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Sediment fingerprinting as a tool to identify temporal and spatial variability of sediment sources and transport pathways in agricultural catchments

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ABSTRACT

Management strategies to reduce soil loss and sediment delivery from agricultural land requires an empirical understanding of sediment sources. Sediment fingerprinting is a technique to apportion sources to a downstream sediment sample which, when applied at high spatial and temporal resolutions, can offer insights into catchment sediment dynamics. However, developing an over-arching tool can be hindered due to indeterminate interactions such as, for example, landuse, soil and geological conditions and multiple sediment source pressures. To address this, a multi-proxy sediment fingerprinting approach was used in three catchment observatories in Ireland, characterised and referred to by their predominant soil drainage and land use characteristics: poorly-drained grassland, well-drained arable and moderately-drained arable. Potential sediment source groups: channels, field topsoils, and roads, were sampled. Target sediment samples were collected from six sites within each catchment over approximately two-years from May 2012 to May 2014. Geochemical, mineral magnetic and radionuclide tracers were measured in source and target sediment samples and, following justified tracer selection, source proportions were estimated using an uncertainty inclusive un-mixing model. Overall, the poorly-, well- and moderately-drained catchments exported 828, 421 and 619 tonnes, respectively (36, 19 and 33 t km^{-2} yr^{-1}). Estimated source contributions from channel, field topsoil and road groups were overall, 67%, 27% and 4% in the poorly-drained grassland, 53%, 24% and 24% in the well-drained arable and 9%, 82% and 8% in the moderately-drained arable catchment outlets. Sub-catchment source estimates were generally consistent with the catchment outlet over space and time. Short-term activation of previously unidentified transport pathways were detected, for example, field sources transported by the road network in the well-drained catchment. In catchments with high hydrological surface connectivity (moderate and poor soil drainage), exposed soils were most sensitive to soil erosion and sediment delivery. Where groundcover is maintained on these soils, sediment connectivity was diminished and flow energy is transferred to the stream network where channel bank erosion increased. In the well-drained arable catchment, sub-surface flow pathways dominated and consequently channel sources, broadly representative of subsoil characteristics, were the largest sediment source. Sediment connectivity contrasted in the studied agricultural catchments according to source availability, and erosion, transport and delivery processes. Effective sediment management strategies in intensive and intensifying agricultural catchments must consider sediment loss risk resulting from catchment specific sediment connectivity and emphasise mitigation strategies accordingly.

1. Introduction

Intensive agricultural systems, resulting in enhanced soil erosion and sediment delivery can pose risks to aquatic ecosystems such as rivers and lakes (Collins and Zhang, 2016; Borrelli et al., 2017; Tiecher et al., 2017; Vanwalleghem et al., 2017). In agricultural catchments, fluctuations in groundcover due to arable cultivation or livestock poaching (soil structural damage due to animal trampling) exposes the soil surface to erosional processes, thereby increasing their sensitivity to soil erosion and subsequent sediment loss (Haygarth et al., 2006). Land management, such as installation of artificial drainage, promotes aeration and alleviates excess soil moisture, thereby increasing the

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productivity of soils (Ibrahim et al., 2013). This also increases the efficiency of hydrological transfers from hillslopes to channels and runoff ratios (Shore et al., 2013). Moreover, landscape modifications interact with local heterogeneous catchment attributes (landscape position, slope, soil drainage, antecedent conditions) and rainfall to alter the distribution of soil erosion and sediment delivery, i.e., sediment connectivity (Sherriff et al., 2016).

In waterbodies, augmented supply of sediments to the channel bed can cause degradation of aquatic habitats resulting in reduced species diversity, as specifically noted in Ireland (Davis et al., 2018) and France (Descloux et al., 2013), and extensively reviewed throughout the world by Kjelland et al. (2015). High suspended sediment concentrations in aquatic ecosystems, for example following rainfall events, also reduce habitat quality for example resulting in increased drifting of invertebrates, commonly used as bioindicators (Kjelland et al., 2015; Béjar et al., 2017). Overall, reduction of ecological diversity challenges the achievement of ecologically "good" status as required under the EU Water Framework Directive (WFD; 2000/60/EC, Official Journal of the European Communities, 2000). Catchment management strategies require identification of sediment sources and an understanding of the spatial and temporal dynamics of physical processes to cost-effectively target and reduce on-farm soil loss and off-farm downstream sediment supply (Walling et al., 2008).

There are difficulties in fully defining catchment sediment risks and monitoring mitigations. Firstly, auditing individual soil erosion and sediment storage components into a catchment sediment budget demands considerable investigation time and resources (Walling and Collins, 2008). Secondly, establishing an evidence-base, relating specific agricultural practices to different sediment sources and delivery pathway fluctuations over multiple seasons, requires a representatively long study period with observations at an appropriate resolution (Sherriff et al., 2015a). Alternative catchment-scale techniques such as sediment fingerprinting have, therefore, emerged as an effective management tool in river catchments (Gruszowski et al., 2003; Rowan et al., 2012; Thompson et al., 2013; Lamba et al., 2015).

The sediment fingerprinting approach assumes that physico-chemical properties of mineragenic sediment, the inorganic component, can be conserved along a transport pathway, providing the numerical basis to 'unmix' the composite-signatures of suspended sediments samples during flood events or from sediment stores such as channel beds, floodplains and lakes (Pulley et al., 2015) and to apportion the relative contribution to their respective upstream sources (Haddadchi et al., 2013). The upstream catchment is subdivided into potential sources (or source group types) that can be distinguished by their properties, for example, according to land use (Gruszowski et al., 2003; Blake et al., 2012), lithology (Collins et al., 1998), or erosional processes (Fox and Papanicolaou, 2008).

Sediment tracers typically employed include geochemistry, mineral magnetics and environmental radionuclides and are potentially numerous considering the availability of modern analytical equipment (Pulley and Rowntree, 2016). However, selected tracers must be conservative (resistant to chemical transformation) and their environmental significance justified in terms of their ability to discriminate between environmentally relevant sources (Koiter et al., 2013). Furthermore, it is assumed the impact of physical processes (erosion, transport, deposition, and re-entrainment) on tracer concentrations due to particle size selectivity and organic matter variation, can be numerically corrected. Simple correction factors are commonly used (Collins et al., 2001), but the appropriateness of these is now disputed (Smith and Blake, 2014) and more refined approaches involving particle size fractionation are an alternative (Motha et al., 2004; Small et al., 2004). Sediment contributions from each source are determined using statistically-based un-mixing algorithms, frequently accompanied by uncertainty estimates (Franks and Rowan, 2000; Sherriff et al., 2015b).

Sediment fingerprinting studies have been applied across a range of scales, designed to explore the variability of sediment sources to a single area of impact, e.g., lake, degraded gravel habitat, or streams (Pulley et al., 2015). Particular advances have included assessing high-resolution temporal changes in sediment sources and investigations across hydrological regimes (Cooper and Krueger, 2017; Rose et al., 2018; Tiecher et al., 2018). However, the negative impacts of excessive sediment transport and/or deposition may extend far upstream of a catchment outlet (Fryirs et al., 2007). As such, there is a need to define sub-catchment variability of sediment sources to overcome the indeterminate potential of interacting land use, soil/geology and source variability issues that exist with sediment dynamics in catchments. This can facilitate interrogation of catchment hydrological and sediment connectivity processes inferred at the catchment scale, and how they relate to the spatially heterogeneous pattern of land use (e.g., crop type, animal grazing) and land management (e.g., riparian vegetation, arrangement of farm tracks – Sherriff et al., 2016).

Correct identification of sediment sources and disentangling the processes controlling soil erosion, sediment entrainment, transfer and deposition will provide an evidence base for application of targeted on- and off-farm sediment management strategies (Rowan et al., 2012). This is particularly important in catchments with contrasting physical and agricultural land management characteristics where targeted strategies may be different (Sherriff et al., 2016). Appropriate source-based mitigation measures are necessary to prevent off-farm nutrient and sediment supply downstream (Evrard et al., 2007; Deasy et al., 2010). Successful application of suitable mitigation measures are essential to reduce on-farm nutrients and soil losses through the preservation of chemical, physical and biological soil quality (Cerdá et al., 2017). These are important considerations to reduce the environmental impact of intensive agriculture and to offset the likely changes occurring as land becomes more intensively managed. Increased or changing land use (crop types, animal numbers), soil drainage and increased machine trafficking are all likely to occur under scenarios of agricultural intensification in Ireland, Europe and worldwide (Ewert et al., 2005; Coyle et al., 2016; Teshager et al., 2016).

The overall aim of this study was to use sediment fingerprinting to define the spatial and temporal variability of sediment sources of in-stream sediments in intensive or intensifying agricultural catchments. The sediment fingerprinting methodology used a multi-proxy suite of environmental radionuclides, geochemistry and mineral magnetics within a statistically based un-mixing framework. This method was applied in three catchment observatories in order to fulfil two objectives. Firstly, to assess relative magnitudes of sediment sources between catchments with contrasting land use and dominant soil drainage characteristics. Secondly, to assess the spatial and temporal variability of sediment sources within each catchment. This analysis was used to recommend catchment and source specific measures to reduce the soil and sediment loss from land.

2. Methods

2.1. Catchment observatories

Sediment fingerprinting studies were focussed on three lowland intensive agricultural catchments in Ireland. Consistent with Sherriff et al. (2016), these catchments are named according to their dominant soil drainage and predominant land use types; poorly-drained grassland, well-drained arable and moderately-drained arable (Fig. 1).