon cycle; it can affect the functioning of aquatic ecosystems (Karlsson *et al.,* 2009); it is expensive to treat in raw water supplies, and it can have negative effects on human health due to trihalomethane formation during water treatment (Chow *et al.*, 2003).

In this study, we investigated the recolonisation of bog pools that were formed through ditch blocking. We hypothesised that shallow pools would be dominated by *E. vaginatum* whilst *Sphagnum* species would form as floating rafts as pool depth increased. Additionally, a link between pool vegetation and characteristics, and DOC was investigated. Finally, the dams are specially designed to feature small overflow paths that channel water to either side of the dam. By measuring DOC concentrations in transects of successive downstream pools we also aimed to resolve whether DOC was produced or degraded between pools, leading to changes in concentrations down pool sequences.

2. Materials and Methods

The study was carried out at the head of the Afon Ddu catchment (latitude 52.97°N, longitude 3.84°W) on the Migneint, an Atlantic blanket bog, in Snowdonia National Park, north Wales (UK). The bog has been extensively drained, with ditches spaced 10-20 m apart, but no peat harvesting has occurred. Ditches were blocked in February 2011 using the infilling method and peat dams, and pools of various sizes formed behind. Pools are typically 2 m wide and 2-3 m long, but much larger ones have formed. Approximately 1600 pools have been created. Sampling took place in August 2012. A random selection of 60 pools was made. This included three transects where either five or seven successive pools in the same ditch were surveyed down-slope. The dimensions of each pool were measured, and a depth measurement taken from the centre of the pool. Vegetation cover at the surface of the pool was estimated by sight to the nearest 5% (except for very low incidences of cover that were estimated at 2.5%), for each species, and the plant species recorded. A water sample was taken from the middle of each pool for lab analysis and stored in the dark at 4^{o}C. All pools were surveyed on the same day to allow a robust comparison, as DOC concentrations can fluctuate seasonally, and according to the prevailing meteorological and hydrological conditions. Additionally, pool size may change following drought or precipitation. Seven control water samples were taken from an unblocked ditch to compare against pool samples.

Water samples were analysed the day after collection. Absorbance was measured at a wavelength of 263 nm using a Molecular Devices M2e Spectramax plate-reader. DOC concentrations were then calculated from this absorbance using a previously established calibration curve for the site. This wavelength was chosen as it gave the highest r^2 (0.91) value and lowest residual variance (RMS = 16.9).

A linear regression model was used to investigate the relationship between pool characteristics and vegetation cover. A multiple regression model using pool depth, area, and species vegetation cover as predictors of DOC was not significant, so a simpler method was used. Mean values were calculated for pools with ≥ 50% cover of *Sphagnum* or *Eriophorum* (one pool where both vegetation types were present at 50% cover was not included). The area from each pool to the top of the slope was measured and used as an estimate of upstream contributing area, and therefore flow rate, although the contributing area was somewhat uncertain due to changes to drainage patterns induced by the restoration work. Statistical analysis was performed using SPSS v16.0.1

(IBM Corporation, http://www-01.ibm.com/software/analytics/spss/products/statistics/).

3. Results

3.1. Physical pool characteristics and vegetation colonisation

There was considerable variation in the physical characteristics of the pools and the proportion of vegetation colonisation (table 1). Pools were mainly colonised by *E. vaginatum* (with some *Eriophorum angustifolium*) and *Sphagnum* species (predominantly *S. cuspidatum*); respective means were 37% (standard error = 3.2%) for *Sphagnum* and 38% (SE = 3.6%) for *Eriophorum*. Two pools showed significant amounts of algal growth, and a small area of one pool had been colonised by *Juncus effusus*. Both mean and median total vegetation cover values were above 75%, and only seven pools had less than 50% vegetation cover, indicating a high level of recolonisation with only small areas of open water.

Table 1. Summary statistics for data from 60 pools. SE is the standard error of the mean.

	Mean	SE	Median	Minimum	Maximum
Depth (m)	0.41	0.04	0.33	0.03	1.15
Width (m)	1.96	0.09	1.9	0.7	4.2
Length (m)	2.78	0.36	1.8	0.7	17.9
Area (m^2)	6.37	1.04	3.48	0.63	46.54
Total vegetation cover (%)	76	3.03	81	10	100
DOC (mg L^{-1})	22.09	0.42	21.6	16.75	30.29

There was a strong negative relationship between pool depth and *Eriophorum* colonisation (figure 2), and at depths greater than 0.5 m *Eriophorum* only grew on the shallow pool margins. The relationship between pool depth and *Sphagnum* cover was positive but weak (figure 3), with large variations in cover at deeper depths; for example, at approximately 0.8 m depth different pools displayed *Sphagnum* cover from 0% to 90%. There was no evidence that upstream contributing area (and therefore flow rate) influenced species cover.

Figure 2. Percentage cover of *Eriophorum* versus pool depth for 60 pools. Linear regression $r^2 = 0.74$, $p < 0.001$. Filled circles indicate pools where *Eriophorum* was only present in the shallow pool margins.

Figure 3. Percentage cover of *Sphagnum* versus pool depth for 60 pools. Linear regression $r^2 = 0.35$, $p < 0.001$.

3.2. DOC concentrations

Mean pool DOC concentration was 22.09 mg L^{-1} (SE = 0.42 mg L^{-1})(table 1). DOC concentration was 22.8 mg L^{-1} (n = 18, SE = 0.8 mg L^{-1}) for *Sphagnum* pools, and 21.6 mg L^{-1} (n = 21, SE = 0.6 mg L^{-1}) for *Eriophorum* pools. This difference was not significant at $p = 0.05$ (two-sample t-test). Further analysis revealed no significant relationships between DOC concentrations and pool area or depth. The results from the three ditch transects measuring DOC concentrations in each successive down-slope pool showed that there was no consistent cumulative production or degradation of DOC down the transects (figure 4). The mean DOC concentration for samples from the unblocked ditch was 20.5 mg L^{-1} (n = 6, SE = 0.4 mg L^{-1}); one sample was removed as its concentration was very low (9.76 mg L^{-1}), possibly due to the ditch intersecting with a groundwater emergence point.

Figure 4. DOC concentrations for three ditch transects (indicated by different lines), where successive down-slope pools were surveyed. Pool number 1 is at the

top of the transect, and each subsequent pool is the next one down-slope along the ditch.

4. Discussion

4.1. Vegetation colonisation

Our results show that ditch blocking has been successful in creating bog pools with consistently high rates of vegetation colonisation after eighteen months. *E. vaginatum* and *S. cuspidatum* were the primary colonising species, with additional colonisation by *E. angustifolium*, *Juncus effusus*, algae, and other *Sphagnum* species. Our hypothesis that shallower pools would favour *Eriophorum* growth was supported, with *Eriophorum* cover decreasing linearly with pool depth. At depths greater than 0.5 m *Eriophorum* was restricted to shallow pool margins, and cover was reduced to ≤5% at depths greater than 0.8 m. Poulin *et al.* (2011) noted a similar response, with pool margins being colonised by *Eriophorum*, and suggested that this invasion might be a transient phase in the early stages of restoration. *Sphagnum* cover increased with pool depth, although this relationship was weaker than that between *Eriophorum* and depth, with large variation in cover at greater depths. There are several possible reasons for this. It has been suggested that deep pools that form behind dams can make vegetation establishment difficult, as the low level of light penetration reduces the rate of vegetation colonisation (Ramchunder *et al*, 2009). DOC can affect photic depth (Monteith *et al.*, 2007) but this seems an unlikely control on vegetation colonisation as *Sphagnum* cover and DOC concentration were unrelated. Additionally, DOC effects on photic depth would only impede vegetation growth if *Sphagnum* was establishing from the base of the pool, not as floating mats. Boatman (1977) established that differences in nutrient supply could explain *S. cuspidatum* growth in bog pools, and there is some spatial variation in ditch nitrate concentrations at the experimental site (M. Peacock, unpublished data). Another possible explanatory factor could be the profile of the ditch sides, as steep sides could impede the establishment of *Sphagnum*.

Numerous restoration studies have reported high methane fluxes from areas of *Eriophorum* (Mahmood & Strack, 2011, Tuittila *et al.*, 2008, Marinier *et al.*, 2004, Komulainen *et al.*, 1998), although *Eriophorum* colonisation on bare peat does lead to the creation of a carbon dioxide sink (Tuittila *et al.*, 1999). Balanced against this, *S. cuspidatum* has been shown to consume methane through symbiosis with methanotrophs (Raghoebarsing *et al.*, 2005) and this mechanism is found in *S. cuspidatum* globally (Kip *et al.*, 2010). *Sphagnum* is also desirable as it enhances the carbon sink of the ecosystem and, for Boreal peatlands, increases the strength of this sink in spring and autumn, relative to vascular plants (Kivimäki *et al.*, 2008). Finally, Pelletier *et al.* (2007) found that methane flux decreased with increasing pool depth at two sites, possibly because lower sediment temperatures reduced methanogenesis (although a third site showed the opposite relationship; this was attributed to greater ebullition). A later study confirmed this result, with larger fluxes of both methane and carbon dioxide being recorded in smaller, shallower pools. Methane fluxes from pools of 0.7 m depth were up to five times smaller than fluxes from pools of 0.3m depth (McEnroe *et al.*, 2009). There is also the opportunity for methane oxidation within the water column itself (Bastviken *et al.*, 2008). Considering this, methane fluxes should be lower in deeper pools.

4.2. Controls on DOC

DOC concentrations were not affected by the dominant type of vegetation colonising the pools. This was somewhat expected; the upstream 'catchment' draining into each pool is typically large, flow rates are moderately high, and water residence times within individual pools are therefore short. A direct influence of pool vegetation on DOC would thus require either rapid consumption or production of DOC within the pools, which is unlikely given the largely terrestrial source of DOC in peat drainage waters (Evans *et al.*, 2007) and the relatively recalcitrant nature of this DOC over short time periods (e.g. Wickland *et al.*, 2007; del Giorgio and Pace, 2008). Instead, it is likely that DOC will be driven by large-scale hillslope characteristics such as terrestrial vegetation cover, soil carbon pool, peat cover and hydrology (Aitkenhead *et al.*, 1999, Palmer *et al.*, 2001, Dawson *et al.*, 2004). The similarity of mean DOC concentrations among pools, down transects and in comparison to an unblocked control ditch also suggests that pools do not exert a strong influence on the processing of DOC. As a final caveat, we acknowledge that a simplified model is presented here; in reality each pool may receive water (and therefore DOC) from the peat upslope and either side of the blocked ditch, as well as from the upslope pools.

4.3. Zoological changes

Ditch blocking on this site created 1600 new bog pools. This large amount of standing water is likely to benefit Tipulidae species and any bird species that predate Tipulidae (Carroll *et al.*, 2011). On the spot observations supported zoological changes, with the pools being used by invertebrates such as diving beetles (genus: *Dytiscus*), whirligig beetles (family: Gyrinidae), and pond skaters (family: Gerridae). The frog species *Rana temporaria* was regularly sighted in pools, and there was evidence that *Lagopus lagopus scotica* (red grouse) used the pools for drinking/feeding.

4.4. Implications for restoration

Taken as a whole these findings suggest that ditch blocking can be used as a suitable restoration technique to create vegetated bog pools. After eighteen months the mean total vegetation cover was 76%. However, there is potential for the pools to gradually paludify in the long term (Lindsay, 2010) and for succession to lead to the growth of species such as *Calluna vulgaris*, *Vaccinium myrtillus*, *Erica tetralix*, and *Empetrum nigrum*. On the other hand, further *Sphagnum* growth may occur, and long-term monitoring is essential to determine if this is the case. At another nearby (1.5 km away) site on the Migneint blanket bog, ditch blocking was observed to lead to extensive *Eriophorum* colonisation on bare peat within ditches, resulting in large methane fluxes to the atmosphere (Cooper *et al.*, 2013). Considering this, restoration techniques should aim to minimise the extent of areas of bare peat between pools. At the site studied here, the creation of bog pools was not a specific restoration objective, but has emerged as a positive side-effect that has increased the biodiversity of the ecosystem. As well as biodiversity, restoration also has the potential to enhance the provision of other ecosystem services, such as landscape aesthetics (Kimmel & Mander, 2010).

To ensure that the restoration achieves the best result in terms of the peatland greenhouse gas balance, our results suggest that pools should be deeper than 0.5 m. This will limit the invasion of *Eriophorum* which would otherwise result in large methane fluxes, and also promote *Sphagnum* growth which can act as a carbon dioxide and methane sink. Lavoie *et al.* (2003) however, point out that restoration activities that result in large areas of *Eriophorum* are not necessarily failures, as a process of vegetation succession has been initiated; this may lead to *Sphagnum* colonisation within 5-10 years (Lindsay, 2010). Deeper pools should also provide a less favourable environment for methanogenesis, and will lead to a longer upward travel time for methane, and hence greater opportunity for methane oxidation, dependent on the oxygen concentration profile of the pool. Neither biotic nor abiotic pool characteristics were associated with DOC concentrations and thus pool creation can be focussed on the balance between carbon cycling, vegetation colonisation, and zoological diversity.

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Figure 1. Ditch blocking at the study site in the Afon Ddu catchment.

Figure(s)

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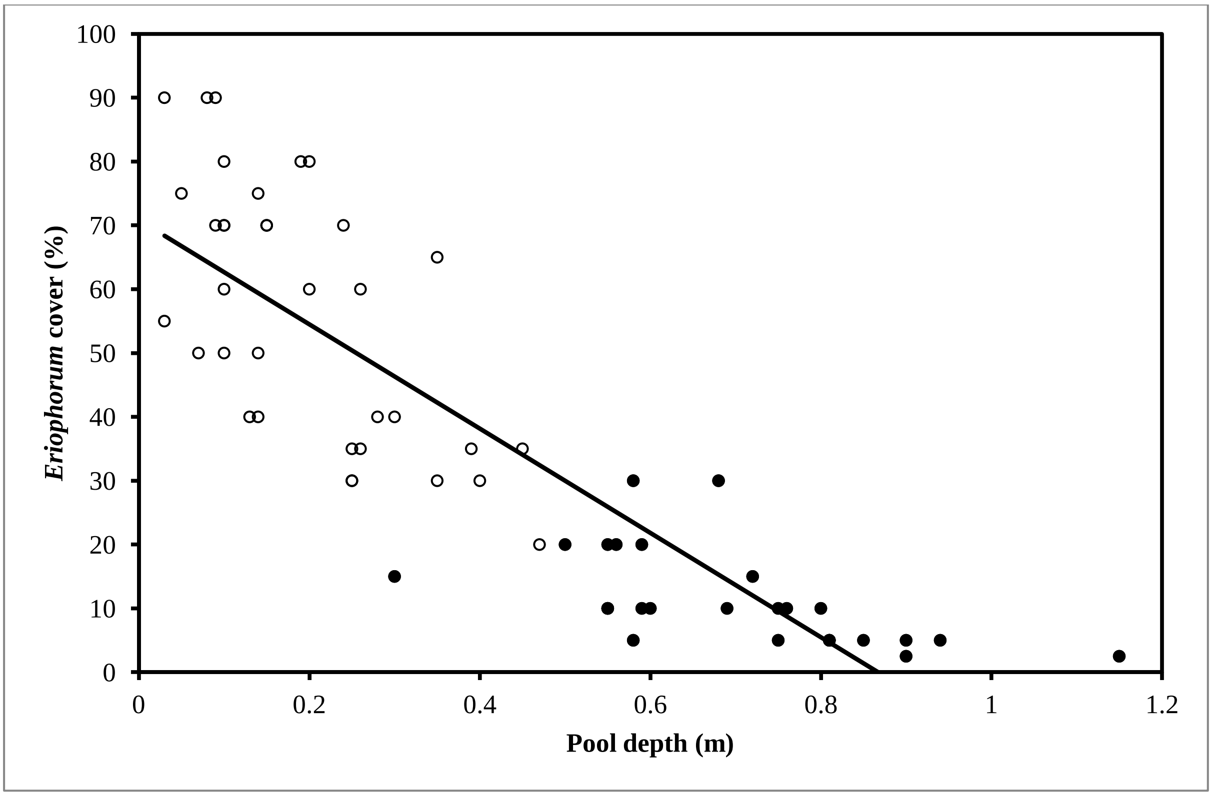

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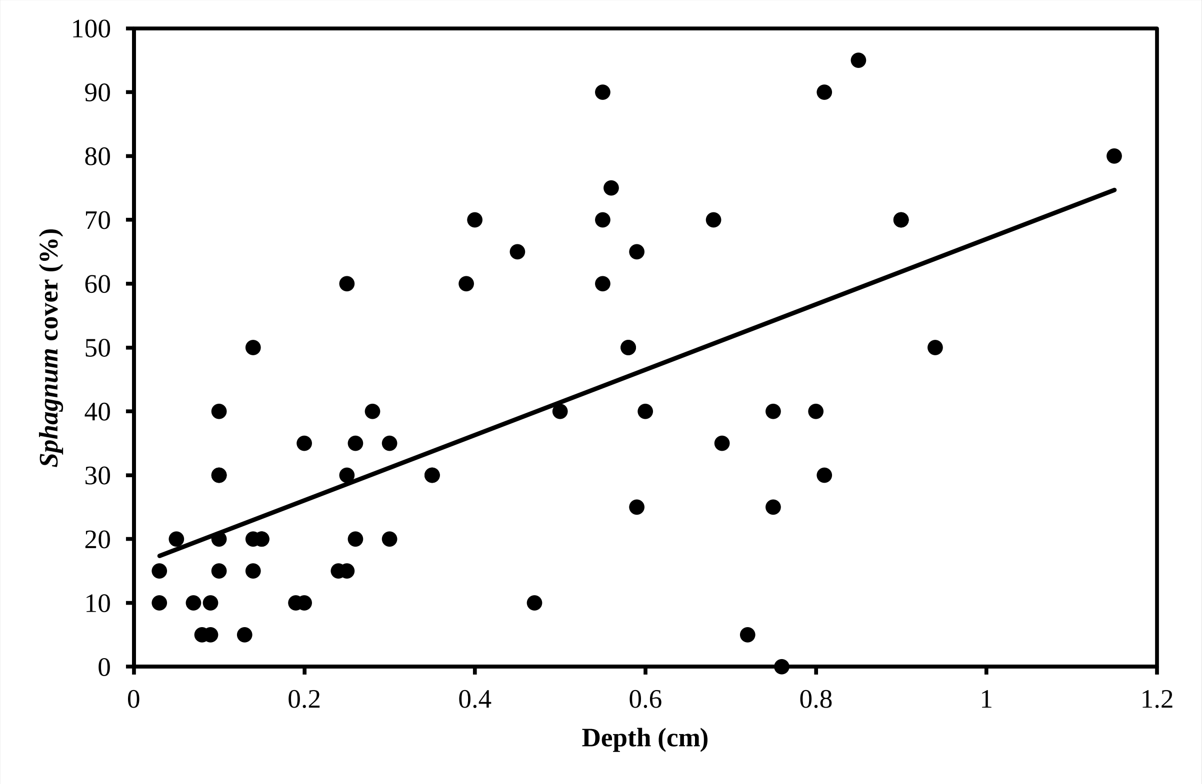

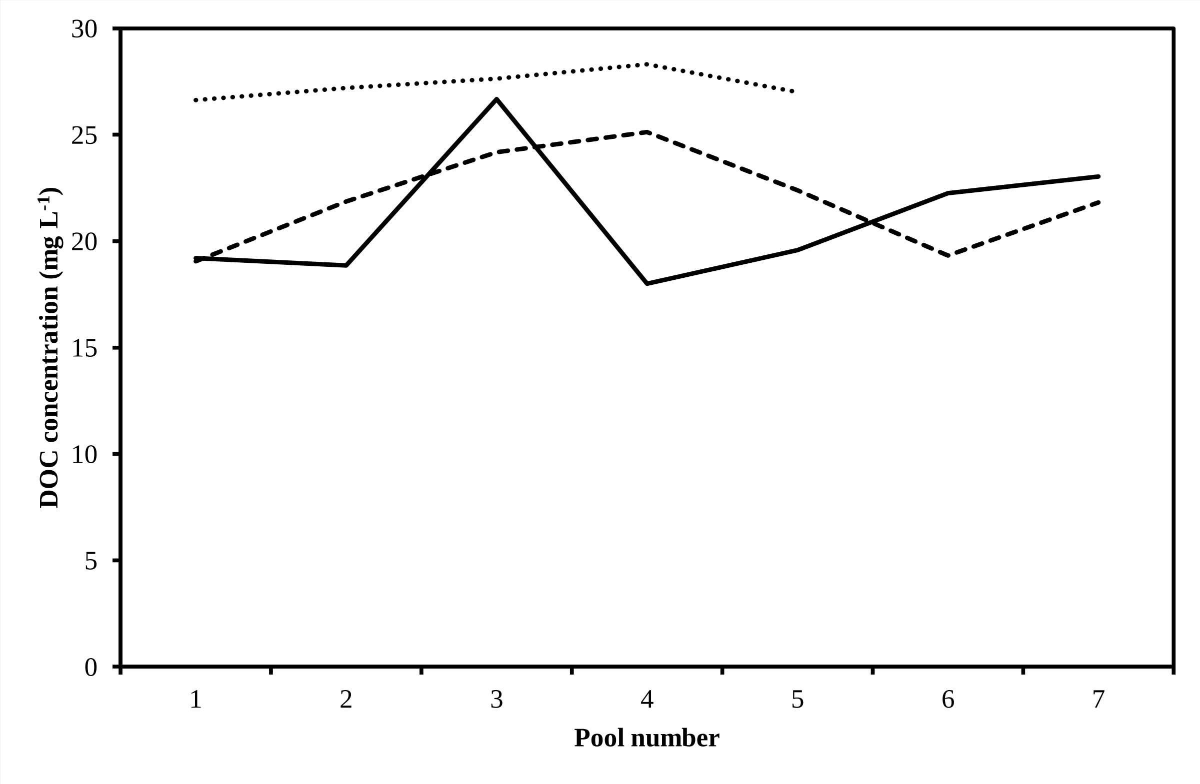
30
25
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DOC concentration (mg L^{-1})
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Pool number