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Understanding the controls on deposited fine sediment in the streams of agricultural catchments

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HIGHLIGHTS

- Field data for deposited fine sediment in agricultural streams are presented.
- Stream power was found to be the most effective explanatory variable.
- The majority of stream beds were saturated with fine sediment.
- Below saturation, deposited fine sediment is related to sediment pressure.
- Target sediment loads need to include the ability of streams to transport sediment.

GRAPHICAL ABSTRACT

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ABSTRACT

Excessive sediment pressure on aquatic habitats is of global concern. A unique dataset, comprising instantaneous measurements of deposited fine sediment in 230 agricultural streams across England and Wales, was analysed in relation to 20 potential explanatory catchment and channel variables. The most effective explanatory variable for the amount of deposited sediment was found to be stream power, calculated for bankfull flow and used to index the capacity of the stream to transport sediment. Both stream power and velocity category were highly significant ($p \ll 0.001$), explaining some 57% variation in total fine sediment mass. Modelled sediment pressure, predominantly from agriculture, was marginally significant ($p < 0.05$) and explained a further 1% variation. The relationship was slightly stronger for erosional zones, providing 62% explanation overall. In the case of the deposited surface drape, stream power was again found to be the most effective explanatory variable ($p < 0.001$) but velocity category, baseflow index and modelled sediment pressure were all significant ($p < 0.01$); each provided an additional 2% explanation to an overall 50%. It is suggested that, in general, the study sites were transport-limited and the majority of stream beds were saturated by fine sediment. For sites below saturation, the upper envelope of measured fine sediment mass increased with modelled sediment pressure. The practical implications of these findings are that (i) targets for fine sediment loads need to take into account the ability of streams to transport/retain fine sediment, and (ii) where agricultural mitigation measures are implemented to reduce delivery of sediment, river management to mobilise/remove fines may also be needed in order to effect an improvement in ecological status in cases where streams are already saturated with fines and unlikely to self-cleanse.

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1. Introduction

Excessive sediment pressure on aquatic habitats has become of increasing concern for river systems around the world (Relyea et al., 2012). In particular, intensification of agriculture has increased fine sediment loading to rivers (Wilcock, 1986; Dearing et al., 1987; Owens and Walling, 2002; Walling et al., 2003a; Foster et al., 2011; Jones and Schilling, 2011), leading to high concentrations of suspended solids and, potentially, deposition of fine sediment. Evidence has also been accumulating, from both field survey and experiments, on the deleterious effects of excessive fine sediment on biota (Waters, 1995; Wood and Armitage, 1997; Matthei et al., 2006; Bilotta and Brazier, 2008; Larsen et al., 2011; Sutherland et al., 2012; Wagenhoff et al., 2012, 2013; Chapman et al., 2014). It is clear from this evidence that the impact of excessive fine sediment on biota is more often related to deposited rather than suspended material (Kemp et al., 2011; Jones et al., 2012a, 2012b, 2014). In the light of this, attempts have been made to identify target values for both deposited fine sediment and sediment loading (Cooper et al., 2008; Collins and Anthony, 2008; Bryce et al., 2010; Collins et al., 2011; Benoy et al., 2012). Yet, the relationship between deposited fine sediment and agricultural sediment pressure is still poorly understood.

Sediment pressure has been variously quantified by catchment or local/network riparian land use (Sutherland et al., 2010), runoff-weighted percentage land use (Wagenhoff et al., 2011) and modelled sediment load apportionment (Collins and Anthony, 2008). Catchment land use has been shown to be related to deposited fine sediment in specific cases of intensification of agriculture (e.g. Niyogi et al., 2007; Sutherland et al., 2010; Wagenhoff et al., 2011). However, at a strategic level, only the approach based on modelled sediment load has potential to link fine sediment deposition with current or future projected land management and, thus, provide information on the likely effectiveness of mitigation measures for fine sediment delivery to rivers in terms of sediment deposition and its biotic impact. The ability to make this link is fundamental to supporting national policies regarding the protection of water resources and ecological status.

Representative field sampling of deposited fine sediment in agricultural streams across England and Wales, carried out as part of a wider national scientific policy support project, provided a unique opportunity to explore the relationship between an instantaneous measurement of deposited fine sediment and sediment pressure. Sampling was specifically designed to cover both the range of agricultural sediment pressure and different biological river types across England and Wales (following Davy-Bowker et al., 2008). The impact on biota is covered elsewhere (Murphy et al., 2015). The aim of this paper is to analyse the sediment data in conjunction with a range of catchment and channel descriptors in order to investigate potential linkages between agricultural sediment pressure and deposited fine sediment in streams. In particular, it is hypothesized that the mass of deposited fine sediment is directly related to the amount of sediment delivered to the channel and inversely related to the capacity of the stream to transport fine sediment.

2. Approach and methods

The approach taken was a synoptic survey of streams in agricultural catchments across England and Wales. Sampling sites were selected from the 12,447 stream sites within the Environment Agency River Habitat Survey (RHS) database. Biological river types were based on the physical attributes of catchment geology, distance from source, altitude and slope; with boundary values loosely based on those associated with RIVPACS IV super end groups (Davy-Bowker et al., 2008). Screening was undertaken to eliminate any sites with a substantial influence from urban areas or sewage effluent (see below). All sites were upstream of any lakes and reservoirs and on independent watercourses; in cases with more than one candidate site per watercourse, the most downstream site meeting the screening requirements was selected. Full details regarding the site selection process are given in Murphy et al. (2015). Some 230 sites were sampled once in either spring or autumn between May 2010 and November 2011. Most samples were collected during low to medium flows as necessitated by the technique and no samples were collected during or immediately after peak flow events. From data on water width, depth and velocity category at the time of sampling, approximately 90% samples were collected when the flow was less than 10% of the estimated median annual flood, or approximately bankfull flow. An independent dataset (Anthony et al., 2012) of 55 similar sites, sampled in both autumn and spring by the same field team and in exactly the same manner between October 2009 and May 2011, was also available for model testing and to assess temporal variability.

2.1. Deposited fine sediment

Fine sediment deposited on, or in, the river substrate to a depth of about 10 cm was collected using the disturbance technique (Duerdoth et al., 2015 adapted from Collins and Walling, 2007a, 2007b). An open-ended, stainless steel cylinder (height 75 cm; diameter 48.5 cm) was carefully inserted into an undisturbed patch of stream bed to a depth of at least 10 cm, until an adequate seal with the substrate was achieved, and the depth of water within the cylinder was measured. To provide an instantaneous measure of the deposited surface drape, the water column was agitated vigorously for one minute using a metal pole, without touching the stream bed. This established a vortex that brought any fine sediment into suspension. This was then immediately sampled, while the water was still in vigorous motion, by plunging two inverted 50 ml tubes to the bottom of the cylinder which then filled as they were turned upright and brought to the surface. To sample the total (i.e. combined surface and sub-surface) deposited fine sediment, the stream bed was then disturbed to a depth of about 10 cm, vigorously agitated for one minute to suspend any subsurface fines and a second pair of 50 ml samples quickly taken. For each river reach sampled, four sampling locations were identified visually by the workers in the field. In broad terms, patches with a propensity to erode fine sediment (erosional) were defined as those higher velocity areas in or close to the thalweg, whereas patches with a propensity to deposit fine sediment (depositional) were in eddies or areas of lower flow velocity such as pools or backwaters. Two sets of samples were collected from erosional and two from depositional zones of the main channel, in order to characterise the reach-scale average (derived from all 4 samples) and provide an indication of within-reach variability.

The samples were refrigerated and kept in the dark until analysed. Deposited fine sediment was characterised in terms of mass, volatile solids (i.e. organic matter derived from loss on ignition) and particle size. Fine sediment mass and volatile solids were measured within one week of return to the laboratory using one of each pair of 50 ml tubes. The samples were passed through a 2 mm sieve, to remove leaves and twigs, prior to filtration using pre-ashed, washed and dried 90 mm Whatman Glass Microfibre GF/C filters (pore size 1.2 μm). The filtered samples were dried in a pre-heated oven at 105 °C overnight and ashed in a pre-heated muffle furnace at 500 °C for 30 min. Reach-average values of sediment mass were calculated using geometric means. Averaging the four samples provided an effective measure of deposited fine sediment at the reach scale (cf. Collins and Walling, 2007a, 2007b) which has been shown to be reliable across a wide range of river types (>60% boulders/cobbles to >60% sand and silt) and not affected by operator bias (Duerdoth et al., 2015). Measurement uncertainty, in terms of 95% confidence intervals, was estimated to be ±0.27 and ±0.32 logarithmic units (i.e. factors of 1.86 and 2.09) on the average total and surface deposited fine sediment, respectively (Duerdoth et al., 2015).

Absolute particle size (<1 mm) was analysed on the second 50 ml tube of each pair using a Malvern Mastersizer 2000. In most cases, the whole sample was analysed using either a HydroS