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Assessing the risk of phosphorus transfer to high ecological status rivers: Integration of nutrient management with soil geochemical and hydrological conditions

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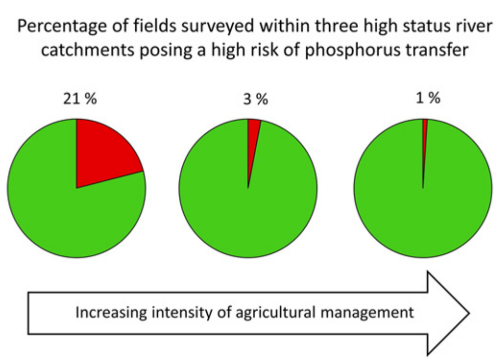
HIGHLIGHTS

- Farm and field phosphorus management was assessed in near-pristine river catchments.
- Field P surpluses found mostly on soils with >20% organic matter and low P sorption
- High risk areas were identified on farms with no nutrient management planning.
- Extensive farmers should have greater access to nutrient management planning.
- Nutrient management planning must incorporate soil conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture has been implicated in the loss of pristine conditions and ecology at river sites classified as at 'high ecological status' across Europe. Although the exact causes remain unclear, diffuse phosphorus (P) transfer warrants consideration because of its wider importance for the ecological quality of rivers. This study assessed the risk of P loss at field scale from farms under contrasting soil conditions within three case-study catchments upstream of near-pristine river sites. Data from 39 farms showed P surpluses were common on extensive farm enterprises despite a lower P requirement and level of intensity. At field scale, data from 520 fields showed that Histic topsoils with elevated organic matter contents had low P reserves due to poor sorption capacities, and received applications of P in excess of recommended rates. On this soil type 67% of fields recorded a field P surplus of between 1 and 31 kg ha^{-1}, accounting for 46% of fields surveyed across 10 farms in a pressured high status catchment. A P risk assessment combined nutrient management, soil biogeochemical and hydrological data at field scale, across 3 catchments and the relative risks of P transfer were highest when fertilizer quantities that exceeded current recommendations on soils with a high risk of mobilization and high risk of transport as indicated by topographic wetness index values. This situation occurred on 21% of fields surveyed in the least intensively managed catchment with no on-farm nutrient management planning and soil testing. In contrast, the two intensively managed catchments presented a risk of P transfer in only 3% and 1% of fields surveyed across 29 farms.

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Future agri-environmental measures should be administered at field scale, not farm scale, and based on soil analysis that is inclusive of OM values on a field-by-field basis.

1. Introduction

Diffuse, non-point pollution remains a major threat to surface waters due to eutrophication caused by nitrogen (N) and phosphorus (P) transfers originating, in part, from agricultural land (Carpenter et al., 1998, EEA, 2012, OECD, 2008). In Ireland, phosphorus (P) transfer from agricultural land has been asserted as the primary cause of degradation in 53% of the river water bodies that failed to achieve 'good' ecological status under the WFD (Byrne and Fanning, 2015). However, it is difficult to make the same assertion about rivers that are at risk of failing to maintain 'high' ecological status due to the uncertainty around the causes of degradation (Irvine and Ni Chuanigh, 2013; Roberts et al., 2016) and also due to natural variations in high status conditions (Irvine, 2004). Nevertheless, P transfer from agriculture does warrant consideration given its wider importance for the ecological quality of rivers.

In productive agricultural systems, nutrient transfer to surface water can be conceptualized along a continuum from source, via mobilization and delivery, to impact (Haygarth et al., 2005). Sources of P include native soil P or P applied in excess of crop demand that can be mobilized during the initial separation of P molecules from their source via geochemical desorption, biological solubilisation, or physical detachment. These processes can be increased under certain soil conditions and managements (Daly et al., 2001; McDowell et al., 2001). From the point of mobilization, P is transported via subsurface or surface pathways, depending on soil hydrological conditions, until it is "delivered" to the water where it can have an "impact" by stimulating excessive algal growth (Beven et al., 2005; Haygarth et al., 2005).

In the European Union (EU), designations under the Water Framework Directive (WFD - OJEC, 2000) include those water bodies deemed at 'high status', i.e. not deviating from pristine or reference conditions according to ecological classifications (Pardo et al., 2012), and which may be particularly sensitive to any external pressure (del Mar Sánchez-Montoya et al., 2012). The number of high status water bodies varies across the EU either due to a natural dearth of water body types or due to ubiquitous impacts that reduce the percentage number overall (Table 1 - EEA, 2012). Ireland and Austria stand out as particularly rich member states in terms of both the number of water bodies (7401 and 5670, respectively) and percentage at high status (both at 18%). The WFD requires member states to maintain high status water bodies and convergence to at least good status for all other water bodies using the same harmonized ecological classification system (ECOSTAT, 2003). This harmonization is based on all EU member states calibrating biological indicators with physico-chemical parameters and based on river typologies.

A key concept underlying the WFD is the integration of existing water policies such as the Nitrates Directive (OJEC, 1991) which is designed to improve water quality by regulating on-farm nutrient use and reduce nutrient and sediment losses to water. To transpose this complex legislation into law, each EU member state must implement measures through a Nitrates Action Programme (NAP) either in specific zones or on a whole territory basis (OJEC, 1991). For example, Ireland's NAP sets limits on P use and requires farms to maintain a zero farm-gate P balance with optimized soil test P (Morgan's P $< 8\ mg\cdot l^{-1}$) values across the farm (SI 31 of 2014). On intensive farms these measures have resulted in reducing P balances at farm scale and reducing the occurrence of fields with excessive soil test P values; however, they fail to account for soil geochemical and hydrological conditions that vary spatially across the agricultural landscape. High ecological status river catchments located in upland areas with a mosaic of mineral and organic soils support a mix of extensive and intensive farm enterprises (Irvine and Ni Chuanigh, 2013; White et al., 2014). Whilst current legislation regulates nutrient use at farm scale, agri-environmental measures in these areas need to take account of soil geochemical and hydrological variation at smaller scales (field) to minimize nutrient losses to water and maintain high ecological status.

Grassland agriculture in Irish high status catchments varies greatly in extent from being completely absent to covering up to 88% of catchment areas. The latter catchments are at the highest risk of failing to maintain high ecological status (Roberts et al., 2016). However, several studies have found a high proportion of fields on low intensity farms with excessive P levels due to surplus P applications over time (Gibbons et al., 2014; Schulte et al., 2009). This risk of P transfer would be elevated further when P surpluses are applied to P saturated soils and soils with poor P retention capacities. Grassland soils that cannot assimilate added P and build up P reserves for draw down by a growing crop have been characterised in Ireland and elsewhere (Daly et al., 2001; Guppy et al., 2005). These include soils with a high % of organic matter (OM) in the surface horizon and categorised here as Histic topsoils. High organic matter content in the surface horizon of soils occludes sorption sites on clay minerals and competes with P for sorption, thereby reducing the soils P sorption capacity and P retention. The implications for P management on these soils centers on their low P sorption capacity which prevents build-up of P reserves onto the soil matrix. Instead, P remains in the soil solution and added fertilizer P is susceptible to leaching and runoff (Daly et al., 2001; Guppy et al., 2005). In addition, if these soils coincide with conditions that promote saturation excess overland flow such as high water tables, large contributing areas and shallow slopes (Beven and Kirkby, 1979; Holden, 2006), there is likely to be a high potential for P transport to streams. However, the importance of these factors have not always been fully appreciated in previous risk assessments or nutrient management approaches for P transfer, which may have, in part, led to the perception that only intensive agriculture with high fertilizer inputs and high stocking rates and/or tillage frequencies can pose a threat to aquatic ecosystems (Doody et al., 2012, 2014; Watson et al., 2009).

Building on this background the objectives of this research were to 1) characterise the geochemical and hydrological setting for agriculture in high status catchments in Ireland, and 2) assess current nutrient management at field scale and the relative risk of P loss under different biogeochemical and hydrological conditions. To address these objectives, field-scale nutrient management data and soil geochemical and hydrological characteristics were collected from 520 fields surveyed across 39 farms set within three case study catchments. Field-scale P requirements, P applications, and P balances were examined along with field characteristics and combined in a field based risk assessment scheme to explore the extent to which current nutrient management practice poses a risk in high status catchments.

2. Methods

2.1. Characterisation of high status catchments

Three case study catchments were selected from an existing database of 508 high status catchments delineated in Roberts et al. (2016). Catchment selection used a simple multi-criteria decision approach to represent agriculture on the dominant soils across the wider high status catchment population. Of the 508 high status catchments those that had monitoring sites situated below 200 m in elevation and on river segments with Strahler stream orders ranging from 2 to 5 were selected