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Field soil and ditch sediment phosphorus dynamics from two artificially drained fields on poorly drained soils

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ABSTRACT

The installation of artificial drains alters soil permeability such that migrating water interacts with soil and sediment biogeochemistry to mobilise or attenuate phosphorus (P). Soil and ditch sediment P chemistry was explored at two artificially drained sites with similar land use, management and drainage class. Site A was characterised by high total P content (282–1437 mg kg^{-1}) and elevated water soluble P (WSP) (10.11 mg kg^{-1}) in a Humic topsoil. Subsurface horizons contained high amounts of leached aluminium (Al) and iron (Fe) and P sorption capacities expressed by the Freundlich K term increased with depth from 338 to 942 mg kg^{-1}. Site B was characterised by low TP (58–476 mg kg^{-1}) and low P sorption capacities (40–173 mg kg^{-1}) that decreased with depth, owing to a high% sand and low Al. Bankside and sediment in the ditch were mostly higher or comparable to P sorption properties measured in subsurface soil horizons from adjacent fields. Dissolved reactive P (DRP) concentrations were monitored in the open ditch, end-of-pipe and in-field piezometers and highest values were recorded in the open ditch (0.03–0.183 mg l^{-1}) at Site A, potentially due to diffuse and point sources on the farm. Higher P concentrations were recorded at end-of-pipe locations compared to piezometers at similar depth, and attributed to a larger contributing area reaching the pipe from the surface and surrounding subsurface layers. Attenuation of WSP by subsoil at Site A was evidenced by low piezometer values (0–0.003 mg l^{-1}). Low P sorption in the ditch at Site B suggests that dredging could expose low P sorbing layers, but adding topsoil could enhance P sorption. Drainage design, maintenance, and measures for P mitigation require an assessment of surface and subsurface P dynamics to ensure a 'right measure right place' approach.

1. Introduction

Pasture based livestock production systems such as dairy farming rely on grass growth as their primary source of animal feed and can be more complex than other international dairy systems where animals are primarily fed a total mixed ration diet in confinement (O'Mara, 2008). Maximising grass utilisation (growth and trafficability) can be constrained by soils with impeded drainage and low soil fertility. Constraints on agricultural production are often addressed by artificial land drainage to improve soil trafficability, grass growth and extend the grazing season. Artificial drainage networks are designed to direct infiltrating water along lateral subsurface pathways to open ditches or surrounding watercourses. Increasing this connectivity between in-field water and nearby watercourses carries a risk of nutrient loss that can adversely affect water quality. For phosphorus (P), the process has been conceptualised by Haygarth et al. (2005) as the P transfer continuum where P bound to soil can be mobilised and transported in pathways to a connecting watercourse where it can impact on surrounding water quality. Sources of soil P have been reported to originate from legacy applications that have built up, and recently applied P that is lost via incidental losses during storm events (Wall et al., 2011).

Assigning risk of P loss from fields has identified surface soil test P (i.e. plant available P) and legacy P as the source of P, but where subsurface pathways dominate most risk assessment schemes rarely considers the role of subsoil in P transfer. In managed grassland available P tends to accumulate at the soil surface with concentrations decreasing with depth in sub soil layers (Daly and Casey, 2005). Lower P concentrations in subsoil layers could allow for sorption of P mobilised from the soil surface in vertical pathways and recent studies have alluded to P attenuation at catchment scale where areas of the landscape can attenuate P thus

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creating dis-connectivity along the transfer continuum preventing delivery of P to receiving waterbodies. This has been reported in karst systems in which biogeochemical attenuation of P by calcium (Ca) has attenuated P transfer to groundwater (Mellander et al., 2012; Fenton et al., 2016) and in surface water-fed catchments characterised by high P fixing soils (Mellander et al., 2016; Shore et al., 2016; Daly et al., 2015).

At the sediment water interface, the source/sink dynamics of P reported in rivers and lake systems are complex processes driven by physicochemical properties such as pH, redox, Fe, Al, Ca, organic matter content, particle size distribution, sediment and pore-water P speciation and equilibrium P concentration in overlying water (Reddy et al., 1999). These interactions are poorly understood in drainage systems where the design and engineering hinges on redirecting water towards subsoil layers that can act as either source or sink for nutrients. End-of-pipe remediation systems (e.g. denitrifying bioreactor) or permeable reactive interceptors (Christianson et al., 2015; Fenton et al., 2016 Fenton et al., 2016) rarely consider the interaction of soil and subsoil biogeochemical characteristics with drainage water before installation. As water moves through artificial subsurface drains and open ditch networks it can access soil and subsoil chemical components that can both mobilise and attenuate P. As surface water can transport agricultural nutrients from the soil surface, these nutrients can continue to be mobilised through the network of artificial subsurface drains and open ditches, or, potentially attenuated through the interaction with soil minerals such as aluminium (Al), iron (Fe) and Ca that have a strong affinity for P (Daly et al., 2015; Shore et al., 2016). In grassland mineral soils, these elements are associated with P sorption and retention processes (Paulter and Sims, 2000; Maguire et al., 2001; Daly et al., 2015; McLaren et al., 2014) through the provision of sorption sites on clay surfaces. However, for high organic matter (OM) soils, such as organo-mineral soils, the presence of large amounts of OM occludes sorption sites provided by clay minerals and reduces sorption capacity and P retention (Guppy et al., 2005; Daly et al., 2001). In Irish grasslands Daly et al. (2001) demonstrated that P in these soils remains in soluble form and is prevented from adsorption onto the soil matrix, by the occlusion of sorption sites by OM. Whilst soil Al, Fe and Ca can promote sorption, elevated OM can prevent this process and P remains in the soil solution, available for transfer into connecting waters. As drainage networks are designed to redirect surface water and increase connectivity to open ditches and watercourses, the extent to which this poses a risk of P loss depends on what soil chemical components drainage water encounters along such migration pathways (overland flow, vertical, lateral or groundwater pathways). An important function of soil-water interaction is water purification by nutrient attenuation which varies according to soil characteristics (Schulte et al., 2014). Overall environmental sustainability of sites could include an assessment of the water purification function and a key question on any intensive managed grassland site is to assess if drainage installation and maintenance (open ditches) alters the soil water purification function, thereby leading to water quality issues.

This work examined the P dynamics of surface and subsurface soils (in-field and open ditch locations) and ditch sediments from artificially drained fields with adjacent open ditch networks. The objective was to assess their potential for mobilisation and attenuation of P through interpretation of their P sorption and desorption characteristics. A sub-objective of this study was to examine the interaction of soil biogeochemical properties with drainage water from surface and subsurface monitoring sites at field scale. Using two case-study sites, we describe and compare P characteristics in soil and ditch sediment, alongside water quality results from two fields with artificial drains installed in 2013. This study looks at the soil and sediment biogeochemistry within the first 2 years of installation during the 'settling down' of backfill materials at the sites. Both fields with receiving ditches were described by soil types with similar drainage class (impeded/poor) but contrasting biogeochemical characteristics.

2. Materials and methods

2.1. Site descriptions and sampling locations

Two commercial farms situated in the south-west of Ireland were used in this study and are currently part of a drainage programme which aims to improve managed grassland productivity and utilisation on poorly-drained soils. This study used fields located on both farms as case study sites, denoted here as A and B, within which, artificial drains were installed in June 2013 on approximately 2 ha of each farm. Drains were installed at 1.1 m depth at site A and 1.7 m depth at site B, surrounded by a gravel pack followed by subsoil and topsoil backfill.

The sites are located, 87 km apart, within regions where impeded or poor soil drainage (O'Sullivan et al., 2015) coupled with climate (precipitation less evapotranspiration) inhibits potential for production and on-farm profitability. Sites A and B are depicted in Figs. 1 and 2, respectively. Annual average (30 year) rainfall in the vicinity is 981.8 mm at Site B and 1621.5 mm in Site A, while annual evapotranspiration is approximately 480 mm in Site B and 430 mm in Site A. A met station was installed at each site, which enabled local rainfall data to be coupled (15 min resolution) with flow data (m^3 day^{-1}) measured by calibrated in-stream flumes (Corbett Concrete, Cahir, Tipperary) in tandem with mini-divers (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands) which monitored water flow rate in open ditches upstream and downstream of both drained sites. Flow data at site B was captured for only a portion of this monitoring period from 21/10/2015 to 6/5/2016.

Both sites are located on dairy farms with rotationally grazed permanent pasture and were stocked at rates of 2.38 and 2.47 cows per hectare on the grazing platform, respectively, during the study period. Agronomic soil testing for P was carried out on field composite samples taken to 10 cm depth and extracted using Morgan's reagent (Peech and English, 1944) and values of 1.8 and 6.5 mg l^{-1} were recorded at site A and B, respectively. Nutrient management plans for both farms were developed based on soil test results and management data to match P inputs with offtakes (Lalor and Coulter, 2008). Site A received 45 kg P ha^{-1} in 2015 and 52 kg P ha^{-1} in 2016. Similarly, site B received 48 kg P ha^{-1} in 2015 and 39 kg P ha^{-1} in 2016, in line with typical fertiliser application rates on both farms. The timing and rates of P applications during the water quality monitoring period are included in Figs. 6 and 7. For more precise field scale soil classification, farms were soil surveyed at a 1:10,000 scale. At each site, soil profiles were excavated to approximately 1 m and samples from each soil horizon were collected, analysed and archived. Both soil profiles were classified as poorly drained. Poorly drained here is defined as those showing mottling throughout the profile and have an argic (very high clay) or spodic (high in Fe, presence of Fe pan) horizon resulting in stagnation (Schulte et al., 2015).

Bankside and sediment samples were collected along the 100 m reach of ditch at Site A at 2 locations marked on Fig. 1 corresponding to the inlet (A1) and outlet (A2) points in the direction of flow along the ditch. Monthly grab samples of open ditch water were collected the same points (A1 and A2) and water collected from the end-of-pipe from an artificial drain feeding into the ditch at a mid-location along the ditch marked on Fig. 1. In addition, subsurface water was collected from an in-field piezometer (fully screened) at 1 m depth in the middle of the field and marked on Fig. 1. Bankside samples in the ditch were taken at 3 depths (25 cm, 65 cm and 1.1 m – end-of-pipe depth) and sediment samples were collected from the base of