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Identifying the role of environmental drivers in organic carbon export from a forested peat catchment

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HIGHLIGHTS

- Loads of 9.5 t DOC km^2 year^{-1} and 6.2 t POC km^2 year^{-1} were exported from peatland.
- Climatic factors explained 59.7% and 58.3% of deviance in stream DOC and POC.
- Soil temperature, discharge and drought were significant drivers of DOC concentration.
- Soil temperature, discharge and rainfall were significant drivers of POC concentration

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ABSTRACT

Carbon export in streams draining peat catchments represents a potential loss of carbon from long-term stores to downstream aquatic systems and ultimately, through mineralisation, to the atmosphere. There is now a large body of evidence that dissolved organic carbon (DOC) export has increased significantly in recent decades at many sites, although there is still debate about the drivers of this increase. In this study, DOC export and particulate organic carbon (POC) export were quantified from a forested peatland catchment in the west of Ireland over two years at a fine temporal resolution. The principle drivers of change in stream DOC and POC concentrations were investigated using a general additive modelling (GAM) approach. The study period included drought conditions in the early summer of 2010 and clearfelling of some commercial forestry in early 2011. The results indicated that annual loads of 9.5 t DOC km^2 year^{-1} and 6.2 t POC km^2 year^{-1} were exported from the catchment in 2010. This combined annual load of 15.7 t C km^2 year^{-1} would represent between 0.01% and 0.02% of typical estimates for peat soil carbon storage in the region. Soil temperature, river discharge and drought explained 59.7% the deviance in DOC concentrations, while soil temperature, river discharge, and rainfall were the significant drivers of variation in POC concentrations, explaining 58.3% of deviance. Although clearfelling was not a significant factor in either model, large spikes in POC export occurred in 2011 after the first forestry clearance. The results illustrate the complexity of the interactions between climate and land management in driving stream water carbon export. They also highlight the sensitivity of peatland carbon stores to changes in temperature and precipitation, which are projected to be more extreme and variable under future climate scenarios.

1. Introduction

Peatlands are one of the largest global reservoirs of carbon, storing approximately 20–25% of the Earth's soil organic carbon (Billett et al., 2010; Montanarella et al., 2006). Carbon is exported in a number of different forms from these systems, including as dissolved inorganic carbon (DIC), dissolved organic carbon (DOC) and particulate organic carbon (POC) in catchment streams, and as gaseous emissions of carbon dioxide (CO_2) and methane (CH_4) from soil carbon stores (Dinsmore et al., 2011). Published estimates of DOC export range from 1.5 t C km^2 year^{-1} to 14.2 t C km^2 year^{-1} (Koehler et al., 2009; Clark et al., 2007; Worrall et al., 2003; Hope et al., 1997) while estimates of POC export range from 0.1 t C km^2 year^{-1} to 31.7 t C km^2 year^{-1} (May et al., 2005; Worrall et al., 2003; Hope et al., 1997). Despite the potential for these two carbon sources to contribute to greenhouse gas emissions when mineralised (Davidson and Janssens, 2006), DOC and POC export from peat stores are often ignored in catchment studies, and are generally not included in national greenhouse gas emissions budgets (e.g. EPA, 2012).

An upward trend in DOC concentrations has been observed in many peat catchments over recent decades (Jennings et al., 2010; Miller and

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McKnight, 2010; Erlandsson et al., 2008; Monteith et al., 2007; Worrall and Burt, 2007; Evans et al., 2005; Hongve et al., 2004). These increases indicate a potential decrease in the stability of peatland stores (Clark et al., 2007) and have implications for the ecology of downstream rivers and lakes (Bade et al., 2007; Jansson et al., 2007) affecting lake transparency and thermal structure (Keller et al., 2008), drinking water quality (Hongve et al., 2004) and contributing to atmospheric CO_2 (Clark et al., 2007; Freeman et al., 2004; Cole et al., 1994). DOC production and transport are highly sensitive to climatic drivers and the proposed explanations for this long-term increase include changes in the intensity, frequency and seasonal patterns of precipitation and snowmelt (Erlandsson et al., 2008; Hongve et al., 2004), higher temperatures (Preston et al., 2011; Freeman et al., 2001a), higher frequency of drought events (Clark et al., 2010; Jennings et al., 2010), as well as changes related to the reversal of anthropogenic acidification (Erlandsson et al., 2008; Monteith et al., 2007). There are, however, also catchment studies where no increase has been found, for example, in the study of Worrall and Burt (2007).

Step change increases in DOC concentrations following drought conditions have been noted for several catchments (Jennings et al., 2010; Worrall et al., 2003; Watts et al., 2001). Drought can cause a change in both the solubility and export of DOC for several reasons. Lower soil moisture levels can result in decreased soil acidity and an increased dissociation of acid functional groups (Clark et al., 2010). Such decreases in acidity may result in an increase in microbial activity in soils (Andersson et al., 2000). However, an increase in oxygen availability within soil during droughts can also lead to higher rates of aerobic decomposition (Fenner and Freeman, 2011; Yallop and Clutterbuck, 2009; Mitchell and McDonald, 1992), and may also trigger an enzymic latch mechanism as described by Freeman et al. (2001b), where phenolic oxidase activity is switched on in the soil pore waters, reducing the concentration of inhibitory phenolic compounds.

The particulate load in a river is influenced by soil type and catchment characteristics. Peat soils are sensitive to erosion owing to their low density (McHugh, 2007). Other factors affecting erosion include steep topography, thin soils, sparse vegetation cover and the presence of bare peat (Grayson et al., 2012; Marttila and Klove, 2010). Wetter winters and warmer summers also have an erosive effect on the peat surface, with droughts leading to cracking and disintegration of surface and lower peat layers (Evans et al., 2005). POC is principally transported during periods of high precipitation, which open up flow pathways and increase the washout to surface waters.

Land use changes, such as the intensification of farming and afforestation, have also been linked to increases in both DOC and POC concentrations (Rodgers et al., 2011; Worrall and Burt, 2007; Cummins and Farrell, 2003). In Ireland, the main land use change in peatland catchments has been the establishment of commercial forestry and subsequent clearfelling. Currently 10.15% or 7000 km^2 of land area in Ireland is under commercial plantation forestry (National Forest Inventory, 2007). It is estimated that 3000 km^2 of this is located on peatland in the west of the country (Rodgers et al., 2011; European Environment Agency's, 2004). Forestry clearfelling and extraction of timber can result in an increase in particulate matter in streams (Rodgers et al., 2011). Other causes of accelerated peat erosion include overgrazing by sheep and other livestock (Grayson et al., 2012; Marttila and Klove, 2010; Stott and Mount, 2004).

Climate projections for catchments in Western Europe point to drier summers, more episodic precipitation and wetter winters (Fealy et al., 2010; Samuelsson, 2010). Given the sensitivity of carbon export to climatic factors, these changes may affect the export of DOC and POC through washout, changes in flow rates and pathways, and changes in rates of decomposition (Clark et al., 2010; Jennings et al., 2010; Clark et al., 2007; Evans et al., 2006). Naden et al. (2010) modelled changes in DOC concentrations under future climate scenarios and projected a 20% increase in DOC export from the Glenamong sub-catchment, the focus of the current study, with the annual median DOC concentration projected to increase from 8.7 mg C L^{-1} to 10.5 mg C L^{-1}.

The aim of this current study was to quantify carbon export from a peatland catchment in the west of Ireland and identify the principle drivers of variability in stream DOC and POC concentrations. The study used high resolution monitoring data to estimate DOC and POC export over a two year period which included a period of summer drought, and forestry clearfelling. The study assessed the importance of a range of drivers using a general additive modelling (GAM) approach. The results give an insight into the effect of climate on carbon dynamics in such systems and have relevance for our understanding of the global carbon cycle. Accurate estimates of carbon exports can also help inform catchment management and national carbon budgets.

2. Material and method

2.1. Site description

The Glenamong sub-catchment (18.21 km^2) is located in the Burrishoole catchment in the west of Ireland (53° 56′50″ N, 9° 34′30″ W) (Fig. 1). The sub-catchment is comprised of 77% upland peat, 23% forestry (dominant species include Sitka spruce (*Pinus sitchensis*) and lodgepole pine (*Pinus contorta*)) and small pockets of transitional woodlands and scrub. The main land use in the sub-catchment is extensive sheep grazing on commonage. The steep slopes result in a hydrological system with a quick reaction time to precipitation events (Müller, 2000). The sub-catchment experiences a moderate climate due to its close proximity to the Atlantic Ocean. The air temperature rarely goes above 25 °C in the summer or below −5 °C in the winter (Fealy et al., 2010) and snowfall is occasional. The ten year average precipitation measured at the Glenamong rain-gauge situated within the sub-catchment was 2022 mm $year^{-1}$ (Fig. 1, Table 1). Forestry clearfelling took place in the Glenamong sub-catchment during two short periods commencing on the 8th of February 2011 (0.15 km^2) and the 1st of July 2011 (0.09 km^2).

2.2. In-situ monitoring of stream parameters

Estimates of DOC and POC export were made using data from in-situ high frequency sensors as proxies for concentration, together with flow data for the site. Chromophoric dissolved organic carbon (CDOM) fluorescence was used as a proxy measurement for DOC concentration, while nephelometric turbidity units were used as a proxy for POC. Data were collated from an automatic river monitoring station (ARMS) located in the Glenamong (Rouen et al., 2005) (Fig. 1). The ARMS was instrumented with a SeaPoint CDOM UV fluorometer (SeaPoint Sensors, Inc., Exeter, NH, USA), a Hydrolab Quanta measuring pH, conductivity, dissolved oxygen and temperature (Hydrolab Corporation 8700 Cameron Road, Suite 100 Austin, TX 78754, USA), and a Chelsea minitracka II nephelometer (Chelsea Technology Group (CTG) sensor Technology, UK). All sensors were continuously submerged and water parameters were measured every two minutes throughout the year. Data were logged and stored by a Campbell Scientific CR1000 data logger (www.campbellsci.com).

The CDOM fluorometer uses UV light emitting diodes (LEDs) as the CDOM excitation source (Ex 370 nm CWL, 12 nm FWHM; Em 440 nm CWL, 40 nm FWHM, where CWL is the centre wavelength and FWHM is the full width at half maximum wave height). The gain was set to 1 for all measurements. The instrument output was in mV and is referred to as relative fluorescence units (RFUs). Assessment of instrument performance was carried out using a quinine sulphate standard as recommended by the manufacturers (1 QSU = 1 μg quinine sulphate L^{-1}). An instrument specific temperature correction coefficient was applied to the raw CDOM fluorescence data (Ryder et al., 2012), providing temperature corrected CDOM fluorescence data