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A sub-field scale critical source area index for legacy phosphorus management using high resolution data

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ABSTRACT

Diffuse phosphorus (P) mitigation in agricultural catchments should be targeted at critical source areas (CSAs) that consider source and transport factors. However, development of CSA identification needs to consider the mobilisation potential of legacy soil P sources at the field scale, and the control of (micro) topography on runoff generation and hydrological connectivity at the sub-field scale. To address these limitations, a 'next generation' sub-field scale CSA index is presented, which predicts the risk of dissolved P losses in runoff from legacy soil P. The GIS-based CSA Index integrates two factors; mobile soil P concentrations (water extractable P; WEP) and a hydrologically sensitive area (HSA) index. The HSA Index identifies runoff-generating-areas using high resolution LiDAR Digital Elevation Models (DEMs), a soil topographic index (STI) and information on flow sinks and effects on hydrological connectivity. The CSA Index was developed using four intensively monitored agricultural catchments (7.5–11 km^2) in Ireland with contrasting agri-environmental conditions. Field scale soil WEP concentrations were estimated using catchment and land use specific relationships with Morgan P concentrations. In-stream total reactive P (TRP) concentrations and discharge were measured sub-hourly at catchment outlet bankside analysers and gauging stations during winter closed periods for fertiliser spreading in 2009–14, and hydrograph/loadograph separation methods were used to estimate TRP loads and proportions from quickflow (surface runoff). A strong relationship between TRP concentrations in quickflow and soil WEP concentrations ($r^2 = 0.73$) was used to predict dissolved P concentrations in runoff at the field scale, which were then multiplied by the HSA Index to generate sub-field scale CSA Index maps. Evaluation of the tool showed a very strong relationship between the total CSA Index value within the HSA and the total TRP load in quickflow ($r^2 = 0.86$). Using a CSA Index threshold value of ≥ 0.5, the CSA approach identified 1.1–5.6% of catchment areas at highest risk of legacy soil P transfers, compared with 4.0–26.5% of catchment areas based on an existing approach that uses above agronomic optimum soil P status. The tool could be used to aid cost-effective targeting of sub-field scale mitigation measures and best management practices at delivery points of CSA pathways to reduce dissolved P losses from legacy P stores and support sustainable agricultural production.

1. Introduction

Diffuse phosphorus (P) losses from agricultural land to surface waters continue to be a major pollution issue worldwide, causing deterioration of water quality and impacts on ecosystem services (European Environment Agency, 2015; McDowell et al., 2015; Sharpley and Wang, 2014). As a result, mitigation measures are part of wide ranging and international environmental policies and

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legislation (Schoumans et al., 2014; McDowell and Nash, 2012). Catchment areas at greatest risk of P transfers are termed critical source areas (CSAs), where high concentrations of mobile P coincide with hydrologically sensitive areas (HSAs) which have high runoff potential (Pionke et al., 2000; Walter et al., 2000). CSAs must be accurately identified if mitigation measures and best management practices are to be targeted, cost-effective and successful in reducing P losses (Doody et al., 2012; Sharpley et al., 2011).

A number of P CSA Indices exist, which range in terms of the source, mobilisation and transport factors used, weightings, formulation, and whether they predict relative P loss risk or quantify P loads (Heckrath et al., 2008; Buczko and Kuchenbuch, 2007). In the USA, where CSA Indices are termed P Indices, concerns have been raised over inconsistencies, state-by-state variability, and the lack of calibration and evaluation using measured P loss data (Osmond et al., 2012; Nelson and Shober, 2012). Slow improvements in water quality following over twenty years of regulatory implementation also suggest that such CSA definitions are limited (Sharpley et al., 2011, 2012), leading to calls for refinements (Sharpley et al., 2013a).

CSA Indices currently use agronomic soil P tests as a source factor. Soils with high total P concentrations have historically received excessive manure or fertiliser P applications that outweighed crop requirements (Kleinman et al., 2011). However, agronomic soil P tests do not consider the mobilisation potential of this residual or 'legacy' soil total P to be released to runoff pathways, despite mobilisation being a fundamental component of the P transfer continuum (Haygarth et al., 2005). The natural affinity of soils to bind and immobilise P varies based on soil properties such as aluminium (Al), iron (Fe), calcium carbonate, clay, pH and organic matter (OM), and hence in some soils, legacy P (total P) is more vulnerable to desorption, solubilisation and transport in surface runoff (Daly et al., 2001, 2015; Maguire and Sims, 2002). Thus different soils can have the same amount of total P, but different amounts of available P, and vice-versa.

Environmental soil P tests such as water extractable P (WEP) (also known as water soluble P) are considered better at replicating the chemical interaction between soil P and runoff and are less affected by soil type, and hence are arguably better at predicting dissolved P concentrations in runoff (Torbert et al., 2002; Pote et al., 1999; Penn et al., 2006). Some CSA Indices already use the WEP test as a 'P source coefficient factor' to predict the mobilisation potential of fertiliser P in runoff (Kleinman et al., 2007; Shober and Sims, 2007). However, the WEP test has not yet been widely applied as a specific legacy soil P risk assessment; exceptions include Regan et al. (2010, 2014), Ulén et al. (2011), Djodjic and Bergström (2005), and Dodd et al. (2012).

Another limitation of conventional CSA definitions is the use of watercourse proximity as a proxy for runoff risk and P transport potential (Gburek et al., 2000; Srinivasan and Mcdowell, 2007). This is recognised as an extreme simplification of reality which does not account for the effects of (micro)topography on the generation, channelisation, convergence and hydrological

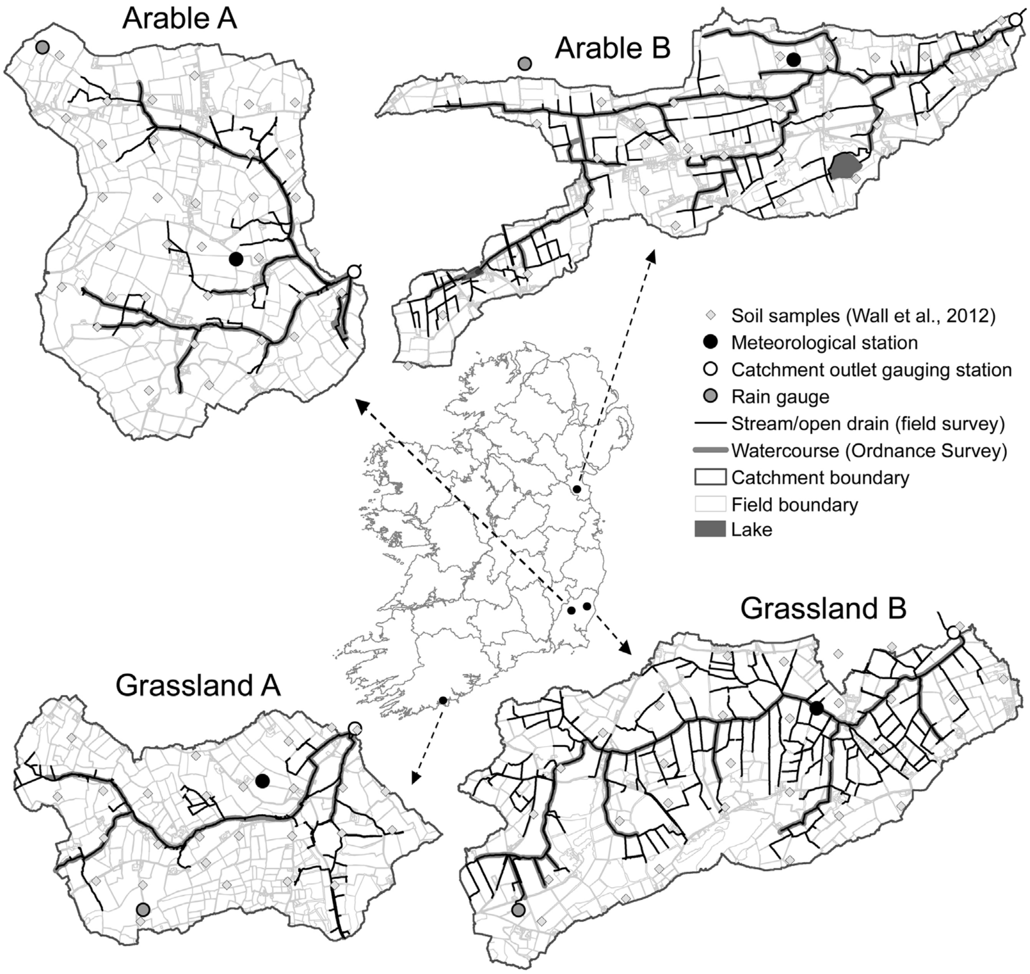

Fig. 1. Locations of the agricultural catchments in Ireland used in the study. Also indicated are the stream and drainage channel networks, catchment outlet gauging station, meteorological station, and locations of the spatially stratified soil samples taken by Wall et al. (2012).