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Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils

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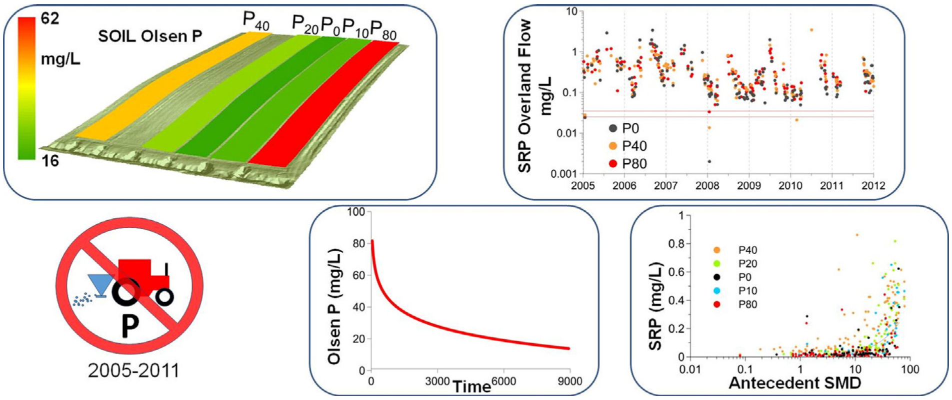
HIGHLIGHTS

- Overland flow and drainage were monitored in plots across a soil Olsen P gradient.
- Soil Olsen P was unrelated to measured concentrations in drainage or overland flow.
- Observed concentrations exceeded environmental quality standards for all plots.
- Higher antecedent soil moisture deficits result in greater P losses.
- Alternative management strategies may be needed to reduce P risk to freshwater.

GRAPHICAL ABSTRACT



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ABSTRACT

Rates and quantities of legacy soil phosphorus (P) lost from agricultural soils, and the timescales for positive change to water quality, remain unclear. From 2000 to 2004 five 0.2 ha grazed grassland plots located on a drumlin hillslope in Northern Ireland, received chemical fertiliser applications of 0, 10, 20, 40, 80 kg P ha^{-1} yr^{-1} resulting in soil Olsen P concentrations of 19, 24, 28, 38 and 67 mg P L^{-1}, respectively, after which applications ceased. Soil Olsen P and losses to overland flow and drainage were monitored from 2005 to 2011 on an event and weekly flow proportional basis, respectively. Soluble reactive P and total P time series were synchronised with daily rainfall and modelled soil moisture deficits.

From 2005 to 2011 soil Olsen P decline was proportional to soil P status with a 43% reduction in the plot at 67 mg P L^{-1} in 2004 and a corresponding 12% reduction in the plot with lowest soil P. However, there was no significant difference in the flow-weighted mean concentration for overland flow among plots, all of which exceeded 0.035 mg L^{-1} in >98% of events. Strong interannual and event variations in losses were observed with up to 65% of P being lost during a single rainfall event. P concentrations in drainage flow were independent of Olsen P and drain efficiency was potentially the primary control on concentrations, with the highest concentrations recorded in the plot at 38 mg L^{-1} Olsen P in 2004 (up to 2.72 mg L^{-1}). Hydrological drivers, particularly antecedent soil moisture, had a strong influence on P loss in both overland and drainage flow, with higher concentrations recorded above a soil moisture deficit threshold of 7 mm. This study demonstrates that on some soil types, legacy P poses a significant long term threat to water quality, even at agronomically optimum soil P levels.

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1. Introduction

Phosphorus (P) is a limiting nutrient for plant growth and has long been applied to agricultural soils to raise grass and crop productivity. In freshwater aquatic ecosystems P availability constrains primary production, with excessive levels contributing to eutrophication and the continued degradation of many waterbodies (Tunney et al., 1998; Uhlmann and Lothar, 1994; Smith and Schindler, 2009). The detrimental impact of P on water quality has been the subject of extensive study and review (e.g. Hart et al., 2004; Ulén et al., 2007; Withers et al., 2014; Jarvie et al., 2013b) and, cognisant of this, strategies to prevent both diffuse and point source losses to water have been implemented through voluntary and regulatory measures in many countries (Kleinman et al., 2015; McDowell et al., 2015).

Diffuse nutrient loss from the agricultural landscape poses a particular challenge as a multiplicity of factors including soil type, climate, connectivity to water courses and land management practices strongly influence the potential for loss and lead to significant temporal and spatial variability (Withers et al., 2014). While advances in the resolution and accuracy of monitoring and research in agricultural catchments (e.g. Jordan et al., 2012; Mellander et al., 2012; Wade et al., 2012; Owen et al., 2012; Dupas et al., 2015) are providing insights into the complexity of the processes involved, many aspects of the “how much”, “where” and “when” of nutrient delivery to surface waters remain ambiguous (Jarvie et al., 2013a).

Failure to improve water quality is a major concern for regulatory authorities where success is linked to achieving a target within a set timeframe. While residence times of nitrogen (N) in soil are short, P has considerable potential for storage and retention, with soil sorption capacities many times that of the corresponding P concentration in solution (Frossard et al., 2000; Sharpley et al., 2013). While controls on nutrient applications and implementation of mitigation measures (Amery and Schoumans, 2014) might serve to reduce inputs and P loss from the system, legacy soil P (Kleinman et al., 2011) is likely to be contributing to the failure to detect significant changes in water quality across Europe and elsewhere (e.g. Bradley et al., 2015; Sharpley et al., 2013). The time required to ‘draw down’ P in agricultural soils is difficult to ascertain, given the complex pathways, long residence times and physico-chemical processes involved in mobilisation and transportion (e.g. Sharpley et al., 2013; Haygarth et al., 2014; Kleinman et al., 2011; Jarvie et al., 2013a). The relationship between soil P status, usually defined in terms of plant availability, and P concentrations in both drainage and overland flow has been investigated in a number of studies, with many reporting a correlation between soil test P and P levels in overland flow (e.g. Tunney et al., 1998, 2002; Pote et al., 1996; Smith et al., 2003; Daly and Casey, 2005). Combining data for a study on 4 grassland fields in Ireland with data from studies by Brookes et al. (1997); Pote et al. (1996); Sibbesen and Sharpley (1997) and Torpey and Morgan (1999); Tunney et al. (2002) found a strong ($r^2 = 0.92$) correlation between soil test P and soluble P in overland flow. Under more controlled conditions in a long-term grassland plot experiment Watson et al. (2007), assessed the relationship between soil P status and P losses in drainage and overland flow and demonstrated that rate of P application impacted on the soluble reactive P (SRP) and total P (TP) concentrations in overland flow and drainage. However, losses were highly variable and confounded by hydrological variability. Others, however, found that larger rates of mineral P application did not necessarily result in greater losses in leachate, with soil P sorption capacity (PSC) and degree of P saturation shown to be of greater influence than soil P as estimated using agronomic tests such as Olsen P (Leinweber et al., 1999).

Common to many of these studies, is that nutrient applications, either as chemical fertiliser or animal manures, were ongoing throughout the period of observation. As such, relationships between soil P and overland flow or drainage concentrations may be obscured by incidental losses of fertiliser or slurry where applications were followed by rainfall (e.g. Tunney et al., 2002; Preedy et al., 2001; Haygarth and Jarvis, 1997; Hahn et al., 2012). Other drivers, such as soil moisture and rainfall intensity, have also been shown to add to the risk of manures and fertilisers being lost to water following application (e.g. Vadas et al., 2011).

Disentangling these diffuse sources and isolating losses relating to soil status alone is challenging and few studies have examined P loss under conditions of declining soil P. An exception is Schärer et al. (2007) who examined P loss from irrigated plots over a 2 year period following cessation of P applications and found no significant change in available P in the soil or in runoff concentrations. In an attempt to provide some further insights into water quality responses following cessation of P fertiliser application, we investigate soil P decline and corresponding trends in P loss in overland flow and drainage from 5 field-scale grassland plots with different soil Olsen P concentrations over a 7 year period. The study investigated:

(1) The extent to which P fertilisation history and Olsen P concentrations affect P loss to surface waters following cessation of P fertiliser application.
(2) The temporal variation in P losses in overland flow and drain flow following the cessation of fertiliser applications.
(3) The soil and hydrological drivers of P loss in overland flow and drain flow following the cessation of fertiliser application.
(4) The implications for agricultural mitigation strategies aimed at reducing eutrophication risks in landscapes with similar soil types.

2. Methodology

2.1. Site description

Five grassland experimental plots were established in 1987, on a hill slope site on the Agri-Food and Bioscience Institute (AFBI) Research Farm near Hillsborough, Co. Down (54° 27.212′ N; 6° 5.010′ W). The site is underlain by Silurian greywacke, which is weakly metamorphosed with low matrix porosity. The overburden is glacial till; a gleyed sandy clay-loam soil composed of 48% sand, 31% silt, 21% clay and 12% organic matter (Watson et al., 2007) classed as a Surface Water Gley (or Dystric Gleysol according to the FAO Classification) (Cruickshank, 1997; Doody et al., 2010). Soil hydraulic conductivity was measured at 0.2 m d^{-1} (Watson et al., 2000), which corresponds to a Hydrology of Soil Type (HOST) Class 24, a slowly permeable mineral soil, gleyed within 40 cm, over impermeable bedrock (Lilly, 2010) and accounting for approximately 54% of the land cover of Northern Ireland (Jordan and Rawlins, 2007).

Each 0.2 ha slope parallel plot (14 × 143 m) on the side of the drumlin was hydrologically partitioned, using a PVC membrane to separate the plots at depth (>1 m) and raised earth along the plot edges to direct any surface water flow. Sub-surface drainage was installed consisting of perforated lateral drains of PVC pipe laid at 10 m intervals across each plot at a depth of 0.8 m dipping to 1.0 m at the western edge of each plot where they connect to a main collector pipe draining to the base of the plot (further detail is provided in Watson et al. (2000)). Overland flow was collected in a surface drain at the base of each plot. The drainage flow and overland flow from each plot were directed to separate v-notch weirs and flows monitored continuously over a range of 0.01 to 7.0 L s^{-1} to an accuracy of ±4% (Watson et al., 2007). Following partitioning and installation of field drains the site was ploughed and re-seeded with perennial ryegrass, so that the hillslope plot and land cover are representative of typical farming conditions in the region.

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