# A carrying capacity framework for soil phosphorus and hydrological sensitivity from farm to catchment scales

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## HIGHLIGHTS

- Soil P and HSA runoff was risk mapped for 7693 fields in a 220 km² catchment.
- Soil P and HSA risks were assessed at field, farm and catchment scales.
- The framework identifies and prioritises areas posing risks to water quality.
- Carrying capacity for above agronomic optimum soil P is 15% of sub-catchment areas.
- Carrying capacity for high soil P and runoff risk is 1.5% of sub-catchment areas.

## GRAPHICAL ABSTRACT
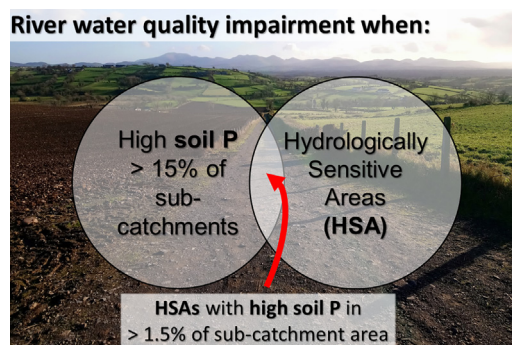
## ABSTRACT

Agricultural fields with above optimum soil phosphorus (P) are considered to pose risks to water quality and especially when those areas are coincident with hydrologically sensitive areas (HSAs) that focus surface runoff pathways. This is a challenge to manage in areas of agricultural intensity in surface water dominated catchments where water quality targets have to be met. In this study, a soil P survey of 13 sub-catchments and 7693 fields was undertaken in a 220 km² catchment. HSAs were also determined as the top 25th percentile risk from a runoff routing model that used a LiDAR digital elevation model and soil hydraulic conductivity properties. Distributions of these spatial data were compared with river soluble reactive phosphorus (SRP) concentration measured fortnightly over one year. The results showed that 41% of fields exceeded the agronomic optimum for soil P across the sub-catchments. When compared with the available water quality data, the results indicated that the high soil P carrying capacity area of the sub-catchments was 15%. Combining high soil P and HSA, the carrying capacity area of the sub-catchments was 1.5%. The opportunities to redistribute these risks were analysed on fields with below optimum soil P and where HSA risk was also minimal. These ranged from 0.4% to 13.8% of sub-catchment areas and this limited potential, unlikely to fully reduce the P pressure to over-supplied fields, would need to be considered alongside addressing this over-supply and also with targeted HSA interception measures.

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## 1. Introduction

Combining agricultural production and environmental targets can be challenging in intensive settings and may result in trade-offs between these objectives (Macintosh et al., 2019). Water quality impacts, for example, through transfer of residual nutrients such as nitrogen (N) and phosphorus (P), pesticides and eroded soil surfaces are well-established pressures (Jarvie et al., 2007; Withers and Lord, 2002) and reported on a global scale (Schoumans et al., 2014; Withers et al., 2014). In European Union member states this agricultural pressure for nutrients is managed through state-based action programmes linked to the Nitrates Directive (91/676/EEC, Council of the European Union, 1991), or by policy driven voluntary schemes to which farmers subscribe (Batáry et al., 2015; Lastra-Bravo et al., 2015; Pavlis et al., 2016).

Compliance with the Nitrates Action Programme in Northern Ireland, which covers both the Nitrates Action Programme Regulations as well as the Phosphorus (Use in Agriculture) Regulations, is compulsory for farmers. The Programme includes constraints to the use and magnitude of nutrient applications via chemical fertiliser or organic manure amendments, the control of application timing and of animal stocking rates on a per hectare basis (The Nitrates Action Programme Regulations (Northern Ireland) 2014 No. 307, 2014). Voluntary schemes provide financial incentives and support to farmers to increase water purification functions through measures which intercept surface runoff pathways and entrap water-borne nutrients, including sediments and other pollutants (DAERA, 2018a). Such options include the use of cover crops to retain nutrients on arable land (Cooper et al., 2017) and the establishment of riparian buffer zones adjacent to watercourses. In many countries, these regulations and schemes are applied at the largest scales as blanket, one-size-fits-all policies either in specifically vulnerable zones or as whole territory measures (McDowell et al., 2016). In the EU, checks, or cross-compliance, against regulatory measures determine Basic Payment Scheme (BPS) support, which is allocated on the basis of farm area as a monetary subsidy.

The specifications for regulations and supported actions in environmental schemes are very tightly restricted to enable auditing and protect against fraud (Fraser, 2012; Hart and Latacz-Lohmann, 2005). However, the resulting rigidity may lead to actions being implemented which fail to deliver (reach their potential) as they may not be adaptable to suit local land use, terrain, soil or hydrology. On a larger scale, catchment carrying capacities have been proposed (Doody et al., 2016) as a means to identify pressure thresholds beyond which water quality is likely to be impacted. The implication is that, inside of these pressure thresholds, opportunities for supporting activities (that cause pressures) exist but which the catchment can absorb. This approach requires practical, adaptive tools to bridge the gap between general measures and specific targeted actions, designed for maximum effect, at field and farm-scale.

Soil with high residual soil P concentrations, particularly beyond those levels required for optimum agronomic production, has been identified as a water quality pressure in areas with intensive agriculture (Jarvie et al., 2013; Sharpley et al., 2013). As a policy instrument, the threshold to agronomic production is used as the upper limit of acceptable soil P fertility with an implication that fertility above this threshold is both of little agronomic utility and poses an increasing environmental risk. Maintaining soil P fertility at or below this upper limit assumes that the water quality risk is reduced (but not entirely removed) and that the needs of good agronomic production are maintained (Macintosh et al., 2019).

Moreover, the principle of critical source areas (CSAs) recognises that the source pressure (i.e. residual and high soil P fertility) requires a mobilisation process to transfer P to watercourses and become a eutrophication impact. In the case of soil P (and sediment), hydrologically sensitive areas (HSAs) have been proposed as zones more prone to surface runoff during storm events (Thomas et al., 2016a) and act to transfer P more readily and particularly when these HSAs are coincident with soils of high soil P fertility (Thomas et al., 2016b). At field scale, micro-topography can influence the generation and impedance of surface runoff and this can be spatially modelled using LiDAR digital elevation data and soil topographic indices (Thomas et al., 2017, based on Beven and Kirkby, 1979).

Scale needs to be considered in identifying field and farm-scale environmental risks and opportunities for soil P fertility (and other conditions) (Wall et al., 2012) and in identifying catchment carrying capacities when water quality is also a factor. With the latter, water body chemical and biological thresholds are used to determine boundaries between what is and is not acceptable which, for chemistry, can include single standard concentrations or more flexible standards based on ambient conditions (Tappin et al., 2018; UKTAG, 2013). More often, for nutrients, these standards in rivers are based on the relationship between time-averaged nutrient concentrations and biological metrics (Bouleau and Pont, 2015). However, setting one-size-fits-all constraints at field and farm scale for pressures, including P, does not necessarily align with the thresholds set for water bodies where quality is an integrated effect from catchment hinterlands. Resolution of risks, opportunities and catchment carrying capacities across the different scales has clear utility for all actors concerned with balancing production and environmental quality needs in agricultural landscapes, from farmers to policy makers.

The aim of this study was to provide a transferable framework for field to catchment scale risks and opportunities based on soil fertility and HSA status. The objectives were to:

1. Assess the distribution of soil P concentration and HSA risk in river catchments.
2. Assess soil P carrying capacity at the catchment scale relating to water quality.
3. Determine the opportunities for redistributing soil P risk within farms and river sub-catchments.

## 2. Methods

### 2.1. Study area

This study was undertaken in the Upper Bann river catchment draining an area of 220 km$^2$ in the Neagh-Bann International River Basin District in Northern Ireland (NI) (Fig. 1). The headwaters rise in the Mourne Mountains, and flow north to the catchment outlet (for this study) near the town of Banbridge. The Upper Bann continues to Lough Neagh (surface area 392 km$^2$ - the largest freshwater lake in the UK and Ireland) as one of six inflowing rivers.

The Upper Bann catchment is underlain by meta-sedimentary and igneous bedrock units; from granites in the headwaters into shale and sandstone greywacke and granodiorite units in the lowlands. Soils are clay-rich glacial tills derived from the underlying parent material and deposited as drumlins and ribbed moraines at the end of the last Glacial Maximum 14–15 ka BP (McCabe et al., 2005). This resulted in an undulating topography of steeply sloping hills and ridges of slowly permeable soil, with flat inter-drumlin areas where peats formed and natural drainage is poor (Cruickshank, 1997). Annual mean rainfall, over the period 1981–2010, is 600–800 mm in the lowlands and 800–1200 mm in the uplands (UKMO, 2018).

Land use in the catchment is dominated by grass-based agriculture (95% grassland) with dairy (13% of the area), beef (26%), sheep (18%) and mixed livestock (32%) enterprises accounting for the majority of farm holdings. Arable crops are grown primarily as feed on mixed enterprises (8%), with <3% of holdings exclusively arable. Farm holdings within the catchment are generally smaller than the NI mean of 41 ha, and these have a mean field size of 0.94 ha (IQR of 0.53–1.57 ha). Enterprises range from larger, intensive (generally dairy) farms with high stocking densities that require a derogation to operate at a higher rate of nutrient application than the default 170 kg N ha$^{-1}$ yr$^{-1}$, to extensively managed small farms with low stock numbers.
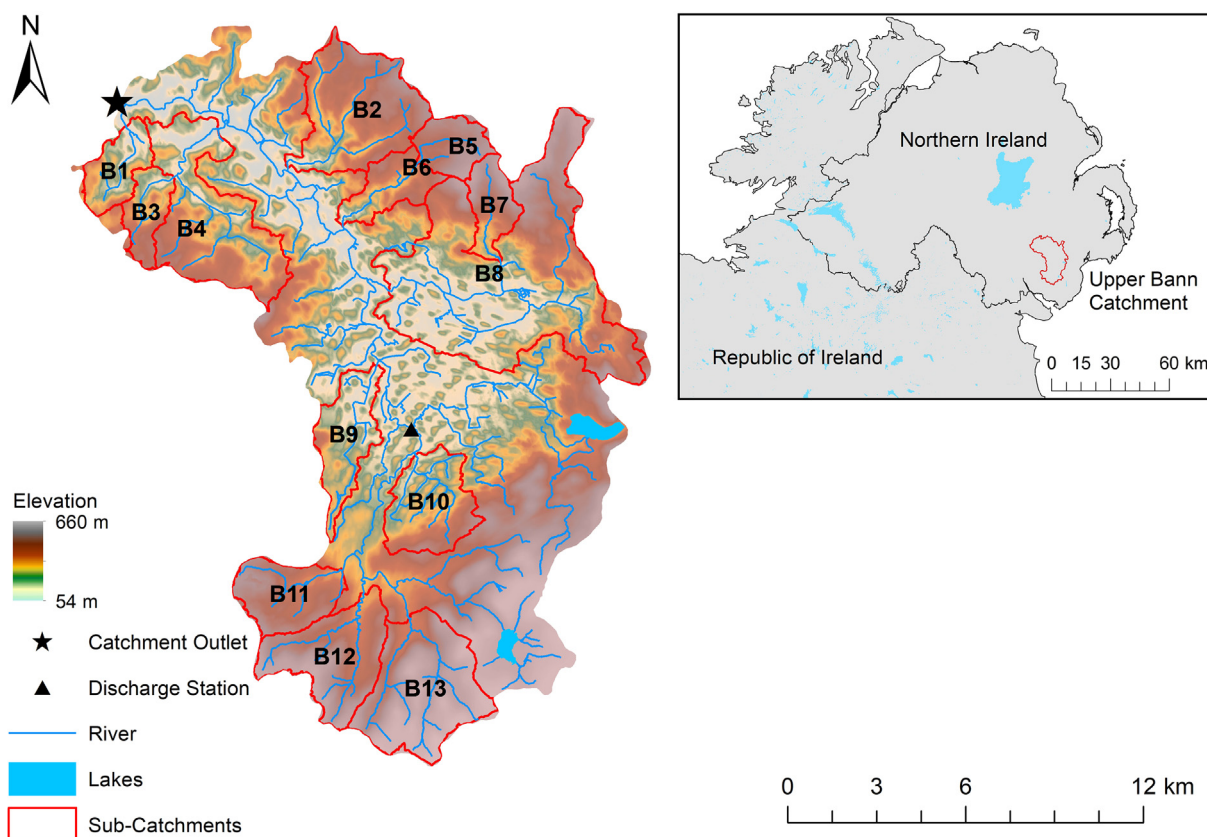
**Fig. 1.** Locations of the Upper Bann catchment and sub-catchments (B1–B13) in which soil sampling, risk mapping and water quality monitoring were undertaken.

A good-moderate soluble reactive P (SRP) chemical water quality boundary (to support biological data) has been defined for the Upper Bann as 48 μg L$^{-1}$, a site specific class boundary value for good-moderate water status at the Upper Bann outlet based on alkalinity and altitude The range of good-moderate class boundary values for Water Framework Directive (WFD) waterbodies within the Upper Bann is 28–55 μg L$^{-1}$ and the median is 48 μg L$^{-1}$.

### 2.2. Soil tests, HSA mapping and water quality

The majority of livestock farms in NI do not routinely test soil fertility and only do so as part of Nitrates Directive derogation requirements at higher stocking densities. This lack of soil testing has been highlighted as a major impediment to agricultural development within NI (Expert Working Group on Sustainable Land Management, 2016). Accordingly, as part of an EU sponsored scheme extended to livestock farmers in 2017–2018 (EU REF Commission Delegated Regulation (EU) 2016/1613; European Commission, 2016) soils within water quality monitoring sub-catchments were tested on a field-by-field basis for soil fertility and lime requirements. On 513 farms operating within 11 sub-catchments of the Upper Bann 7772 fields soils were sampled between November 2017 and February 2018. Soils in a further 718 fields on 18 farms in two additional sub-catchments (B3 and B5), were sampled as part of a linked project earlier in 2017 and were appended to the data set to extend coverage. A total of 7693 fields lie exclusively within the 13 sub-catchment boundaries.

In each field, 40 representative soil sub-samples were collected using a 15 mm inner diameter, open-sided agronomic soil sampler and following the standard "W" pattern to maximise coverage across the field extent. Plug cores were taken to a depth of 7.5 cm, avoiding any disturbed ground or animal manure, and composited into one sample in a sealed, labelled bag with a unique identification. GPS tracks of all sampling paths were recorded and used to cross-check and verify the

samples. Soil samples were air-dried at 30 °C and ground and passed through a 2 mm sieve prior to analysis.

For each 10 mL soil sample, Olsen P (the agronomic soil P test in NI) was determined on a 1:20 soil to 0.5 M sodium bicarbonate solution ratio at pH 8.5 (Olsen et al., 1954) shaken in an orbital incubator at 180 rpm at 20 °C for 1 h. The concentration of P in the filtered extract (8 μm, Whatman No. 40, 11 cm) was determined colorimetrically (at 880 nm) using a Skalar San$^{++}$ auto-analyser following Murphy and Riley (1962) and expressed on a soil volumetric basis (mg P L$^{-1}$). Each batch of 50 processed samples contained a quality control (QC) soil sample in positions 1, 25 and 50. Calibration standards and QC check standards were read in each batch and analysis repeated if any of the QC checks failed. Each soil sample P concentration was then assigned its corresponding agronomic Olsen P Index (0–9) using RB209 (DEFRA, 2010), the UK standard for soil fertility recommendations and advice (Table 1).

HSA risk maps were also generated using LiDAR data to indicate areas at risk of contaminant mobilisation and transport in surface runoff pathways at field scale. A LiDAR survey of the Upper Bann catchment

**Table 1**
Soil test P indices used in Northern Ireland.

| Soil test P index | Olsen extractable phosphorus (P) (mg P L$^{-1}$) | |
|---|---|---|
| 0 | 0–9 | |
| 1 | 10–15 | |
| 2− | 16–20 | |
| 2+ | 21–25 | Agronomic optimum |
| 3 | 26–45 | |
| 4 | 46–70 | |
| 5 | 71–100 | |
| 6 | 101–140 | |
| 7 | 141–200 | |

was commissioned in 2015 with data capture at a bare-earth resolution of 4–10 points m$^{-2}$. The raw LiDAR point cloud was converted to a 2 m raster Digital Elevation Model (DEM) to optimise surface and subsurface flow routing and account for micro-topography (Thomas et al., 2017). The river, stream and open ditch drainage networks were manually digitised, using the LiDAR DTM and ortho-imagery as a guide, and burned into the DEM by a user-defined depth of 100 m within SAGA GIS (Conrad et al., 2015) to hydrologically correct it. Flow sinks were filled using the XXL method of Wang and Liu (2006), which is a more computationally efficient algorithm for high resolution LiDAR datasets. Flow direction and flow accumulation (Deterministic Infinity, Tarboton, 1997), slope (Zevenbergen and Thorne, 1987) and topographic wetness index (TWI; Beven and Kirkby, 1979) rasters were then calculated using SAGA GIS (Conrad et al., 2015). To account for variations in soil hydraulic properties the TWI was developed into a Soil Topographic Index (STI) using the mean saturated hydraulic conductivity in the soil profile and soil depth for each soil series (1:50,000 General Soil Map of Northern Ireland, AFBI, 2009) in the catchment using historical data and expert judgement where required. This method and workflow are described in detail in Thomas et al. (2016a). In summary, each 2 m pixel was assigned an STI value:

$$STI = \frac{a}{\tan\beta} - K_{sat}D \tag{1}$$

where $a$ is the cumulative upslope contributing area per unit contour length (m), $\tan\beta$ is local slope (radians), $K_{sat}$ is the mean saturated hydraulic conductivity (horizon depth weighted, m day$^{-1}$) and $D$ is the total soil depth (m) (Walter et al., 2002). Higher STI values are reflective of higher accumulated field runoff potential.

In the 13 sub-catchments' outlets, water samples were collected on a fortnightly basis by manual grab sampling. Polythene sample bottles (2 L volume) were kept chilled during transit and returned directly to the laboratory once the sampling round was complete. Following filtration (0.45 μm), samples were analysed in batches for SRP on a Thermo Scientific Aquakem using the standard colorimetric method of Murphy and Riley (1962). Calibration was undertaken at least daily and re-run if the fit of the calibration line was r$^2$ < 0.9950 and absorbance values were >0.520 nm for a standard solution of 1000 μg L$^{-1}$ SRP. QC standards were run in each batch of samples analysed. Data were used for one hydrological year (October 2016–September 2017) leading up to the period of soil sampling. This water sampling protocol follows an established and long-term programme for the Upper Bann and other Northern Irish catchments based on fortnightly sampling described by Foy and Kirk (1995) and Barry and Foy (2016). The Upper Bann water quality dataset was, therefore, compared with the annual hydrograph to place SRP concentration data into context with the hydrological conditions of the sampled river water. This hydrograph was from a Rivers Agency hydrometric station at the approximate centre of the catchment (shown on Fig. 1) which records stage height and converts to discharge at five minute intervals. For each of the 13 sub-catchments the proportion of the sampled sub-catchment area exceeding the agronomic optimum soil test P was calculated and compared to the annual median SRP concentration at each outlet calculated using the fortnightly SRP data using least-squares regression. This temporal resolution is justified as the analysis was based on ambient river SRP concentrations as indicators of ecological status, and not annual loads where the inclusion of storm event data would be more important.

### 2.3. Data analysis

All data collected for this study are strictly protected to ensure farmer anonymity and so spatial data are not available for publication. However, distributions of soil P indices and HSA risks were extracted for comparison and collated at the field, farm and sub-catchment scale following Wall et al. (2012).

Phosphorus was demarcated at the upper limit of the optimum Olsen P Index 2+ (16–25 mg L$^{-1}$) where higher concentrations (≥26 mg L$^{-1}$) are considered residual to agronomic optimum performance and an environmental risk.

To delineate HSAs using the STI, Thomas et al. (2016a) estimated the total runoff generating area (HSA size) during storm events in intensively monitored agricultural catchments in Ireland based on the volume of direct runoff from discharge hydrographs (m$^3$) divided by rainfall (m). They then selected the catchment areas with the highest STI values until the area selected was the same as that empirically estimated (using catchment STI value distributions and their cumulative catchment area to define a threshold STI value above which is a runoff-generating-HSA). In this study, similar hydrometeorological data were not available at sub-catchment level and so risk was based on ranked percentiles where the top 25% of STI values were determined as high risk HSAs and the top 10% as very high risk HSAs. This decision was based on expert judgement (using the HOST (Hydrology of Soil Types) classification of gleyed soils across the Upper Bann catchment; Cruickshank (1997)) and field observations of overland flow during storm events.

Fields were classified based on visual inspection of detailed ortho-imagery to identify grassland fields with <50% rye grass cover, or where rush or scrub growth was present, typical of rough or lower intensity grazing practices. These low intensity areas were omitted from an analysis that identified theoretical opportunities for increasing soil P concentrations, due to higher overall inherent risk to water quality and lower economic potential for recovering nutrients in grass (i.e. poorly drained).

Fields, and sub-field areas, providing a theoretical opportunity for P amendments were identified at farm scale, where the full holding irrespective of the sub-catchment boundaries was considered, and at sub-catchment scale, where holdings were clipped to the sub-catchment boundary. Areas of opportunity were identified based on four criteria which each needed to be met: (1) a field soil test P below the agronomic optimum (2) the avoidance of high risk HSA by at least a 5 m buffer (adopting current regulations for spreading near waterbodies) (3) current land use not classed as low intensity and (4) the area being a compact block of not <0.2 ha. The latter criterion is based on the minimum area which would be practical for the application of cattle slurry or farmyard manure, using a standard tractor and spreader configuration (33.5 m$^3$ ha$^{-1}$ = a 1500 gal slurry tanker spread on a half-acre). From a subset of fields meeting criteria (1) to (3) the remaining area of each field was polygonised and quantified to exclude those <0.2 ha. To limit the set to those polygons with a regular, blocky shape suitable for application the ratio of polygon area to perimeter was used to exclude polygons with a ratio of <0.4.

## 3. Results

### 3.1. Distribution of soil P concentration and HSA risk

Soil test P varied among and within farms, and across the sub-catchments. The arithmetic mean of soil test P across all fields was 26.9 mg P L$^{-1}$ (Index 3), just in excess of the agronomic optimum defined as Index 2+ (21–26 mg L$^{-1}$ Olsen P) (Table 1). Within the entire sample set (n = 7693) 41% of fields exceeded the agronomic optimum, with a majority of those (28.9%) at Index 3 (Fig. 2a). A larger proportion (45.7%) was below the agronomic optimum (<21 mg L$^{-1}$ Olsen P), with 9.9% of fields at Index 0. A majority of farms exhibited an imbalance in soil fertility across fields; with a tendency to have high soil P in large fields close to the farm compared with those at the extremity of the holding.

The mean proportion of the area of all fields on individual farm holdings (n = 531) exceeding the agronomic optimum soil test P was 36.8%, while the proportion of field area also classed as high HSA risk was 7.4%. Fifty-five holdings recorded >95% of their area above the agronomic
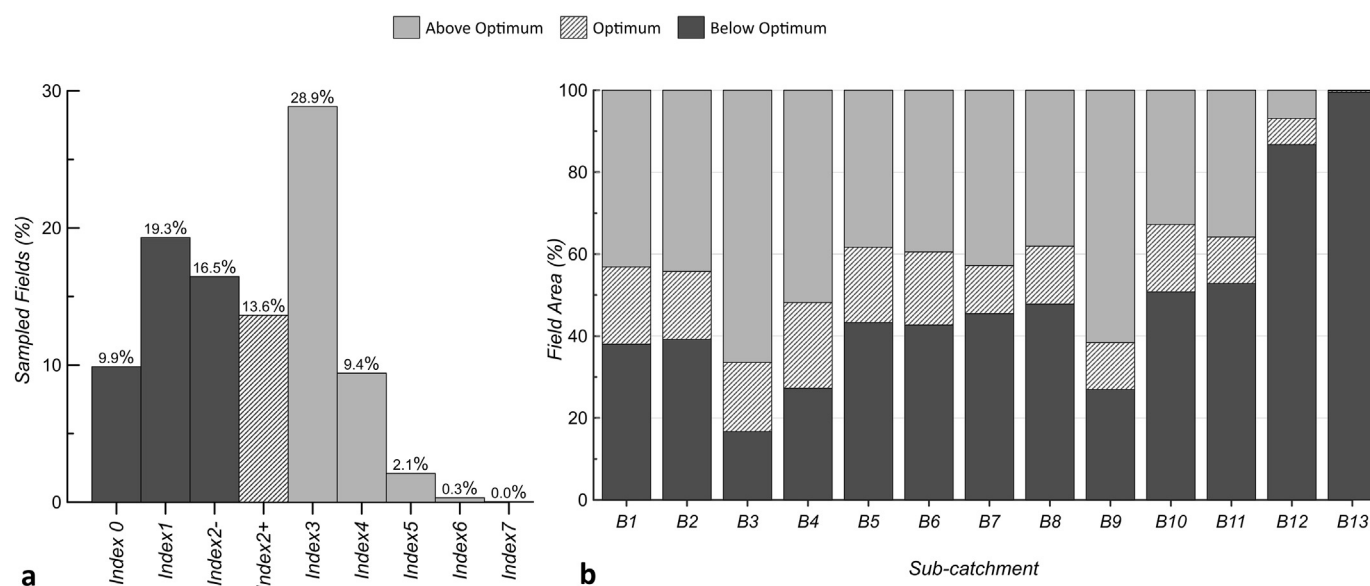
**Fig. 2.** (a) Olsen P distributions by index for fields sampled within the sub-catchments (n = 7693). Numbers above, below and at optimum soil test P are indicated. (b) Distributions of soil Olsen P status across the fields sampled in 13 sub-catchments (B1–B13 in Fig. 1).

optimum and, within those, the proportion of the holding with a high HSA risk ranged from 1% to 59% with a mean of 19.7%.

Across farm types, covering a range in intensity from sheep to dairy and 'mixed livestock and arable' farms, the proportion of farm area above the agronomic optimum varied. Within the 142 beef farms sampled, a mean of 40% of holdings were above the agronomic optimum; for the 70 dairy farms this was 49% and for 95 sheep farms 23%. The mean proportions of farmed areas above the agronomic optimum and classed as high HSA risk in these groups were 7.5%, 9.6% and 4.5%, respectively. Of 177 farms defined as mixed livestock (any combination of beef or sheep) the mean area of holdings above the agronomic optimum was 34% and for 44 enterprises defined as 'mixed livestock and arable' this was 48%. The mean farm area proportions above the agronomic optimum and classed as high HSA risk in these groups were 6.9% and 12.2% respectively. Only one fully arable enterprise was included in the sample set with 73% of its area above Index 2+ and 22.3% of the area also at high HSA risk.

For each sub-catchment the proportion of each area above, below and at the agronomic optimum was calculated based only on fields within the sub-catchment boundary (Fig. 2b and Table 2). The proportion of high (25th percentile) HSA risk within each category was also

calculated (Table 2), with field HSA risk area recalculated in any cases where fields were clipped at the sub-catchment boundary.

The least intensively farmed sub-catchments (B13 and B12) in the south of the catchment have 0.1% and 6.9% of area above optimum, with the majority (99% and 87%, respectively) below optimum. This reflects the upland character of the sub-catchments, with large areas extensively farmed and mainly grazed by sheep. The proportion of these sub-catchments at high HSA risk and above the agronomic optimum is low; 0.03% in B13 and 0.9% of B12.

In all other sub-catchments between 32.8% and 66.4% of the area is above the agronomic optimum, with the proportion at high HSA risk and above optimum ranging from 4.3% to 22.9%. Three sub-catchments, B3, B4 and B9 have >50% of coverage exceeding the agronomic optimum (66.4%, 51.8% and 61.6%, respectively). Within each, the areas above the agronomic optimum and classified as at high HSA risk ranged from 11.4% in B9 to 22.9% in B3. Other sub-catchments ranged between 32.8%–44.2% of sub-catchment area above optimum and 4.25–11.4% also coinciding with high HSA risk.

**Table 2**
Summary calculations of areas of risk and opportunity within catchments. The relationship of each sub-category (columns B–H) is as follows: (i) B + D + E = ~100% (may differ slightly due to rounding); C is a sub-set of B; F is a sub-set of E; G is a sub-set of F; H is a sub-set of G.

| Sub-catchment | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| | Total catchment area, km$^2$ | Area > optimum, % | Area > optimum & HSA, % | Area optimum, % | Area < optimum, % | Area < optimum and not extensive, % | Area < optimum & not extensive & not HSA, % | Opportunity, % |
| B1 | 4.52 | 43.1 | 11.0 | 18.8 | 38.0 | 37.7 | 26.8 | 6.2 |
| B2 | 14.40 | 44.2 | 11.4 | 16.6 | 39.2 | 36.7 | 24.2 | 3.8 |
| B3 | 3.80 | 66.4 | 22.9 | 16.9 | 16.7 | 16.7 | 10.5 | 1.3 |
| B4 | 20.01 | 51.8 | 17.0 | 20.9 | 27.3 | 26.0 | 16.8 | 2.7 |
| B5 | 4.08 | 38.3 | 8.3 | 18.4 | 43.3 | 37.9 | 28.6 | 5.3 |
| B6 | 8.80 | 39.5 | 10.3 | 17.8 | 42.7 | 39.1 | 27.8 | 5.5 |
| B7 | 4.10 | 42.8 | 4.7 | 11.7 | 45.5 | 27.8 | 25.2 | 13.7 |
| B8 | 42.72 | 38.0 | 4.3 | 14.2 | 47.8 | 30.2 | 27.4 | 13.8 |
| B9 | 6.95 | 61.6 | 11.4 | 11.4 | 27.0 | 26.8 | 22.4 | 6.8 |
| B10 | 8.36 | 32.8 | 6.2 | 16.5 | 50.8 | 46.3 | 33.0 | 7.7 |
| B11 | 7.07 | 35.8 | 5.8 | 11.3 | 52.8 | 47.7 | 36.6 | 9.7 |
| B12 | 10.93 | 6.9 | 0.9 | 6.4 | 86.7 | 42.8 | 36.6 | 9.8 |
| B13 | 14.93 | 0.1 | 0.0 | 0.4 | 99.5 | 3.4 | 2.9 | 0.4 |

## 3.2. Soil P carrying capacity at the catchment scale relating to water quality

Water quality data (n = 27 samples per site) for the hydrological year prior to soil sampling were used (October 2016–17). Annual median SRP concentrations across the 13 sub-catchments ranged between 8.5 and 145.5 μg L$^{-1}$, with strong seasonal variation. Lowest concentrations were measured in sub-catchment B13 (IQR 5.5–17.5 μg L$^{-1}$; min-max range 1–48 μg L$^{-1}$) and highest concentrations in sub-catchment B1 (IQR 99.25–253.3 μg L$^{-1}$; min-max range 57–1392 μg L$^{-1}$). Increased storm events in autumn and winter are when HSAs and multiple transport pathways are most active, including diffuse overland flow pathways. Notable, from the start of April onward, as the catchment begins to dry, is a pattern of increasing concentrations in all sub-catchments, to a peak in August, following which flows (and dilution) increase (Fig. 3).

Analyses of the soil and water quality data sets examined the distribution of soil P concentration and HSA risk in the river sub-catchments relative to water quality. For each of the 13 sub-catchments the proportion of the sampled sub-catchment area exceeding the agronomic optimum soil test P was calculated and compared to the median SRP concentration at each outlet (Fig. 4).

Based on a linear fit to the data (r$^2$ = 0.93), and the intersection of the best fit line with the river SRP good-moderate class boundary concentration line (48 μg L$^{-1}$), the model indicates that to reach this boundary no >15% of sub-catchment land area should exceed the agronomic optimum soil test P. Only two of the 13 sub-catchments meet this requirement, B12 and B13 in the upland headwaters, with the rest having 30–55% of the sub-catchment area above the agronomic optimum. Two outliers are notable (identified using two iterations of the Cook's Distance algorithm at P < 0.05; Mellander et al., 2018), with lower median annual SRP concentrations. These sub-catchments differ from the other streams as they are characterised by heavily channelised stream networks with deep and extensive deposits of sediment. It is assumed that retention of P in sediments in these streams reduces lower flow concentrations, with P subsequently lost during large winter storm events that are not captured by fortnightly sampling.

A further analysis integrated the HSA risk with the field soil test P to establish, for each sub-catchment, the relationship to median annual SRP concentrations (Fig. 5). A power-law fit was the best model for the data (r$^2$ = 0.97, possibly indicating scale-invariant influences of micro-topography), and the intersection of the best fit line with the SRP good-moderate class boundary concentration line (48 μg L$^{-1}$). This indicates a carrying capacity of 1.5% of the sub-catchment area in
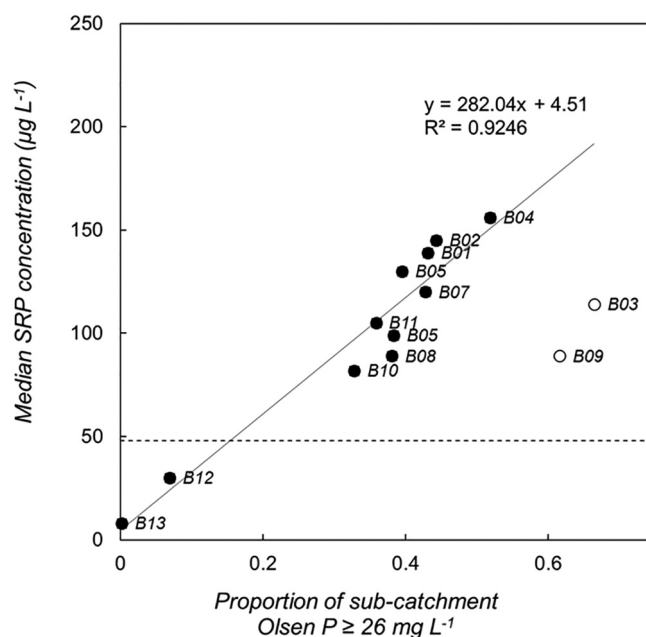


**Fig. 4.** Relationship between the median annual SRP concentration at the outlet and the proportion of each sub-catchment in excess of the agronomic optimum (26 mg L$^{-1}$ Olsen P). Open symbols are outliers to the linear trendline, identified using Cook's Distance and omitted from the model. The dashed horizontal line indicates the site specific class boundary SRP concentration used to differentiate between moderate and good ecological status classification.

this highest risk category to avoid exceedance of the median annual 48 μg SRP L$^{-1}$ river concentration. Effectively, when uncertainties are considered, this precludes any coincidence of soil test P above the agronomic optimum and high HSA risk areas if water quality targets are to be met using river SRP concentration as the indicator.

## 3.3. Opportunities for soil P risk redistribution

Across farms the area of land below the agronomic optimum soil test P that has potential to receive nutrients, and provide buffering to avoid exceedance elsewhere, varied considerably. Potential for redistribution by farm size and sub-catchment are shown in Table 3 and Table SI-1, with breakdowns by the area of sampled farm holdings summarised.
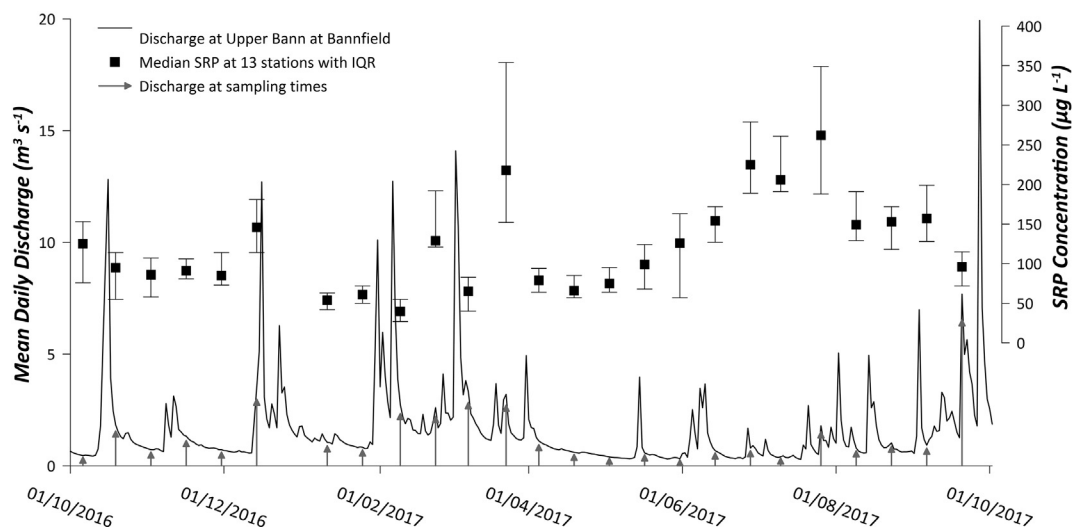


**Fig. 3.** Concentration time series for 13 sub-catchments of the Upper Bann catchment. Box-whiskers indicate the median and interquartile range (IQR) for SRP concentrations at fortnightly sampling intervals relative to daily discharge at the mid-catchment hydrometric station (upstream catchment = 107.2 km$^2$). Vertical arrows indicate the flow conditions at the time when SRP grab samples were taken.
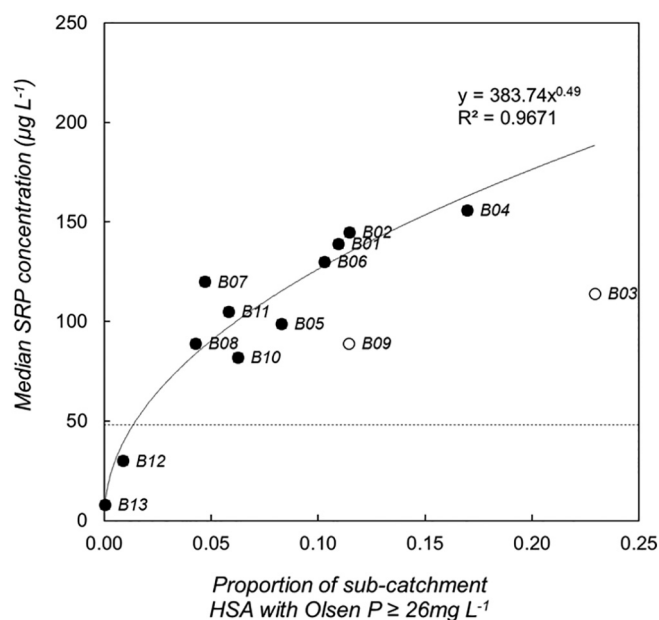
**Fig. 5.** Relationship between the median annual SRP concentration at the outlet and the proportion of each sub-catchment in excess of the agronomic optimum (26 mg L$^{-1}$ Olsen P) with a high (25th percentile) HSA risk. Open symbols are outliers to the power-law trendline identified using Cook's Distance. The dashed horizontal line indicates the site specific class boundary SRP concentration used to differentiate between moderate and good ecological status classification.

In the intensively farmed sub-catchments (B3 and B4) only 43.8 and 49.3% of farms had any capacity to potentially redistribute nutrients on-farm. Of those the mean area available was 1.44 and 1.71 ha, respectively, though with substantial variability among farms. By contrast farms in sub-catchments B7, B8, B12 and B13 all had capacity on over 70% of farms, with B7 and B8 having the greatest areas available on-farm, with a mean of 6.86 and 4.09 ha per farm. Smaller holdings have a larger % area of opportunity on-farm compared to larger farms, reflecting the lower likelihood of those farms to be intensively farmed.

Within sub-catchments the total area of opportunity for receiving excess nutrient surpluses from elsewhere was estimated based only on the area farmed within the sub-catchment boundaries. Although the proportion of sub-catchment areas at below optimum soil test P and at a lower HSA risk ranged between 2.9% (B13) and 36.6% (B11, B12), when the criteria for identifying blocks of land suitable for nutrient application are applied, only between 0.4% (B13) and 13.8% (B8) of the sub-catchment areas were estimated to be available. Sub-catchments with the lowest area of opportunity were B3 (1.3%), B4 (2.7%) and B13 (0.4%), the two former being particularly intensively

**Table 3**
Summary of on-farm opportunity for P redistribution by sub-catchment. Detail of breakdown by farm size is given in Table SI-1.

|  | No. of holdings | No. of holdings with opportunity | Mean area available, ha | Mean area available, % |
|---|---|---|---|---|
| B1 | 12 | 10 | 2.65 | 14.1 |
| B2 | 51 | 28 | 1.51 | 7.3 |
| B3 | 16 | 7 | 1.44 | 6.0 |
| B4 | 73 | 36 | 1.71 | 8.5 |
| B5 | 22 | 15 | 2.47 | 10.2 |
| B6 | 39 | 26 | 2.05 | 10.0 |
| B7 | 24 | 18 | 6.86 | 19.4 |
| B8 | 139 | 108 | 4.09 | 20.1 |
| B9 | 29 | 16 | 3.54 | 13.6 |
| B10 | 58 | 36 | 1.97 | 12.7 |
| B11 | 36 | 22 | 2.22 | 17.2 |
| B12 | 43 | 35 | 2.31 | 10.7 |
| B13 | 10 | 7 | 3.22 | 9.0 |

farmed while the latter reflects the exclusion of fields currently farmed at a low intensity and which, due to higher overall inherent risk to water quality and lower economic potential for recovering nutrients in grass (i.e. poorly drained), should not receive further P fertiliser applications.

## 4. Discussion

Practically, the framework developed in this study provides an objective, physically based mechanism for identification of areas posing greatest risk to river water quality from diffuse pollution and prioritisation of mitigation measures. It is also a basis for the development of feasible solutions at farm and sub-catchment scale based on field scale soil P and hydrological sensitivity data (see Fig. 6 for an illustrative example), or the development of alternatives.

For this exemplar surface water dominated catchment, comparisons with water quality monitoring data indicate that, to attain good chemical water quality for SRP, a target of <15% of sub-catchment area above the agronomic optimum should be set. In addition, a target of <1.5% of sub-catchment area above the agronomic optimum and with high HSA risk should be set. Two sub-catchments appeared as outliers to these models, related to heavy sedimentation, and a means to characterise similar channels in an automated way will be required in developments of the framework when applied elsewhere.

Nevertheless, achieving core targets in the Upper Bann sub-catchments will require varied and possibly concurrent approaches based on options such as:

1. Redistribution of P within the farm to areas of opportunity

Within farm redistribution (e.g. Ruane et al., 2014) avoids any concerns regarding biosecurity and transfer of pathogens between farms, maintains farmer autonomy over applications and minimises transport distances, but will depend on the area available relative to on-farm P loading and overall soil status and may require additional storage if access to the target fields is limited by trafficability. Within the sub-catchments on-farm opportunity ranges from a mean of 6% in B3 to 20% in B8. Many holdings have no on-farm capacity for nutrient redistribution (from 17% of farms in B1 to 56% of farms in B3) which limits their options to reducing stocking rates or moving nutrients off-farm.

2. Redistribution of P among farms in the same sub-catchment

This option is feasible where a less intensive farm (e.g. sheep enterprise) is willing to accept nutrients, either to offset chemical fertiliser costs or as an incentivised traded arrangement (e.g. Cox et al., 2013). This depends on the availability of opportunity areas within the sub-catchment and on the existence of a simple, formalised arrangement to allow exchange. For each trading opportunity, maps of the total available area will be needed, the appropriate loading of slurry or manure calculated and farm nutrient budgets for both farms calculated. Most probably this would be facilitated as an online tool for farmers and farm advisors. The formalisation of transfers will be challenging, costs of transport will increase and additional issues around biosecurity may be off-putting for many farmers. However, where farms are nearby it is more likely that there will be social interactions and a level of trust. Redistribution of manure nutrients among farms, although not restricted by regulation (Article 21 of Regulation (EC) 1069/2009), is of concern to farmers due to the prevalence of tuberculosis in NI. Where poultry litter is concerned there are also concerns over the airborne spread of botulism (Souillard et al., 2017). Approaches to eliminate biosecurity risk will be necessary to encourage farmers to receive organic nutrients from other farmers.
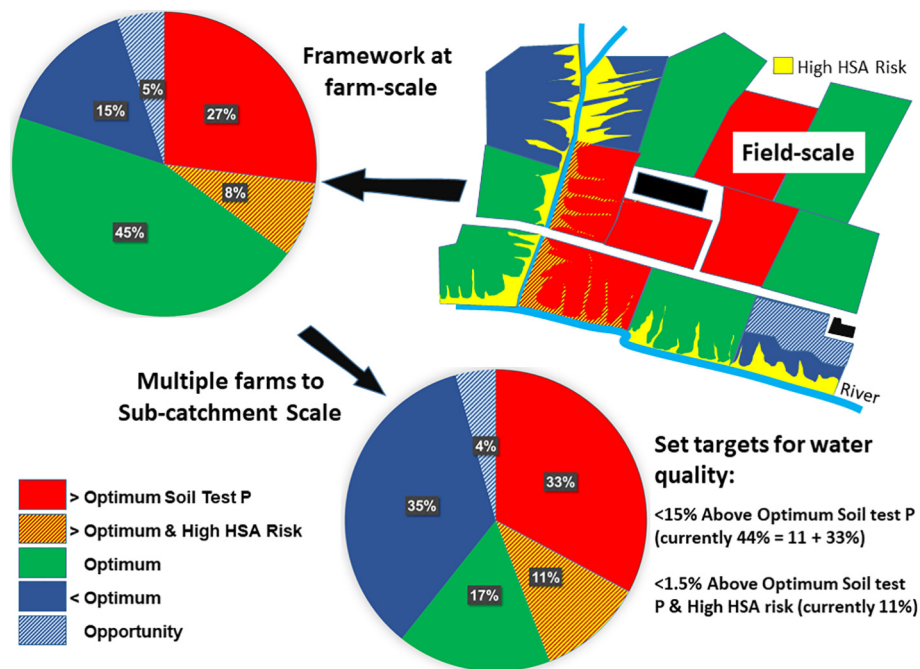
3. Redistribution of P among sub-catchments

**Fig. 6.** Schematic of the assessment framework applied at field, farm and sub-catchment scales to identify risk (high soil P and high HSA), opportunities (low soil P and no HSA) and management targets for nutrients relative to water quality. Note that the field schematic and farm scale pie chart summaries are illustrative examples (due to farm data confidentiality) but the sub-catchment summary is based on actual data for B2.

This option is similar to (2) but made more complex by greater transport distances and the lower likelihood of neighbourly interactions with the receptor farm, which precludes informal negotiations and limits trust regarding issues such as biosecurity. The development of an online marketplace or sub-catchment and farm advisor led negotiations to trade nutrients will be more important in these cases. This will also require the incorporation of more checks and balances to provide assurance to the receptor farms. In the Upper Bann the distances to transport nutrients from a low opportunity sub-catchment such as B3 to a high opportunity sub-catchment such as B6 are ~12–20 km, which, depending on the load capacity of the vehicles used for transport, may be practical.

The distance slurry or manure must be transported becomes a consideration once it exceeds the normal operational boundary of the farm. Some farms may not have vehicles suited to long distances on paved roads so contractors may have to be employed, adding cost. All these factors need to be incorporated into the cost-benefit in terms of yield. Figures for NI are not available; however, a study in the Republic of Ireland by Fealy and Schröder (2008) indicated that manure transport from livestock farms to arable farms becomes of limited benefit economically beyond 50–75 km when using trucks and much less than that for tractors. For long distance transport a solution such as slurry separation, adopted in the Netherlands (Schoumans et al., 2014), which would allow the lighter dry matter content to be transported at lower cost and the residual liquid, with lower P and higher weight applied locally. The costs of such a system would make this feasible only for the largest, high intensity, farm enterprises or cooperatives.

However, there are limits to the area available for HSA related P redistribution, and transfer of nutrients between sub-catchments alone is not likely to reduce surpluses sufficiently. For example, in sub-catchments B3 and B4 the proportions of the area in exceedance and with high HSA risk are 17.0% and 22.9% (Table 2), respectively. When nutrients are redistributed to areas of opportunity within these catchments (1.3 and 2.7% of the area, respectively), there still remains an additional 15.7% and 20.2% of the sub-catchment area, where nutrient amendments must cease in order to draw down soil P and which

require an external surrogate area for redistribution of those nutrients (an area of 0.6 and 4.0 km$^2$, respectively). Of sub-catchments having additional capacity (B7, B8, B11, B12, B13) a total area of 8.27 km$^2$ could be available for imports from outside those sub-catchments. Further considerations could be:

4. Soil P drawdown and reduced farm P balance

Nutrient redistribution alone will not be enough to achieve a target of <15% of the sub-catchment area above optimum soil test P in the study sub-catchments currently at moderate WFD status for SRP river concentration. For sub-catchment B3, for example, soil test P will have to be reduced in fields covering 51% of the sub-catchment, 47% of B9 and 36% of B4. Eliminating high P soils in high risk HSAs for these sub-catchments will affect 22.9, 17.0 and 11.4% of their areas, respectively. It is not likely that these targets can be met through sustaining current practices or redistribution either within or among sub-catchments.

In the first instance a priority must be to cease P build up through redressing on-farm balances (e.g. Schulte et al., 2010), which in NI are high (>10 kg P ha$^{-1}$), and driven by imports of high P concentrate feed and chemical fertilisers. This impacts farm profitability (42% of farm income is spent on feedstuffs in NI relative to 22% in the UK as a whole, DAERA, 2018b) and drives pollution through a broken cycle of excess P lost to soil and water (Elser and Bennett, 2011). More widely, closing the gap in the P cycle is essential to protecting food security in a volatile global market. Better on-farm utilisation of nutrients and pH correction (liming) (Fertiliser Association of Ireland, 2016) will be an important step towards improving grassland dry matter production and drawing down existing soil P. Increased silage offtakes and rotations of other crops can be used to amplify this effect (e.g. Wall et al., 2013).

5. Targeted interception measures

In some cases it may not be feasible for a farm to reduce or export nutrients to lower soil P in all HSA risk areas. In such cases mitigation

measures to intercept and block nutrient transfer in-stream becomes an option. Diverse approaches, such as riparian buffers, sediment traps and barriers exist, and have been trialled in many studies (e.g. Adams et al., 2018; Collins et al., 2007; Cooper et al., 2017; Darch et al., 2015; Dorioz, 2013; Dupas et al., 2015). With interception of runoff prior to entering the river system, measures ideally should involve the removal of the nutrient either using a fast growing harvestable crop (for feed or fuel) or a technological solution such as P sorption media which could be extracted and potentially re-enter the P market. Key elements of using such measures, however are that the measure used is appropriate, is optimised to the landscape and land use, and is maintained. A challenge within any environchemical scheme incentivising their use through payment is to allow flexibility to suit the landscape and characteristics of HSA risk areas. For auditing purposes most schemes are very prescriptive in terms of the dimensions and construction of any measures.

Options 1 to 4, above, consider the need for smart incentives for P use optimisation at the field, farm and sub-catchment level and this is important as P as a mineral fertiliser becomes more of a national and international resource issue for food security (e.g. Scholz et al., 2013). Translation of targets defined using the framework described in this study into operational plans on farms and within sub-catchments is the next stage and will require a concentrated and coordinated effort among all the stakeholder groups involved, including both advice and scheme development. This is recognised as a challenging next stage as the data required from farmers for options such as P redistribution and P drawdown in soils requires collection and organisation. The development of decision support tools, to include both maps and graphical presentation of soil agronomic status, risk and opportunity for redistribution (following a format based on that in Fig. 6) will be an intrinsic component of the communication process among stakeholders and in implementing the framework. Ongoing decision support tool development within the Department of Agriculture in NI is making provision for maps such as those generated in this study to be integrated in farm level nutrient management tools (initially for on-farm use).

It is possible that in large catchments like the Upper Bann, with little carrying capacity and a landscape (soil and topography) which is prone to runoff, that, as a sixth option, greater restrictions on stocking rates and farming intensity may be the only option (or at least compensated for) if water quality pressures linked to high soil P and HSA risks are to be mitigated. Proposed changes to the way in which EU agricultural subsidies are directed, away from a focus on production to the provision of environmental and other public goods (Bateman and Balmford, 2018) will be important in achieving this. Or else, as a seventh option, a less stringent water quality threshold is set for a no net deterioration target if sub-catchment production targets and economies are to be maintained (or increased). The catchment level assessment applied as part of this framework could feed into the development of a land use choices matrix integrating environmental, social, economic and cultural concerns, for use in other national or international river catchments, and as advocated in the Land Use Suitability concept of McDowell et al. (2018).

A final consideration acting on all of these options will be internal catchment biogeochemical processes related to P legacies in soils and sediments that will prolong the influence of land-water P transfers. This has been reported in Ireland (Schulte et al., 2010) and elsewhere (Sharpley et al., 2013) and adds to the challenge of expectation from investments in catchment P mitigation goals.

## 5. Conclusions

In a framework for assessing soil P risks, when compared with a target SRP river concentration threshold of $48\ \mu g\ L^{-1}$ in a wider catchment, this study indicated that the carrying capacity for above agronomic optimum soil P was 15% of the individual sub-catchments' area. The study also indicated that the catchments could carry almost no HSAs with above agronomic optimum soil P (<1.5%).

The framework also indicated soil P opportunities for redistributing these risks, adaptively and concurrently across scales from field, to holding to sub-catchment possibly as part of developed advice provision and new schemes, in integrated nutrient management planning or trading. The framework recognises both P source and transport risk as part of this redistribution potential with the necessity for soil P drawdown/reducing P balances considered alongside targeted HSA interception at field scale, identified using high resolution LiDAR DEM elevation data.

In catchments at high risk of P transfers to surface waters, similar to the one investigated here, less intensive agriculture to meet the water quality thresholds, or less ambitious thresholds to support sub-catchment economies would be the last two options to consider if P risk redistribution opportunities were not considered or did not provide the desired end-points.

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