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Use of a flashiness index to predict phosphorus losses from subsurface drains on a Swedish farm with clay soils

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ABSTRACT

Risk assessment for elevated leaching losses of phosphorus (P) from agricultural land is commonly based on indices, since such losses are highly episodic and difficult to predict. Here a flashiness index (FI) representing changes in daily water flow from drainage systems was estimated from measured discharge (agrohydrological years 2004–2013) after reconstruction of subsurface drainage systems in 16 fields on a former swine farm. The fields were analysed for ammonium lactate-extractable soil P (P-AL), clay, carbon and other soil parameters in 2004. Transport of total P (TP), dissolved reactive P (DRP) and unreactive P (UP) was estimated from concentrations in composite water samples taken flow-proportionally up to 20 times per year. On average, 2.20 kg TP ha^{-1} yr^{-1} was leached, with 27% in DRP form, from the entire farm. FI was significantly negatively correlated (Pearson correlation coefficient $p < 0.05$) to mean yearly discharge from each field. Stepwise regression demonstrated that FI index was the most important single explanatory parameter for flow-proportional yearly mean concentration of unreactive P losses (UP) from each field, with a coefficient of determination (r^2) of 0.67. The corresponding concentration of dissolved reactive P (DRP) was significantly positively correlated ($p = 0.015$) to soil P-AL and FI. A regression model for TP leaching losses based on FI, P-AL and yearly discharge (*Q*) from 11 of the fields over nine years ($r^2 = 0.67$, $p = 0.002$) was validated against TP leaching from the remaining five fields (32% of farm area). Root mean square error (RMSE) was 0.43, which represented 20% of measured leaching (mean 2.14 kg TP ha^{-1} yr^{-1}). For individual years, RMSE for different fields was 37–80% of measured TP leaching (0.8–3.7 kg TP ha^{-1} yr^{-1}). The FI index could be used together with soil P test to predict P leaching from individual fields of a drained farm.

1. Introduction

Eutrophication continues to be a great concern for lakes, rivers and brackish estuaries around the world, with losses of phosphorus (P) from arable land being a major contributor (Sharpley et al., 2015). It is generally assumed that agronomic soil status affects P losses, primarily in the form of dissolved reactive P (DRP) (McDowell and Sharpley, 2001), but high soil P status may also affect the transfer of erosion-bound P to water (Schärer et al., 2007). Partitioning between DRP and erosion-bound P is highly important from an ecological point of view (King et al., 2015) and for modelling P losses (Radcliffe et al., 2015). The latter point out the importance of subsurface drains in modifying the hydrological regime, making it a factor which should be taken into account in P risk assessments.

Land drainage is a common and necessary practice for crop production in areas of precipitation surplus and/or soils world-wide with poor natural drainage properties (King et al., 2015). Glacial clay soils have often high water-holding capacity and low hydraulic conductivity, with prolonged water-logging if poorly drained. With improved drainage, less water is stored semi-permanently on the soil surface and in the topsoil and less water is evaporated (Blann et al., 2015). In cold areas with flat topography, effective drainage is mostly important to avoid surface runoff in spring and snowmelt flooding (Jin et al., 2008).

In Sweden, half the arable land in use today has subsurface drainage, with collection tubes or pipes arranged in more or less regular systems and commonly placed at a depth of 1 m. The distance between drains varies between 8–30 m and is usually 12–16 m, even at sites where a closer drain spacing would be appropriate to meet the drainage needs. Another 20% of Swedish arable land has drainage systems with a few single pipes which cover the most essential drainage needs. Most systems are old (Elmquist, 2014) and they often need to be renovated, e.g. by repairing pipes or

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changing to a modern drainage system. The oldest Swedish systems consist of tile drains which were installed manually in the 1930s and 1940s. From the 1970s, machines for digging and placement of flexible corrugated plastic tubes became available and filters in the form of coarse gravels were placed around the corrugated tubes. Water enters through perforations located in the troughs of the pipe corrugations. Elongated openings ('slots') are common, usually with diameter 0.6–2 mm, but circular openings are also used. The openings are usually evenly distributed in at least four rows around the pipes. Since they represent a large inlet area (at least 10 $cm^2\ m^{-1}$ for pipes of 50 mm diameter and 12 $cm^2\ m^{-1}$ for pipes of >63 mm diameter), drainage has become more effective than in the past, when the use of tiles restricted water intake to the joins between the pieces of tile. For erosion-prone silty–clayey soils with an 'open structure' with cracks and macropores, accumulated sediment transported via such pathways may block the drainage pipes after some years (Øygarden et al., 1997). In more silty soils, stratified gravel (8–16 mm) backfill is commonly used to protect the drains from clogging.

Extremely fast and dynamic channel water flow from the topsoil down through the soil (commonly named preferential flow) may be the main reason for elevated concentrations of P and pesticides in drains (Jarvis, 2007). In addition, strong indications of preferential particle transport from topsoil via backfill into drains were reported by Øygarden et al. (1997). In a Swedish study, a gradient in preferential flow along the 400 m distance towards the centre of a flat valley with clay soil was suggested to be the explanation for spatial variation in P leaching, since it followed the same spatial pattern as leaching of various pesticides (Ulén et al., 2013). 'Peak flows' (quick flows evident as peaks on hydrographs) are generally reduced by improved drainage. Losses of sediment and sediment-bound P from artificially drained arable soils are also usually small compared with losses from arable soils on naturally well-drained uplands (Skaggs et al., 1994). The general assumption is that a change in the runoff generation mechanism from overland flow to subsurface drainage flow can occur and that such effects are especially pronounced for waterlogged, clay-rich soils (Rahman et al., 2014). Skaggs et al. (1994) also speculated about frequent preferential flows and sediment losses in swelling–shrinking clay soils.

Subsurface drainage water is a mixture of shallow groundwater and precipitation water that has infiltrated into the soil and moved downwards, mainly by preferential flow or through drain backfill (Stamm et al., 2002). Dilution of the P-rich water from the topsoil may take place when mixed with groundwater, which is usually poor in P. Such dilution may be one reason for the weak relationship or lack of relationship between P leaching (estimated as water discharge multiplied by P concentration) reported for different subsurface drainage systems in the same area (Madramootoo et al., 1992; Macrae et al., 2007). This also implies that the hydrological characteristics of water flow through the drain may be highly important for water quality.

A simple hydrological index is the run-off coefficient, i.e. water runoff (or drain discharge, Q) divided by precipitation (Prec), but this index does not include any flow dynamics. Another hydrological index is the frequent used base flow index (BI), i.e. the ratio between shallow groundwater and total water in a stream or river. In a watershed stream, BI has been demonstrated to be higher in agricultural areas with more subsurface drainage, since a larger fraction of flow is transported through subsurface pathways (Shilling and Helmers, 2008). The BI index can be estimated from hydrographs using different methods (e.g. Gustard et al., 1992), but this is problematic for small ditches and subsurface drains which frequently run dry in dry summers and periods of winter frosts. Moreover, the BI index does not illustrate the highly dynamic flows from the soil surface downwards through the soil. A suitable index should cover all rapid flow periods, but also water flow conditions following rewetting of dried soil and thawing of frozen soil, since both drying and freezing have a significant impact on soil P solubility and sorption (Peltovuori and Soinne, 2005). A 'flashiness' index (FI), known as the Richards–Baker index, representing the changed water-flow from the time-step before the actual time period was introduced by Baker et al. (2004). Total flow is usually one year and may be expressed as mm^{-yr}. Actual time-step is usually one day. A time resolution of hour has also been suggested (Deelstra et al., 2014). However, even hourly resolution is much longer than the time taken for macropore-induced infiltration through the soil profile, which may be a few minutes or even seconds (Beven and Germann, 2013). Nevertheless, any dampening in water movement induced by a rising groundwater level and prolonged recession might be indicated by FI values derived from flow measurements stored as daily values.

In estimating any P index for the risk of high P losses (Lemunyon and Gilbert, 1993) both source factors and transport factors are used. The P index was originally developed to reflect potential P losses with surface runoff and as an overall field rating to the edge-of-field. In later studies, the P index has also been regarded as a model and has been used for estimating more or less absolute P losses, even in drained areas (Radcliffe et al., 2015). In some risk indices, subsurface drains are only regarded as a risk factor in terms of location of outlets relative to surface water (Reid et al., 2012), while any general effect from good drainage is overlooked. However, Sharpley et al. (2013) propose that more attention should be given to the contribution to P leaching made by accumulated P from former surpluses. Phosphorus leaching from such 'legacy P' (caused by more P being applied than is removed by the crop) may require a recovery period of many years to several decades before P concentrations start to decrease (Sharpley et al., 2014).

The overall aim of the present study was to present P concentrations and leaching losses from a well-drained farm studied for 9 years. An additionally aim was to evaluated how the FI factor (characterising flow dynamics) together with a soil P test (soil P-AL concentration), and representing topsoil P source, affected DRP and UP concentrations in drain tile water for each individual field of a farm. A specific aim was to derive a local regression model for P leaching based on some of the fields and validate from P leaching from the remaining fields.

2. Materials and methods

2.1. Site description

The research farm Logården is a former swine farm, but currently without livestock, situated in SW Sweden (Fig. 1). Nitrogen (N) and P leaching over a 4-year period have been evaluated for this farm, primarily using information on general agricultural management and soil characteristics (Stenberg et al., 2012). No liquid manure was used in the period (9 years) analysed in the present study. The farm has 16 experimental fields (2–4.2 ha) which since 1991 have been managed conventionally (2 fields), organically (7 fields) or in an integrated system (7 fields) (Fig. 1). Conventional farming without livestock requires import of N and P in mineral fertiliser. Tillage operations for incorporation of crop residues, management of weeds and soil loosening commonly comprise mouldboard ploughing of the topsoil, which may take place in autumn in preparation for either autumn crops or spring crops. In organic farming, no mineral fertilisers are used and only certified organic fertilisers are accepted. Green manure (grass-legume leys) can supply P to the topsoil by root uptake and P release on incorporation. Intensive ploughing and other soil tillage operations