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Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: an overview of key issues

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Introduction

The science of the export of sediment and colloids from grassland to water presents many new challenges for hydrologists, soil scientists and environmental chemists, in terms of increasing awareness and pressures to control, reduce and mitigate diffuse pollution from livestock dominated areas (Bechmann *et al*., 2005; Bennion *et al*., 2005; Haygarth *et al*., 2005; Heathwaite *et al*., 2005a; Neal and Jarvie, 2005). Sediment and colloids are well-established at being efficient 'carriers' of rogue pollutants, such as nutrients (particularly phosphorus) (Haygarth *et al*., 1997; Heathwaite *et al*., 2005b), metals (Citeau *et al*., 2001; 2003), pathogens (Oliver *et al*., 2005a; 2005b) and persistent organic pollutants (POPs) (Gaveo and Jones, 2002). The problem that arises with nutrients is eutrophication, particularly of surface waters (Bennett *et al*., 2001; Bennion *et al*., 2005; Hession and Storm, 2000), while pathogens can cause sickness in humans, with an almost immediate effect (Jones, 2002). POPs, on the other hand, have a more long-term influence, presenting threats to ecosystem health and, after passing through the food chain, accumulating in mammalian adipose tissue (McLachlan, 1996). In addition to the carrying of pollutants, sediments and colloids can themselves contribute problems because of soil loss from productive land (soil erosion) and also because of siltation of river beds, particularly gravel-bedded rivers where silts undermine salmon spawning and thus have a deleterious effect on fish reproduction (Greig *et al*., 2005; Harrod and Theurer, 2002; Owens *et al*., 2005).

Despite the immediate and topical nature of sediment and colloid transfers, there are, surprisingly, some key aspects of their fate and transport that remain poorly understood. Particularly in relation to intensive grassland systems, exemplified by the dairy pastures common in North-west Europe (Haygarth *et al*., 1998), which are deficient of research attention. As a consequence, some key questions remain. This, and the set of related commentaries that follow, aim to highlight these questions. Herein, we are rethinking our understanding of sediment and colloid transfers from intensive grassland to examine critical deficiencies in existing knowledge and define key

questions and priorities for future science. What follows takes the form of a critical review and is the result of an inter-disciplinary collaborative team effort involving soil scientists, geomorphologists, analytical chemists, hydrochemists, hydrologists and mathematical modellers, assembled at the beginning of a project funded, by the UK government Department for Environment, Food and Rural Affairs (Defra) PE0120, to address this topic. This study is focussed on improving our knowledge and ability to model sediment, colloids and phosphorus losses from intensive grassland. There are four areas around which our key questions are centred that form the focus of this commentary.

Uniqueness and Extent of Grasslands and their Inadequate Inventories

There has been surprisingly little research conducted on erosion from intensively managed pastures. This results in a lack of information on sediment and colloid losses from these systems, seemingly passed over in favour of studies of overtly more 'dramatic' sediment- and colloid-yielding environments of their arable counterparts. This is—on the face of it—surprising, especially when one considers: (1) that these systems are characterized by frequent returns of potentially erosive maritime rainfall often occurring (in marked contrast to arable land) on sloping ground; (2) that intensive grassland systems have a high nutrient turnover that presents a high risk of eutrophication to fresh water systems and; (3) the wide extent of such systems across many parts of the world, including Western Europe, Australia (Nash *et al.*, 2000), New Zealand (Cameron *et al.*, 2002) and the United States (Sims and Coale, 2002).

So why have intensive grasslands been overlooked in terms of sediment and colloid yield? We suggest that this arises because losses from intensive grasslands can be deceptive, for a number of reasons:

- Grassland *appears* to have a good vegetation cover, and we associate good vegetation cover with low erosion rates. For the majority of grasslands, this may well be the case. However, sediment losses have a high proportion of fine material that is highly concentrated with contaminants. Quinton (2001) demonstrated that this selectivity could account for higher-than-expected phosphorus losses from an arable site. We hypothesize this may be true for intensive grasslands. Furthermore, the organic matter content of (intensive) grasslands is generally higher than land under arable cropping. Bellamy *et al.* (2005) noted that the relative rate of carbon (hence organic matter) loss from UK soils increased with soil carbon content, irrespective of land use.
- There is a tendency to overlook some of the erosion losses because, at first glance, we do not obviously see signs of rilling or gullying on grasslands. Current remote sensing techniques tend to miss the more subtle processes, such as interrill erosion, and these processes are difficult to monitor directly (Bilotta *et al.*, 2007). Also, being human, field operators tend not to go out in the rain and thus overlook key erosion events and activities.
- Erosion is episodic and spatially discontinuous. Poached and overgrazed areas may be important, but they quickly recover during the spring and summer. It is therefore difficult to establish the *true* vegetation cover.
- Analytical techniques promoted by chemists often omit the detection of the fine colloidal material and the organic fraction of sediments, both of which we believe are important components of eroded material from intensive grasslands (Quinton, 2004) (see also 'definitions' section below and Gimbert *et al.* (2007)).
- The presence of excreta and recycled animal manure, along with the generally high organic matter content of the surface of grassland soils, is very often overlooked as a sediment-source in grassland systems (see 'organic matter' section below and also Granger *et al.* (2007)).

Definitions, Analytical Failings, New Challenges and Opportunities

The problems herein undermine the quality and reliability of contemporary inventories of sediment

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and colloid emissions (Gimbert *et al*., 2007). Sediment and colloid transfer occurs due to soil disturbance, causing the soil to be suspended as mud or sediment in turbid water. Sediment is defined as any particulate matter that can be transported from land to natural waters and can include clay (<2 μm), silt (2–60 μm), sand (60 μm–2 mm), pebbles (2–60 mm), cobbles (60–256 mm) and even boulders with sizes greater than 256 mm. Colloidal material is defined as particles in the size range 1 nm–1 μm and spans the widely used operationally defined 0·45 μm threshold between 'dissolved' and 'particulate' phases, based on separation using a 0·45 μm filter. Specifically, it is our belief that the predominating field and analytical methodologies that have been used to determine sediment and colloid budgets cause problems for various reasons. These might be because of confusions over terminology, inadequate sampling, use of inappropriate membranes for filtration (inappropriate either in terms of filtration size or in terms of material) (Haygarth and Sharpley, 2000; Haygarth *et al*., 1997), or even use of inaccurate means of separating and quantifying particles (Gimbert *et al*., 2005). Critically, with the all-pervading use of 0·45 μm membrane as the world water industry 'standard' threshold to separate 'sediment and particles' from 'solute and dissolved', we are failing to determine a highly functional range of material that spans the key range between 0·1 and 1 μm. We believe that this range is particularly important for losses from grasslands, and yet falls between optimal operational ranges for key instrumentation. In fact, particles, sediment and colloids do not cease to exist <0·45 μm, but soil-, run-off- and stream-solutions are comprised of a continuum of particle and colloid material down to molecular size (Haygarth *et al*., 1997).

It is therefore our hypothesis that, probably as a result of the 'dogma' arising from use of the 0·45-μm membrane, we are failing to determine latent colloid dispersion and release from grasslands that, in conventional technologies, is simply not being accounted for. To understand sediment and colloid mobilization further, it is essential to have reliable analytical techniques in order to elucidate the role sediment and colloid mobilization play in contaminant transport. However, because sediment fractions and colloidal material consist of a continuum of particle size ranges, the analytical methods used are commonly based on operationally defined thresholds, which cause us difficulties and potential confusions that we have to overcome. One new and exciting approach that has the ability to study colloidal material is a separation technique called field-flow fractionation (FFF) and such new approaches need further development to help us tease apart new understandings (Gimbert *et al*., 2003; 2005; 2007).

Organic Matter: a Non-Quantified Colloid Source

Intensive grasslands are characterized by high amounts of organic matter (Bellamy *et al*., 2005), brought about by deposits of excreta and recycled animal manure, along with contributions from decaying surface vegetation. All these sources present a poorly understood but important source of colloids and sediment that may significantly contribute to undermining downstream water quality. Intensive grasslands systems also often incorporate a mixture of production of fodder crops, for example, maize that require harvest (and therefore vulnerable bare soil) during autumn months. This exacerbates the potential for grasslands to contribute to problems of sediment and colloid yield and thus the quality of receiving waters. We believe that these sources contribute to 'latent' or 'discrete' colloid budgets. What is required is an improved means of estimating the contribution of these processes using tracers to investigate the contribution of excreta, manures and slurries (Haygarth *et al*., 1998; Preedy *et al*., 2001) and other fine-sized sources of organic matter (Granger *et al*., 2007).

Tracers offer great potential in understanding agricultural diffuse pollution and there are a variety of well- and less-established techniques that provide a range of opportunities when studying sediment, particle and associated phosphorus loss from grasslands. There is a fundamental need to: (1) apportion sources of sediment and colloids and associated pollutants between soil processes and agricultural amendments; and (2) understand

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Table I. Summarizing the key reasons why processes affecting erosion, sediment and colloids and associated phosphorus transport from intensively farmed grasslands are deficient in our knowledge and some suggested remedies

Area of deficiency	Specific deficiency	Priorities for future science
Inadequate inventories	Grasslands are passed over in favour of studies of overtly more 'dramatic' sediment- and colloid-yielding environments of their arable counterparts	We need to change the way in which grassland systems are perceived and monitored—this commentary and the ones that follow may help start to achieve this
	Grassland *appears* to have a good vegetation cover, and we associate good vegetation cover with low erosion rates	As above
	There is a tendency to overlook some of the erosion losses because, at first glance, we do not obviously see signs of rilling or gullying on grasslands	As above
	Erosion is episodic and spatially discontinuous. Poached and overgrazed areas may be important, but they recover quickly during the spring and summer. It is, therefore, difficult to establish the *true* vegetation cover	As above
Confusion with definitions and general analytical failings	By adopting the use of 0·45-μm membrane as the world water industry 'standard' threshold to separate 'sediment and particles' from 'solute and dissolved', we are failing to determine a highly functional range of material that spans the key range between 0·1 and 1 μm	A requirement for a wider acceptance of a 'continuum' of sediment and particles and processes from molecular to >1 μm
	Confusions over terminology	Clarity with operational definitions and an acceptance of the strengths and weaknesses of analytical tools
	Use of inappropriate membranes for filtration (inappropriate either in terms of filtration size or in terms of material)	Use of new techniques such as field-flow fractionation
Organic matter as an unquantified colloid source	The role of organic matter as sources of colloids and sediment are poorly appreciated	Need to develop new tracer techniques in order to: (1) apportion sources of sediment and colloids and associated pollutants between soil processes and agricultural amendments; and (2) understand the timing and response of the different transfer pathways (dissolved, colloidal and particulate) by which agricultural amendments (manure, fertilizer), contribute to the load delivered to receiving waters
	Grassland systems often incorporate production of fodder crops, for example, maize, that require harvest (and therefore vulnerable bare soil) during autumn months. This exacerbates the potential for grasslands to contribute to problems of sediment and colloid yield and thus the quality of receiving waters	As above
Towards greater integration of modelling with field science	A divergence of interests between the modelling and field-science communities, which is exacerbated by a failure to understand their respective aims and requirements	Integrated inter-disciplinary team working is encouraged, discipline polarization discouraged

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Table I. (*Continued*)

Area of deficiency	Specific deficiency	Priorities for future science
	A requirement to balance the need to incorporate modelled processes with the need to account adequately for sample variability, model uncertainties, and therefore develop models with an optimum (and appropriate) level of complexity, based on the data available	Field scientists must fully appreciate the variability of observations, and modellers need to understand the uncertainty in model processes and model outputs

the timing and response of the different transfer pathways (dissolved, colloidal and particulate) by which agricultural amendments (manure, fertilizer), contribute to the load delivered to receiving waters. Established sediment-tracing techniques (Granger *et al*., 2007) have been used to identify the source of sediment, and by implication, the attached phosphorus mobilized by erosion processes. However, they have not addressed the question of the role of agricultural amendments (and associated organic matter) nor really established a direct link with phosphorus. There are a number of new approaches that we feel ought to be further examined in context with grassland systems:

- The natural abundance (^{13}C) carbon tracer technique is potentially very useful because various forms of phosphorus play a role in soils and some of those forms are associated with carbon.
- The use of natural fluorescence characteristics to detect the presence of animal wastes and manures in water. Recent advances in fluorescence spectroscopy allow rapid determination of excitation-emission matrices that enable the identification of different fluorophores within a water sample.
- There is potential for fluorescent-labelled and DNA-labelled particles to provide multiple tracers that are highly sensitive to detection, which presents an advantage with small signal-to-noise ratios.

Towards Greater Integration of Modelling with Field Science

Computer modelling enables the evaluation and integration of these new field-science opportunities in order to improve our understanding of sediment loss from intensive grasslands, but models will have limited benefit if they fail to be properly integrated with field observation and experimental programmes (Krueger *et al*., 2007). We perceive a divergence of interests between the modelling and field-science communities, which is exacerbated by a failure to understand their respective aims and requirements. This needs to be overcome if mutual understanding and thus progress is to be made. Modelling approaches must also adopt a fully integrated landscape systems-based approach that takes account of the full range of processes, from source, mobilization to delivery (Beven *et al*., 2005; Haygarth, 2005). Moreover, we believe that there is an urgent need in field science to fully appreciate the variability of observations, for example, variable spatial sources of soil phosphorus around a catchment (Page *et al*., 2005). Consequently, there is a requirement to balance the need to incorporate modelled processes with the need to adequately account for sample variability, model uncertainties, and therefore develop models with an optimum (and appropriate) level of complexity, based on the data available.

Clearly there is a need for new data and this will advance understanding of the biogeochemistry of intensive grassland systems and their relationship with downstream water quality. The new data will be used to inform numerical models, to formalize our knowledge about intensive grassland systems and allow quantitative predictions under changing and complex conditions. However, in the overall approach, it is important to note that we believe our perceptual understanding of the field biogeochemistry is better than our potential for

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actual translation of these perceptions into numerical models. This is a challenge that we need to overcome within an integrated team-working framework. Thus, ultimately, the aim of understanding and predicting phosphorus, sediment and colloid transfers in intensive grassland-dominated catchments is something that can only be achieved if modellers, field and laboratory scientists work together.

Summary of Key Issues and Defining the Future Scientific Priorities

We consider that here are four key issues and priorities for hydrological sciences in respect to sediment, phosphorus and colloid transfers from intensive grasslands (Table I). These are inadequate inventories, analytical challenges, the neglected role of organic matter and challenges for modelling and integration. We need to change the way in which grassland systems are perceived and monitored; this commentary and the ones that follow may help start to achieve this. There is also a critical requirement for a wider acceptance of a 'continuum' of sediment and particles and processes from molecular to >1 μm, including clarity with operational definitions and an acceptance of the strengths and weaknesses of analytical tools. A variety of new tracer techniques are available for helping assess the role of organic matter in contributing to transfers and these must be applied. Field scientists must fully appreciate the variability of observations, and modellers need to understand the uncertainty in model processes and model outputs. Overall, however, the critical message is that integrated inter-disciplinary team working is encouraged, discipline polarization is discouraged because it undermines progress. To that end, in the assembly of commentaries that follow (Bilotta *et al*., 2007; Gimbert *et al*., 2007; Granger *et al*., 2007; Krueger *et al*., 2007) we are presenting ideas as part of an integrated project team that is attempting to improve our knowledge and ability to model sediment, colloids and phosphorus losses from intensive grassland, with—we hope—some wider generic relevance for the hydrological community.

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