

Prepared for: Mr Brian McCreadie, SEPA, Inverdee House, Aberdeen

Prepared by : Dr Alex H Sinclair and Dr Bill Crooks, SAC Consulting

Dr Tony C Edwards, Leurbost, Isle of Lewis

Dr David Lumsdon, Malcolm Coull and Dr Charles Shand, James Hutton Institute

Contact : SAC Consulting

Environment and Design

Ferguson Building

Craibstone Estate

Bucksburn

Aberdeen

AB21 9YA

Phone: 01224 711236

Fax: 01224 711268

e-mail: alex.sinclair@sac.co.uk

Date : 7th January 2013



Assessing the potential risks to water quality from phosphate leaching: SEPA contract number R11123STA

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1. Executive summary

1.1 Introduction

The report "Soil phosphorus levels in diffuse pollution priority catchment: SEPA contract reference 30107", 2011, aimed to identify the potential role of soil P levels by examining SAC's unique advisory extractable soil P data base and assessing if it can be linked to soil P saturation and the increased risk of soil P leaching. The report concluded that soil and site attributes combine to modify the relationship between soil P tests (SPT) and leaching risk. As outlined in the current study this relationship is more complex than is generally understood due to the role of soil type and other soil management practices on P dynamics.

1.2 Basic theory of managing P in intensive agriculture has been reviewed

The basic approach used for the management of soil P in intensive modern agriculture is to build-up and maintain a reserve over time in the soil such that plant-available forms are present on an annual basis in adequate amounts to meet crop requirements. This approach to P management has been adopted because P present in soil is primarily in a form that is unavailable for plant uptake. This approach works because even in soils with a large potential capacity for binding of P the reserves held are dynamic and a small proportion of bound P will be released in a plant-available form in the year of production. The objective of the fertiliser use of P is to supply enough to this soil reserve to ensure that this relatively small amount that is available annually is sufficient to meet crop requirements. The main management tool is SPT in the topsoil which predicts the amount of P present in soil in a form that plants can use. The primary assumption of this approach is that the SPT will not change significantly in the short term (3-4 years) since only small amounts of the total, soil mediated P reserve will be made available to the plant or be available for leaching at one time.

1.3 Literature background to linking soil P test (SPT) and soluble P loss from agricultural land

Re-analysis of Scottish data from Hooda et al. (1997) provided a strong suggestion that a common (national) relationship might not exist between SPT and loss of soluble P. This is perhaps not surprising considering the very different drainage status of the two groups of soils in the study. Additional studies by Hooda et al. (2000; 2001) showed the potential advantage of including fundamental sorption characteristics which are related to parent material and drainage conditions. Although based on only three points there might be the suggestion of a relationship within the NE Scotland soils between SPT and stream water P.

1.4 Maps of P sorption index based on development of a model of the relationship between attribute data for soil associations and inherent P sorption capacity

In the past 10 years soil geochemists have made much progress in developing models for describing ion adsorption phenomena by mineral surfaces. The CD-MUSIC model has been used in combination with other relevant processes (e.g. solution speciation, P-mineral solubility equilibria and cation retention on soil organic matter) to estimate the inherent P sorption capacity of soil. This calculation

is referred to as the Soil P Sorption Model (SPSM) and has been applied to a data set of 399 soil samples representing 38 soil associations. The 38 soil associations have been ranked according to their P sorption capacity into P sorption indices from 1 (very low capacity) to 5 (very high capacity). In order to extend this ranking to a national scale, soil associations (both at 250K and 25K scales) have been grouped into 20 categories. P sorption indices by soil association group have been mapped at a national scale and for the 14 SEPA Priority Catchments and 2 Diffuse Pollution Monitored Catchments. Soil associations at the very low P sorption index 1 end of the scale include Auchenblae, Millbuie and Arkaig whereas associations including Stirling, Darleith and Insch are in the very high P sorption index 5.

1.5 SAC soil P test data to determine the *potential* risk of leaching of soluble P

The JHI has access to the Ordnance Survey Address Point © data for Scotland through the Ordnance Survey Mastermap © dataset. This dataset contains a georeferenced location for each postcode in Scotland. By using this dataset as a 'lookup' table, the postcode for each of the SAC advisory data collected from 1996 to 2010 has been located spatially and therefore can be plotted on a map. Due to changes in postcodes, errors in recording, and other issues of data quality, around 5% of the advisory samples could not be plotted; there were c91,000 georeferenced correctly by this method.

1.6 Limitations in use of postcode data in ascribing soil properties to advisory data

Samples submitted to SAC's advisory sample database are located according to the postcode of the submitter. While this ensures a level of anonymity, it presents a challenge when trying to assign further information to each sample based on its location. Each postcode covers a geographic area the size of which varies greatly across the country. In more remote rural areas, postcodes are larger than in urban areas. The coverage of soil maps available digitally for Scotland varies according to scale. The whole country is covered at 1:250,000 (mapping is done by map units, as part of soil associations), but only part of the country is covered at 1:25,000 where each polygon represents a specific soil series (the level at which much of the other soil data is available). These two factors in combination mean that assigning soil information other than soil association to advisory samples is problematic.

1.7 Summary of SPT data at a nation scale

The SPT data have been summarised into 4 broad agricultural regions and sub-divided by soil type. Each soil type is further broken down into land capability for agriculture classes (LCA). There is a general decline in STP as LCA changes from 1 to 6. This is particularly the situation for NE and SE Scotland where averaged STP concentrations declined by more than a half between LCA 1 to 4.

1.8 Summary of data in SEPA priority catchments plus two DPMCs

There are no LCA 1 samples within the PC+DPMC areas. The grand total area of the 14 PCs + 2 DPMCs is 1,396,871 ha. 79% of the total area of the 14 PC and 2 DPMCs is covered by the soil associations (or grouped associations at 250K scale) that are used to rank associations in order of P sorption capacity. No clear relationship was found between the average SPT and the P sorption ranking, probably reflecting the SAC recommendation to fertilise to target moderate P status. The review of the relationship between LCA and assessment of the Cessnock database appear to show that the relationship between advisory SPT and P sorption index may only become coherent at the sub-catchment scale where individual soil types are more associated with specific LCA, farm types, and land management systems.

1.9 Maps of potential leaching of soluble P from the topsoil

A risk matrix of potential leaching of soluble P from the topsoil has been proposed based on soil P sorption index and SPT status. Four risk categories from very low to high have been mapped at a

national scale and for the PCs and DPMCs. Urban areas and areas with no P sorption data are also mapped. The Lunan Water catchment has clearly the largest percentage of moderate and high risk areas, followed by Eye Water, River South Esk and River Tay. Catchments with more than 80% of area in very low or low risk are River Ythan, River Deveron and Stewartry Coastal. The River Ayr has the largest percentage of area with no data, while N Ayrshire Coastal and River Irvine have largest percentage of urban area.

2.0 Estimates of the change in P when increasing/decreasing STP

Well designed P fertiliser policies should have a build-up or run-down component for low/high P status respectively in order to target the moderate P status. It is known that build-up/run-down rates vary with soil type but currently only very general guidelines are provided. The assignment of P sorption indices to different soil associations provides a significant advancement in the understanding of the amount of P required to change SPT. Estimates based on the soil P sorption model (SPSM) of the change in P when increasing STP have been made. Change in P on an area basis (kg P/ha) are estimates, and differences should be thought more relative than absolute. Much more P is required moving to moderate P status in P sorption index 5 (high) soils than an index 1 (very low) soil. Soils with a high P sorption index will require about 3 times as much P to be added, or removed, to achieve the same change as low P sorption soils. In addition the data could be used to quantify the P pool size on a catchment basis, e.g. at any given SPT value the index 5 soils will have a much greater pool of sorbed P.

2.1 Recommendations

1. Confidence in the P sorption index predictions, and hence risk of potential leaching of soluble P from the topsoil, can be increased by the collection of more soil attribute data across more associations. This recommendation is based on the following summary of the measured data set:
 - About 80% of the total area of the 14 PC and 2 DPMCs is covered by soil associations that were used to rank associations in order of P sorption capacity, but 18 of the 38 associations with actual data were ranked based on either one or two samples.
 - A further 79 associations not covered by the 38 with measured values, but part of 20 categories of linked association groups, were assigned an index. A precautionary 'risk' based principle that the lower the sorption value, the greater risk of soluble P leaching was used to assign indices. Any associations with no measured values were put into the lowest index of any from the same group.
 - All alluvial soils were grouped together in index 3. It is expected that different P sorption indices will exist for different alluvial soils as all alluvial soils are not formed from a single soil association group.
 - Based on the above precautionary principle, there is currently a bias towards lower P sorption indices.
2. Confidence in the SPT data in the PCs and DPMCs, and hence risk of potential leaching of soluble P from the topsoil, can be increased by targeted sampling for advisory soil testing across catchments with low coverage of SPT data within individual postcodes. This recommendation is based on the following summary of the SPT data set:
 - On average 16% of postcodes with P sorption indices have actual SPT data in the PCs and DPMCs, the remainder are assumed to have M- (lower moderate) status in mapping risk of potential leaching of soluble P.

- Less than 10% of postcodes with P sorption indices have actual SPT data in the SW catchments of North Ayrshire Coastal, River Doon, River Garnock and River Irvine. These catchments need to be targeted for collection of more SPT data from individual postcodes.
 - Eye Water followed by the River Ythan has the best coverage of actual SPT data.
3. Future emphasis could be placed upon the improved tailoring of the P management of soil having different P sorption properties. It may be possible to refine the component of the P fertiliser recommendation which covers build-up or run-down of P status. SAC has recently launched a GPS soil sampling service. It is recommended that sampling for PK analysis should be in zoned areas based on the farmer's knowledge of cropping performance, but also based on soil type. Soil type should include zoned areas of different P sorption index. SAC advisory staff requires training in the new knowledge developed in the current project. The new GPS soil sampling service needs to be promoted to the farming community.
 4. Future work needs to focus on informing this soluble P leaching risk matrix at the sub-catchment scale using localised understanding of land management variables and SPT. The sorption P index provides the opportunity, in conjunction with a P leaching risk matrix which encompasses land management variables, to provide a mechanism to target key soils for testing across sub-catchments.
 5. A strategy for the further collection of local management information and direct measures of SPT should be devised.
 6. The relationship between LCA and P sorption index should be further assessed at the catchment and sub-catchment scale with a focus on variability in management at the field level. The LCA is a prediction of land capability for production which can be linked to potential cropping options and yield. Linking the LCA to the soil P sorption index and land management provides a tool for understating the balance between total agricultural P inputs versus crop off take and the portion leached to surface waters.
 7. A relationship between SPT levels and leaching to surface waters needs to be analytically quantified for soils with differing P sorption indexes. It is theorised that for a given soil at a moderate P status the diffuse pollution loading occurring directly from soluble forms of P arising from soil mediated process will be small as compared to the amount from natural soil erosion. This should be quantified as it will be important to a further understanding of the relationship that tries to link regional variations in land management to P loading. The soil mediated P contribution may be small but it is this fraction that will be the primary focus of any future attempts to understand or change agricultural P management in Scotland as its variances has a direct link to economically viable crop production in Scotland.
 8. The Hooda et al. work underpinning the relationship between SPT and volume weighted P concentrations in surface waters requires replication and understanding. This requires a value for the volume weighted water P concentrations in each of the PC and DPMCs along with improved assessments of P load apportioning. Quantifying such a potentially significant variance at a national level at an early stage will assist in establishing meaningful regional mitigation priorities. This approach on two catchments will also provide a mechanism to further refine and transform the risk matrix into an operation process.
 9. Consider the possibility of integrating the current 'leaching' related aspects with separate 'erosion' based risk assessment. There is a need to develop understanding of how P would be released from soil particles entering the water environment as it cannot be assumed soils with high P would release more soluble P after entering watercourses.

2. Introduction

2.1 Background

Phosphorus (P) is one of the major causes of water bodies in Scotland being at less than good status and diffuse agricultural sources are known to be a significant source.

The sources and transport pathways of P are many and varied, but there is a lack of data on the degree of soil P saturation in Scottish soils resulting from soil mediation following application of P fertilisers, livestock manures and other bulky organic fertilisers. The data would fill a specific knowledge gap on soils leaching potential for soluble P, and could also help SEPA to assess whether regulated activities such as waste spreading under Waste Management Licensing exemptions pose a risk to the environment.

SEPA previously commissioned SAC to collate data on extractable soil P concentrations across Scotland to try and identify the potential risk of phosphate leaching and also identify land use associated with high P concentrations. This highlighted that there were some soils present that had levels of extractable P in excess of crop requirements (SAC 'Very High' phosphorus index), and that the crop types most associated with excess P were vegetable and potatoes.

However, SAC reported that extractable P alone could not be used as an accurate measure of leaching risk. Leaching is influenced by soil attributes such as texture and therefore to quantify actual risk would require additional steps:

1. Develop a clear model of the relationship between soil attributes e.g. P sorption capacity and soluble P leaching risk.
2. Obtain soil association/attribute data to determine *inherent* leaching risk using the relationship identified in step 1.
3. Overlay this with SAC soil P test data to determine the *potential* risk of leaching of soluble P.

2.2 Objectives

The aim of this current piece of work is to develop and ground truth a relationship between soil attributes and soil mediated P leaching potential in Scotland so that potential risks to water quality can be mapped and measures (such as awareness raising) targeted to where they are required.

2.3 Development of a model of the relationship between soil attributes and soluble P leaching risk from the topsoil

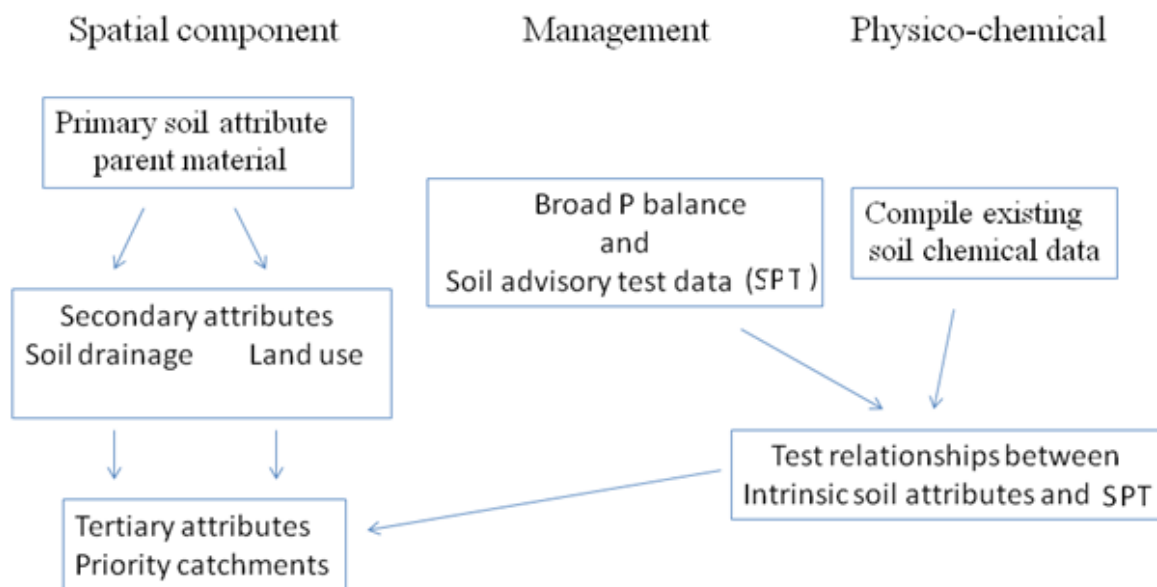
SAC's advisory data set will be used in conjunction with the JHI's National Soil Map of Scotland (MISR, 1984) in order to establish the relationship between soil P and leaching risk of soluble P from the topsoil. In addition, research soils (NSIS-2) which have been used by the JHI to examine relationships between differing soil P tests (Olsen and acetic acid extractable P) will be analysed for Modified Morgan's extractable P in order to increase the understanding of the relationship between differing soil P test methods. An index of P sorption capacity based on soil association attribute data will be established. This index will be used along with average SAC extractable P concentrations (SPT) in individual postcodes to produce a map for Scotland of potential risk of soluble P leaching from the topsoil.

Commentary will be given in the report on the methodology used, describing the importance of soil organic matter content, structure and pH value. Assumptions, limitations and suitability for intended use will be detailed in the report.

Commentary will also be given on how the potential leaching risk data may be used to derive *actual* leaching risk assessments. For example, if the potential leaching risk assessment could be combined with field specific data such as topography, climate, distance to waterbodies and presence of operational tile drains to derive a site specific *actual* risk assessment and identification of most significant pathways. The practicality and uncertainty of the proposed methodology to identify mitigation measures at the field and waterbody scale will be discussed.

A schematic plan of the experimental approach and linkages between individual components are given below:

Developing individual components of model



2.4 Work in progress on relevant Scottish Government funded work

Soil P concentrations from other ongoing Scottish Government funded work e.g. Environmental Focus Farms in the Cessnock and Lunan will be used to 'ground truth' the SAC advisory dataset to help assess its representativeness and to provide a context at the catchment level.

Risks from other pathways such as surface run-off will be dealt with separately but commentary will be given in the report on what the findings of this work mean for other pathways through which P is transferred to water.

3. Basic theory of managing P in intensive agriculture

The basic approach used for the management of soil P in intensive modern agriculture is to build up and maintain a reserve over time in the soil such that plant available forms are present on an annual basis in adequate amounts to meet crop requirements. This can be contrasted to nitrogen management where the principle is to supply the majority of the crop N requirement in the year of production.

This approach to phosphorus has been adopted because P present in soil is primarily in a form that is unavailable for plant uptake. Very few modern fertilisers or approach to fertiliser management can cost effectively supply P in a form that is adequate to meet the requirement of a growing crop in the year of production. Both the biology of the soil environment and the underlying inorganic chemistry of most soils result in applied P being either bound (sorbed) to soil particles or being quickly transformed in unavailable forms such as those present in the organic fraction and precipitated secondary minerals (see diagram below).

This approach works because even in soils with a large potential capacity for inorganic binding (sorption, precipitation) of P the reserves held are dynamic and a small proportion of bound P will be released (desorbed, dissolved) in a plant available form in the year of production. The objective of the fertiliser use of P is to supply enough to this soil reserve to ensure that this relatively small amount that is annually available is sufficient to meet crop requirements. The risk associated with the leaching of this small, annual available P is therefore referred to as soil mediated leaching risk.

The main management tool is SPT in the plough layer, or 7.5cm depth in long-term grassland, which predicts the amount of P present in soil in a form that plants can use. The primary assumption of this approach is that the SPT will not change significantly in the short term (3-4 years) since only small amounts of the total soil P reserve will be made available to the plant or be available for leaching at one time. Once a SPT shows that the available P level is sufficient (on target) then it can be assumed that a similar amount of P will be plant available each year in the short term (3-4 years).

The relationship between total P reserve (that which is in a form that could potentially be plant available) and SPT is largely anecdotal since it can vary for different soil types and soil management practices. Similarly fertiliser recommendations for P have developed based in part on field trials but also on the demonstrated yield responses and economic viability for individual regions. Methods used to test SPT and P fertiliser recommendation vary both nationally and internationally to reflect in part changes in soil.

In Scotland this approach to P management has been highly successful and crop yield and quality issues related solely to deficiencies in P are no longer a major restriction to production. As shown by the assessment of the SAC advisory soil database in the report to SEPA contract reference 30107, a substantial amount of Scotland's agricultural topsoil is now at or near the target range for SPT. This has been achieved through the systematic application of P fertilisers over time in sufficient quantities to ensure that the annual amount desorbed, dissolved, or mineralised by soil process during crop growth are sufficient to meet demand.

The current study is focusing on the relationship between SPT and amounts of P held in a sorbed or precipitated form. The only reason for this investigation is the identified issue of excessive loading of P to Scotland's surface waters with the potential that soluble forms of P arising from historical and contemporary fertiliser P management practice are a potential source. Loading arising from soil erosion and direct surface runoff are both strongly related to total soil P reserves but are not presently factors in determining appropriate fertiliser management practices.

Fertiliser P management is partly modified by soil structure and drainage linked to soil mineralogy, organic matter and soil pH:

1. Soil mineralogy: This is a combination of the geochemistry of the parent material and age of the soil. In intensive agriculture it might be argued that soil mineralogy is not directly linked to P fertiliser practice since most of Scotland's agriculturally managed soils with high P available from mineral sources will have been modified by crop demand and topsoil processes arising from cultivation and acidity management. However, experimental work reported by Reith et al (1987) demonstrated that soil series can have marked effects on the levels of SPT that are likely to give comparable responses to applied P. This work showed that the SPT levels in common use at that time should be modified for Countesswells, Inch, Foudland, Tarves, Dreghorn and Whitsome soil series.

Mineralogy is a factor in the establishment of the potential sorption and precipitation capacity of individual topsoil. Mineralogy will also have a role in determine the drainage capacity of the soil which can impact soil geo-chemistry and potential leaching arising from artificial drainage. The key mineralogical parameters and their role in non-calcareous soils are

- Oxalate-extractable aluminium and iron for P sorption capacity and precipitation;
- Mechanical analysis (sand, silt, clay) for P sorption capacity and drainage.

2. Soil organic matter (SOM): Generalised fertiliser recommendations are typically developed for mineral soils where SOM < 15% (Sinclair et al., 2009). When dealing with humose and peaty soils the role of the organic fraction becomes an increasing important dominate factor as the capacity for immobilisation of P increases.

3. Soil Acidity: In intensively managed agriculture soils acidity (pH) needs to be managed since it impacts a range of factors that impact crop growth. For P availability the soil acidity levels impact the nature of the soil mineralogy. In particular it can change the forms of aluminium and iron that are available which will impact the degree of precipitation of P to secondary minerals.

4. Literature background to linking soil P test (SPT) and P loss from agriculture

Schoumans and Groenendijk (1998) predicted the impacts of fertilisation reduction measures on P loads from intensive livestock production systems to surface water. These authors developed a methodology for non-calcareous sandy soils in flat areas where soil mediated P loss by subsurface runoff is the dominating pathway. This approach was based on the kinetics of P sorption and desorption of these soil types, P accumulation in soils which allowed inorganic P concentrations in soil solution to be modelled. A further development related to the linking of soil chemical P processes to commonly used soil P tests (SPT) which allowed an initial mechanism for estimating the potential risk of P leaching and runoff.

Guo and Yost (1997) used acid ammonium oxalate (P_{ox}) for estimating available soil P pools in diverse weathered soils where Fe and Al oxides are usually abundant. Results indicated that P_{ox} in all soils appeared to be largely plant-available. P_{ox} was found unsuitable for quantifying the available P pool in the calcareous, slightly weathered soils. Carbonates raised the pH of the oxalate solution and reduced the concentration of the oxalate anion to differing degrees, thus making this method unreliable for quantifying available P pools in calcareous soils. In highly weathered soils, the relationship between the quantity of available P and P_{ox} was described by a linear equation, $Y = 294.7 + 1.05 X$ ($r^2 = 0.81$), where Y is estimated available P in mg P kg⁻¹, and X is P_{ox} in mg P kg⁻¹.

Pote et al. (1996) demonstrated that several SPT methods gave results that were significantly correlated to dissolved reactive P (DRP) levels in runoff, but for that particular soil distilled H₂O and NH₄-oxalate methods gave the best correlations. In a subsequent paper Pote et al. (1999) tested the relationship for three additional soils and also identified the most consistent SPT method for predicting soil mediated DRP levels, whilst also determining effects of site hydrology on correlations between SPT and runoff DRP concentrations. Surface soil (0-2 cm depth) of pasture plots was analysed by a range of SPT methods (Mehlich III, Olsen, Morgan, Bray-Kurtz P1, NH₄-oxalate, and distilled H₂O methods together with three different methods for estimating P saturation. Simulated rain (75 mm/h) produced 30 min of runoff from each plot. All correlations of SPT to runoff DRP were significant ($P < 0.01$) regardless of soil series or SPT method, with most SPT methods giving high correlations ($r > 0.90$) on all three soils (Table 1).

Table 1. Results of soil P test (SPT) methods correlated to dissolved reactive P (DRP) in runoff from three Ultisols (from Pote et al., 1999).

Soil test method	Soil 1		Soil 2		Soil 3	
	r	Regression	r	regression	r	regression
Mehlich III	0.908	$y = 0.0036x - 0.45$	0.916	$y = 0.0035x - 0.38$	0.932	$y = 0.0016x + 0.00$
Olsen	0.869	$y = 0.0088x - 0.43$	0.864	$y = 0.0093x - 0.56$	0.935	$y = 0.0043x - 0.02$
Morgan	0.907	$y = 0.0181x - 0.18$	0.941	$y = 0.0115x - 0.25$	0.932	$y = 0.0038x + 0.04$
Bray-Kurtz P1	0.913	$y = 0.0043x - 0.42$	0.95	$y = 0.0042x - 0.46$	0.943	$y = 0.0027x - 0.02$
NH ₄ -Oxalate	0.806	$y = 0.0018x - 1.03$	0.914	$y = 0.0021x - 0.63$	0.908	$y = 0.0009x - 0.19$
Distilled H ₂ O	0.923	$y = 0.0107x - 0.18$	0.928	$y = 0.0104x - 0.11$	0.968	$y = 0.0055x - 0.03$
P saturation (oxalate method)	0.903	$y = 0.0820x - 2.03$	0.928	$y = 0.0397x - 0.62$	0.933	$y = 0.0251x - 0.24$
P saturation (M3-PSI method)	0.916	$y = 0.0080x - 0.08$	0.928	$y = 0.0065x + 0.04$	0.937	$y = 0.0045x + 0.03$
P saturation (H ₂ O-PSI method)	0.932	$y = 0.0262x + 0.03$	0.921	$y = 0.0215x + 0.06$	0.978	$y = 0.0159x + 0.01$

Tunney et al. (1997) suggested that the national average Morgan extractable P concentrations have increased from 1 to 9 mg/L soil over a fifty year period from 1950 and, overall, agricultural P inputs remained in considerable surplus to P removals. These authors also made the important statement that *'However, relating diffuse P losses in the field to soil P concentrations requires considerable monitoring effort, and isolating the effect of SPT is often complicated by the confounding effects of climate, hydrology, incidental and point-source losses.'*

Soil analysis in Ireland uses Morgan's reagent and they collect samples to 10 cm depth (Daly and Casey, 2005) and importantly for our current study it was shown that SPT could be related to DRP in surface runoff from two experimental plots. The Morgan's reagent showed the closest similarity of ratio between the two treatment plots to the estimated ratio. It is likely that these results are not directly transferable to the SAC procedure as there are some differences in the two methods and it would appear that the Irish method extracts less P.

McDowell et al. (2001) compared change points for a range of soils and these ranged between 20 – 112 mg P/kg. The critical change point has been estimated using various soil/extractant combinations. Horta and Torrent (2007) compared Olsen P at various water: soil ratios. The narrower the ratio the lower is the Olsen P concentration.

These important conclusions were taken from Styles et al. (2006) *'It is inferred from the strong linear relationships observed between Morgan P and moist sample P solubility that the risk of elevated surface water P concentrations, and consequent eutrophication, increases linearly with increasing soil Morgan P content. This emphasises the importance of controlling soil Morgan P concentrations within management strategies aimed at limiting diffuse soil P losses. The average Irish soil Morgan P concentration of 9 mg P/L is at the upper end of recommended agronomic optimum soil P status, and concentrations above this level pose unnecessary risk to surface waters.'*

Soil OM content was found to significantly affect P solubility in soils, once the dominant Morgan P effect was accounted for. There were insufficient data in this study to differentiate all the soil groups differentiated by Daly et al. (2001), but there was a clear difference between the P solubility of predominantly mineral compared with peat soils. At a given Morgan P content, P solubility in peat soils was approximately one quarter of that in mineral soils.

The modest success of the P desorption index developed here, when applied across sub-catchments of varied typology, indicates an importance of both Morgan P and soil-type in determining the scale of diffuse soluble P losses. In Ireland there is a large database of Morgan P, and a nationwide soil map, which could be used to assess relative soluble P loss risk on a catchment-scale, following the example set by Daly et al. (2002).'

In a series of papers the work of a short (two-year) study funded by the Scottish Office produced a number of important papers that explored the nutrient dynamics in streams draining six relatively small agricultural catchments (Hooda et al., 1997). The specific objectives of this study were to: (i) assess and compare phosphorus concentrations and losses from two contrasting regions in Scotland which differ considerably in land use, rainfall, soil type, P inputs and other farming practices; (ii) compare upstream and downstream P concentrations in order to assess the overall influence of land use and management practices within the catchment reaches; and (iii) examine the distribution of various P fractions in stream flow.

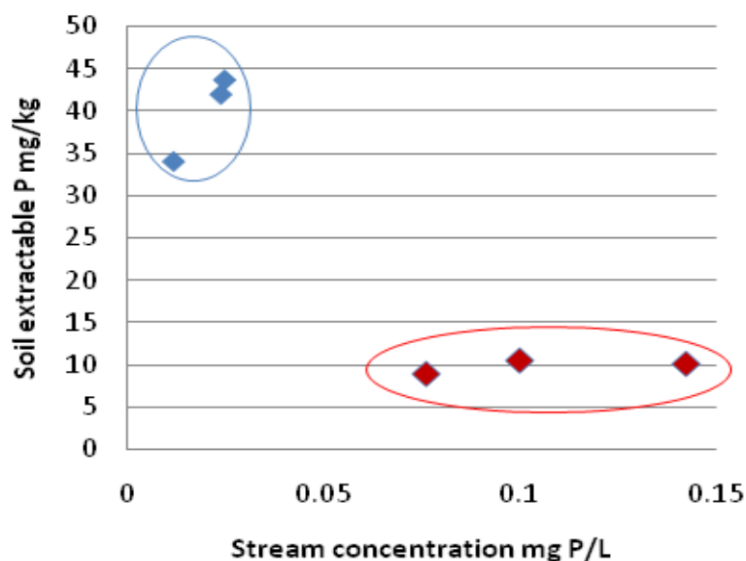
The west catchments: Logan, Caddell and Killoch are situated in Ayrshire in one of the most intensive dairy farming regions in the UK, and the major land use is maintained grassland on the farms with a mixture of woodland or rough grazing in the upper reaches of Logan and Caddell, respectively. In the NE the catchments Kirkhill, Elrick and Glensaugh cover a wider range of land uses, including arable with livestock including beef and poultry systems.

The soils in the western catchments are mainly non-calcareous gleys, calcareous gleys, and humic gleys, with localised occurrence of basin peat. These soils are generally poorly drained and are medium to very fine in texture (Anon, 1984). Although subsurface tile drains are common on the farms, the combination of rolling topography and slow draining soils means that surface runoff forms a significant component of the catchment water (Boorman et al., 1995). Light textured Podzols, with iron Podzols, are the dominant soils in the north eastern catchments, with some brown forest soils (Anon, 1984). These brown forest soils are well-drained while the Podzols vary between poorly- to freely-drained. The soils in the north eastern catchments have much larger content of extractable P compared with those in the western catchments.

One of the main purposes for re-analysing this very interesting data set was to see if any robust relationship between extractable (advisory) soil P (here acetic acid) and loss of soluble P could be identified (Figure 1). Despite needing to show some caution with extrapolating this data, there is a strong suggestion that a common (national) relationship might not exist. This is perhaps not so surprising considering the very different drainage status of these two groups of soils and the early understanding of the Soil Survey of Scotland that this together with parent material is a key attribute on which to group/classify soils (Williams, 1959).

In light of Figure 1 it is possible to question the value of 'advisory soil data' in terms of its potential for providing additional information that might have an environmental context/significance. Various strengths and weakness exist.

Figure 1. Comparison of the relationship between extractable soil P (acetic acid) and volume weighted averaged stream water molybdate-reactive P for three west coast (red) and east coast (blue) catchments.



International literature does suggest that useful relationships can be obtained. However, important clarifiers are required, and in particular a need to modify relationship for broad groups of soil, which for Scotland would mean association (parent material) and drainage (series). Early advisory information using analytical data based on acetic acid extracts did include an 'association' qualifier.

Some additional studies using Scottish soils showed the potential advantage of including fundamental sorption characteristics (which are again related to parent material and drainage conditions). This would provide a basis against which this advisory data can be re-interpreted. For example, although it is only based on three points there might be the suggestion of a relationship within the NE soils (Figure 1) between soil P status and stream water.

In a second series of papers Hooda *et al.* (2000 and 2001) investigated the potential for relating soil properties to P leaching risk and demonstrated for a wide range of soils that the use of degree of soil saturation with P (DSSP) was superior to many SPT methods. Their conclusions were '*The net total P accumulation in the soils across the sites ranged from 16 to 232 kg P /ha/y. The effects of long-term P surpluses were a significant reduction in P-retention capacity and increase in DSSP. The sites investigated would attain 25% DSSP in 10-150 years, depending upon the size of P surplus and sorption capacity. A combination of large P surplus and low P-sorption capacity could saturate soils to 25% DSSP within 10-30 years.*' These soils would then be of a very high risk for soluble P leaching.

5. Development of a model of the relationship between soil association attribute data and inherent P sorption capacity

5.1 Estimates of P sorption capacity for Scottish soils based on soil attributes

Fertiliser use over recent decades has improved the P status of Scottish soils to the extent that on some agricultural soils losses of P may be impacting surface water quality. P loss from agricultural land can occur via three pathways:

- Direct surface runoff of inorganic and organic forms of P applied as fertiliser (dissolved, un-dissolved and organically-bound P)
- Loading of P bound to eroded soils (un-dissolved sediment-bound P)
- Loading of soluble forms of P in surface runoff or from tile drainage systems. This is referred to as soil mediated P leaching.

It is desirable to be able to forecast which soil types are inherently prone to soil mediated P leaching losses and those which have the capacity for high P sorption in order to meet agricultural P management targets. To do this an analysis and interpretation of the processes involved are required.

Previous work on the behaviour of P fertilisers applied to soil focussed on the identification of reaction products formed by the interaction of soils and fertilisers. The dissolved concentration of P in soil solution is seldom in equilibrium with known P compounds (Lindsay, 1979; Lindsay et al. 1989), and it is generally accepted that dissolved P concentrations are controlled by mechanisms involving adsorption to soil mineral constituents (Saunders, 1965; Weng et al., 2011).

The concentration of soluble P in the water percolating through soil and the P losses through subsurface drainage are usually small compared to the losses that occur via soil erosion and surface runoff, due to sorption of P by reactive soil mineral constituents; especially iron /aluminium (hydr)oxide (Sharpley et al., 2001). However, drainage losses can be similar to surface runoff when the soil has a low P-sorption capacity or has been saturated with P (over fertilised), and when depth and hydrological conditions are suitable for leaching (Sims et al., 1998; Dils and Heathwaite, 1999). Therefore to provide better predictions of P loss via leaching it is necessary to develop estimates of soil P sorption capacity. In principal P sorption isotherms could be determined for soils on a national scale. Alternatively it should be possible to estimate P sorption capacity using existing data and a sound knowledge of soil chemistry.

It is known that soil P-sorption capacity is related to the quantity of iron and aluminium (hydr)oxide minerals present in the soil, and is also pH dependent. Therefore, in order to develop a P-sorption index it is necessary to have a soil data set containing information on the iron/aluminium hydroxide phases in combination with other data relating to P solubility. Acid ammonium oxalate extractable Fe and Al can be used to quantify the Fe/Al phases (Parfitt and Childs, 1988). In section 3.2.2 below a dataset is described consisting of Scottish soils with a wide range of chemical properties that can be used to estimate P-sorption characteristics.

Studies of P adsorption by natural occurring and synthesised minerals (Antelo et al., 2010) have shown that amorphous and cryptocrystalline forms adsorb more P than crystalline minerals. These

differences in adsorption capacity are attributed to the reactive surface area of the mineral. Typically the more crystalline Fe hydroxides such as goethite have surface areas in the region of 70-90 m²g⁻¹, whereas for modelling amorphous phases such as ferrihydrite the surface area required can be in the range 600-750 m²g⁻¹ (Dzombak and Morel, 1990; Gustafsson, 2001).

Ferrihydrite is a poorly crystalline iron oxide ubiquitously occurring in soils and plays a significant role in phosphate adsorption by soils. Soils analytical methods based upon selective dissolution procedures have been developed to estimate the soil content of these amorphous phases (Parfitt and Childs, 1988). In particular acid ammonium oxalate extractable Fe and Al has been used to estimate the soil content of amorphous Fe and Al soil minerals (McKeague et al., 1971; Farmer et al., 1983).

Good correlations have been found between P adsorption capacity and acid ammonium oxalate extractable Fe and Al (e.g. Evans and Smillie, 1976, Freese et al., 1992, Börling et al., 2001). Based on the results obtained, by Börling et al., 2001 oxalate-extractable Fe plus Al was used for predicting P sorption capacity in Swedish soils.

Ideally soil P sorption capacity can be determined using adsorption isotherms (Bache and Williams, 1971). However, P sorption isotherms are labour intensive. Therefore studies using Al and Fe extracted by acid ammonium oxalate have been conducted to estimate the P sorption capacity of noncalcareous soils (Borggaard et al., 1990; Freese et al., 1992).

It is known that adsorption of P by Fe/Al oxides and clays is pH dependant and that the adsorption properties of the oxide minerals can be altered by adsorbed Ca (Rietra et al., 2001) and soil organic matter (Weng et al., 2008; Weng et al., 2012). To take account of these effects new models have been developed to estimate P adsorption using surface complexation theory (Dzombak and Morel, 1990). Good progress has been made with this modelling approach (e.g. Hiemstra, 2010a,b; Weng et al., 2011), but as yet these models have not been widely tested on soils. Furthermore, the simplifying assumptions that have to be made regarding the properties of the soil organic matter that competes for adsorption sites with phosphate on the mineral surfaces have not been deciphered. It has been shown that dissolved P is sensitive to dissolved organic carbon concentrations (DOC) (Hiemstra et al., 2010b); therefore better information may be required on the nature of DOC. However, they can be used in a semi-quantitative way to predict P sorption so long as the simplifying assumptions are understood.

In order to estimate an intrinsic soil P adsorption index, at the very least data consisting of soil oxalate extractable Fe, Al, % clay and % organic carbon is a minimum requirement. We propose using three approaches to rank Scottish soils in relation to their intrinsic P sorption capacity. These three approaches are (1) use literature values for the reactive surface area and surface adsorption site concentrations and sum this value for Fe, Al oxides and phyllosilicate clay; (2) use established regression relationships between P adsorption and oxalate extractable Fe and Al that have been published in the scientific literature; and (3) use new mechanistic models in a simplified manner to estimate various P adsorption indices.

5.2 Soil data

To estimate the intrinsic P sorption capacity of Scottish soils a data set consisting of 399 soil samples and representing 38 different soil associations have been assembled.

The data consist of a combination of five datasets. These are

(i) 43 soil Ap horizons from the National Soils Inventory Scotland (NSIS-2). The NSIS-2 data has been supplemented with new measurements for Modified Morgan's extractable P. This may be useful in providing improved interpretation of the SAC advisory data set;

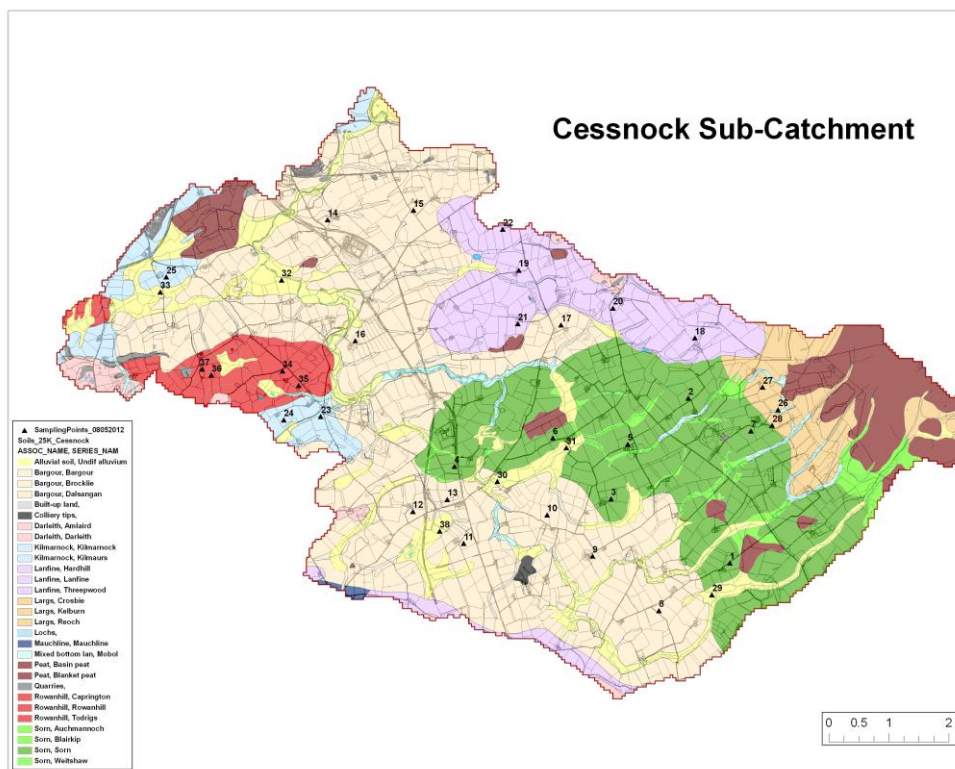
(ii) A research data set consisting of soil sampled (n= 60) from the Lunan Catchment;

(iii) A research data set with 264 soil samples (A horizons) which were originally selected to include both freely and poorly drained soils covering 10 major soil associations of Scotland.

(iv) A further research data set of 7 soils from the JHI.

(v) The main soil association in the Cessnock (Bargour) and a secondary (Lanfine) are not covered by the data above so a sampling programme and analysis was undertaken in order to link with the P sorption modelling work. Representative samples from each soil from across the catchment were taken in May, 2012, targeting agriculturally managed land and different soil types. In total 33 samples were taken (Figure 2) and 27 of these have been included in the current modelling. This work was carried out as part of the Scottish Government funded research work package WP 2.3 "Effectiveness of measures to manage water quality and control diffuse pollution". Further details of the soil associations in the Cessnock sub-catchment are given in Appendix 1.

Figure 2. Sampling locations across the Cessnock sub-catchment.



Consistent across all 5 data sets are values for oxalate extractable Fe, Al and P, %organic carbon, %clay and soil pH. For each soil association the average soil properties have been determined (Table 2). These average values have been used to derive parameter input values for the various modelling approaches described below. Standard deviation data for the properties of the 38 soil associations are given in Appendix II.

Table 2. Mean soil properties for 38 Scottish soil associations.

	Association	n	pH water	C %OC	CLAY %	Ox-Al mg/kg	Ox-Fe mg/kg	Ox-P mg/kg	Total_P P mg/kg	Olsen_P P mg/kg
1	Alluvial soil	12	5.85	4.00	2.2	2660	6953	656	1049	27.2
2	Arkaig	16	5.63	5.83	10.6	3177	5338	821	931	19.5
3	Auchenblae	1	5.02	1.59	1.7	2352	1901	34	697	23.8
4	Balrownie	60	5.94	3.13	11.4	3577	4723	708	974	27.6
5	Bargour	7	5.76	4.61	19.0	2074	8613	543	815	27.5
6	Boyndie	3	6.05	2.17	4.4	2941	3871	1241	1529	71.8
7	Corby	35	5.65	4.45	8.2	3391	5589	763	1021	22.5
8	Countesswells	33	5.60	4.84	14.6	3361	5595	830	1118	18.6
9	Darleith	24	5.51	7.96	17.5	9821	14149	1270	1645	13.1
10	Darvel	1	5.11	2.32	3.9	2117	4802	574	889	28.2
11	Eckford	3	5.83	2.37	4.2	2923	4863	1000	1121	54.4
12	Ettrick	30	5.87	5.03	19.4	3840	8009	855	1293	21.5
13	Forfar	13	5.83	2.41	5.0	3415	5067	901	1246	48.7
14	Foudland	31	5.61	3.66	16.0	3369	8113	893	1070	17.2
15	Insch	2	5.34	5.27	11.0	9034	14859	1431		9.2
16	Kilmarnock	3	5.66	3.82	6.9	1594	6130	562	874	21.0
17	Kintyre	1	5.11	3.12	3.2	1792	7572	531	1017	7.4
18	Kippen	1	5.03	4.22	6.1	3263	5515	438	860	3.5
19	Lanfine	3	5.70	5.56	12.0	5338	10270	997	1161	34.6
20	Largs	2	5.35	5.29	6.0	2261	6344	424	474	16.6
21	Millbuie	1	6.14	1.89	3.1	1161	2843	577	927	42.4
22	Minto	1	5.76	1.56	4.8	1225	3989	318	643	11.7
23	Mountboy	8	5.83	2.23	4.9	3634	4399	782	1182	41.2
24	North Mormond	1	5.86	2.06	6.1	2507	5632	498	947	19.4
25	Ordley	1	5.95	2.26	7.2	2501	6544	573	1044	27.4
26	Panbride	2	6.16	2.98	4.5	4539	5451	1060	1662	48.2
27	Rowanhill	5	5.78	4.89	8.5	2665	8984	666	1103	23.1
28	Sorn	7	5.82	4.61	5.8	1732	5745	584	986	36.3
29	Sourhope	19	5.85	5.55	12.0	7123	7285	1117	1331	18.3
30	Stirling	2	6.52	2.73	24.4	1826	8637		916	12.7
31	Stonehaven	1	5.48	4.08	14.0	4025	5475	824		8.5
32	Strichen	31	5.50	4.72	16.9	2810	6887	667	988	12.7

33	Tarves	31	5.70	4.12	15.0	5264	8623	961	1218	19.2
34	Thurso	2	5.41	4.59	6.5	2437	5076	449	957	13.5
35	Tipperty	1	6.24	0.37	41.0	2601	4392			
36	Tomintoul	1	5.48	3.16	4.4	3482	5253	593	1158	10.6
37	Tynet	2	6.25	3.26	4.3	3292	5733	507	1128	24.8
38	Yarrow	2	5.85	4.92	3.9	4622	7516	1297	1906	55.9
	sum	399								
	max	60	6.52	7.96	41	9821	14858	1431	1906	71.8
	min	1	5.02	0.37	1.7	1161	1900	34	474	3.54
	Mean		5.73	4.37	12.49	4017	6933	824	1112	22.91

Number of soils in each association (n), acid ammonium oxalate extractable Al, Fe (Ox-Al, Ox-Fe), Total P by sodium metaborate fusion (Total_P), Olsen extractable P (Olsen_P).

5.3 Calculation of P sorption capacity

To estimate P sorption capacity three approaches are used. These are:

1. Estimate “adsorption” capacity based upon the soil content of Fe, Al, %OC, %clay.
2. Use previously established regression relationships between P sorption and soil properties such as oxalate extractable Fe and Al.
3. Use advanced soil chemical modelling to estimate P adsorption capacity

1. P sorption capacity based on adsorption sites of individual adsorbents

In this approach the potential total soil concentration of adsorption sites is based upon a summation of the adsorption site associated with each major soil component that can adsorb P. Three different adsorption surfaces are assumed; amorphous Fe hydroxides, Al hydroxides and phyllosilicate clay minerals. The Fe and Al hydroxide content is estimated from the oxalate extractable Fe. To estimate the phyllosilicate clays content the <2µm particle size fraction (i.e. %clay) is used. The estimates are a simplification. For example, oxalate extractable Fe and Al may over estimate the concentration of the Fe and mineral containing phases because some of the Fe and Al extracted might be derived from Fe and Al bound to organic matter. The use of “%clay” does not distinguish the different phyllosilicates clay minerals and the fact that their reactive surface areas may vary. Another factor not considered is that other chemical species in the soil could compete for the adsorption sites, thereby altering the potential P adsorption capacity, this is especially so for Ca²⁺ and H⁺.

The adsorption site concentration is calculated according to equation [1]:

$$[1]. \quad [AS] \text{molkg}^{-1} = (g_{\text{Fe-Ox}} \text{ Kg}^{-1} * SA_{\text{FeOx}} * SD_{\text{FeOx}}) + (g_{\text{Al-Ox}} \text{ Kg}^{-1} * SA_{\text{AlOx}} * SD_{\text{AlOx}}) + (g_{\text{Clay}} \text{ Kg}^{-1} * SA_{\text{Clay}} * SD_{\text{Clay}})$$

Where [AS]molkg⁻¹ is the concentration of adsorption site per kg of soil, SA is the reactive surface area (m²g⁻¹) and SD is the concentration of adsorption sites (mol m⁻²) and g kg⁻¹ are the contents of either iron oxide (Fe-Ox), aluminium oxide (Al-ox) and clay (Clay).

For the Fe-Ox, a SA = 600 m² g⁻¹ and SD = 3.86 x 10⁻⁶ mol m⁻² (Dzombak and Morel, 1990). For the Al-Ox, a SA = 50 m² g⁻¹ and SD = 3.86 x 10⁻⁶ mol m⁻² (Gustafsson, 2001). For the clay, a SA = 24 m² g⁻¹ and SD = 2.22 x 10⁻⁶ mol m⁻² (Manning and Goldberg, 1996) are used which are based on the reported properties for illite. For clay SA refers to the edge surface area and not the basal plane. For P adsorption on

The ranking of the soil associations P sorption according to equation [1] is shown in Appendix III. The results are expressed as mmol kg⁻¹.

2. *P sorption capacity based on regression relationship between P adsorption and oxalate extractable Fe and Al*

For this approach a suitable data set is required where a regression relationship can be established between measured P adsorption capacity and the soil oxalate extractable Fe and Al. Evans and Smillie (1976) report such data for 27 Irish soils covering a wide range of soil developed on differing parent materials. This approach benefits from the fact that the P adsorption index was actually measured by adding a large spike of P (2500 mg kg⁻¹) to the soils and measuring the amount adsorbed. The amount added is rather large but can be viewed as an ion probe that is used to differentiate the P adsorption capacity of the different soils.

The regression equation relating P adsorption capacity to the oxalate extractable Fe and Al is given in equation [2]:

$$[2]. \quad P \text{ adsorption capacity} = (1102 * \%Al_2O_3) + (439.9 * \%Fe_2O_3) + 594.7$$

Where the P adsorption capacity is in mg kg⁻¹ and %Al₂O₃ and %Fe₂O₃ are the oxalate extractable Fe and Al expressed as a % of their oxide equivalent.

The ranking of the soil associations P sorption according to the regression equation is shown in Appendix II. The results are expressed as mg P_(adsorbed) kg⁻¹ of soil.

3. *P sorption capacity based on advanced chemical modelling.*

In the past 15 years soil geochemists have made much progress in developing models for describing ion adsorption phenomena by both mineral and organic soil constituents. These models are known generically as surface complexation models and consist of several modelling approaches depending on how the mineral surface-solution interface is conceptualised. It is hypothesised that from an understanding of how soil surfaces behave, these findings can be extrapolated to explain adsorption processes in soils.

These models were developed to provide an internally consistent framework that could simultaneously account for the observed effects of pH, the synergistic and competitive effects of other ions and solution ionic strength on ion adsorption. In principal these models can provide valuable information on the behaviour of chemical elements in soil environments, but require specialist knowledge to apply them.

Recently in a special issue (Emerging technologies to remove non-point P sources from surface water and groundwater) in the Journal of Environmental Quality, Weng et al. (2012) have used a surface complexation approach to describe P adsorption by iron oxides using the CD-MUSIC model. The

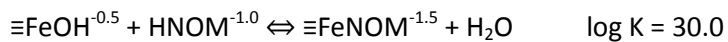
process-based nature of the CD-MUSIC model allows prediction of effects of pH and the synergistic and competitive effects of cations and other anions. We have used the CD-MUSIC model in combination with other relevant processes (e.g. solution speciation, P-mineral solubility equilibria and cation retention on soil organic matter) to estimate the P sorption capacity of soil. We will refer to this calculation as the Soil P Sorption Model (SPSM).

Model parameters for ions that are relevant to the soil environment are cited in the literature (Weng et al., 2012). The parameter set used in the following calculations for P adsorption by goethite (Fe-oxide) were taken from Hiemstra et al. (2010b).

P adsorption by surface adsorption sites ($\equiv\text{FeOH}^{-0.5}$) can be described using two inner-sphere complexes: the bidentate and protonated monodentate. The formation reactions for these surface phosphate species can be written as:



The model also attempts to include the competitive interactions of natural organic matter (NOM), by including a surface reaction, which is written as:



To apply the model, oxalate extractable Fe and Al were used to derive the soil content of “oxide” surface, which is derived by multiplying the gravimetric Fe content by an assumed mineral reactive surface area of $600 \text{ m}^2 \text{ g}^{-1}$ (Dzombak and Morel, 1990). The exact reactive surface area of these minerals in soils is unknown, and is therefore a cause of uncertainty in the calculations. In general less crystalline phases have greater surface areas and hence more adsorption potential. The soil value of NOM was based on assuming the soil organic carbon content was 30% humic material with a concentration of NOM of 1 mol kg^{-1} . Of course this assumption may not be valid for all soils. A Ca concentration of 0.001 mol l^{-1} was assumed.

The simplest way to use the model was to calculate the adsorption for an arbitrary addition of P at a fixed pH value. The arbitrary P concentration was chosen to provide modelled dissolved P concentrations of the same order of magnitude as those that would occur in field soils. If the addition of P chosen is too small, then the model predicts nearly 100% adsorption for all soils and the soils cannot be differentiated. If too much P is added, the adsorption capacity is calculated with unrealistically large dissolved P concentrations. Furthermore, this approach eliminates the requirement to make a decision on what soil P test should be used to input the amount of soil P. The model-calculated, dissolved P at pH 4.8 provides a way to rank the soils in relation to their P adsorption capacity.

The ranking of the soil associations in relation to P sorption according to the soil P sorption model (SPSM) is shown in Appendix III, where calculated soluble P at pH4.8 is expressed as mg kg^{-1} .

5.4 Ranking of P sorption capacity into an index system

The order of ranking of soil associations by methods 1 and 3 was more similar than the order by method 2 (Appendix III). Method 2 did not include %C and %clay. It was decided to proceed with the

more recently developed method 3. Table 3 was produced from the mean of the calculated amount of P at 3 pH values (4.8, 5.6 and 6.2) that must be added to bring the soil solution concentration to 50µg/L P. For this approach the larger the number the greater the P sorption capacity. The numbers in Table 3 have been used to rank the soils into a P sorption index system from 1 (very low) to 5 (very high) P sorption capacities. The actual numbers are "theoretical" (a model constructs). The magnitude of the numbers reflects the translation from oxalate Fe to a reactive surface area of Fe oxide for each soil. The same rule is used for all soils. If a lesser reactive surface area for Fe is assumed all the calculated amounts to obtain 50 µg/L would be less. Conversely, if more reactive surfaces are included in the model the amount of P needed to fill them to obtain 50µg/L dissolved P would be greater. The concentration 50µg/L is a common maximum concentration for the majority of rivers before they drop out of WFD "good" status, but for some rivers the maximum concentration is 120µg/L (personal communication, SEPA).

Table 3. Ranking of 38 soil associations in relation to P sorption index.

Association	Mean sorption P mg/kg	P sorption index
Auchenblae	45.1	1
Millbuie	82.2	1
Arkaig	92.2	1
Thurso	110.4	2
Boyndie	124.4	2
Countesswells	135.7	2
Corby	140.7	2
Balrownie	141.1	2
Sorn	141.8	2
Kippen	142.7	2
Mountboy	148.1	2
Minto	150.3	2
Largs	151.5	2
Stonehaven	152.9	3
Tomintoul	160.5	3
Darvel	165.9	3
Eckford	167.8	3
Forfar	176.1	3
Panbride	176.5	3
Tynet	181.2	3
Kilmarnock	183.9	3
Sourhope	192.7	3
Strichen	202.8	3
Yarrow	215.4	3
North Mormond	216.1	3
Alluvial soil	218.6	3
Tipperty	246.9	3
Ettrick	250.5	3
Ordley	258.1	3

Kintyre	284.5	4
Bargour	291.4	4
Rowanhill	292.2	4
Foudland	295.5	4
Tarves	305.2	4
Lanfine	336.5	4
Stirling	360.8	5
Darleith	454.4	5
Insch	579.9	5

5.5 National mapping of P sorption index

In order to extend P sorption index to a national scale, soil associations (both at 250K and 25K scales) have been grouped into 20 categories (Table 4) using the approach presented in Paterson et al. (2003). This approach resulted in assigning indices to a further 79 associations. Soil associations with parent material and % of total land area are presented in Appendix IV. Twenty-four % of the national land area which are mapped by soil association had no data to allow assignment of an index (Appendix V).

Table 4. Soil associations grouped into 20 categories

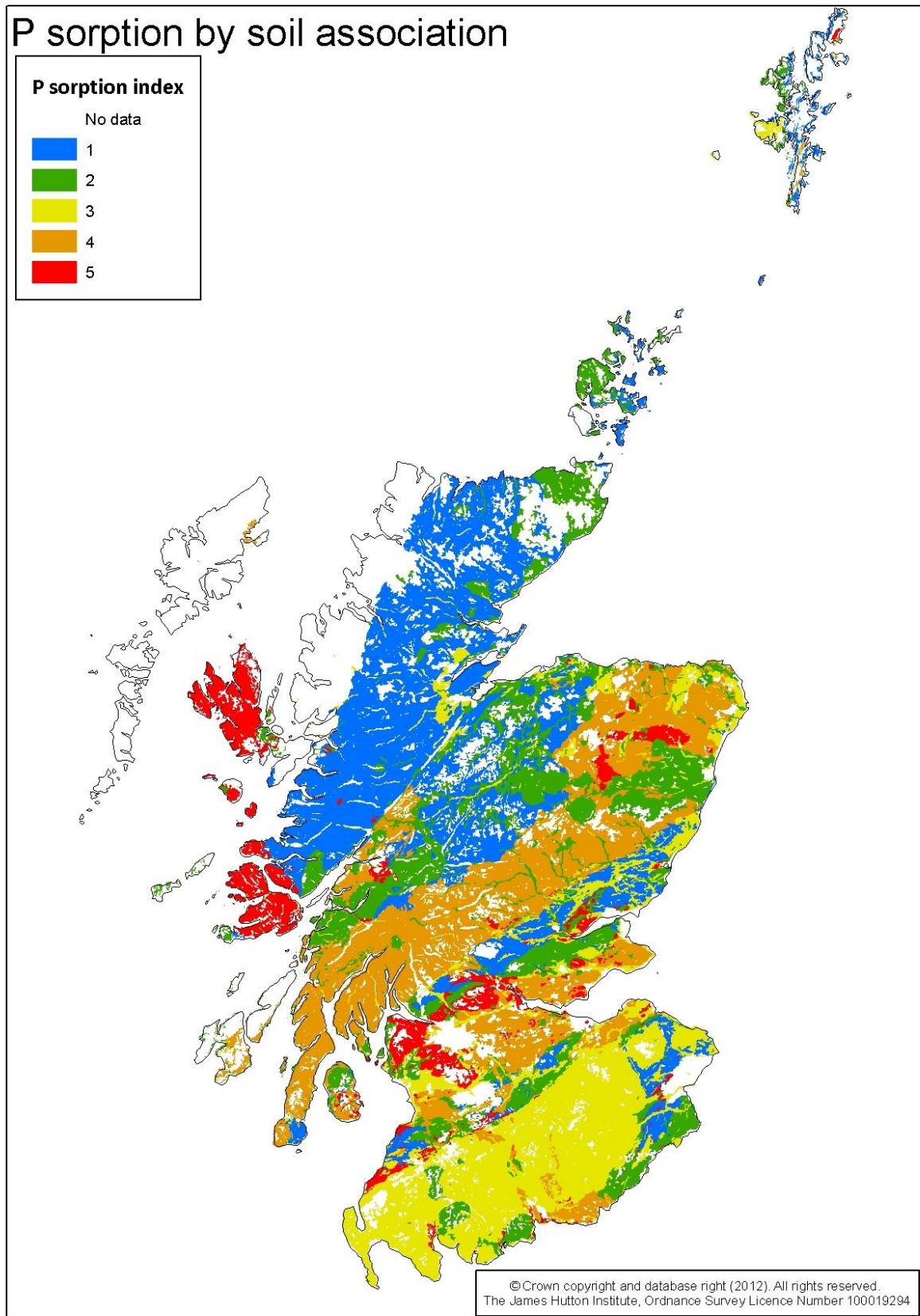
	Linked associations
1	Arkaig, Ardvanie
2	Balrownie, Berriedale, Cairncross, Canisbay, Cromarty, Elgin, Forfar, Glenalmond, Hatton, Hobkirk, Kippen, Lauder, Laurencekirk, Millbuie, Rackwick, Sabhail, Skelberry, Thurso, Tynet
3	Corby, Brightmony, Doune
4	Counteswells, Aberlour, Bemersyde, Creetown, Dulsie, Knockskae, Dalbeattie, Priestlaw
5	Darleith, Benan, Corriebreck, Insch, Lethans, Nochty, Smailholm, Torosay
6	Durnhill
7	Ettrick, Barncokrie, Blair, Craigdale, Kirkcolm, Linfern, Minto, Rhins, Shawhill, Tynehead, Yarrow
8	Foudland
9	Lochinver
10	Peat
11	Rowanhill, Arbigland, Ashgrove, Bargour, Bogtown, Carter Drongan, Hayfield, Hindsward, Sorn, Winton, Giffnock
12	Sourhope, Mountboy, Symington
13	Strichen, Gourdie, Kintyre

14	Tarves, Gruline, Kilmarnock
15	Torridon, Dunnet
16	Arran, Canonbie, Durisdeer, Holywood, Lanfine, Mauchline
17	Carpow, Darvel, Dreghorn, Eckford, Gleneagles
18	Deecastle, Fraserburgh, Inchkenneth, Inchnadamph, Staffin, Whitsome, Leslie
19	Ethie, Lyndardy, North Mormond, Ordley, Peterhead, Stonehaven, Walls
20	Alluvisols

For soil associations that are not in Table 3 with measured values, then the association groupings from Table 4 were used to assign an index to associations that did not have measured values. A precautionary 'risk' based principle that the lower the sorption value, the greater risk of P leaching was used to assign indices. This 'risk' assessment is based on the sorption capacities estimated from the inherent soil attributes used in the SPSM model. Any associations with no measured values were put into the lowest index of any from the same group e.g. Gruline association (group 14 in Table 4) was given index 3 because that is the lower index in Table 3 of the other associations in group 14 i.e. Kilmarnock (index 3) and Tarves (index 4). Group 2 has 19 associations with measured values for 4 associations. The P sorption indices for these 4 associations are Millbuie index 1, Balrownie index 2, and Forfar and Tynet index 3. Using the 'risk' based principle that any associations with no measured values were put into the lowest index of any from the same group, then the other 15 associations in group 2 were assigned an index 1. Associations from Table 3 and 4 are listed in Appendix IV with the appropriate P sorption index, along with the area (ha) of each association. All alluvial soils have been grouped together in index 3. It is expected that different P sorption indices will exist for different alluvial soils as all alluvial soils are not formed from a single soil association group. Based on the precautionary principle described above, there is currently a bias towards lower P sorption indices. Confidence in the P sorption index predictions can only be increased by the collection of more data across more associations.

Data from Appendix V have been used to create a national map of ranking of P sorption index from 1 (very low) to 5 (very high) (Figure 3). Ranking "0" covers built-up areas, open water, rock and scree, organic soils, and associations in an association group with no measured P sorption data (Appendix V).

Figure 3. National map of P sorption index from 1 (very low) to 5 (very high) by soil association



5.6 Mapping of P sorption index in SEPA priority catchments plus two DPMCs.

Associations described in Table 4 cross geographical boundaries (because they are geology based) and may cross climatic zones and so may not link 'farming types' together. Therefore, the national map has been summarised into 4 broad agricultural regions, further sub-divided by soil type, land capability for agriculture (LCA) and area (ha) (Appendix VI).

Broad land use areas within the 4 regions, together with the location of the Priority Catchments (PCs) plus River Ythan and Lunan Water DPMCs, are given in Table 5.

The distribution of agricultural land varies between regions with the largest proportion of arable being located in the SE. A further breakdown of the arable land shows the large proportion of grassland (<5 years old) in the SW. The majority of PCs are distributed between regions 1 and 3 (NE and SW) with only the single small Eye Water located in the SE.

Table 5. Broad land use area (ha) within the four agricultural regions together with the location of PC + 2 DPM catchments.

Region	Arable*	Grass over 5 years old	Total area**	Soil/land cover area	PC + 2 DPM catchments
Scotland	903,225 (33)	917,738	6,240,409 (29)	7,417,567	
1 North East	425,575 (26)	173,628	1,325,148 (45)	1,594,105	Buchan Coastal, Deveron, Ythan, Ugie, Dee, Tay, Lunan, S. Esk
2 South East	226,424 (22)	137,823	607,458 (60)	733,786	Eye
3 South West	156,772 (61)	427,757	1,577,492 (37)	2,165,372	Stewartry Coastal, Irvine, Ayr, Garnock, Doon, N. Ayrshire Coastal, Galloway Coastal
4 North West	94,453 (48)	178,530	2,725,221 (10)	2,924,303	

* Proportion (%) of arable area <5 years old grass

**data from SEPA P report (2011) where data appear low as all islands may not be included.

***New data totalled from summing the soil or land cover areas and is close to a total land area of 7,700,000ha, the small difference is due to inland waters etc.

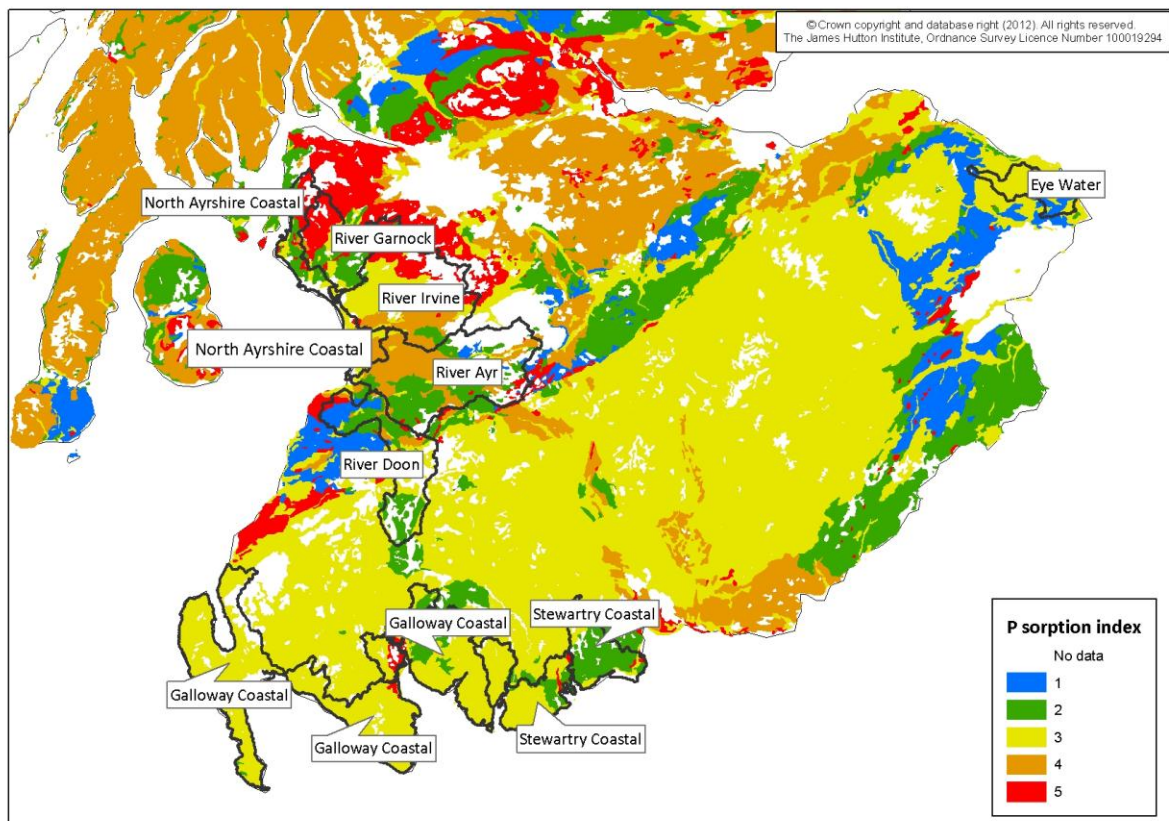
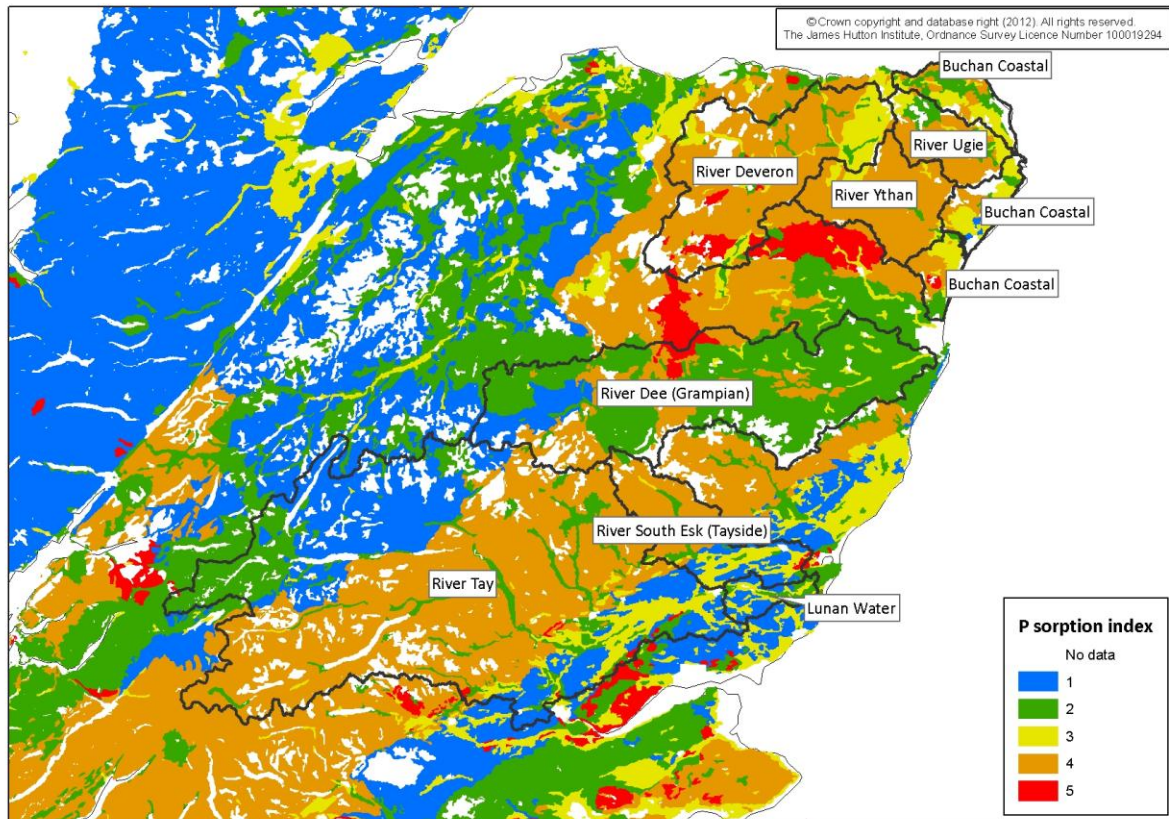
Coverage of areas of associations with P sorption analytical data within the 14 PC and 2 DPMCs with soils at the 250 and 25K scales (at 250K a few associations are shown as grouped) are shown in Table 6. Due to the scale of mapping, alluvial soils are underestimated at 1:250K.

Table 6. Association areas (ha) within the 14 PC+2 DPMC catchments

Soil associations	250K		25K
Alluvial soil	27,405.2	Alluvial soil	50,305.5
Arkaig	88,919.4	Arkaig	0.0
Auchenblae		Auchenblae	455.7
Balrownie	42,578.0	Balrownie	42,114.1
Bargour	7,989.9	Bargour	6,948.1
Boyndie		Boyndie	9,466.1
Corby/ Boyndie/ Dinnet	68,104.1	Corby	28,070.4
Countesswells/ Dalbeattie/ Priestlaw	166,714.3	Countesswells	67,819.8
Darleith/ Kirktonmoor	27,537.9	Darleith	24,289.6
Darvel	3,761.8	Darvel	2,590.2
Eckford/ Innerwick	283.9	Eckford	219.5
Ettrick	78,656.9	Ettrick	13,346.1
Forfar	25,770.7	Forfar	24,068.0
Foudland	84,157.8	Foudland	69,779.5
Gleneagles/ Auchenblae/ Collieston/ Darnway	5,538.6		
Insch	13,595.9	Insch	11,453.0
Kilmarnock	19,246.1	Kilmarnock	17,123.2
Kippen/ Largs	4,194.4	Kippen	435.5
Lanfine	7,609.3	Lanfine	6,804.6
Largs		Largs	3,910.8
Mountboy	3,539.4	Mountboy	3,721.0
North Mormond/ Orton	4,674.9	North Mormond	2,571.4
Ordley/ Cuminstown	13,441.4	Ordley	9,848.0
Rowanhill/ Giffnock/ Winton	14,962.9	Rowanhill	8,961.2
Sorn/ Humbie/ Biel	8,273.3	Sorn	6,156.9
Sourhope	1,895.1	Sourhope	1,124.9
Stirling/ Duffus/ Pow/ Carbrook	4,211.8	Stirling	104.9
Stonehaven	2,980.6	Stonehaven	3,512.3
Strichen	270,546.7	Strichen	60,226.8
Tarves	87,382.7	Tarves	51,481.6
Tipperty/ Carden	4,896.6	Tipperty	4,090.7
Tomintoul	0.0	Tomintoul	56.4
Tynet	14.8	Tynet	8.9
Yarrow/ Fleet	12,967.2	Yarrow	523.2
Grand Total	1,101,852.0	Grand Total	531,587.8

The grand total area of the 14 PCs + 2 is 1,386,505 ha (Table 7). A comparison of grand totals in Tables 6 shows that 79% of the total area of the 14 PC and 2 DPMCs is covered by the soil associations (or grouped associations at 250K scale) that are used to rank associations in order of P sorption capacity. Data from Appendix V have been used to map P sorption index in the 14 PCs and 2 DPMCs (Figure 4).

Figure 4. Map of P sorption index from 1 (very low) to 5 (very high) by soil association in the 14 PCs and 2 DPMCs



The distribution of P sorption index across the whole country and the area of PC + 2 DPMCs across the 4 regions are shown in Tables 7 and 8, and distribution (ha) by individual PC+2 DPMCs (Table 9).

Table 7. Distribution (ha) of P sorption index across the whole country and the area of PC + 2 DPMCs across the 4 regions.

	P sorption index						Grand Total
	0	1	2	3	4	5	
Total area whole	1,545,362	1,634,028	1,154,860	1,866,869	812,912	420,782	7,434,814
PC+2DPMCs in each region							
1: North East	92912	131654	211959	326766	184962	16307	964560
2: South East	78	2788	1	9071	0	0	11938
3: South West	48856	5778	73896	185697	36211	29461	379900
4: North West	756	6202	2615	0	0	0	9573
Total PC+2DPMCs	162602	146471	288471	521534	221173	45768	1365971

Table 8. Distribution of P sorption index as a % of the total area of PC+2 DPMCs for each region.

Region	0	1	2	3	4	5
1	10.60	13.50	21.74	33.52	18.97	1.67
2	1.00	23.0	0	75.71	0.00	0.00
3	12.86	1.52	19.45	48.88	9.53	7.76
4	7.89	64.79	27.32	0.00	0.00	0.00
Grand Total	10.44	10.72	21.12	38.18	16.19	3.35

Table 9. Distribution (ha) of P sorption index soils by individual PC+2 DPMCs and estimated losses of orthophosphate-P from terrestrial sources .

	0	1	2	3	4	5	Area (ha)	mg*	kg P/ha
Buchan Coastal	15.28	1.25	20.33	46.28	15.77	1.09	52,782		0.014; 0.609
Eye Water	0.65	23.35	0.01	75.98	0.00	0.00	11,938	0.081	0.075; 0.428
Galloway Coastal	8.42	0.00	8.66	80.75	0.00	2.17	110,380		0.016; 0.947
Lunan Water	0.00	45.06	22.13	32.81	0.00	0.00	13,328		0.061; 0.642
North Ayrshire Coastal	11.46	0.00	19.97	30.77	16.79	21.01	19,668		0.269; 1.231
River Ayr	26.55	2.42	29.00	4.08	35.20	2.75	57,972	0.014	0.269; 1.231
River Dee (Grampian)	9.72	7.50	60.32	7.65	12.78	2.03	207,178		0.047; 0.488
River Deveron	13.27	0.00	5.02	29.49	45.33	6.89	122,972	0.047	0.015; 0.502
River Doon	15.30	13.46	32.62	22.89	8.68	7.04	30,928		0.269; 1.231
River Garnock	6.21	0.00	36.40	15.66	1.21	40.51	22,583	0.012	0.269; 1.231
River Irvine	16.59	0.00	4.35	41.78	18.49	18.80	46,130	0.011	0.269; 1.231
River South Esk	2.81	17.74	8.67	58.89	11.00	0.89	55,819	0.045	0.047; 0.488
River Tay	9.87	21.86	13.87	47.84	6.09	0.47	484,733	0.013	0.061; 0.642
River Ugie	11.04	0.00	15.15	28.76	45.05	0.00	33,306	0.09	0.014; 0.609
River Ythan	2.74	0.00	2.33	11.08	83.23	0.63	53,817	0.05	0.047; 0.488
Stewartry Coastal	6.41	0.00	34.56	56.02	0.00	3.01	42,436		0.016; 0.947
Grand Total	10.44	10.72	21.12	38.18	16.19	3.35	1,365,971		

* mg ortho P/L from averaged HMS data for the year 1987 which was an average rainfall year

The estimated losses of orthophosphate-P for modelled areas taken from Heath et al. (2002) are shown in Table 9. The first value represents the averaged loss (kg P/ha/y) and the second value is calculated on the basis of agricultural land area. The estimated loads are from terrestrial sources only with those from urban waste water treatment sources removed. It might be suggested that P losses from agricultural soils on the east coast are less than those in the west, which is consistent with Figure 1, section 4, based on Hooda et al. (1997).

6. SAC soil P test data (SPT) in relation to P sorption index

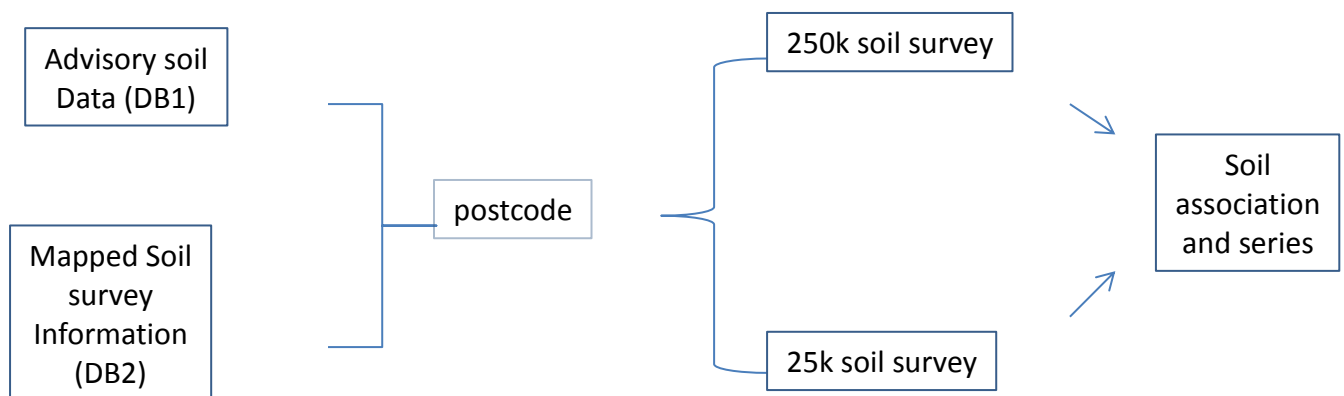
6.1 Linking SAC advisory P data with mapped soil survey information

Data have been extracted from mid 1996 to 2010 for advisory soil samples that were submitted from the 23 SAC agricultural office areas within Scotland which vary widely in area and farming systems. The full data set comprises of >130,000 topsoil samples and were reported on in full to SEPA in contract reference 30107. The data were summarised and interpreted at a national, regional and for SEPA priority catchments (plus 2 DPM catchments). The SEPA priority catchments (plus 2 DPM catchments) account for <30% of the total soil samples and in addition ~20% of samples do not have any post code. These data will be used in conjunction with the results of section 5 above in an attempt to determine the *potential* risk of leaching.

The JHI has access to the Ordnance Survey Address Point © data (<http://www.ordnancesurvey.co.uk/oswebsite/products/address-point/index.html>) for Scotland through the Ordnance Survey Mastermap © dataset. This dataset contains a georeferenced location for each postcode in Scotland. By using this dataset as a 'lookup' table, the postcode for each of the advisory samples can be located spatially, and therefore plotted on a map.

Due to changes in postcodes over time (some codes are converted to new codes, or removed), errors in recording, and other issues of data quality, around 5% of the advisory samples cannot be plotted; there are still over 97,000 which can be georeferenced correctly by this method.

The following schematic representation shows how the advisory soil data and the mapped soil survey information are linked and soil attributes employed to provide groupings and to define risk based summaries.



Having obtained a georeference for these advisory samples, they were overlaid on 2 soils datasets held by JHI using ArcGIS software. This process allows the user to assign the soil information from these data sources to the points which lie on them. The 2 soils data sources are:

1:25,000 soils data ('soil series'). Soils are mapped by JHI (formerly MISR – Macaulay Institute for Soil Research) at this scale according to soil series. Series are determined by the underlying soil parent material (the 'soil association') modified by drainage. Each series is a specific soil type (e.g. brown earth, humus iron podzol). Whilst this is the most detailed level at which soils are mapped in

Scotland, only a proportion of the maps are available digitally; c25% of the advisory samples fall outwith this coverage.

1:250,000 soils data ('map units'). At this scale, soils are mapped as 'map units' – combinations of soil series which occur together in the landscape. Some map units consist of only 1 series, while others have 2 or more component series. The methodology behind this classification is detailed in 'Organisation and Methods of the 1:250,000 Soil Survey of Scotland' published by MISR in 1984. This coverage is available digitally for the whole of Scotland, but individual series cannot be assigned to advisory points due to the nature of the map units; only the association can be recorded unambiguously (see section 6.3).

The final dataset has c91,000 advisory points with soil information.

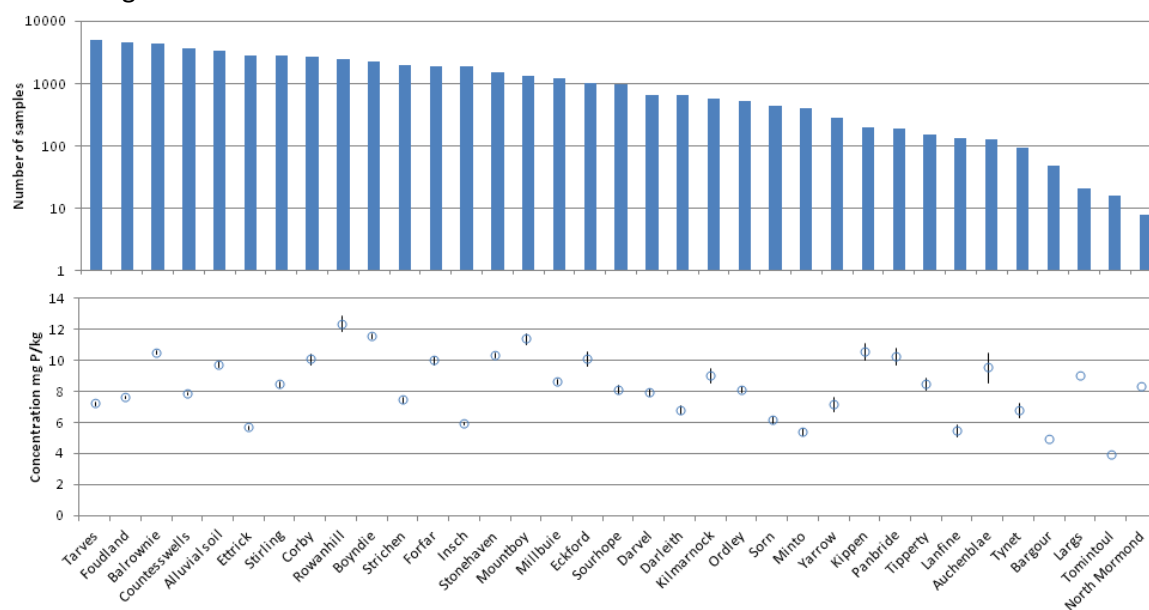
While soil information has been assigned to the points according to their location, it is important to bear in mind that this 'location' is not necessarily an accurate reflection of where the sample was taken from for 2 reasons:

- Firstly, the georeferenced location for each postcode is typically the centroid of an area. Within any given postcode it is possible that an individual point could vary by some distance; significantly so in rural postcodes which cover large areas of land.
- Secondly, all samples taken by a client are given the same postcode in the SAC database, typically the location of the registered office for a farm or business. Therefore, samples taken across a range of locations by a client (for example a number of different fields on a farm) will all be generalised to the same postcode.

6.2 Summary of data at national scale

Relationship between soil type (250K) and soil P status for all samples is given in Appendix VIII. Information from the 38 associations with measured P sorption data that are mapped in the 25K soil survey resulted in a total number of 68,700 advisory samples (Figure 5). Three of the 38 associations are not mapped at 25K and therefore do not appear in Figure 5.

Figure 5. Number of soil samples for individual soil associations identified from the 25K soil survey and averaged P concentrations for each soil association.



6.3 Relationship between SPT and P sorption index

Distribution (% total number) of advisory P status across the P sorption indices is given in Table 10. A summary of extractable P (mg/l) with P sorption index across the total area is shown in Table 11.

Table 10. Distribution (as a % of total number) of advisory P status across P sorption index.

P sorption index	VL	L	M-	M+	H	VH	Total
0	7.8	25.7	37.4	13.7	11.7	3.7	9420
1	4.6	19.0	39.4	19.1	15.2	2.7	14648
2	6.2	25.4	41.0	14.2	11.5	1.7	20533
3	6.2	24.5	39.8	14.5	12.7	2.1	27060
4	4.2	24.0	47.6	13.2	9.0	1.8	16741
5	7.2	26.2	41.9	11.7	9.9	3.1	6644
Grand Total	5.8	24.0	41.4	14.7	11.9	2.3	95046

Table 11. Summary of extractable P with P sorption index across the total area.

P sorption index	Average of ext.-P (mg/l)	Number of samples
0	9.5	9420
1	9.7	14648
2	8.3	20533
3	8.6	27060
4	8.3	16741
5	8.6	6644
Grand Total	8.7	95046

A listing of P sorption indices from section 5 with soil advisory data is shown in Table 12. It appears that there is no clear relationship between the average SPT and the P sorption index, which probably reflects the SAC recommendation to fertilise to target moderate P status.

Table 12. Soil association, advisory SPT (mg/l) and P sorption index.

	N	Mean	SE Mean	Median	P sorption index (from Table 3)
Alluvial soil	3394	9.76	0.170	7.24	3
Arkaig					1
Auchenblae	127	9.57	0.970	8.49	1
Balrownie	4395	10.53	0.126	9.08	2
Bargour	49	4.95	0.412	4.34	4
Boyndie	2215	11.58	0.181	9.55	2
Corby	2715	10.10	0.325	7.06	2
Countesswells	3642	7.89	0.090	6.80	2
Darleith	649	6.83	0.279	5.20	5
Darvel	658	7.97	0.227	6.68	3
Eckford	1011	10.15	0.465	6.83	3
Ettrick	2826	5.69	0.125	4.07	3
Forfar	1899	10.03	0.255	8.02	3
Foudland	4475	7.67	0.081	6.69	4
Insch	1830	5.95	0.075	5.46	5
Kilmarnock	574	9.06	0.448	5.41	3
Kintyre					4
Kippen	201	10.57	0.541	8.96	2
Lanfine	131	5.50	0.373	4.22	4
Largs	21	9.05	2.230	5.33	2
Millbuie	1214	8.65	0.126	8.15	1
Minto	401	5.40	0.221	4.26	2
Mountboy	1342	11.40	0.335	9.25	2
North Mormond	8	8.34	0.909	8.98	3
Ordley	532	8.13	0.180	7.30	3
Panbride	187	10.28	0.524	8.92	3
Rowanhill	2496	12.38	0.492	6.85	4
Sorn	440	6.19	0.243	4.77	2
Sourhope	964	8.14	0.251	6.12	3
Stirling	2771	8.49	0.190	5.79	5
Stonehaven	1481	10.37	0.177	8.57	3
Strichen	2003	7.49	0.201	5.82	3
Tarves	4961	7.24	0.099	6.26	4
Thurso					2
Tipperty	153	8.48	0.372	7.52	3

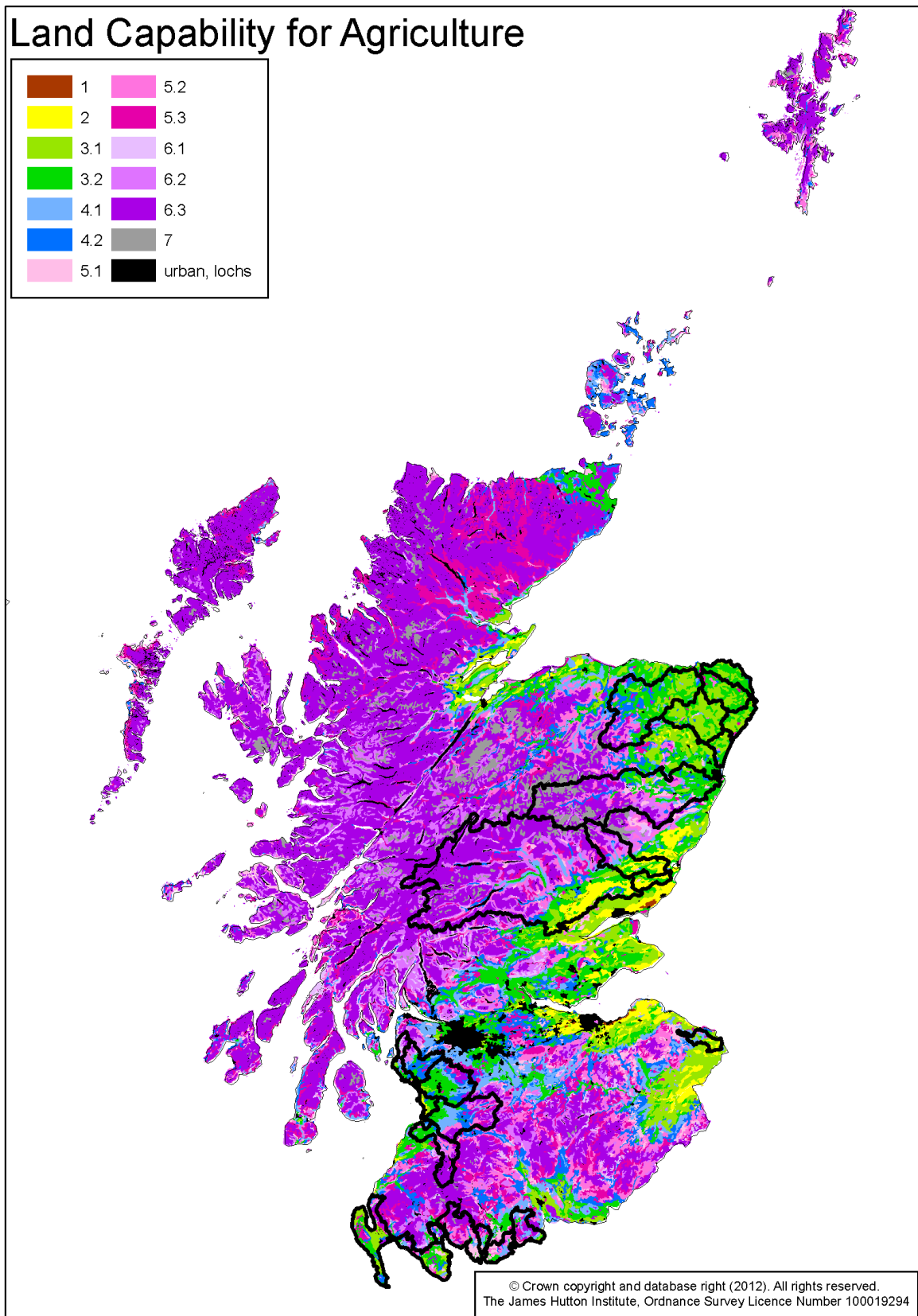
Tomintoul	16	3.95	0.410	4.32	3
Tynet	95	6.83	0.461	5.79	3
Yarrow	282	7.18	0.483	4.96	3

Another management target is to replace crop and grass P offtake with added P (Sinclair et al., 2010a, b). The Land Capability Classification for Agricultural (LCA) in Scotland (Bibby et al., 1982) ranks land on the basis of its potential productivity and cropping flexibility determined by the extent to which its physical characteristics (soil, climate and relief) impose long term restrictions on its agricultural use. Land suited to arable uses is included in classes 1 – 4, and not suited to arable use in classes 5 – 7. There are no divisions within Class 1, 2 and 7; Classes 3 and 4 each have 2 divisions and Classes 5 and 6 three divisions. Land in Classes 1, 2 and 3.1 is capable of producing consistently high yields of a range of crops and grass, and high inputs of P will be expected to replace P offtake. It is therefore considered relevant to compare P sorption index and SPT across the different LCA Classes.

6.4 Land Capability Classification for Agriculture (LCA) and P sorption index

The national Land Capability for Agriculture map is shown along with the PC boundaries (Figure 6).

Figure 6. Land Capability for Agriculture map with PC boundaries.



The relationship between Land Capability for Agriculture (LCA) and P sorption index as a proportion (%) of the total area in each LCA class is shown in Table 13.

Table 13. The relationship between LCA class and P sorption index as a proportion (%) of the total area in each LCA class.

LCA	P sorption index					Total area (ha)
	1	2	3	4	5	
1.0	12.8	3.0	69.3	14.6	0.3	3863
2.0	29.6	8.9	41.0	17.3	3.1	157617
3.1	17.8	13.6	34.2	28.1	6.3	413261
3.2	13.8	26.7	29.3	25.2	4.9	676053
4.1	13.8	27.7	31.2	15.9	11.4	353857
4.2	14.1	28.7	29.9	22.3	5.0	433751
5.1	10.6	23.6	44.4	7.7	13.7	143619
5.2	14.3	21.3	42.6	13.8	8.0	528955
5.3	38.2	16.5	29.6	12.7	3.0	535324
6.1	4.4	14.3	47.4	19.6	14.2	128620
6.2	29.5	12.5	37.7	8.2	12.0	494782
6.3	43.1	16.9	26.5	6.3	7.2	1846111
7.0	39.8	33.6	18.8	5.3	2.4	146433
Total	27.7	19.6	31.7	13.8	7.2	5862246

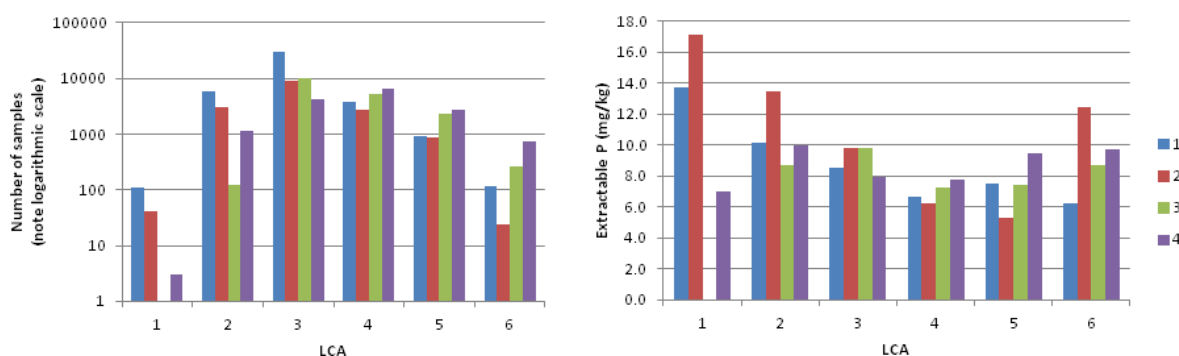
6.5 Summary of SPT data in 4 regions with LCA classes.

Averaged extractable P across LCA classes for the 4 agricultural regions is given in Table 14 and Figure 7. Data for each agricultural region divided into soil type, LCA and area (ha) are tabulated in Appendix VI and VII.

Table 14. Averaged extractable P across land capability classes for the four agricultural regions (numbers of samples are shown in brackets).

LCA	Region				Total
	1	2	3	4	
1	13.7(108)	17.13 (42)		7.04 (3)	14.54 (153)
2	10.18 (5818)	13.50 (3067)	8.73 (121)	9.96 (1167)	11.14 (10173)
3	8.53 (30284)	9.80 (8820)	9.79 (10219)	7.96 (4221)	8.94 (53544)
3.1	8.6 (14628)	9.4 (5942)	11.1 (2857)	9.4 (2123)	9.1 (25550)
3.2	8.5 (15656)	10.7 (2878)	9.3 (7362)	6.5 (2098)	8.8 (27994)
4	6.63 (3806)	6.21 (2787)	7.25 (5265)	7.80 (6474)	7.16 (18332)
4.1	6.7 (2270)	5.6 (1242)	7.0 (3130)	7.4 (2187)	6.8 (8829)
4.2	6.6 (1536)	6.7 (1545)	7.6 (2135)	8.0 (4287)	7.5 (9503)
5	7.48 (938)	5.31 (863)	7.42 (2280)	9.46 (2659)	7.96 (6740)
6	6.26 (113)	12.41 (24)	8.67 (265)	9.74 (733)	9.2 (1135)
Total no.	41067	15603	18150	15257	90077

Figure 7. A comparison of the distribution of LCA classes attributed to the SPT data averaged for the four agricultural areas.



There is a general decline in SPT as LCA changes from 1 to 6. This is particularly the situation for agricultural regions 1 and 2 (NE and SE) where averaged SPT concentrations declined by more than a half between LCA 1 to 4.

6.6 Summary of SPT data in PCs plus 2 DPMCs with LCA classes.

Averaged extractable P across LCAs for the priority catchments (plus two DPMCs) is given in Table 15, and a summary of P status in Table 16. There are no LCA 1 samples within the PC+DPMC areas.

Table 15. Averaged extractable P across LCAs 2 to 6 in PC and DPMCs

	Extractable P (mg/l)					Number of samples				
	2	3	4	5	6	2	3	4	5	6
PC and DPMCs										
Buchan Coastal		8.14	4.78	8.72	5.92		2193	68	16	59
Eye Water		7.13	3.83				103	147		
Galloway Coastal	24.89	11.05	10.54	7.62	5.20	15	1204	196	424	33
Lunan Water	8.80	8.64		10.91		39	277		23	
North Ayrshire Coastal	14.61	12.21	4.63		3.10	3	180	19		6
River Ayr		5.04	5.76				63	165		
River Dee (Grampian)		7.31	7.97	7.01	5.86		1624	697	355	25
River Deveron		7.68	4.35	6.88			3625	180	39	
River Doon		5.51	8.08	3.28			57	22	13	
River Garnock		3.44	4.26				21	71		
River Irvine		5.84	11.98				172	61		
River South Esk (Tayside)	8.80	9.89	3.39	8.00		761	509	17	19	
River Tay	10.01	7.90	5.25	4.86	4.59	2256	1257	1046	168	34
River Ugie		7.26		5.01			1436		14	
River Ythan		8.06	6.01				4444	26		
Stewartry Coastal		7.78	6.11	6.13	10.46		171	313	258	9
Grand total	9.77	8.10	6.33	6.80	5.64	3074	17336	3028	1329	166

Table 16. Summary of P status with LCA in PC and DPMCs

								Buchan Coastal	
P status	VL	L	M-	M+	H	VH	summary		
Total number of samples	73	566	1046	339	227	26	2277		
sum of LCA2+3.1	61	376	647	226	138	13	1461		
% of total samples	2.7	16.5	28.4	9.9	6.1	0.6	64.2		
% LCA<3.2 with STP M+ or greater								16.6	
								Eye Water	
	VL	L	M-	M+	H	VH	summary		
Total number of samples	58	110	56	9	14	3	250		
sum of LCA2+3.1	8	48	24	8	13	2	103		
% of total samples	3.2	19.2	9.6	3.2	5.2	0.8	41.2		
% LCA<3.2 with STP M+ or greater								9.2	
								Galloway Coastal	
	VL	L	M-	M+	H	VH	summary		
Total number of samples	71	404	724	321	282	70	1872		
sum of LCA2+3.1	14	135	276	168	158	52	803		
% of total samples	0.7	7.2	14.7	9.0	8.4	2.8	42.9		
% LCA<3.2 with STP M+ or greater								20.2	
								Lunan Water	
	VL	L	M-	M+	H	VH	summary		
Total number of samples	5	31	183	90	30		339		
sum of LCA2+3.1	1	13	98	50	9		171		
% of total samples	0.3	3.8	28.9	14.7	2.7		50.4		
% LCA<3.2 with STP M+ or greater								17.4	
								North Ayrshire Coastal	
	VL	L	M-	M+	H	VH	summary		
Total number of samples	21	85	42	14	16	30	208		
sum of LCA2+3.1	1	4	1	0	13	28	47		
% of total samples	0.5	1.9	0.5	0.0	6.3	13.5	22.6		
% LCA<3.2 with STP M+ or greater								19.8	
								River Ayr	
	VL	L	M-	M+	H	VH	Summary		
Total number of samples	12	97	96	18	4	1	228		
sum of LCA2+3.1	0	0	0	0	0	0	0		
% of total samples	0	0	0	0	0	0	0		
% LCA<3.2 with STP M+ or greater								0	
								River Dee (Grampian)	
	VL	L	M-	M+	H	VH	Summary		
Total number of samples	100	656	1370	373	172	30	2701		
sum of LCA2+3.1	3	61	164	23	28	6	285		
% of total samples	0.1	2.3	6.1	0.9	1.0	0.2	10.6		
% LCA<3.2 with STP M+ or greater								2.1	
								River Deveron	

	VL	L	M-	M+	H	VH	summary
Total number of samples	141	1033	1844	466	327	33	3844
sum of LCA2+3.1	12	116	378	95	41	6	648
% of total samples	0.3	3.0	9.8	2.5	1.1	0.2	16.9
% LCA<3.2 with STP M+ or greater							3.8
River Doon							
	VL	L	M-	M+	H		Summary
Total number of samples	7	29	45	9	2		92
sum of LCA2+3.1	0	0	0	0	0		0
% of total samples							0
% LCA<3.2 with STP M+ or greater							0
River Garnock							
	VL	L	M-	M+			summary
Total number of samples	17	42	28	5			92
sum of LCA2+3.1	0	0	0	0			0
% of total samples							0
% LCA<3.2 with STP M+ or greater							0
River Irvine							
	VL	L	M-	M+	H	VH	summary
Total number of samples	12	72	123	16	6	4	233
sum of LCA2+3.1	0	0	0	0	0	0	0
% of total samples							0
% LCA<3.2 with STP M+ or greater							0
River South Esk (Tayside)							
	VL	L	M-	M+	H	VH	summary
Total number of samples	37	144	760	208	126	31	1306
sum of LCA2+3.1	25	99	509	97	60	26	816
% of total samples	1.9	7.6	39.0	7.4	4.6	2.0	62.5
% LCA<3.2 with STP M+ or greater							14
River Tay							
	VL	L	M-	M+	H	VH	summary
Total number of samples	353	1073	1868	777	643	47	4761
sum of LCA2+3.1	143	335	948	561	519	38	2544
% of total samples	3.0	7.0	19.9	11.8	10.9	0.8	53.4
% LCA<3.2 with STP M+ or greater							23.5
River Ugie							
	VL	L	M-	M+	H	VH	summary
Total number of samples	37	348	765	197	95	8	1450
sum of LCA2+3.1	23	153	437	133	63	2	811
% of total samples	1.6	10.6	30.1	9.2	4.3	0.1	55.9
% LCA<3.2 with STP M+ or greater							13.6
River Ythan							
	VL	L	M-	M+	H	VH	summary
Total number of samples	28	702	2684	671	355	30	4470

sum of LCA2+3.1	22	473	1928	454	236	19	3132
% of total samples	0.5	10.6	43.1	10.2	5.3	0.4	70.1
% LCA<3.2 with STP M+ or greater							15.9
					Stewartry Coastal		
	VL	L	M-	M+	H	VH	summary
Total number of samples	36	243	333	102	33	4	751
sum of LCA2+3.1	0	0	11	8	6	0	25
% of total samples	0	0	1.5	1.1	0.8	0.0	3.3
% LCA<3.2 with STP M+ or greater							1.9

Galloway Coastal and Stewartry Coastal are not represented in the 25K soil association coverage.

7 Relationship between P sorption index, SPT and potential risk of soluble P leaching from the topsoil

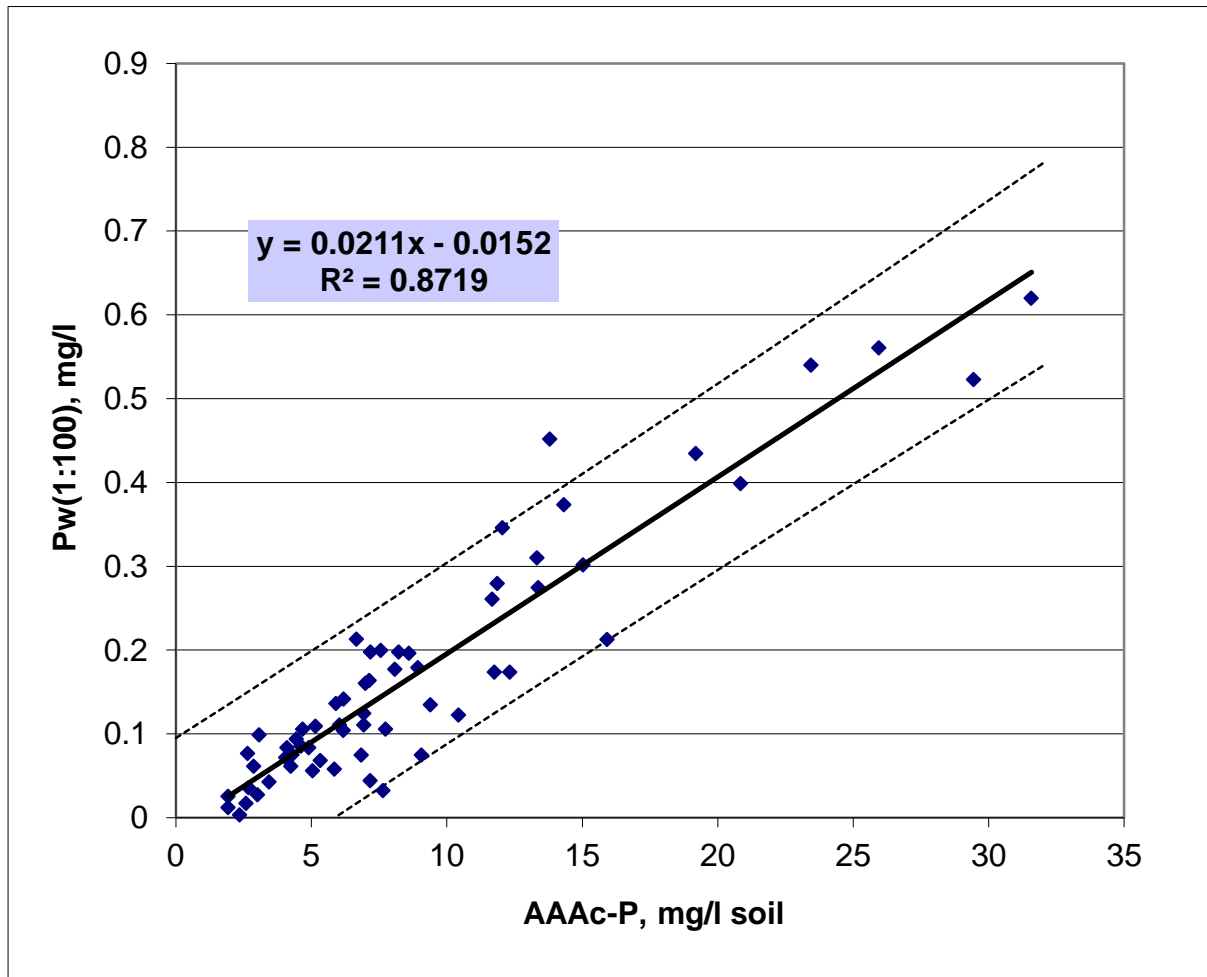
7.1 Introduction

In this section the relationship between the advisory soil P test (SPT) data (section 6) and the soil P sorption properties for the soil associations given in section 5 are examined. In principle a robust relationship between the SPT data and water soluble P is required. Such a relationship based on soils with a wide range of properties shows profound variation. The variation between SPT and water soluble P can be illustrated using the data of Uusitalo and Jansson, (2002), which is shown in Figure 8. The data shows water soluble P in well equilibrated (18 hours) soil solutions as a function of acid ammonium acetate extractable P (this extraction procedure is almost the same as the MM-P except that the pH is buffered at 4.65 instead of 4.8 as used for the MM-P procedure). The 64 soils in the data set included a wide range of chemical properties e.g. textures from loamy sands to clays, and pH in the range 4.9 to 7.2. The relationship in Figure 8 illustrates the problem of using simplified relationships to predict water soluble P for soils of varied properties. The prediction interval for water soluble P for a SPT value of 10 mg/l shows that the predicted water soluble P would lie in the range from 87 ppb to 303 ppb.

The prediction interval shows that an AAAC-P value of 10 mg/l would give a water soluble value between 0.087 and 0.303 mg/l. More research is needed to explain the scatter of the data, but it is most likely related to soil properties that control the P sorption and buffering. Caution is required regarding interpretation based on an assumed linear relationship for plots with multiple soil types, especially for use at a national scale.

Given that inherent soil properties profoundly influence the relationship between water soluble P and SPT values (e.g. MM-P); we propose as an initial approximation to use SPT values in combination with the likely P sorption capacity of a soil to predict the risk of soluble P loss from topsoils.

Figure 8. Relationship between acid ammonium acetate (pH = 4.65) extractable P (SPT) for 64 Finish soils (Data taken and redrawn from Figure 2 of Uusitalo and Jansson (2002)) and water extractable-P (Soluble P) (L:S = 100, 18 hour equilibration period) showing the 95% prediction interval, with dashed lines.



7.2 A proposed risk matrix of potential leaching of soluble P from the topsoil

In order to prepare a risk matrix of potential leaching of soluble P based on soil P sorption index and SPT status, some limitations and conditions have to be identified. The proposed matrix is based on P sorption indices derived from soil association attributes and does not take account of pedological drainage i.e. soil series, or existence of artificial drainage. Therefore, the matrix is restricted to the risk of leaching of soluble P from the topsoil. The advisory soil samples are taken from the topsoil to varying depths depending on factors such as plough depth, arable, rotational or permanent grassland. The risk matrix is presented in Table 17. An increasing number of “+” denotes increased risk. A non-numeric assessment has been made in order to emphasise that the actual magnitude of the risk remains to be determined through either direct measurement or by additional modelling capable of incorporating additional soil and management factors. Under the Scotland Rural Development Programme 2007-2013 funded water quality improvement measures aimed at reducing P loading assume that soil bound P is the primary issue (SRDP : Arable reversion to

grassland/unfertilised grassland (Tier 3)). The proportion of loading that can be attributed to soluble P is not fully quantified. Howarth et al. (1995) said globally about 90% of total P lost in rivers is in particulate form. This proportion decreases as 'urban' proportion increases.

Table 17. Matrix of potential leaching risk of soluble P from the topsoil based on P sorption index and SPT status.

P sorption index	SPT status	Potential risk of soluble P leaching from topsoil
1	VH/H	++++
1	M+	++++
1	M-	+++
1	VL/L	++
2	VH/H	++++
2	M+	+++
2	M-	++
2	VL/L	+
3	VH/H	++++
3	M+	+++
3	M-	++
3	VL/L	+
4	VH/H	++++
4	M+	+++
4	M-	++
4	VL/L	+
5	VH/H	+++
5	M+	++
5	M-	+
5	VL/L	+

+ very low risk; ++ low risk; +++ moderate risk; ++++ high risk

The 4 risk categories have been mapped in Figure 9 at a national scale and Figure 10 for the PCs and DPMCs.

Figure 9. National map of potential risk of soluble P leaching from the topsoil based on P sorption index and SPT status.

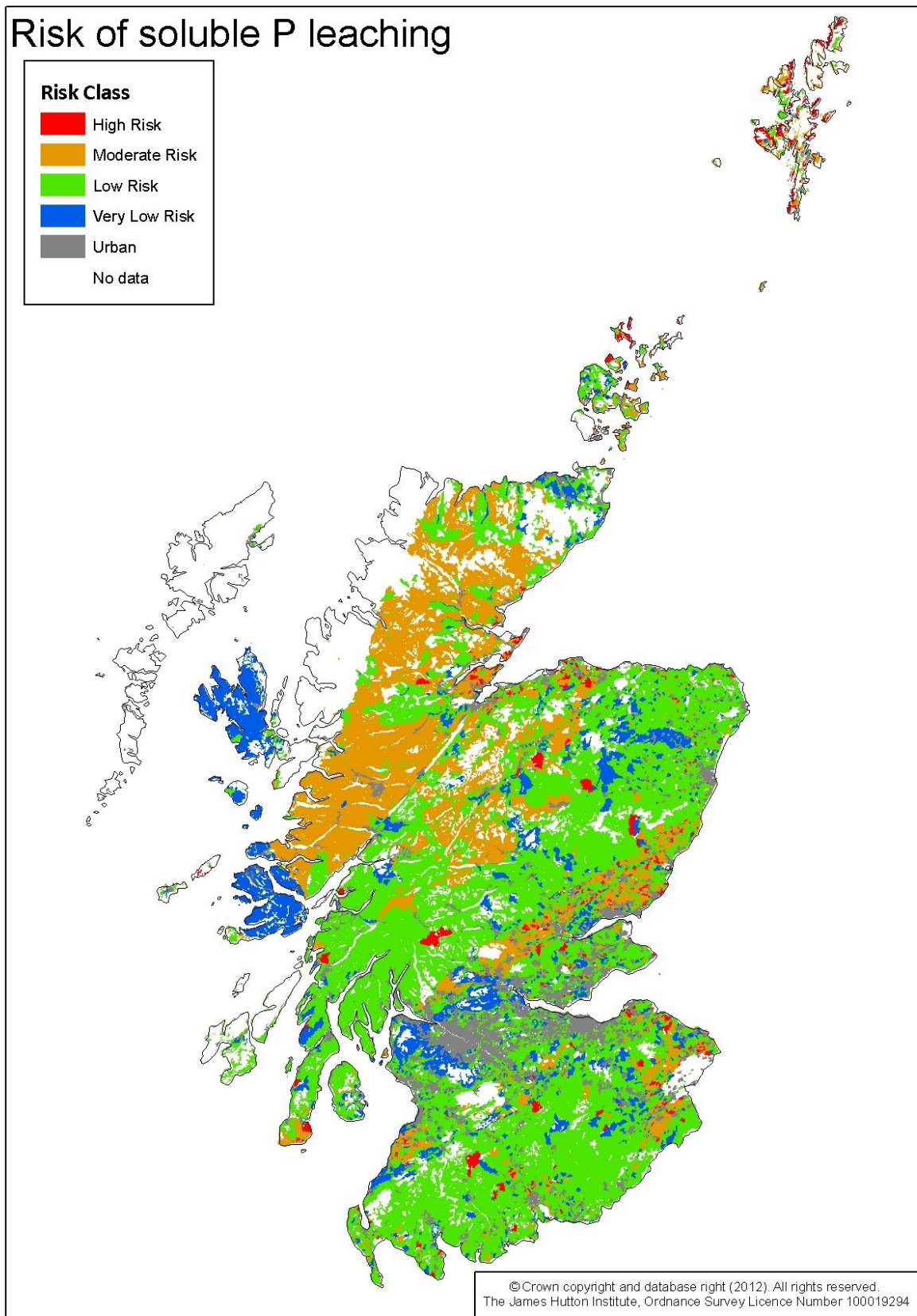
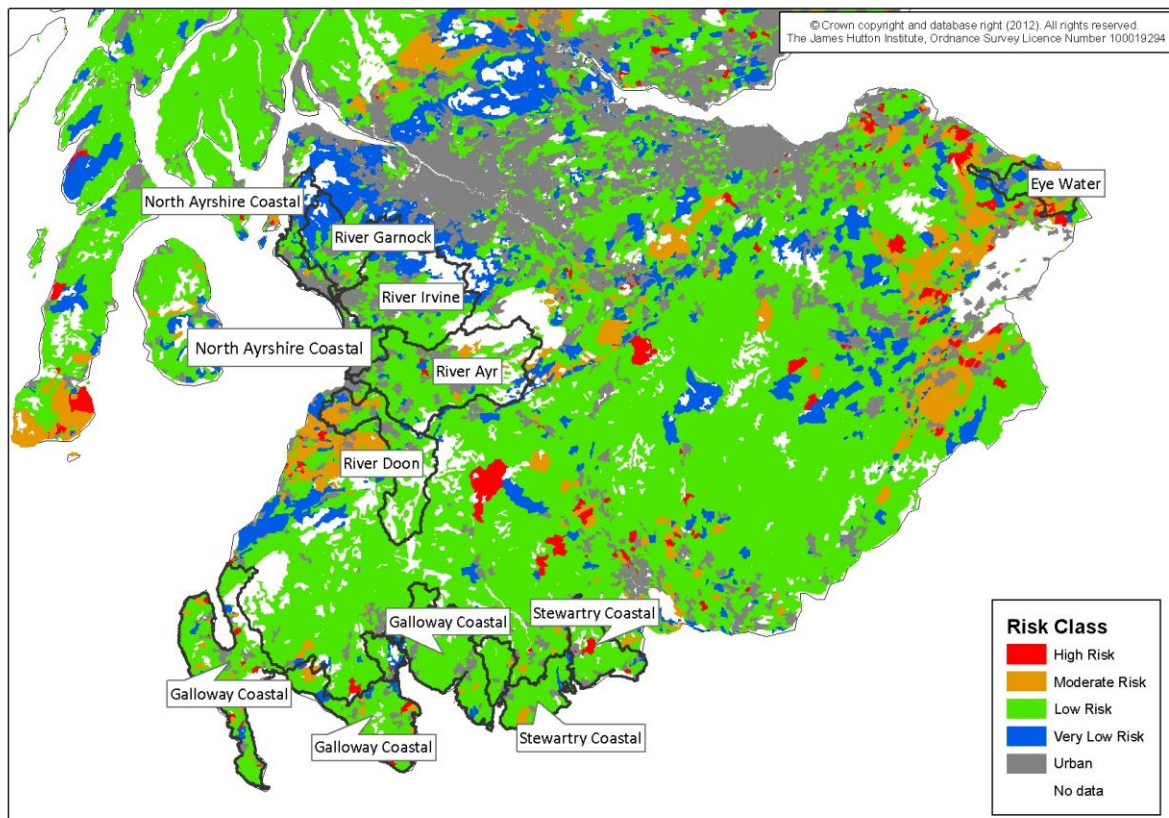
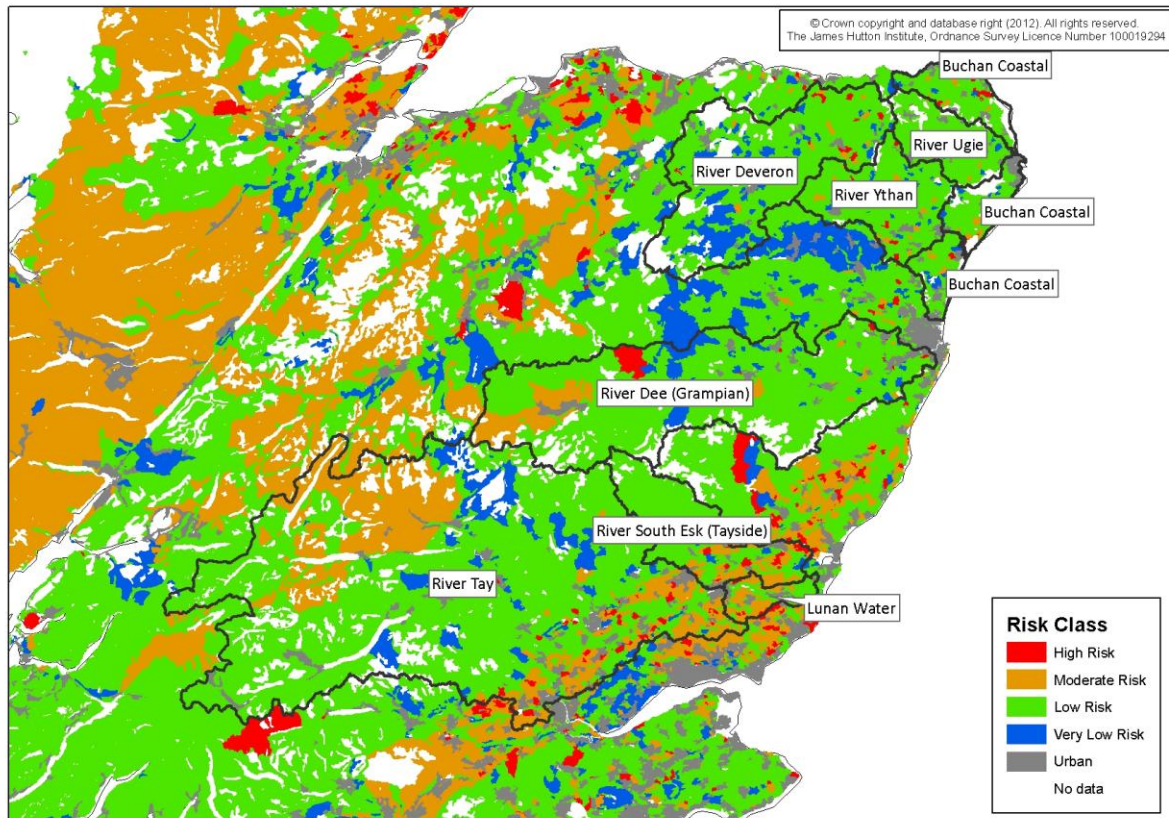


Figure 10. Priority catchments and DPMCs map of potential risk of soluble P leaching from the topsoil based on P sorption index and SPT status.



Mapping conditions that were used include:

- No data areas are those from Appendix V where there are no P sorption index data;
- Where there are both P sorption index and SPT data in a postcode then the SPT data were averaged and the appropriate P status assigned to the postcode;
- Where there is a P sorption index assigned but no SPT data in a postcode then M- status is assumed as M- is the most dominant P status, reported as 40% of samples in the report “Soil phosphorus levels in diffuse pollution priority catchment: SEPA contract reference 30107”, 2011.
- Where postcodes have more than one P sorption index the overlaying mapping process creates a separate polygon for each combination of SPT status and sorption index. The risk class is calculated on the basis of each combination resulting in potentially more than one risk class within an individual postcode which was mapped according to the polygon.
- In order to screen out urban postcodes (where soluble P leaching will be a result of different processes), a coverage of urban areas had to be overlaid onto the postcode boundaries. Attempts were made to identify urban postcodes using the Scottish Government's 'Urban Rural Classification 2011 2012' but this resulted in too many postcodes which also contained agricultural land (with measured SPT data) being removed. A second attempt was made using CEH's Land Cover Map 2007, but this was also rejected on the basis that it often misclassifies areas of rock as 'urban' or 'urban industrial' (parts of the Outer Hebrides and NW Scotland suffer particularly in this respect). Of the remaining available data sources, the one which gave the best representation of urban development is the Macaulay Institute (now James Hutton Institute) Land Cover of Scotland (1988). It should be noted, however, that this data source is now 25 years old, and so areas of more recent urban expansion will not have been accounted for.

Table 18 shows the breakdown of the area of each risk category, urban postcodes and area where there is no P sorption index data as a percentage of the total area of individual Priority Catchments and DPMCs. The River Ayr has the largest percentage of area with no data, while N Ayrshire Coastal and River Irvine have largest percentage of urban area. The Lunan Water has clearly the largest percentage of moderate and high risk areas, followed by Eye Water, River South Esk and River Tay. Catchments with more than 80% of area in very low or low risk are River Ythan, River Deveron and Stewartry Coastal.

Table 18. Breakdown of the area of each risk category, urban postcodes and area where there is no P sorption index data as a percentage of the total area of individual Priority Catchments and DPMCs.

Priority Catchment and DPMC	+	++	+++	++++	urban	no data	Total (%)
Buchan Coastal	5.1%	61.6%	3.8%	1.6%	13.2%	14.6%	100.0%
Eye Water	15.2%	43.9%	15.1%	5.3%	19.8%	0.7%	100.0%
Galloway Coastal	5.7%	71.4%	4.1%	1.9%	8.1%	8.9%	100.0%
Lunan Water	0.0%	41.7%	40.3%	3.5%	13.8%	0.7%	100.0%
N Ayrshire Coastal	18.6%	33.2%	1.0%	0.6%	38.6%	7.9%	100.0%
River Ayr	4.2%	51.2%	2.9%	0.4%	14.8%	26.5%	100.0%

River Dee	5.2%	70.8%	8.0%	1.9%	4.0%	10.0%	100.0%
River Deveron	17.2%	64.7%	1.5%	1.0%	2.4%	13.2%	100.0%
River Doon	9.2%	52.6%	10.9%	0.0%	10.5%	16.8%	100.0%
River Garnock	38.3%	37.8%	0.8%	0.0%	16.4%	6.6%	100.0%
River Irvine	17.2%	44.7%	0.1%	0.0%	21.8%	16.2%	100.0%
River South Esk	2.3%	73.0%	14.6%	3.3%	3.8%	2.9%	100.0%
River Tay	6.5%	59.9%	17.8%	0.9%	4.2%	10.5%	100.0%
River Ugie	2.3%	77.1%	1.0%	0.0%	8.5%	11.0%	100.0%
River Ythan	3.6%	83.5%	3.1%	1.4%	5.6%	2.8%	100.0%
Stewartry Coastal	3.6%	76.4%	2.6%	2.2%	8.5%	6.6%	100.0%

The breakdown between number of postcodes mapped with averaged, actual SPT data and those using assumed M- status is not visible in Figures 9 and 10. This breakdown is important in relation to the level of confidence in the leaching risk map and to the assessment of the need for more SPT data. The breakdown is shown in Table 19. Data in Table 19 show that less than 10% of postcodes with P sorption data have actual SPT data, the remainder are assumed M- status, in the SW catchments of North Ayrshire Coastal, River Doon, river Garnock and River Irvine. These catchments need to be targeted for collection of more SPT data from individual postcodes. Eye Water followed by the River Ythan has the best coverage of actual SPT data.

Table 19. Breakdown of number of postcodes mapped with averaged actual SPT data and with assumed M- status in individual Priority Catchments and DPMCs.

Priority Catchment and DPMC	No. of postcodes mapped using averaged actual SPT data	No. of postcodes mapped using assumed M-status	Actual as % of actual plus assumed M-status
Buchan Coastal	87	531	14
Eye Water	20	41	33
Galloway Coastal	106	522	17
Lunan Water	19	95	17
North Ayrshire Coastal	9	174	5
River Ayr	34	267	11
River Dee (Grampian)	157	732	18
River Deveron	214	770	22
River Doon	9	123	7
River Garnock	9	249	3
River Irvine	26	423	6
River South Esk (Tayside)	38	174	18
River Tay	170	882	16
River Ugie	35	264	12
River Ythan	139	449	24
Stewartry Coastal	41	216	16
Grand Total	1113	5912	16

7.3 Validation work in progress on Cessnock soils and link between soil P sorption and SPT

While analysis of the Cessnock data set in the River Irvine catchment is on-going, a preliminary review shows an interesting relationship between P sorption index and SPT. For example, the Sorn association occurs over about 21% of the catchment area and has a P sorption index of 2, according to the current study. As shown in Table 20 the SPT results for all the Sorn association soils are at a moderate or high status. This is contrasted with the results from the Largs association which have the same P sorption index but low SPT. Work is currently on-going to review these results in relation to LCA, farm type and recorded land management variables. This work is being carried out as part of the Scottish Government funded research work package WP 2.3 “Effectiveness of measures to manage water quality and control diffuse pollution”.

Table 20. Individual soil sample results for the Cessnock soil database showing P sorption index and SPT (mg/l) for each soil association

Soil association	P sorption index	SPT (mg/l)	SAC status
Largs	2	1.5	VL
Largs	2	2.7	L
Sorn	2	16.3	H
Sorn	2	6.5	M -
Sorn	2	6.8	M -
Sorn	2	5.3	M -
Sorn	2	11.5	M +
Alluvial	3	4.1	L
Alluvial	3	1.3	VL
Alluvial	3	1.2	VL
Alluvial	3	2.3	L
Alluvial	3	7.2	M -
Alluvial	3	2.7	L
Kilmarnock	3	3.4	L
Kilmarnock	3	4.4	L
Bargour	4	6.2	M -
Bargour	4	2.2	L
Bargour	4	3.4	L
Bargour	4	3.9	L
Bargour	4	2.6	L
Bargour	4	4.5	M -
Bargour	4	7.2	M -
Lanfine	4	5.2	M -
Lanfine	4	3.2	L
Lanfine	4	5.4	M -
Rowanhill	4	2.4	L
Rowanhill	4	7.6	M -

Given the dominance of grassland as the major crop in the Cessnock, catchment variance in inputs of P for production can be predicted to be uniform with variance being prescribed to a set of predictable management pressures and land characteristics outlined in Table 21.

This initial assessment of the soil P sorption index along with a small set of measured results is designed to highlight where knowledge gaps are in our ability to understand and predict available and total P levels at the catchment scale.

Table 21. Summary of available input variables

Variable	Proxy measure or assumption
Land capacity for production	LCA
Soil P sorption	P sorption index
Best practise	Moderate status for – P
Local management	IACS returns and GIS analysis
SPT	Soil P Test results

While this is simplistic it is a required first step in assessing our ability to predict and subsequently understand soil P dynamics on a landscape scale given the high degree of variability introduced by individual land management practices (see Figure 11).

Figure 11. Overview of model

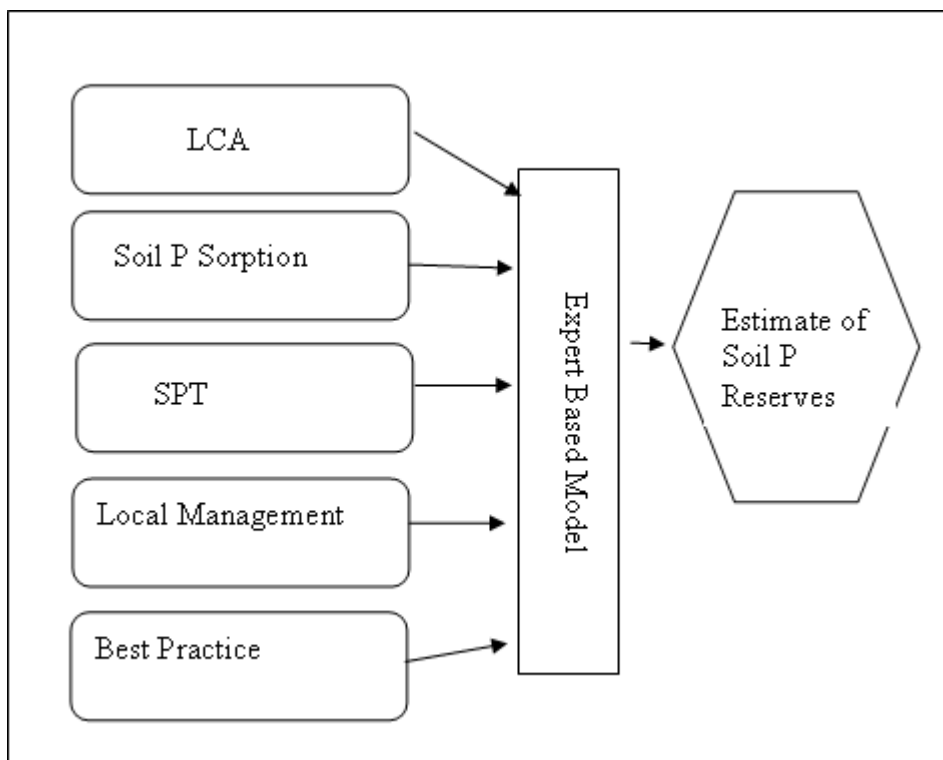
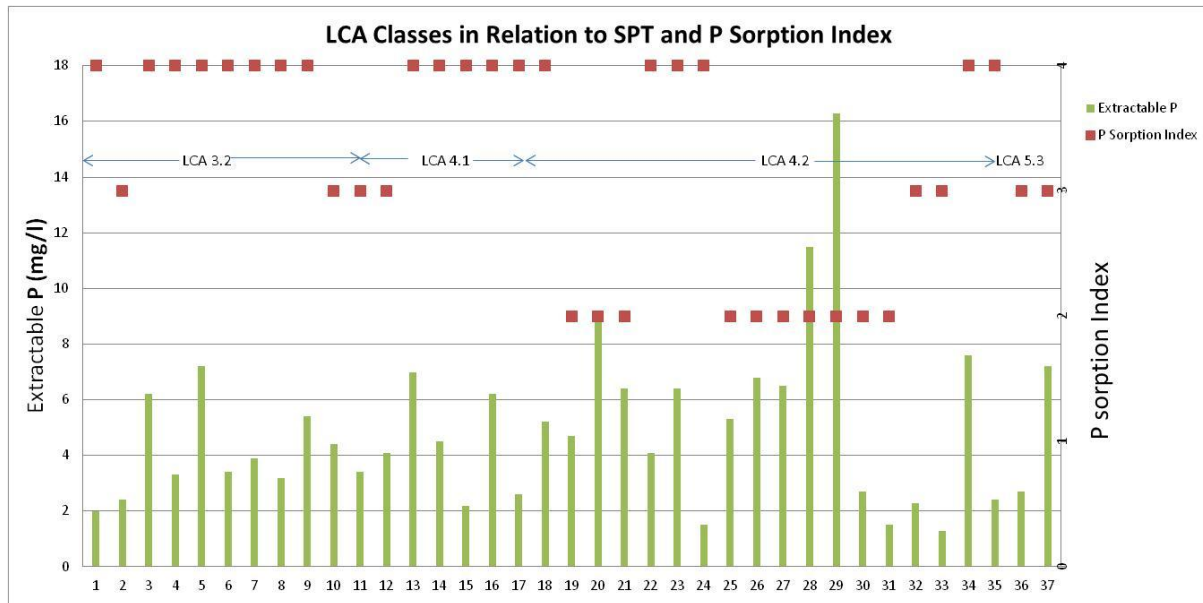


Figure 12 shows the SPT and P sorption index results for the field work conducted to date in relation to LCA. This constitutes the analytical input to the expert based assessment. The next step is to include available management data from IACS returns and GIS analysis to determine if a catchment relevant relationship between these databases and SPT can be established to “predict” or understand the soil P dynamic on this scale. Other factors being developed include a transfer function for “leaching risk” that can be adequately informed by these available inputs.

Figure 12. LCA classes in relation to SPT and P sorption index



8 Commentary on methodology to identify mitigation measures at the field and waterbody scale and limitations and uncertainty for intended use.

8.1 Effects of P sorption index, P sorbed pool size and estimated amount to change SPT

Well designed P fertiliser policies should have a build-up or run-down component for low/high status respectively in order to target the moderate status. It is known that build-up rates vary with soil type but currently only very general guidelines are provided (e.g. Withers and Sinclair, 2000; Sinclair et al., 2010b). The assignment of P sorption indices to different soil associations provides a significant advancement in the understanding of the amount of P required to change SPT. The soil P sorption model (SPSM) is used here to estimate changes in sorbed P pool size for 3 scenarios of SPT change. The changes are increments of SPT from 1 to 5 mg/l; 5 to 10 mg/l; and 10 to 15 mg/l (Table 22). Change in P on an area basis (kg P/ha) are estimates, so differences should be thought more relative than absolute. The estimated amount to change SPT will be closer to the total P required when P is applied as inorganic, soluble P at a small surplus to build-up SPT slowly over a number of years, compared with single, large applications of P in bulky organic fertilisers.

Table 22. The effect of P sorption index on quantity (kg P/ha) required to change SPT.

P sorption index	Scenario A: Change in P when increasing STP from 1 to 5 mg/l	Estimated* change in P on an area basis for scenario A (kg P/ha)	Scenario B: Change in P when increasing STP from 5 to 10 mg/l	Estimated* change in P on an area basis for scenario B (kg P/ha)	Scenario C: Change in P when increasing STP from 10 to 15 mg/l	Estimated* change in P on an area basis for scenario C (kg P/ha)
1	29.8(7.5) [§]	71.5(17.9) [£]	17.3(3.5) [§]	41.5(8.3) [£]	14.4(2.9) [§]	34.4(6.9) [£]
2	40.6(10.2)	97.4(24.3)	22.5(4.5)	54.0(10.8)	17.7(3.5)	42.5(8.5)
3	50.4(12.6)	121.0(30.3)	26.8(5.4)	64.2(12.8)	20.0(4.0)	48.0(9.6)
4	64.9(16.2)	155.8(39.0)	33.6(6.7)	80.6(16.1)	24.5(4.9)	58.8(11.8)
5	95.3(23.8)	228.7(57.1)	47.2(9.4)	113.3(22.7)	32.5(6.5)	78.1(15.6)

*using an estimated amount of soil in 1ha to 20cm depth as 2400 t

[§] mg P/kg required to raise SPT by 1 mg P/l shown in brackets for each scenario

[£] kg P/ha required to raise SPT by 1 mg P/l shown in brackets for each scenario

Data in Table 22 could be used to predict the change in P management required to alter P status for a given soil. The table shows that much more P is required moving to moderate P status in P sorption index 5 soils than an index 1 soil. Soils with a high P sorption index will require about 3 times as much P to be added, or removed, to achieve the same change as low P sorption soils. In addition the data could be used to quantify the P pool size on a catchment basis e.g. at any given SPT value the index 5 soils will have a much greater pool of sorbed P.

Current best practice described in SAC Technical Notes TN632 and TN633 recommends that SPT levels in agriculturally managed soils should be actively increased to a moderate status (SAC - 4.5 mg/l to 13.4) and then maintained at this levels using nutrient management and continued SPT testing (Sinclair et al., 2010a,b). An upward adjustment of P fertiliser of about 17.5 kg P/ha/year to move from a low to moderate P status soil is recommended in these TNs. For high P status soil a downward adjustment of about 7 kg of P/ha is advised to move the soil toward M status.

Future emphasis could be placed upon the improved tailoring of the P management of soil having different P sorption properties. It may be possible to redefine and adjust the advisory P status boundaries in order to improve P fertiliser recommendations. More likely is a refinement in the component of the P fertiliser recommendation which covers build-up or run-down of P status. SAC has recently launched a GPS soil sampling service. It is recommended that sampling for PK analysis should be in zoned areas based on the farmer's knowledge of cropping performance, but also based on soil type. Soil type should include zoned areas of different P sorption index.

The P sorption maps, combined with estimates of sorbed P pool size, provide the opportunity to move toward quantifying the potential impact of soil eroded P from agriculture and other land management activities such as forestry and mining. The magnitude of the P pool size that is potentially available for erosion can inform decision making on activities with a known risk of increasing soil disturbance and erosion.

8.2 Possible future work on improving modelling and predicting actual P leaching

It is not part of the remit of the current project, nor is it possible to use the data presented in this report, to create a Scottish map of actual leaching risk. Development of maps of actual P leaching

risk will require incorporating other relevant factors such as soil series identifying pedological drainage status, topography, slope and pathways to waterbodies. This would still fall short of identifying working, artificial drainage schemes and actual P leaching.

Issues associated with use of soil series are identified here. Unfortunately there is no data set for acid ammonium oxalate extractable Fe and Al at a soil series scale. Also, currently the only national scale soils data set available digitally is the 1:250,000 data held by the James Hutton Institute, and soon to be made available through the Scottish Environment website (<http://www.environment.scotland.gov.uk/>). Soils are delineated as map units, collections of soils formed from the same parent material (the soil 'association'). An example of soils mapped by association is shown in Figure 13. An example of the same area shown as map units is given in Figure 14.

Figure 13. Example of soils mapped at 1:250,000 and classified by soil association

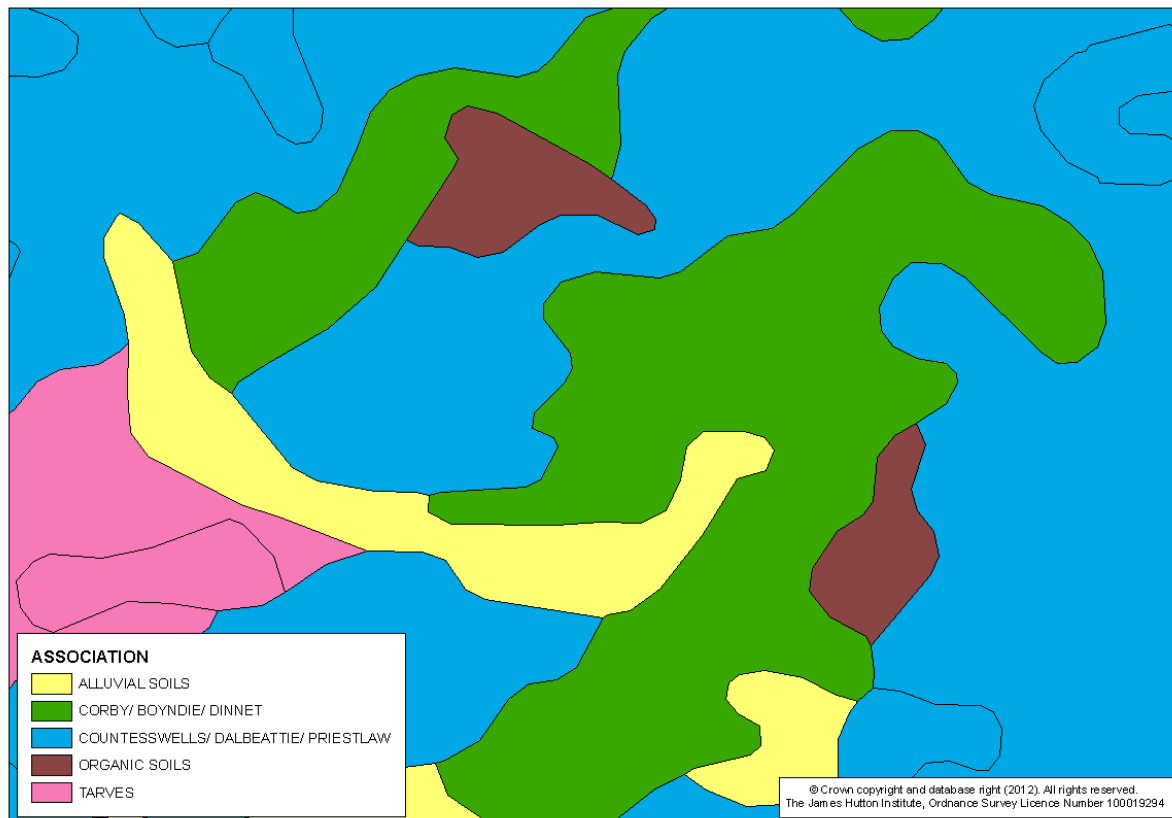
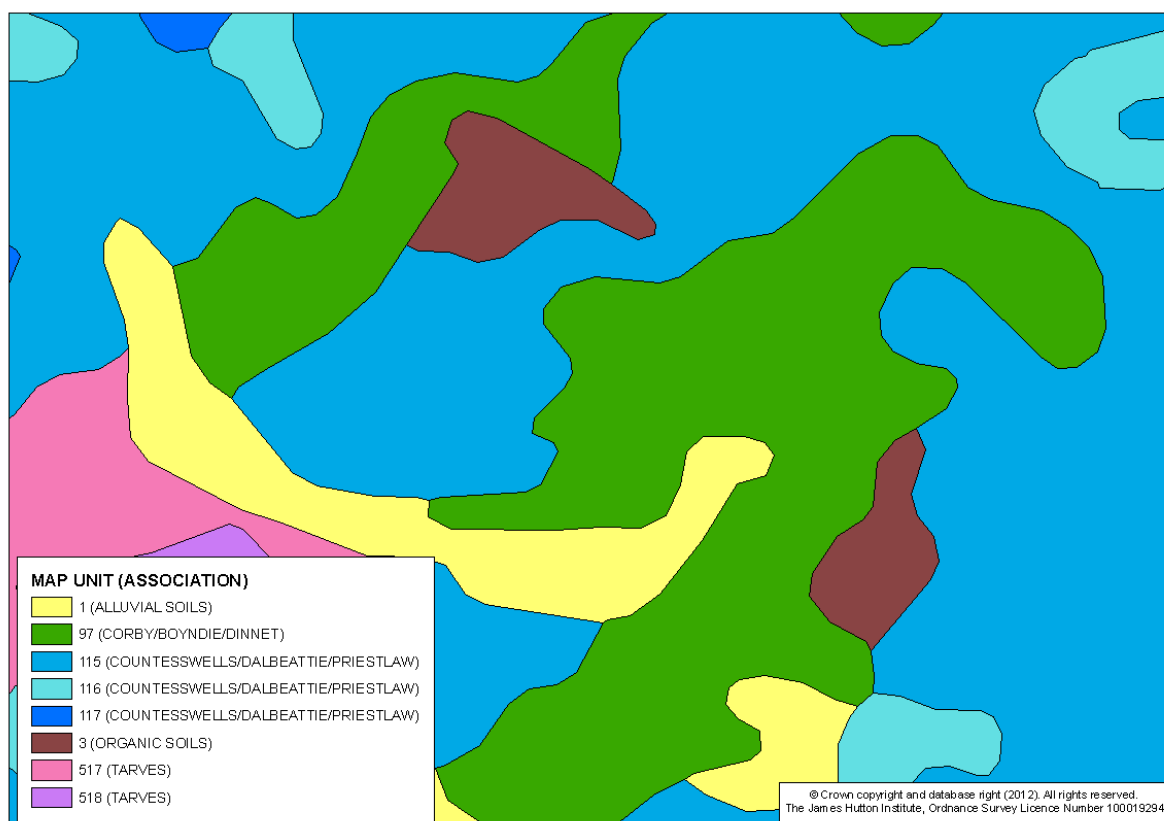


Figure 14. Example of soils mapped at 1:250,000 and classified by map unit



Map units have 1 or more components – soil series. Data for these series is collated within the Scottish Soils Knowledge and Information Base (SSKIB), also held by the James Hutton Institute, and also being made available online. In order to use soil series data for predicting P sorption index additional soil analysis would be required, e.g. oxalate extractable Fe, Al and P. An example of the proportions of series within map units is given in Table 23.

Table 23. Proportion of soil series within selected map units

Map Unit	Association	Series	Soil Type	% of unit
116	Countesswells	Drumlasie	Peaty gley	30
		Terryvale	Noncalcareous gley	70
518	Tarves	Pettymuck	Peaty gley	50
		Pitmedden	Noncalcareous gley	50

At present, it is not possible to explicitly, spatially define where each series is found within a map unit. In the example above, for map unit 116, there is no way to determine where within the unit one might find Drumlasie series soils, or Terryvale soils, only that they occur roughly in the proportions listed within the unit. Future work is planned under the Scottish Government’s Rural and Environment Science and Analytical Services Division (RESAS) portfolio of Strategic Research (2011-16) using digital soil mapping techniques to disaggregate the map units to individual series.

While the issue of ascribing data to advisory samples based on postcodes will still be present (see section 8.3 below), the capability of modelling soil processes based on measured data for soil series will open up further opportunities for assessing the risk of leaching and transport of P and other

chemicals. Additionally, as data on drainage, texture and other physico-chemical properties for series is made more widely available, farm advisors will be able to offer more detailed advice on P application rates and timings tailored to the needs of individual farmers.

8.3 Use of postcode data in ascribing soil properties to advisory data

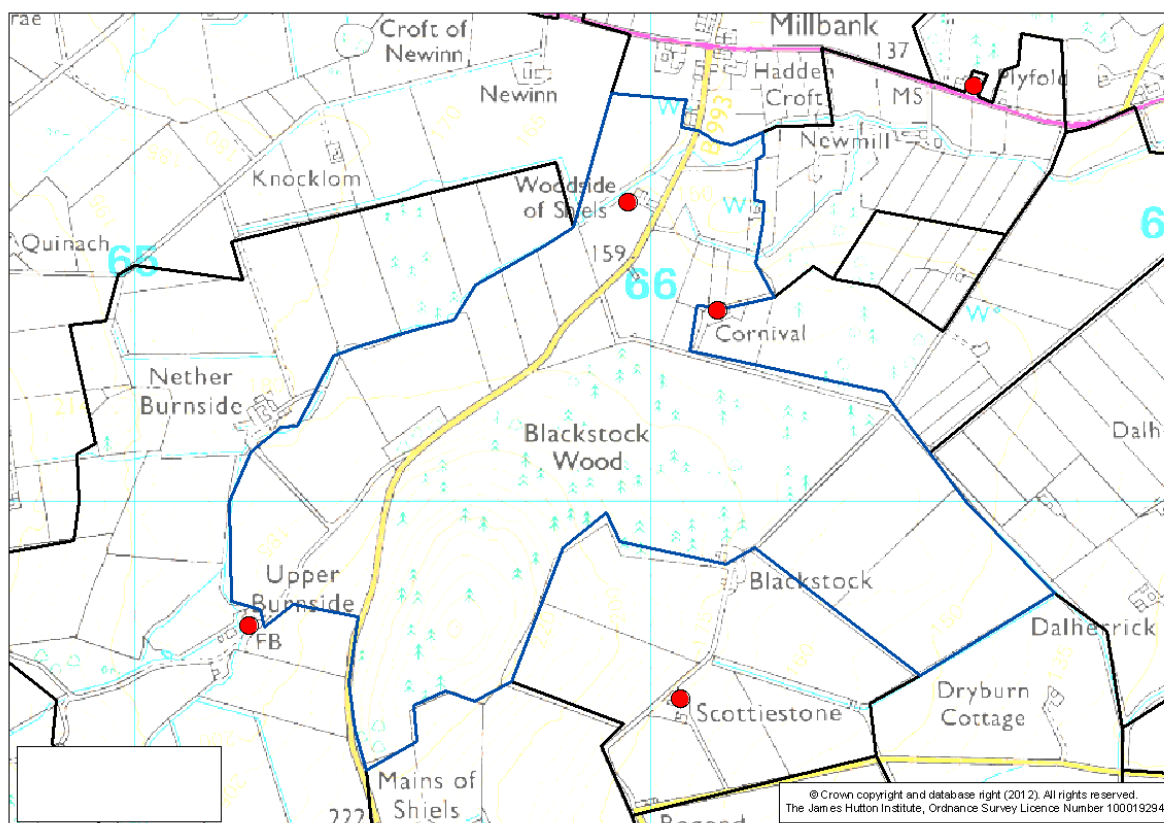
Samples submitted to SAC's advisory sample database are located according to the postcode of the submitter. While this ensures a level of anonymity, it presents a challenge when trying to assign further information to each sample based on its location. Each postcode covers a geographic area the size of which varies greatly across the country. In more remote rural areas, postcodes are larger than in urban areas. Some statistics are given in Table 24.

Table 24. Postcode sizes by broad agricultural region

Region	Approx Area (km ²)	Approx no of postcode areas	Mean Postcode size (km ²)	Largest Postcode (km ²)
1: North East	16300	30000	0.48	124.6
2: South East	7750	31000	0.21	52.1
3: South West	23100	68000	0.25	99.6
4: North West	31250	7300	2.45	249.3

Each area also has a single point within it which has the same code. According to Wikipedia *'For domestic properties the postcode refers to up to 100 properties in contiguous proximity (e.g. a short section of a populous road, or a series of less populous neighbouring roads). The postcode plus the number or name of a property is not always unique, particularly in rural areas'*. An example of the relationship between the postcode 'area' and the 'point' with the same code is shown in Figure 15.

Figure 15. Postcode areas with their respective point locations



If a sample is submitted with a particular postcode, it could have been taken a significant distance from the address associated with the submission point. Typically a farmer might sample a number of fields as part of a routine soil test, but all of the samples will be 'located' at a single point.

The coverage of soil maps available digitally for Scotland varies according to scale. The whole country is covered at 1:250,000 (mapping is done by map units, as part of soil associations), but only part of the country is covered at 1:25,000 where each polygon represents a specific soil series (the level at which much of the other soil data is available). Details of how this coverage varies across the country are listed in Table 25.

Table 25. Area of each broad agricultural region covered by digital soil maps

Region	Approx area (km ²)	Total area covered by 1:25K soil series data (km ²)	% of region covered by 1:25K soil series data
1	16300	10500	65
2	7750	6000	75
3	23100	6000	25
4	31250	500	2

These two factors in combination mean that assigning other soil information to advisory samples is problematic. Looking at regions 1 and 2 where there is the greatest % cover of higher resolution map data, differences can be seen between 1:250,000 (association) and 1:25,000 series in Figures 16 and 17. From these figures it is possible to see that a point from the postcode highlighted in blue could theoretically come from 5 different series, but only 1 association.

Figure 16. Example of soil series by postcode

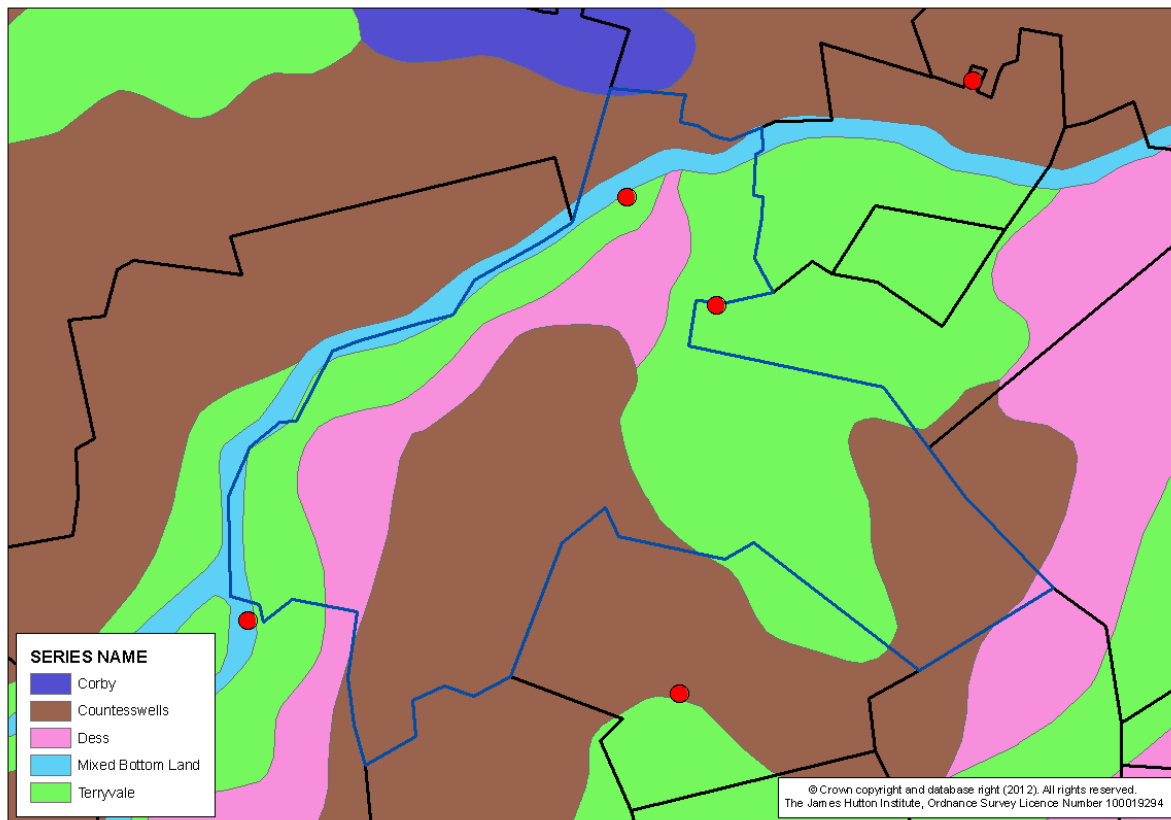
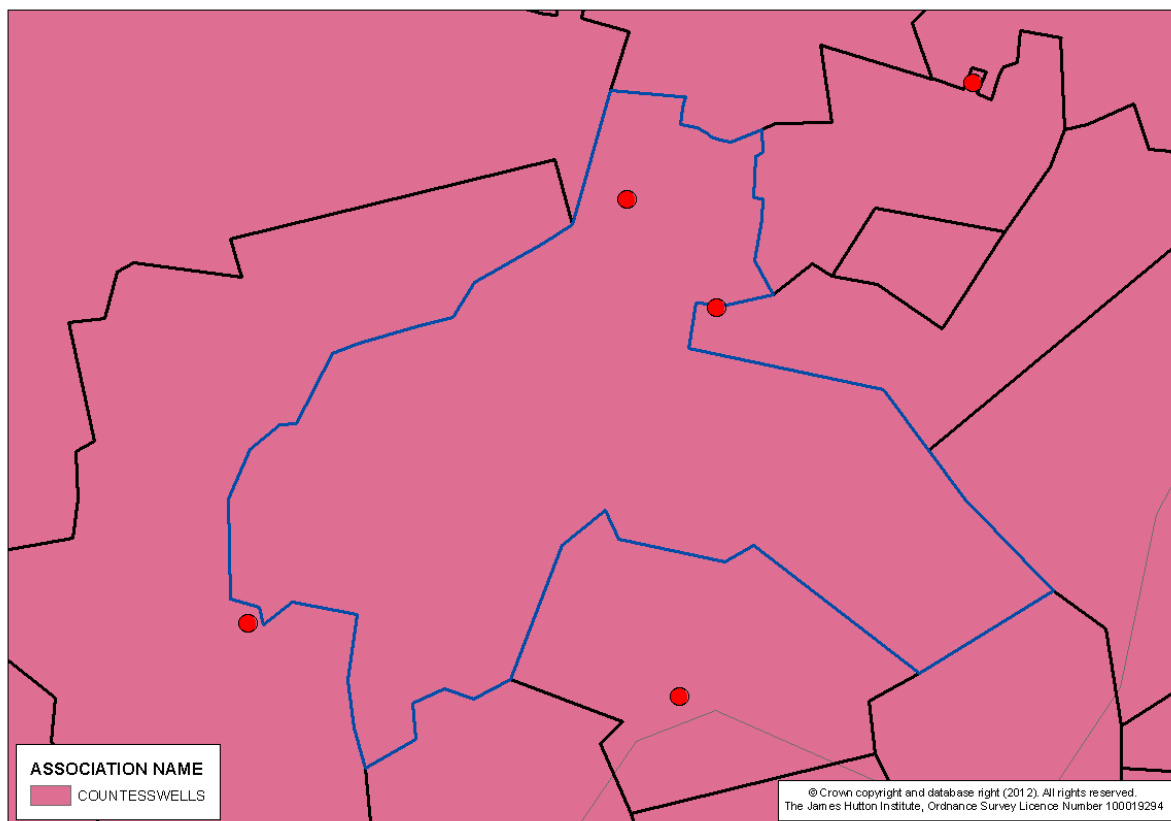


Figure 17. Example of soil association by postcode



9. Conclusions and recommendations

9.1 Conclusions

An understating of the relationship between inherent attributes of soils and agricultural usage of P is a key requirement for formulating an effective diffuse pollution mitigation strategy in Scotland. As outlined in this study this relationship is more complex than is generally understood due to the role of soil type and other soil management practices on P dynamics. This complexity will make it difficult to improve upon best management advice on agricultural use of P without potentially introducing contradictions and impacting economically sustainable yields.

The soil P sorption model (SPSM) has been applied to a data set of 399 soil samples representing 38 soil associations in order to estimate the inherent P sorption capacity of Scottish soils based on values for oxalate extractable Fe, Al and P, %organic carbon, %clay and soil pH. The 38 soil associations have been ranked according to their P sorption capacity into P sorption indices from 1 (very low capacity) to 5 (very high capacity). In order to extend this ranking to a national scale, soil associations (both at 250K and 25K scales) have been grouped with linked associations into 20 categories. P sorption indices by soil association group have been mapped at a national scale and for the 14 SEPA Priority Catchments and 2 Diffuse Pollution Monitored Catchments. Soil associations at the very low P sorption index 1 end of the scale include Auchenblae, Millbuie and Arkaig whereas associations including Stirling, Darleith and Inch are in the very high P sorption index 5.

A risk matrix of potential leaching of soluble P from the topsoil has been proposed based on soil P sorption index and SPT status. Four risk categories from very low to high have been mapped at a national scale and for the PCs and DPMCs. Urban areas and areas with no P sorption data are also mapped. The Lunan Water catchment has clearly the largest percentage of moderate and high risk areas, followed by Eye Water, River South Esk and River Tay. Catchments with more than 80% of area in very low or low risk are River Ythan, River Deveron and Stewartry Coastal. The River Ayr has the largest percentage of area with no data, while N Ayrshire Coastal and River Irvine have largest percentage of urban area.

There is no clear relationship between mapped P sorption index and average SPT data, which probably reflects the SAC recommendation to fertilise to target moderate P status. Another management target is to replace crop and grass P offtake with added P once a moderate status has been achieved. The Land Capability Classification for Agricultural (LCA) in Scotland ranks land on the basis of its potential productivity and cropping flexibility determined by the extent to which its physical characteristics (soil, climate and relief) impose long term restrictions on its agricultural use. Land suited to arable uses is included in classes 1 – 4, and not suited to arable use in classes 5 – 7. Land in Classes 1, 2 and 3.1 is capable of producing consistently high yields of a range of crops and grass, and high inputs of P will be expected to replace P offtake. It is therefore considered relevant to compare P sorption index and SPT across the different LCA Classes, and hence potential leaching of soluble P from the topsoil. There is a general decline in STP as LCA changes from 1 to 6. In the North East and South East average STP concentrations declined by more than a half between LCA 1 to 4. This is an important finding that needs to be built into future publications on P management advice. There are no LCA 1 areas within the PC + DPMCs.

The review of the relationship between LCA and assessment of the Cessnock database appear to show that the relationship between advisory SPT and P sorption index may only become coherent at the sub-catchment scale where individual soil types are more associated with specific LCA, farm types, and land management systems.

Well designed P fertiliser policies should have a build-up or run-down component for low/high status respectively in order to target the moderate P status. It is known that build-up/run-down rates vary with soil type but currently only very general guidelines are provided. The assignment of P sorption indices to different soil associations provides a significant advancement in the understanding of the amount of P required to change SPT. Estimates based on the soil P sorption model (SPSM) of the change in P when increasing STP have been made. There are big health warnings on the estimated change in P on an area basis (kg P/ha), and differences should be thought more relative than absolute. Much more P is required moving to moderate P status in P sorption index 5 soils than an index 1 soil. Soils with a high P sorption index will require about 3 times as much P to be added, or removed, to achieve the same change as low P sorption soils. In addition the data could be used to quantify the P pool size on a catchment basis, e.g. at any given SPT value the index 5 soils will have a much greater pool of sorbed P.

9.2 Recommendations

1. Confidence in the P sorption index predictions, and hence risk of potential leaching of soluble P from the topsoil, can be increased by the collection of more soil attribute data across more associations. This recommendation is based on the following summary of the measured data set:
 - About 80% of the total area of the 14 PC and 2 DPMCs is covered by soil associations that were used to rank associations in order of P sorption capacity, but 18 of the 38 associations with actual data were ranked based on either one or two samples.
 - A further 79 associations not covered by the 38 with measured values, but part of 20 categories of linked association groups, were assigned an index. A precautionary 'risk' based principle that the lower the sorption value, the greater risk of soluble P leaching was used to assign indices. Any associations with no measured values were put into the lowest index of any from the same group.
 - All alluvial soils were grouped together in index 3. It is expected that different P sorption indices will exist for different alluvial soils as all alluvial soils are not formed from a single soil association group.
 - Based on the above precautionary principle, there is currently a bias towards lower P sorption indices.
2. Confidence in the SPT data in the PCs and DPMCs, and hence risk of potential leaching of soluble P from the topsoil, can be increased by targeted sampling for advisory soil testing across catchments with low coverage of SPT data within individual postcodes. This recommendation is based on the following summary of the SPT data set:
 - On average 16% of postcodes with P sorption indices have actual SPT data in the PCs and DPMCs, the remainder are assumed to have M- status in mapping risk of potential leaching of soluble P.

- Less than 10% of postcodes with P sorption indices have actual SPT data in the SW catchments of North Ayrshire Coastal, River Doon, River Garnock and River Irvine. These catchments need to be targeted for collection of more SPT data from individual postcodes.
 - Eye Water followed by the River Ythan has the best coverage of actual SPT data.
3. Future emphasis could be placed upon the improved tailoring of the P management of soil having different P sorption properties. It may be possible to refine the component of the P fertiliser recommendation which covers build-up or run-down of P status. SAC has recently launched a GPS soil sampling service. It is recommended that sampling for PK analysis should be in zoned areas based on the farmer's knowledge of cropping performance, but also based on soil type. Soil type should include zoned areas of different P sorption index. SAC advisory staff requires training in the new knowledge developed in the current project. The new GPS soil sampling service needs to be promoted to the farming community.
 4. Future work needs to focus on informing this soluble P leaching risk matrix at the sub-catchment scale using localised understanding of land management variables and SPT. The sorption P index provides the opportunity, in conjunction with a P leaching risk matrix which encompasses land management variables, to provide a mechanism to target key soils for testing across sub-catchments.
 5. A strategy for the further collection of local management information and direct measures of SPT should be devised.
 6. The relationship between LCA and P sorption index should be further assessed at the catchment and sub-catchment scale with a focus on variability in management at the field level. The LCA is a prediction of land capability for production which can be linked to potential cropping options and yield. Linking the LCA to the soil P sorption index and land management provides a tool for understating the balance between total agricultural P inputs versus crop off take and the portion leached to surface waters.
 7. A relationship between SPT levels and leaching to surface waters needs to be analytically quantified for soils with differing P sorption indexes. It is theorised that for a given soil at a moderate P status the diffuse pollution loading occurring directly from soluble forms of P arising from soil mediated process will be small as compared to the amount from natural soil erosion. This should be quantified as it will be important to a further understanding of the relationship that tries to link regional variations in land management to P loading. The soil mediated P contribution may be small but it is this fraction that will be the primary focus of any future attempts to understand or change agricultural P management in Scotland as its variances has a direct link to economically viable crop production in Scotland.
 8. The Hooda et al. work underpinning the relationship between SPT and volume weighted P concentrations in surface waters requires replication and understanding. This requires a value for the volume weighted water P concentrations in each of the PC and DPMCs along with improved assessments of P load apportioning. Quantifying such a potentially significant variance at a national level at an early stage will assist in establishing meaningful regional mitigation priorities. This approach on two catchments will also provide a mechanism to further refine and transform the risk matrix into an operation process.
 9. Consider the possibility of integrating the current 'leaching' related aspects with separate 'erosion' based risk assessment. There is a need to develop understanding of how P would be released from soil particles entering the water environment as it cannot be assumed soils with high P would release more soluble P after entering watercourses.

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Acknowledgements

The SAC advisory data were provided by Mr A Gay and further organised by Mr I Buchan. Soil analytical data from The James Hutton Institute were provided by Dr. R. Wendler and Mrs S. Richards.

11. Appendix

I. The River Irvine Priority Catchment: Cessnock Sub-Catchment soil sampling.

The Cessnock is a sub catchment of the River Irvine and drains 7592 ha of mainly lowland soils. The Cessnock and the River Irvine to which it drains have been identified as being under pressure from diffuse pollution loading of P from agricultural activity. Table 11.1 shows the result from monitoring results between 2007 and 2009 from two points along a tributary of Cessnock Water.

Table 11.1: Water quality monitoring results from the Cessnock (2007 - 2009)

	Summer (May to September)					
	Orthophosphate-P (mg/l)			Total P (mg/l)		
	Average	Max	Min	Average	Max	Min
Station A	0.21 (n = 65)	0.61	0.01	0.22 (n = 29)	0.51	0.08
Station B	0.23 (n = 60)	0.95	0.04	0.25 (n = 30)	0.79	0.05
Winter (October – April)						
Station A	0.18 (n = 29)	1.2	0.01	0.26 (n = 29)	1.61	0.033
Station B	0.16 (n = 31)	0.69	0.06	0.22 (n = 31)	1.02	0.07

This monitoring demonstrates the potential magnitude of P loading. Further assessment on the degree of non-agricultural loading is required before a fixed loading pressure from soil mediated sources can be determined.

Accurately proportioning the loading from each P loading mechanism is a basic requirement to implementing effective mitigation strategies. This is made more complex when dealing with intensive agricultural production since annual applications of P cannot be linked directly to yield in the year of application and records of individual applications are not a reliable indicator of the amount of available P present in the soil due the variation that can occur based soil type and the history of previous P applications.

Phosphorus as a limiting factor to production has largely been eliminated within this catchment due to the effective application of inorganic and organic forms of P over many years. The P buffering capacity of soils in the Cessnock has entailed the application of P across the sub catchment in amounts that exceed crop removal. This has resulted in the build-up of P within the managed topsoil layer to levels that allow agronomical relevant amounts of P to be plant-available on an annual basis.

With grassland being the dominant land use the risk of soil erosion across the catchment is deemed low.

The purpose of the current study is to acquire a baseline set of soil analytical results to provide information into:

- Current levels of available soil P across the sub-catchment
- Representative samples from each of the main soil types
- Land use survey
- Drainage status

This work was carried out as part of the Scottish Government funded research work package WP 2.3 “Effectiveness of measures to manage water quality and control diffuse pollution”.

The soils of the Cessnock

Within the Soil Survey of Scotland there are 10 mapped soil associations and 23 different soil series across the sub catchment. The two dominate soil associations are Bagour and Sorn which represent ~ 60% of the soils in the catchment (Figure 11.1 and Table 11.2). Of the 23 individual soil series the majority of the soils (>75%) are from series which are defined and have the same name as the association.

Figure 11.1. Soils of the Cessnock

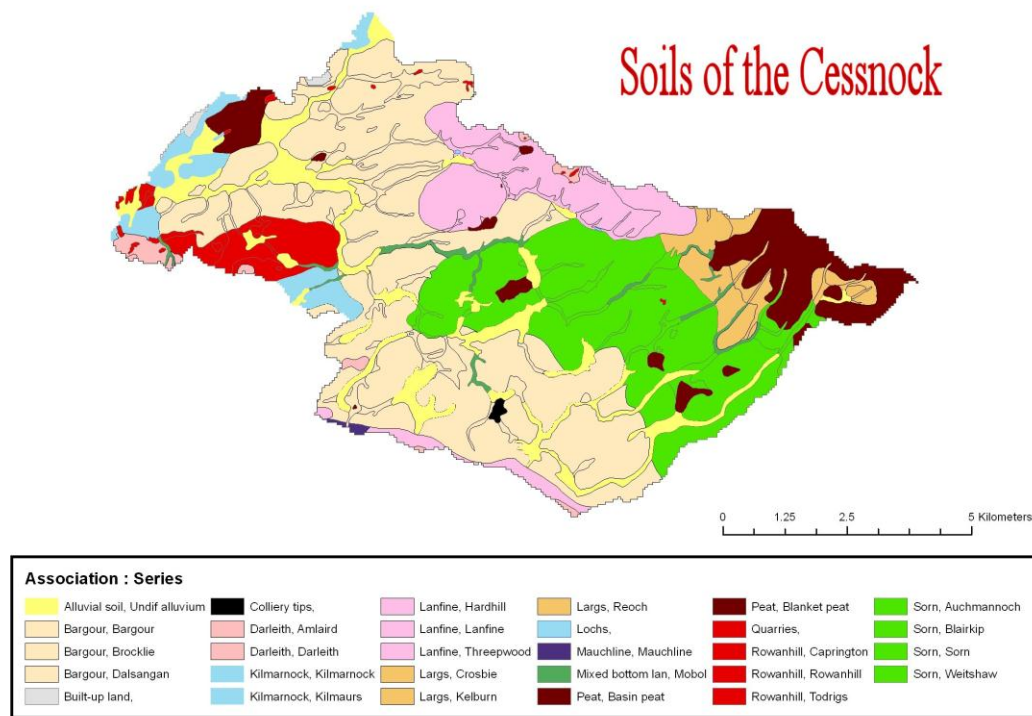
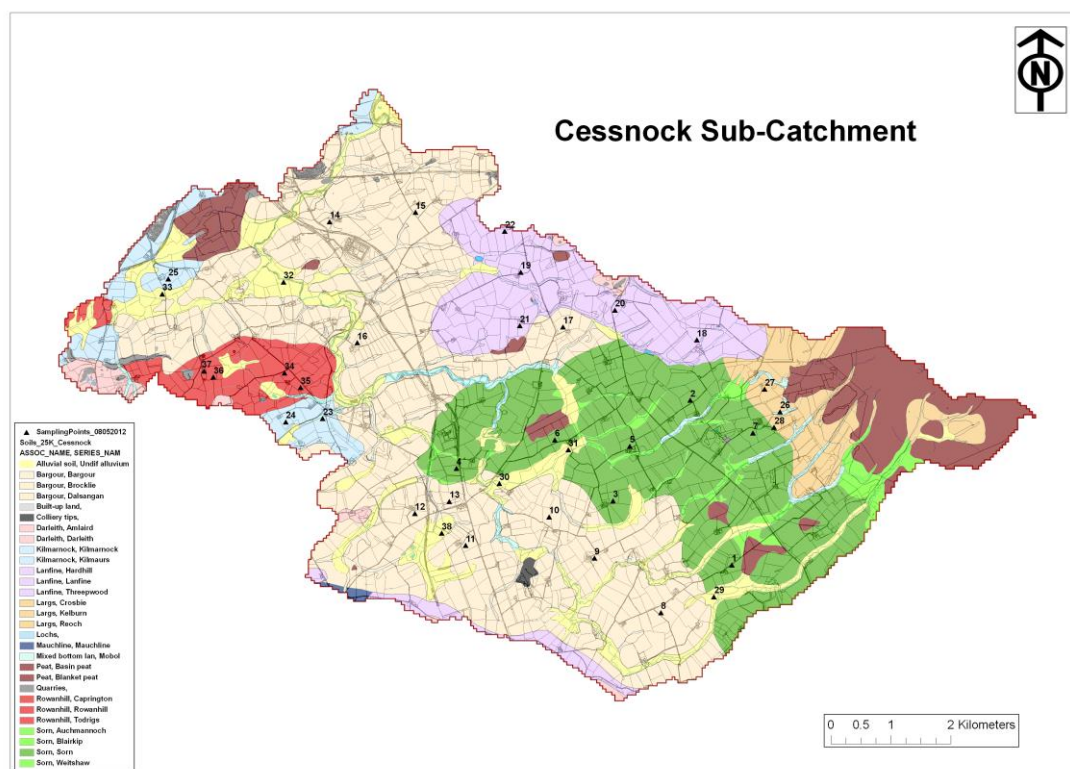


Table 11.2. Soil association and series in the Cessnock Sub-Catchment

Association	Area (ha)	Series	Area (ha)
Bargour	2899	Bargour	2597
		Brocklie	269
Darleith	83	Darleith	81
		Amlaird	1.8
Kilmarnock	249	Kilmarnock	238
		Kilmaurs	11
Lanfine	748	Hardhill	9.5
		Lanfine	590
		Threepwood	147
Largs	321	Crosbie	26
		Kelburn	201
		Reoch	95
Mauchline	10	Mauchline	10
Sorn	1527	Auchmannoch	17
		Blairkip	104
		Sorn	1357
		Weitshaw	49
Other Types		Description	
Peat	596	Basin peat	172
		Blanket peat	424
Mixed bottom land	95		
Alluvial soil	722		

Representative samples from each soil from across the catchment were taken in May, 2012, targeting agriculturally managed land and different soil types. In total 33 samples were taken (Figure 2).

Figure 11.3. Sampling locations across the Cessnock



The number of samples taken from each soil association was weighted based on the area of each (Table 11.3).

Table 11.3. Number of samples from each soil association

Association	Ref	Number of Samples
Bagour	1	10
Sorn	2	8
Lafine	3	2
Alluvial	4	5
Largs	5	5
Rowanhill	6	4
Kilmarnock	7	3

Samples were collected exclusively from agriculturally managed land away from field boundaries and other obstacles. The soil sample is representative of the entire topsoil depth except from alluvial soils where topsoil depth exceeded 40 cm. Each sample was collected from individual fields and ~ 20 individually managed farming units are represented.

As part of work package WP 2.3 additional associated information is being collected from a range of sources to assist in providing a context for these analytical results and to assist in additional project objectives such as the evaluation of effectiveness and multi benefits of various diffuse pollution mitigation options.

II. Standard deviation of mean for the soil properties of the 38 soil associations.

	Association	N	pH water	C	CLAY	Ox-Al	Ox-Fe	Ox-P	Total_P	OLSEN_P
1	Alluvial soil	12	0.36	4.54	1.89	2122	4482	420	567	16.1
2	Arkaig	16	0.55	2.25	7.10	1008	1935	358	288	12.4
3	Auchenblae	1								
4	Balrownie	60	0.54	2.38	9.12	1435	1731	263	298	15.3
5	Bargour	7	0.37	0.96	0.00	518	1759	273	229	9.5
6	Boyndie	3	0.75	0.53	2.19	1666	1677	538	540	20.6
7	Corby	35	0.50	2.23	5.06	1556	2906	361	443	20.4
8	Countesswells	33	0.39	1.81	5.25	1212	3155	362	373	9.5
9	Darleith	24	0.69	4.19	10.36	7757	6423	510	490	10.1
10	Darvel	1								
11	Eckford	3	0.08	0.09	0.51	890	1271	373	69	26.3
12	Ettrick	30	0.49	2.54	10.47	1860	4379	434	650	11.9
13	Forfar	13	0.43	0.97	0.78	1485	1580	370	362	18.1
14	Foudland	31	0.35	1.11	6.91	1667	2659	391	428	9.2
15	Insch	2	0.50	1.25	4.24	1181	8459	24		
16	Kilmarnock	3	0.34	1.44	0.17	1243	4434	438	44	14.5
17	Kintyre	1								
18	Kippen	1								
19	Lanfine	3	0.69	1.87	0.00	2105	2763	911	316	10.7
20	Largs	2	0.21	1.87	0.00	607	1983	108	30	5.3
21	Millbuie	1								
22	Minto	1								
23	Mountboy	8	0.35	0.50	0.78	1221	616	244	268	12.4
24	North Mormond	1								
25	Ordley	1								
26	Panbride	2	0.01	0.00	0.27	140	210	33	55	0.9
27	Rowanhill	5	0.38	1.27	8.08	1219	3257	230	315	10.3
28	Sorn	7	0.41	1.53	1.00	883	3051	209	286	20.3
29	Sourhope	19	0.45	3.17	7.45	4530	4920	420	516	12.2
30	Stirling	2	0.16	1.11	17.80	98	1913			
31	Stonehaven	1								
32	Strichen	31	0.62	3.76	8.37	917	3197	362	421	8.3
33	Tarves	31	0.41	1.31	6.39	4410	4930	524	450	8.5
34	Thurso	2	0.05	3.32		1347	579	54	64	3.6
35	Tipperty	1								
36	Tomintoul	1								
37	Tynet	2	0.17	2.71	0.44	2603	3438	28	498	8.2
38	Yarrow	2	0.45	2.61	0.74	1269	3525	325	494	3.1

III. Ranking of 38 soil associations in relation to P sorption by 3 methods.

Association	Adsorption potential mmol/kg	Association	Regression P retention index mg/kg	Association	P diss at pH 4.8 mg/kg
	(method 1)		(method2)		(method3)
Auchenblae	4.6	Millbuie	1434	Auchenblae	264.7
Millbuie	6.6	Minto	1604	Millbuie	198.1
Boyndie	10.2	Auchenblae	1811	Boyndie	129.1
Minto	10.6	Kilmarnock	2026	Arkaig	128.6
Thurso	10.9	Sorn	2035	Thurso	117.6
Darvel	11.5	Darvel	2077	Balrownie	108.4
Sorn	11.7	Tipperty	2227	Minto	96.4
Mountboy	12.0	Thurso	2244	Mountboy	93.5
Eckford	12.2	Kintyre	2289	Countesswells	91.3
Tomintoul	12.4	Boyndie	2303	Corby	85.7
Kippen	12.6	Largs	2330	Stonehaven	83.5
Largs	12.6	North Mormond	2343	Kippen	82.2
Arkaig	12.7	Eckford	2420	Sorn	77.7
Forfar	13.3	Stirling	2437	Tomintoul	66.7
Tynet	13.3	Ordley	2455	Darvel	65.5
Alluvial soil	13.7	Bargour	2537	Eckford	64.0
Panbride	13.7	Alluvial soil	2572	Largs	61.1
Corby	13.7	Arkaig	2585	Forfar	56.5
Kilmarnock	14.1	Strichen	2626	Panbride	50.7
North Mormond	15.2	Kippen	2642	Kilmarnock	44.1
Balrownie	15.3	Forfar	2650	Tynet	43.4
Yarrow	15.8	Mountboy	2657	Sourhope	30.3
Kintyre	16.4	Balrownie	2674	Strichen	29.7
Countesswells	16.9	Tynet	2682	North Mormond	21.7
Stonehaven	17.5	Countesswells	2693	Tipperty	19.1
Ordley	17.7	Tomintoul	2701	Yarrow	13.7
Sourhope	20.3	Corby	2705	Alluvial soil	13.0
Rowanhill	20.8	Rowanhill	2829	Ettrick	7.35
Strichen	21.0	Stonehaven	2954	Ordley	6.00
Foudland	25.0	Foudland	3013	Foudland	2.26
Ettrick	25.2	Panbride	3165	Bargour	2.08
Tarves	26.0	Ettrick	3195	Rowanhill	1.85
Bargour	26.0	Yarrow	3458	Kintyre	1.56
Lanfine	26.3	Tarves	3864	Tarves	1.48
Stirling	31.3	Lanfine	4101	Lanfine	0.45
Tipperty	34.3	Sourhope	4469	Stirling	0.25
Darleith	37.6	Insch	6213	Darleith	0.025
Insch	38.5	Darleith	6451	Insch	0.001

IV. Soil associations, parent material and % of total land area

% of total land area	Soil association	Parent material
16.2	Arkaig	Coarse-textured drifts derived from schists, gneisses, granulites and quartzites principally of the Moine Series
1.8	Balrownie	Drifts derived mainly from sandstones of Lower Old Red Sandstone age, often water-modified
5.8	Countesswells	Drifts derived from granites and granitic rocks
3.1	Corby	Fluvioglacial and raised beach sands and gravels derived from acid rocks. Soils of the Boyndie Association (fluvioglacial and raised beach sands) are also included.
3.5	Darleith	Drifts derived from basaltic rocks.
1.6	Durnhill	Drift derived from quartzites and quartzose grits
9.3	Ettrick	Drifts derived from Lower Paleozoic greywackes and shales
3.3	Foudland	Drifts derived from slates, phyllites and other weakly metamorphosed argillaceous rocks.
4.7	Lochinver	Drifts derived from Lewisian gneisses
9.9	Peats	Organic deposits
3	Rowanhill	Drifts derived from Carboniferous sandstones, shales and limestones
1.7	Sourhope	Drifts derived from Old Red Sandstone intermediate lavas
8	Strichen	Drifts derived from arenaceous schists and strongly metamorphosed argillaceous schists of the Dalradian Series
2.1	Tarves	Drifts derived from intermediate rocks or mixed acidic and basic rocks, both metamorphic and igneous.
2.3	Torridon	Drifts derived from Torridonian sandstones and grits.

V. Grouping of associations into the various P sorption indices and their areas (ha).

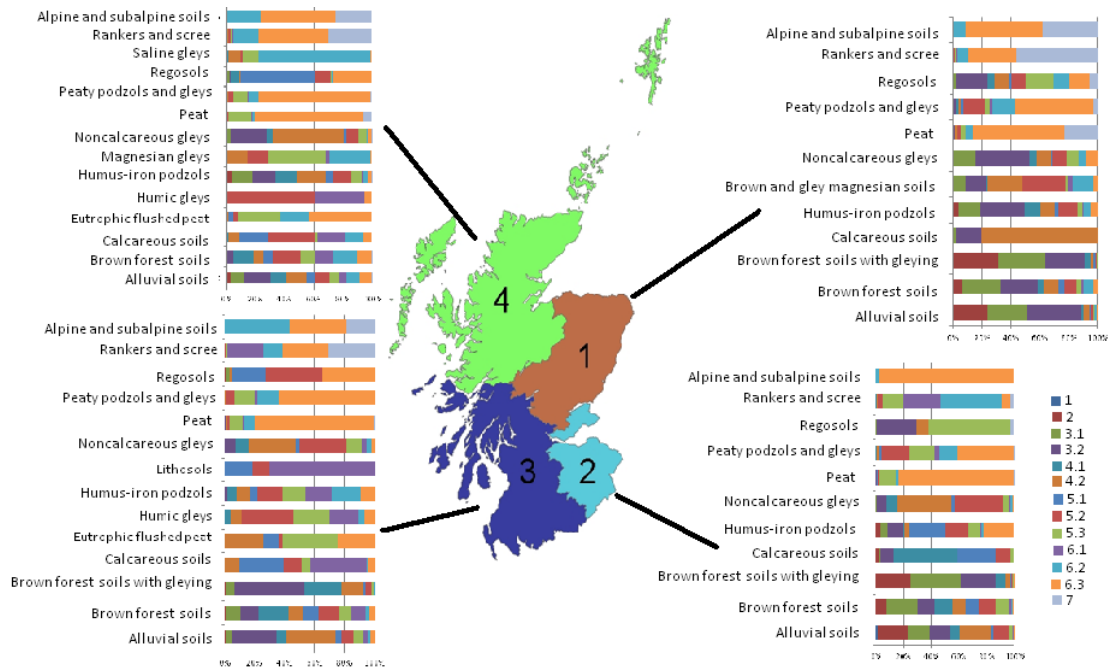
Association	P sorption index						Grand
	no data	1	2	3	4	5	
ABERLOUR			27261				27261
ALLUVIAL SOILS				130031			130031
ARBIGLAND			422				422
ARDVANIE		4273					4273
ARKAIG		1241679					1241679
ARRAN					9264		9264
ASHGROVE			13166				13166
BALROWNIE		135900					135900
BARGOUR					9754		9754
BARNCORKRIE				191			191
BEMERSYDE			5105				5105
BENAN						4036	4036
BERRIEDALE		29395					29395
BLAIR				5266			5266
BOGTOWN			1061				1061
BRAEMORE/ KINSTEARY	4980						4980
BRIGHTMONY			2113				2113
CAIRNCROSS		2621					2621
CANISBAY		27404					27404
CANONBIE					27785		27785
CARPOW/ PANBRIDE				15874			15874
CARTER			29757				29757
CORBY/ BOYNDIE/ DINNET			233022				233022
CORRIEBRECK						3554	3554
COUNTESSWELLS/			438603				438603
CRAIGDALE				680			680
CRAIGELLACHIE/ POLFADEN	938						938
CREETOWN			3799				3799
CROMARTY/KINDEACE		23020					23020
DARLEITH/ KIRKTONMOOR						265246	265246
DARVEL				36723			36723
DEECastle	10952						10952
DOUNE			3843				3843
DREGHORN				17774			17774
DRONGAN			5233				5233
DULSIE			19367				19367
DUNNET	8026						8026
DURISDEER					1384		1384
DURNHILL	118953						118953
ECKFORD/ INNERWICK				30322			30322
ELGIN		6686					6686
ETHIE				1591			1591

ETTRICK				725904			725904
FORFAR				37367			37367
FOUDLAND					242340		242340
FRASERBURGH	19538						19538
GLENALMOND/ MAYBOLE		28230					28230
GLENEAGLES/		14739					14739
GOURDIE/ CALLANDER/					35548		35548
GRULINE				2671			2671
HATTON/ TOMINTOUL/				23767			23767
HAYFIELD			2641				2641
HINDSWARD			18153				18153
HOBKIRK		55057					55057
HOLYWOOD					13769		13769
INCHKENNETH	11039						11039
INCHNADAMPH	6381						6381
INSCH						51907	51907
KILMARNOCK				33282			33282
KINTYRE					47357		47357
KIPPEN/ LARGS			28510				28510
KIRKCOLM			569				569
KIRKWOOD	3976						3976
KNOCKSKAE			8466				8466
LANFINE					9672		9672
LAUDER		16444					16444
LAURENCEKIRK		9233					9233
LESLIE	8232						8232
LETHANS						1792	1792
LINFERN				273			273
LINKS	17247						17247
LOCHINVER	326090						326090
LYNEDARDY				307			307
MAUCLINE/ AUCHINLECK					8927		8927
MILLBUIE		18961					18961
MINTO			11146				11146
MOUNTBOY			28152				28152
NIGG/ PRESTON	15133						15133
NOCHTY						855	855
NORTH MORMOND/				22719			22719
ORDLEY/ CUMINESTOWN				16025			16025
ORGANIC SOILS	754648						754648
PETERHEAD				12748			12748
RACKWICK		161					161
REPOCH	12291						12291
RHINS				44106			44106
ROWANHILL/ GIFFNOCK/					248739		248739
ROY	4016						4016

SABHAIL/ MOUNTEAGLE		20225					20225
SHAWHILL				181			181
SKELBERRY				6103			6103
SKELMUIR	2092						2092
SMAILHOLM						3125	3125
SORN/ HUMBIE/ BIEL			45964				45964
SOURHOPE			123884				123884
STAFFIN	5261						5261
STIRLING/ DUFFUS/ POW/						35802	35802
STONEHAVEN				24650			24650
STRICHEN				608733			608733
SYMINGTON			2772				2772
TARVES					158374		158374
THURSO			101850				101850
TIPPERTY/ CARDEN				5443			5443
TOROSAY						54467	54467
TORRIDON	160915						160915
TYNEHEAD				5224			5224
TYNET				4039			4039
WALLS				9514			9514
WHITSOME	32037						32037
YARROW/ FLEET				45358			45358
Grand Total	1,522,745	1,634,028	1,154,860	1,866,869	812,912	420,782	7,412,197

VI. Each agricultural region divided into soil type, LCA and area (ha)

Four agricultural regions.



ha	1	2	3.1	3.2	4.1	4.2	5.1	5.2	5.3	6.1	6.2	6.3	7	Grand Total
Alluvial soils	223	15892	19406	36163	7128	21887	3212	8336	4929	2887	3285	3631	71	127049
1	8	11140	13269	17696	1212	1765	199	958	374	25	718	367	66	47797
2	215	3521	2394	2433	928	3660	297	1682	617	71	71	7		15896
3		340	1753	11524	2657	13114	1582	3285	2321	1544	472	1115		39709
4		890	1990	4510	2331	3347	1133	2410	1617	1248	2023	2142	5	23648
Alpine soils							41	29	7		7901	11771	30951	50701
1								28	7		1682	6488	21697	29902
3											187	188	553	928
4							41	2			6032	5095	8700	19871
Brown calcareous soils		45	31	202	839	661	3197	489	369	1135	40	252		7260
1			4	36		161								201
2		45	27	159	824		520	155	76					1806
3						199	737	117	23	46	10	74		1206
4				7	15	300	1941	217	270	1089	30	179		4048
Brown forest soils	1841	37147	173868	154656	146000	100552	85046	142063	71704	71219	49704	37092	121	1071011
1	749	15215	67207	66164	10021	24310	10633	22571	7046	5381	17250	6719	55	253321
2	1092	18010	65774	31601	34838	28061	20906	36660	23210	7996	2777	1954		272879
3		3759	40483	51910	84157	40580	45004	61263	30563	43436	9890	15633	49	426726
4		162	404	4981	16984	7601	8503	21568	10886	14406	19788	12785	17	118086

Brown forest soils with gleying	1074	85194	123405	199139	76165	47291	4798	15737	5326	911	513	577	6	560135
1	471	37345	39167	33659	4302	2015	2205	1178	1047	5	28	13	6	121441
2	603	46688	68967	48972	11495	7604	867	3252	956	118	149	49		189721
3		1161	15271	116507	60368	37672	1725	11306	3324	788	336	515		248973
Brown magnesian soils		23	225	140	29	397		482	2	95	321	76		1792
1		23	225	140	29	397		482	2	95	321	76		1792
Brown rankers				25	115	55	5	80	93	5403	814	468	32	7090
1				25	115	33		23	6	276	574	388	32	1471
3							5	57	88	5128	70	79		5427
4						22					170			193
Brown rendzinas						0	338	1749	170	891	2242	875		6265
4						0	338	1749	170	891	2242	875		6265
Calcareous gleys					46	1197	77	1771	15		25	104		3235
4					46	1197	77	1771	15		25	104		3235
Calcareous regosols				55	100	256	1645	2728	138	2707	85	179	32	7924
3					3	44	44	211	133	935		46	7	1422
4				55	97	212	1601	2517	5	1772	85	133	24	6502
Eutrophic flushed peat						103	67	25	316	1	123	363		999
3						95	39	7	138			89		368
4						8	28	18	178	1	123	274		631
Humic gleys					387	687	39	3567	2350	1967	337	717		10051
3					387	687	39	3364	2350	1860	337	697		9721
4								203		107		20		330
Humus-iron podzols	726	30268	99385	192061	88150	96155	34754	111034	44226	19188	47964	46206	365	810482
1	621	20237	69419	154524	51671	47074	14962	65371	15616	2939	24159	25476	315	492385
2		1066	1114	3181	256	1172	6947	4652	2307	262	487	6090		27534
3			8	1589	5322	6708	3812	13109	12391	13988	15679	7677	2	80285
4	105	8964	28845	32766	30901	41201	9033	27902	13911	2000	7639	6962	48	210278
Lithosols								40	22		150			212
3								40	22		150			212
Magnesian gleys				258		1104		1190	2214	115	1678	77		6635
1				258		277		352	35		84	0		1006
4						827		838	2178	115	1594	77		5629
Noncalcareous gleys		2385	23469	97493	34423	154391	11206	112032	42621	7460	16423	21197	72	523173
1		1480	21508	51757	6531	14580	1729	13979	10832	633	6872	11822	53	141776
2		7	490	3941	5112	24283	802	21884	2019	587	1447	698		61269
3		144	195	16902	18608	70223	6899	68466	24858	6091	7562	5115	10	225073
4		755	1276	24893	4172	45305	1776	7703	4913	148	541	3562	9	95055
Peat		13	483	2630	1955	5677	1593	12423	153208	2799	35413	855956	88516	1160669
1		13	266	1491	313	1964	434	3909	6542	154	7487	98326	36954	157852
2			26	121	64	146	56	467	3111	161	396	23498	7	28053
3			174	742	882	1762	617	2527	18746	1931	14625	168762	1216	211985

4			17	277	696	1805	487	5520	124810	553	12906	565371	50339	762779
Peaty gleys			25	244	2155	8553	3860	39794	139988	14085	99180	1058545	5425	1371852
1					25	175	0	111	370	77	1687	15079	403	17928
2			25	38	385	1927	157	6522	16313	59	4319	16058	8	45810
3			0	178	1161	3531	2032	16943	75527	9246	49409	333760	1233	493021
4				28	583	2920	1670	16217	47778	4702	43765	693648	3781	815093
Peaty podzols		11	719	6706	5150	14697	9366	112019	152092	11831	170785	698742	13248	1195366
1			665	5923	3037	5609	4071	39983	10882	2564	41987	132180	8026	254928
2			37	5	338	1079	1159	18423	6746	2281	11646	34963	4	76680
3				155	450	888	1636	22861	42517	4732	73981	200382	895	348496
4		11	17	623	1325	7122	2500	30752	91946	2254	43172	331218	4323	515262
Peaty rankers								24	12		21	3301	691	4049
1											19	176	329	524
3									12			940	362	1314
4								24			2	2185		2211
Podzolic rankers						34	27	148	1015	1761	985	125		4095
2						34	27	148	1015	1761	985	125		4095
Rankers			106	152	664	79	1405	1373	1694	18564	48209	33888		106135
1					44	23	192	96	128	1833	9581	17450		29347
2				21	18	57	3	33	36	139	2228	320	211	3066
3					12	11	8	120	88	1342	3304	6241	3354	14480
4				85	121	552	46	1060	1153	85	11200	32067	12873	59243
Regosols	4	37	258	2721	550	1223	1747	1757	3667		844	2483	582	15873
1	4	9	142	1660	362	851	101	740	1500		835	1110	430	7745
2		9	25	1054		325			2154				152	3719
3		11	50	2	10	30	449	767				708		2027
4		8	41	5	178	16	1197	251	13		9	665		2383
Rock and scree							11	41	45	603	2403	3544	15942	22588
1											152	603	730	1485
3							0	21	35	39	384	1131	4846	6456
4							11	20	9	563	1867	1810	10366	14646
Saline gleys					20	109	6	11	133		960	9		1247
4					20	109	6	11	133		960	9		1247
Subalpine podzols											75	6229	165	6468
4											75	6229	165	6468
Subalpine soils						14	0	286	187	204	76000	168995	64951	310636
1							0	95	1	56	3693	28909	3656	36410
2									0	5	104	4636	22	4767
3									3	24	17905	15659	7255	40846
4						14		191	183	118	54298	119791	54018	228613
Grand Total	3868	171015	441275	692600	363364	455705	161153	569242	626201	147105	536685	2969724	255058	7392993

VII. Relationship between soil type (250K) and soil P status for all samples

Count of P_STATUS	Number							%						
	VL	L	M-	M+	H	VH	Grand Total	VL	L	M-	M+	H	VH	
Alluvial soils	320	1069	1839	598	488	59	4373	7.3	24.4	42.1	13.7	11.2	1.3	
Brown calcareous soils	26	19	32	17	17	29	140	18.6	13.6	22.9	12.1	12.1	20.7	
Brown forest soils	1656	7498	12205	4309	3570	642	29880	5.5	25.1	40.8	14.4	11.9	2.1	
Brown forest soils with gleying	758	3729	6556	2970	2380	523	16916	4.5	22.0	38.8	17.6	14.1	3.1	
Brown magnesian soils	3	33	37				73	4.1	45.2	50.7	0.0	0.0	0.0	
Brown rankers		5	1		1		7	0.0	71.4	14.3	0.0	14.3	0.0	
Brown rendzinas	7	9	2	1	1		20	35.0	45.0	10.0	5.0	5.0	0.0	
Calcareous gleys	10	28	16	3	11	11	79	12.7	35.4	20.3	3.8	13.9	13.9	
Calcareous regosols	10	21	25	8	15	12	91	11.0	23.1	27.5	8.8	16.5	13.2	
Eutrophic flushed peat		6	9	1	4	18	38	0.0	15.8	23.7	2.6	10.5	47.4	
Humic gleys	2	1	2				5	40.0	20.0	40.0	0.0	0.0	0.0	
Humus-iron podzols	1013	4736	11046	3878	2971	418	24062	4.2	19.7	45.9	16.1	12.3	1.7	
Lithosols				2			2	0.0	0.0	0.0	100.0	0.0	0.0	
Magnesian gleys	14	33	27	15	17		106	13.2	31.1	25.5	14.2	16.0	0.0	
Noncalcareous gleys	1023	3645	4906	1228	918	181	11901	8.6	30.6	41.2	10.3	7.7	1.5	
Peat	20	59	83	26	28	9	225	8.9	26.2	36.9	11.6	12.4	4.0	
Peaty gleys	147	256	296	122	187	82	1090	13.5	23.5	27.2	11.2	17.2	7.5	
Peaty podzols	62	247	297	94	109	25	834	7.4	29.6	35.6	11.3	13.1	3.0	
Peaty rankers	1	8	29	15	21	5	79	1.3	10.1	36.7	19.0	26.6	6.3	
Rankers	19	14	8				41	46.3	34.1	19.5	0.0	0.0	0.0	
Regosols		23	49	13	17	11	113	0.0	20.4	43.4	11.5	15.0	9.7	
Grand Total	5091	21439	37465	13300	10755	2025	90075	5.7	23.8	41.6	14.8	11.9	2.2	

VIII. Area of LCA class by Priority Catchment

Priority Catchment	Area of LCA class (ha)													Total
	2	3.1	3.2	4.1	4.2	5.1	5.2	5.3	6.1	6.2	6.3	7	Other	
Buchan Coastal	123.4	19607.4	27170.4	217.7	2376.3	109.8	667.3	1549.4	0.0	1576.1	0.0	79.6	1092.9	54570.2
Eye Water	1885.7	4215.4	437.6	3516.9	46.2	381.6	1093.6	369.8	0.0	0.0	0.0	0.0	44.5	11991.2
Galloway Coastal	110.7	21515.0	19075.0	7122.8	7082.1	9006.7	11053.6	10690.1	3097.6	4171.0	19543.1	641.1	1087.1	114195.9
Lunan Water	6201.0	1963.8	4491.9	302.6	0.0	372.3	0.0	0.0	0.0	0.0	0.0	0.0	92.9	13424.5
N Ayrshire Coastal	1034.9	3632.3	5099.4	1459.1	1622.1	312.1	1015.5	322.5	1640.5	2344.5	1362.7	0.0	2794.7	22640.3
River Ayr	299.5	0.0	8316.3	11066.4	8453.4	81.9	7642.3	4349.5	168.0	4064.1	13412.9	0.0	572.9	58427.2
River Dee	0.0	5224.7	33990.4	6116.5	11656.6	10162.8	19431.9	2639.2	1141.9	16533.6	63001.5	36869.1	1541.0	208309.1
River Deveron	0.0	19314.8	46690.7	6399.2	20375.4	130.9	14324.3	3175.2	111.7	524.5	9850.6	2031.4	313.3	123242.0
River Doon	138.4	0.0	6300.0	1067.2	1420.0	41.7	4518.0	1034.2	187.6	2784.9	13078.4	381.0	1260.0	32211.3
River Garnock	0.0	215.9	3166.3	3747.0	8965.5	432.6	873.3	725.7	65.6	3620.2	728.9	0.0	976.9	23517.8
River Irvine	0.0	1392.3	17989.8	8857.4	8896.1	0.0	1009.6	3130.1	0.0	208.0	4631.7	0.0	2026.1	48141.0
River South Esk	8033.4	3656.8	9843.7	3657.1	1184.1	308.7	6238.9	1363.7	418.7	7326.2	9786.0	4017.7	364.1	56199.1
River Tay	26023.9	14568.9	33829.2	16596.3	17455.2	7560.5	34449.6	24963.6	3568.1	67177.8	217663.4	21593.3	13672.6	499122.5
River Ugie	0.0	11691.9	17488.7	283.7	160.9	0.0	994.1	2664.7	0.0	0.0	0.0	0.0	33.7	33317.7
River Ythan	0.6	33300.1	17266.8	1106.2	937.0	0.0	376.3	370.8	370.8	80.7	0.0	0.0	81.2	53890.5
Stewartry Coastal	0.0	595.3	5042.3	10746.9	1168.9	6328.8	7134.7	4189.7	236.3	1145.3	6493.9	0.0	633.1	43715.1
Grand Total	43851.6	140894.4	256198.3	82263.0	91799.8	35230.4	110823.0	61538.1	11006.9	111556.8	359552.9	65613.3	26586.9	1396915.4