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Accelerated export of sediment and carbon from a landscape under intensive agriculture

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HIGHLIGHTS

- Two adjacent study catchments with contrasting agricultural and semi-natural land use
- Compared total suspended sediment and fluvial carbon concentrations and fluxes
- Sediment and particulate carbon export higher from intensive agricultural catchment
- Agricultural land use affected both the quantity and quality of exported DOC
- Semi-natural catchment more resilient to enhanced sediment and carbon exports

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ABSTRACT

The export of total organic carbon (particulate and dissolved) from terrestrial to aquatic ecosystems has important implications for water quality and the global carbon cycle. However, most research to date has focused on DOC losses from either forested or peaty catchments, with only limited studies examining the controls and rates of total fluvial carbon losses from agricultural catchments, particularly during storm events. This study examined the controls and fluxes of total suspended sediment (SS), total particulate (TPC) and dissolved organic carbon (DOC) from two adjacent catchments with contrasting intensive agricultural and semi-natural land-use. Data from 35 individual storm events showed that the agricultural catchment exported significantly higher SS concentrations on a storm-by-storm basis than the semi-natural catchment, with peak discharge exerting a greater control over SS, TPC and DOC concentrations. Baseflow DOC concentrations in the agricultural catchment were significantly higher. DOC quality monitored during one simultaneous rainfall event differed between the two study catchments, with more humic, higher molecular weight compounds prevailing in the agricultural catchment and lower molecular weight compounds prevailing in the semi-natural catchment. During an eight month period for which a comparable continuous turbidity record was available, the estimated SS yields from the agricultural catchment were higher than from the semi-natural catchment. Further, the agricultural catchment exported proportionally more TPC and a comparable amount of DOC, despite a lower total soil carbon pool. These results suggest that altered hydrological and biogeochemical processes within the agricultural catchment, including accelerated soil erosion and soil organic matter turnover, contributed to an enhanced fluvial SS and carbon export. Thus, we argue that enhancing semi-natural vegetation within intensively farmed catchments could reduce sediment and carbon losses from these areas and increase their resilience to more extreme hydrological events, anticipated as a result of climate change.

1. Introduction

The stability of natural carbon pools under changing climates is of major concern (Whitehead et al., 2006) and ecosystem carbon management must play a critical part in the global effort to mitigate climate change. The terrestrial biosphere contains approximately three-times as much carbon in the soil and vegetation as the atmospheric carbon pool, thus a small change in the terrestrial carbon pool may have significant implications for atmospheric CO_2 concentrations (Schuman et al., 2001). The fluvial export of total organic carbon (TOC), composed of dissolved (DOC) and particulate (POC) fractions, plays an important, yet often overlooked role in the loss of carbon from catchment systems. Whilst the total riverine organic carbon flux from UK rivers has been estimated to be fairly modest, when compared to Britain's national fossil fuel emissions (less than 1% in total in 1993), it is similar in magnitude to the estimates of carbon sequestration by wetlands and afforestation (Hope et al., 1997b).

Abbreviations: SS, total suspended sediment; TPC, total particulate carbon; DOC, dissolved organic carbon; DOM, dissolved organic matter.

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DOC is thought to be the major component of fluvial TOC in most aquatic systems (Dawson et al., 2002; Hope et al., 1997a; Stanley et al., 2012). DOC is the 'chemical backbone' of aquatic ecosystems (Stanley et al., 2012), influencing the light regime, energy and nutrient supply, pH and metal toxicity in the aquatic environment (Hope et al., 1994; Wallage et al., 2006; Whitehead et al., 2006). Human activities are undoubtedly altering DOC dynamics. Whilst increasing DOC concentrations over the past decades have been reported in rivers across Western Europe and North America (Evans et al., 2005), the consequences of these increasing concentrations for fluvial ecology and the global carbon cycle are not clear and are rarely assessed on a catchment scale (Evans et al., 2005; Stanley et al., 2012).

Since the onset of agriculture, human activities have accelerated soil erosion rates 10- to 100-fold above all estimated natural background levels (Montgomery, 2007a), resulting in an increased input of fine sediment and organic carbon into aquatic environments. Whilst significant amounts of particulate organic carbon are delivered to surface waters and re-deposited in the landscape through soil erosion, the ultimate fate of this carbon remains poorly understood (Lal et al., 2004a, 2004b; Quinton et al., 2010; Van Oost et al., 2004). National estimates of soil carbon losses by water erosion suggest that rivers are either a small source of C or can act as sinks by deposition of alluvium (Quinton et al., 2006).

Many factors, including soils, topography, hydrological regime and vegetation are known to influence the fluvial export of carbon from catchments (Hope et al., 1997b). In temperate ecosystems, most of the terrestrial organic carbon is stored in the soil pool (Aitkenhead et al., 1999; Dawson and Smith, 2007; Hope et al., 1997a, 1997b; Milne and Brown, 1997), which has been found to be a good predictor of DOC in stream water, particularly in smaller catchments (Aitkenhead et al., 1999; Hope et al., 1997a). Agriculture alters the quality of dissolved organic matter in soils (Chantigny, 2003), with a corresponding impact on the qualitative composition of fluvial DOC (Stanley et al., 2012). However, to date most work has focused on fluvial DOC losses from either forested or peaty upland watersheds (Dawson et al., 2002; Hope et al., 1997a) with only limited studies examining the controls and rates of combined total carbon (dissolved organic and particulate) fluxes from agricultural catchments (Dawson and Smith, 2007; Hope et al., 1994; Vidon et al., 2008). So far, the direction and magnitude of the agricultural impact on fluvial DOC dynamics in agricultural catchments are equivocal (Stanley et al., 2012), demonstrating the great challenge in understanding the effects of anthropogenic impact on DOC dynamics at catchment (Hernes et al., 2008) and ultimately national scales.

This study tested the assumption that quality and quantity of the total sediment and fluvial carbon export will differ between two neighbouring study catchments with contrasting land use. We hypothesised that 1) the agricultural catchment will support increased concentrations, fluxes and yields of sediment, due to more intensive land use and altered soil physical properties and 2) the concentrations, fluxes and yields of total particulate carbon (TPC) and DOC will be greater from the semi-natural catchment, due to the prevalence of more carbon-rich soils and a greater total soil carbon pool.

Specifically, this study aims to contribute to the understanding of total organic carbon dynamics in agricultural and semi-natural watersheds by:

1. Comparing event-based hydrological characteristics of two adjacent study catchments with contrasting intensive agriculture and semi-natural land-uses;
2. Examining the controlling factors on total fluvial carbon fluxes in both catchments;
3. Examining the qualitative differences in DOC composition between the two study catchments;
4. Quantifying the fluvial fluxes of total suspended sediment, total dissolved and total particulate carbon.

2. Materials and methods

2.1. Study site

Two adjacent, yet contrasting, study catchments, the Aller and Horner Water were chosen as they represent a hydromorphological and land use gradient that permits examination of the effects of contrasting land use on hydrological and biogeochemical processes (Fig. 1). Climate, geology, soils and land use characteristics of the two study catchments are described in Glendell (2013) and Glendell et al. (2014a, 2014b). Briefly, the catchments are located on the north-east edge of Exmoor National Park in south west England (51°11′52 N 3°34′41 W). The Aller catchment covers 18 km^2 with an altitude range of 4–425 m a.s.l. Arable, short-rotation grassland and permanent pasture account for 56% of land use in this predominantly agricultural catchment, with most intensive land use located in the lower lying middle reaches of the catchment. Horner Water covers 22 km^2 with an altitude range of 20–516 m a.s.l. and is dominated by semi-natural vegetation (broadleaved woodland and upland moorland) that accounts for 74% of land use. Steep valley sides near the watercourse are covered by extensive woodland that serves as a buffer from the effects of agricultural land use on some flatter parts of the upper reaches of the catchment. Whilst enhanced sediment input from diffuse sources has been observed in the agricultural Aller catchment during high flow events, the semi-natural Horner Water runs clear during all but the most extreme hydrological events. Mean annual rainfall ranges between 951 mm and 2584 mm per year, depending on altitude. The average 30-year mean summer temperature is 9–19 °C and winter temperature is 0–7 °C. Soils are predominantly loams, with some clay in the lower area of the agricultural catchment and shallow peat on the highest ground of the semi-natural catchment (Glendell, 2013; Glendell et al., 2014a, 2014b).

2.2. Field sampling

Rainfall data from two UK Environment Agency weather stations (one in each catchment) were used in all analyses. The location of rainfall and water quality monitoring sites is presented in Fig. 1.

Time-integrated storm samples were collected using ISCO 3700 samplers (Teledyne Isco, Lincoln, USA) programmed to sample on discrete, high-resolution time-steps of 30 (Aller) and 60 (Horner Water) min respectively, based on the analysis of the catchment hydrological response. The samples were collected as soon as possible after each rainfall event, usually within 24 h, and immediately transferred to a refrigerator on return to the laboratory where they were analysed for dissolved organic carbon (DOC), total suspended sediment (SS) and total particulate carbon (TPC).

In addition, DOC was sampled monthly at the two catchment outlets in baseflow and near-baseflow conditions between 25th February 2010 and 26th November 2012. The samples were filtered in the field through 0.45 μm glass microfiber filters into acid-washed and furnaced (at 450 °C for 4 h) glass bottles with PTFE lids and acidified with 1 M HCl to pH ≈ 2.

At the Aller catchment outlet (A7) stage was recorded in 15-min intervals using an ISCO 4230 flow meter (Teledyne Isco, Lincoln, USA) and was converted to discharge using a stage–discharge rating equation. Horner Water catchment outlet monitoring point (H5) was located at the UK Environment Agency hydrometric station No. 51002 (Marsh and Hannaford, 2008), that provided the discharge data for this study.

A continuous turbidity record was collected at the Aller catchment outlet A7 using a self-cleaning Analite 195/4/30-G 400 NTU turbidity probe (McVan Instruments, Mulgrave, Australia) between July 2011 and January 2013. At H5, a self-cleaning turbidity sensor, the Greenspan TS3000 1000 NTU (Greenspan Analytical, Milperra, Australia) was deployed between January 2012 and January 2013.