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Comparison of soil phosphorus index systems for grassland in the cross-border region of Ireland

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ABSTRACT

Background:

The use of soil phosphorus (P) tests and index systems provides a guide for agronomic nutrient requirements and frequently, is also used to estimate risk of P losses to watercourses. Use of soil testing and management based on the results thereof, is mandated in some regions. Several P extraction methods are available which evaluate different P pools and are designed for particular soil types. Further to this, index systems categorising specific ranges of plant-available P, differ. Hence, translation between different tests and index systems is not straightforward. In cross-border regions, where hydrologic basins encompass more than one political jurisdiction, different tests and rules are implemented in adjacent lands. This can create disparities in land management, confusion as to what legislation applies, and obscures the impacts of best management practices at catchment scale.

Aims

The aim of this research was to compare the Morgan’s and Olsen soil tests used to quantify plant-available P and the respective index systems, in a border region of the Republic of Ireland (ROI) – Northern Ireland (NI).

Methods

Olsen, Morgans, and water extractable P (WEP) were evaluated (N=1,038). Statistical analysis was conducted to derive conversion equations to translate between the statutory test methods and comparison of the respective index categories was performed.

Results

The conversion equations compared favourably with previous attempts. A stronger relationship was observed between Morgan P and WEP (R^2=0.60) than between Olsen P and WEP (R^2=0.45) (including pH and site as interaction factors). The ROI index system was found to indicate lower levels of plant available P in the soil compared to the NI system, for the same soils.

Conclusions

The differences in categorization of P availability using either index system creates differences in fertiliser recommendations and also perceived aquatic risks even within small cross-border catchments. This study points to a wider implication for international cross-border catchments, suggesting that evaluation of the relationships between adjacent national soil index systems is required to achieve harmonised management of shared waterbodies.

Keywords: Phosphorus, Soil fertility, Soil Index Systems, Water quality, grassland, harmonization

1. INTRODUCTION

Management of waterbodies requires understanding of and use and management, climate, geology, and soil characteristics. This becomes increasingly complex in hydrologic catchments which span multiple political jurisdictions with distinct approaches to both regulation and characterisation. The European Environment Agency technical report (EEA, 2012) identified the need for vertical integration between adjacent states sharing waterbodies, including elements of spatial planning and environmental characterisation, if Water Framework Directive (WFD) objectives are to be achieved. This could similarly be said of any water quality goals in transboundary regions, including those outside of the EU. It has been estimated that 310 international river basins exist, spanning 47.1% of Earth's surface and including 150 nations (McCracken and Wolf, 2019). Discrepancies in approaches to data collection relevant for hydrologic modelling and apportionment of nutrient pressures on waterbodies is a challenge to characterisation and to the design and implementation of effective mitigation measures. This was illustrated in modelling of the Nemunas river, as one example, the basin of which includes areas of Belarus, Lithuania, Poland, and Kalingrad Oblast (Čerkasova et al., 2018). That study identified several challenges in modelling transboundary waters, including the unification of measurements used in individual nations and the need for 'flexibility' in using commonly available fertilizer, land use, and crop data to derive model inputs.

Soil phosphorus (P) is one issue around which such discrepancies occur, which bears particular relevance within the agricultural sector and landscapes due to the concurrent need to satisfy crop requirements and to achieve national and international quality goals for shared waterbodies. A variety of methods are available for estimating the amount of plant available P in soils using extraction methods which evaluate different P pools. Standardised soil testing has been devised primarily as a means to determine fertiliser requirements, but frequently, elevated soil P has been correlated with sub-optimal water quality exceeding target thresholds for dissolved phosphorus (Cassidy et al., 2017; Daly et al., 2002; Horta and Torret, 2007; Jordan et al., 2000; and others). Index systems are widely used to categorise ranges of soil P according to their ability to satisfy crop requirements and/or the level of environmental risk via runoff (Tóth et al., 2014). As described by Tóth et al. (2014) P recommendations in Europe are derived from a three-step development process. Firstly, statutory extraction methods are selected based on soil type. Secondly, index ranges for soil P are identified based on the results of yield response trials, typically specifying the likelihood of response to additional fertilizer. Finally, fertilizer recommendations are made according to the index of an individual field or parcel, and in some instances crop, soil, or pH characteristics. Conversely, in other parts of the world including much of the United States, index systems are primarily oriented towards environmental risk, rather than yield (Sharpley et al., 2017). In the present study, the two index systems used on the island of Ireland refer primarily to crop yield, although extensive work has subsequently related both index systems to environmental risk (Roberts et al., 2020; Cassidy et al., 2017; Roberts et al., 2017; Watson et al., 2007; Jordan et al., 2000).

Within the island of Ireland, which includes the Republic of Ireland (ROI) and Northern Ireland (NI), two statutory soil test methods (STP) are implemented for determining grassland P requirement. In ROI Morgan extract (Morgan, 1941) is used, while in NI, Olsen extract (Olsen, 1954) is used. Other differences in the statutory soil testing methodologies between these two regions are a) different depths of sampling, and b) different index systems. Ireland represents a relatively simple transboundary scenario, involving just two nations, and so provides an example to evaluate the mechanics and consequences of contrasting approaches. There are 7 cross-border surface-water catchments on the island (Bann, Castletown, Erne, Fane, Flurry, Foyle, and Lough Melvin) which represent c. 17% of the total land area (McCracken and Wolf, 2019). The objective of this study was to compare the classification of soil P availability according to the ROI and NI grassland index systems and to examine the catchment management implications of using either index system in a border-region region.

1.1 ROI Approach

Statutory agronomic soil P testing is conducted on mineral soils in ROI cored to a depth of 10 cm in a W-shaped pattern across fields or paddocks, composited, dried (40°C) and sieved (2 mm). For farms availing of derogation to the Nitrates Directive, soil testing must be conducted every four years. Estimates of the proportion of ROI farmers regularly soil testing have been reported in the literature: 63% (n=1009) (Daxini et al., 2018), or 66% (Buckley et al., 2015). The Morgan extraction process used in this region extracts P held in the labile pool (available and readily available) and is considered to be suitable for neutral and acidic soils. For naturally alkaline soils (≥7.5 pH), the Morgan extraction may overestimate plant available P due to its efficiency in breaking Al and Fe bonds and the low solubility of Ca-P (Courtney and Harrington, 2010; Fan et al., 2021).

1.2 NI Approach

Agronomic soil P testing in NI is conducted in alignment with the rest of the United Kingdom. Soil coring is shallower than in ROI; cores are extracted to a depth of 7.5 cm, air dried, and sieved (2 mm). The Olsen test used in this region extracts phosphate which is exchangeable with bicarbonate and some readily soluble calcium phosphate (Rowell, 1994). Lumsdon et al. (2016) indicated that the Olsen extraction process likely causes the desorption of organic and inorganic P bound to (oxy)hydroxide mineral particles. The Olsen test is considered to be suitable for calcareous soils (Mallarino, 1995), although it is generally suited to most soils and is widely used.

1.3 Comparing Morgan and Olsen P

Past comparisons of the Morgan and Olsen extraction processes have developed regression equations by which they can be correlated. Poulton et al. (1997) ascertained the following relationship (R^2=0.67) for soils across ROI [Eq. 1]:

$$P^{Olsen} = 5.8 + 2.91P^{Morgan} \qquad \text{[Eq. 1]}$$

Further to that work, Foy et al. (1997) examined the relationship between Morgan and Olsen P values for 199 soils in the cross-border region of Ireland. They established a non-linear relationship (R^2=0.74) [Eq. 2]:

$$P^{Olsen} = 5.96(P^{Morgan})^{0.773} \qquad \text{[Eq. 2]}$$

The previous studies, and others, have described relationships between the Olsen and Morgan methods for individual soil types. Although the Morgan's and Olsen tests are fundamentally different extraction methods, the common principles behind the resulting index systems are the same i.e., whether there will be a plant response to added fertilizer P and from which fertilizer recommendations for farmers are formulated. In the UK, the Olsen Index system has been derived from comprehensive agronomic trial data from multiple sites across the country. These trials have demonstrated that as the amount of plant-available phosphate in the soil increases from a very low level, plant yield increases rapidly at first and then more slowly until it reaches a maximum. Typically, maximum yield of grass was reached at Olsen P Index 2 (AHDB, 2019). Above Index 2 there would be no further agronomic response. The ROI system specifies indices from 1-4, where 1 indicates low plant available P and a definite response to fertilizer while 4 indicates excessive P and no response to fertilizer addition. The NI index system is divided from 0-4, where 2 is sub-divided into 2- and 2+ (DAERA, 2019). The index ranges for both systems are described in Table 1. An optimal index under the ROI system (Index 3) is not equivalent to the target index in the NI system (Index 2- or 2+). From an agronomic perspective, this may lead to under or over-application of fertiliser P with respect to plant demands. From an environmental perspective, although both index systems have been used as indicators of potential P loss to watercourses (Cassidy et al. 2017; Roberts et al., 2017; Daly and Casey, 2005; Daly et al., 2002; Jordan et al., 2000 and others), they were each developed solely from an agronomic perspective. If used as a basis for inferences of potential risk of P loss to waterbodies, it is unclear which system provides a more adequate indicator of risk, or whether the perceived levels of risk are the same. Indeed, tests including water extractable P (WEP), DESPRAL, or degree of P saturation may provide a more realistic assessment of the potential for loss to watercourses. For example, McDowell et al. (2020) used Olsen P and WEP in conjunction, to project timeframes of soil P decline from excessively loaded soils (from an agronomic perspective) to environmental targets. The WEP test identifies only that phosphorus in the sample which is readily available and so most vulnerable to loss (Kleinman et al., 2002). However, transfer of

P is contingent upon connectivity to a receptor (Haygarth et al., 2005). At present, only the agronomic tests are required by law in ROI and NI for the purpose of farm level nutrient accounting.

Although Foy et al. (1997) compared the Olsen and Morgan extraction methods, no comparison of the index systems is currently available. Discrepancies between the two approaches confounds assessment of P legacy and accounting for whole-island P load. In the cross-border region (counties Armagh, Cavan, Donegal, Down, Fermanagh, Monaghan, and Tyrone) many farmers own or lease land in both NI and ROI. These individuals must adhere to the respective soil testing regulations and fertilizer application rates corresponding to their geographic location. Lack of clarity as to the relationship between both the STP extraction methods and between the NI and ROI index systems makes farm-level decision making difficult.

From scientific and policy perspectives, models of soil P loading and loss to watercourses, interpretation of outlet data, and catchment-scale decision making requires consistent characterisation of inputs and land management. Models which use either quantitative values of soil P (such as PSYCHIC – Davison et al., 2008, which uses Olsen P as an input variable) could more easily be applied in jurisdictions using the alternative STP or index system if conversion factors were available. While the STP conversion equations mentioned previously (Foy et al., 1997 and Poulton et al., 1997) can convert between soil tests, no evaluation of index systems was provided there, so the second instance of difference is not addressed. At present, catchment scientists and advisory agencies are forced to make *ad hoc* equivalencies, which preclude consistency across individual studies.

In this study soil samples from the cross-border region of Ireland were analysed using both Olsen and Morgan extraction methods and characterised according to the respective index systems. Statistical analysis was conducted to derive equations for conversion between tests, and the consequences are contextualised within the framework of nutrient management best practices.

2. Materials and Methods

2.1 Soil Sampling

Three individual datasets are used in the present study, combining both new soil testing and archived material/previous soil analyses. While the Blackwater and its sub-catchment fall within a similar overall area, the sampled farms do not overlap, and samples were taken during separate campaigns. The three sites are all agriculturally dominated, grassland catchments in the border region of Ireland. Sample sites are summarized in Table 2. In all cases, paddocks were sampled using a W-shaped sampling protocol (20-40 cores per sample), and composited. Depth of sampling varies depending on study and is detailed in Table 2. Samples were dried at 40°C and sieved to 2 mm.

Corduff is a 5.7 km^2 catchment in Co. Monaghan. The catchment is poorly drained and has a drumlin topography. Soil type varies depending on slope position, with acid brown earths on hilltops and stagnic luvisols and gleys on slopes and valley bottoms. This catchment is part of the Teagasc Agricultural Catchments Programme (Shortle and Jordan, 2017). Soil samples were taken in December 2013 – February 2014 to a depth of 10 cm on all farms within the catchment.

Blackwater is a 1,491 km^2 catchment participating in the INTERREG CatchmentCARE project. Soil samples were taken on 17 participating study farms within the catchment during January-February 2019, in order to deliver nutrient management advice. The 17 farms were scattered throughout the catchment. Samples were taken to a depth of 7.5 cm.

A 5 km^2 sub-catchment within Blackwater was investigated by Campbell et al. (2015) as part of the TRACE project. The sub-catchment is located in the south of the Blackwater catchment. Sampling was conducted in December 2004-February 2005. Samples were taken to a depth of 7.5 cm.

2.2 Laboratory Analysis

The Morgan test was conducted in accordance with Morgan (1941). In brief, samples were extracted using a buffered 10% sodium acetate (pH 4.8, 1:5 (v/v) soil to solution ratio) extraction over 30 minutes. The Olsen extraction process (Olsen, 1954) used a 0.5 M $NaHCO_3$ solution buffered at pH 8.5. Samples were extracted at a 1:20 v/v soil to solution ratio for 30 minutes at 180 rpm. Extracts were filtered (No.40 Whatman filter paper). Results were categorised into the respective indices according to both the ROI and NI statutory index systems. WEP was measured by shaking 2 g soil with 20 ml distilled water (1:10 (v/v) soil to solution ratio), followed by centrifugation at 6,000 rpm. Subsequently, for each analysis samples were filtered (°2 Whatman filter paper) and analysed colorimetrically using a Skalar San Plus Autoanalyser.

2.3 Statistical Analysis

Statistical analysis was conducted using STATA (2017). Linear regression was performed to estimate the relationship between Olsen P and Morgan P. Data was not transformed. To account for collinearity between pH and P, an interaction term is included. A binary variable, that takes on a value of one for all observations from the Corduff site, and zero otherwise (Blackwater CatchmentCARE and Trace sites), is also included to reflect a statistically significant difference in the relationship between Olsen P and Morgan P at that site, compared to the other two. Two empirical models are estimated, to identify conversion factors both to and from each extraction method, respectively [Eqs. 3 and 4]. In each case, the required P value is predicted based on a constant (a), and the three independent variables described above multiplied by a coefficient (b).

$$P^{Olsen} = a_1 + b_1 P^{Morgan} + b_2(pH \times P^{Morgan}) + b_3 S^{Corduff} \qquad \text{[Eq.3]}$$

$$P^{Morgan} = a_2 + b_4 P^{Olsen} + b_5\left(pH \times P^{Olsen}\right) + b_6 S^{Corduff} \qquad \text{[Eq.4]}$$

To test for evidence of differences in how well Olsen and Morgan P can be used to predict WEP, four empirical models are estimated independently, using both univariate regression and also a multivariate regression adding in the pH interaction term and site dummy (equations not shown).

3. RESULTS

3.1 Soil Analysis

Summary statistics are shown in Table 3. Median Olsen and Morgan P values fell within the high and optimal ranges for the NI and ROI index systems, respectively. Regarding pH, while the overall range was wide, standard deviation was low, and most samples fell below the optimum value for grassland (6.2). At the most recent evaluation, 19% of Irish soils were close to the median pH observed in this study (Plunkett et al., 2020).

3.2 Relationship between Olsen and Morgan soil test values

Regressions between Morgan P and Olsen P for all soils are shown in Figure 1. As expected, there is a positive relationship between the two soil tests for each site. Variability increases at higher P values. The Corduff catchment typically exhibited higher Olsen P values relative to Morgan P, compared to the Blackwater catchment and sub-catchment, which showed no significant difference in relationship.

Results of the multiple linear regressions to convert between Olsen and Morgan P including pH and site factors are shown in Table 4. No significant difference was observed between the Blackwater catchment and sub-catchment soils, however the Corduff catchment did differ significantly ($P \leq 0.001$)[1] and so was treated as a factor. The interaction term between pH and P is also statistically significant.

3.3 Relationship between Olsen and Morgan soil test values and WEP

As expected, and in agreement with the literature, there is a significant positive relationship between each statutory test and WEP although the strength of these relationships was moderate. Olsen P vs. WEP exhibited an R^2 of 0.39, which improved to 0.45 when pH and site were added as

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[1] A version of the empirical model was run with all three sites differentiated (a reference case and two binary indicators), however the Corduff site was the only statistically significant indicator. Therefore, it is the only site dummy included in the final empirical model reported here and used within the pilot conversion tool.

interaction terms. Morgan P vs. WEP exhibited an R^2 of 0.58, which improved to 0.60 when pH and site were added as interaction terms. The relatively low R^2 indicates that to improve predictions of WEP, additional variables need to be identified and empirically tested.

3.4 Relationship between indices

As the ROI and NI grassland index systems have a different number of individual indices it is not possible to directly compare across approaches. However, the individual indices can be clustered into deficient (NI 0 and 1, ROI - 1 and 2), optimal (NI - 2- and 2+, ROI 3) and excessive (NI - 3 and 4, ROI - 4) P indicative categories. The percentage of soils in each index group (deficient, optimal, and excessive) for the NI (A) and ROI (B) index systems are shown in Figure 2. The NI system tends to overestimate P availability relative to the ROI system. In other words, the NI system is more likely to assume adequate or surplus P than the ROI system, for the same soil. For the sampled soils, the ROI system suggests that 37% more soils are deficient in P compared to the NI system, while the NI system suggests 30% more soils are excessive in P. Comparing across individual samples using both index systems (Fig. 2C), 41% of soils received the same indicative categories. However, 57% of samples were placed in a higher category when the NI system was used, relative to the ROI system. Within that group, 26% diverged by two classes, indicating high P (NI index 3 or 4) versus low P (ROI 1 or 2).

When the conversion equations [Eq. 3 and 4] were applied to convert between soil tests the appropriate index was allocated 60% and 70% of the time for NI to ROI and ROI to NI, respectively. A higher index was estimated 16% and 24% of the time, respectively, and a lower 14% and 16%.

4. DISCUSSION

4.1 Comparison of Olsen and Morgan Tests

Three practical differences occur in the standard approaches to soil testing in ROI and NI; different sampling depths, extraction methods, and index systems. The present study examined the latter two discrepancies with a view to comparing how land in cross-border catchments is characterised depending on jurisdiction. Based on the analysis, the relationship between Olsen and Morgan tests exhibited similar R^2 values to previous studies including Foy *et al*. (1997) – R^2=0.74, Poulton et al. (1997) – R^2=0.67, Stutter and Richards (2018) – R^2=0.75. In the current study the conversion of Olsen to Morgan R^2=0.801 [Eq. 4], while conversion of Morgan to Olsen R^2=0.805 [Eq. 3]. Such conversion may be sufficient for modelling studies using legacy or available soil data but not replace soil test P analysis, where possible. For fertility testing prescribed by legislation (i.e., for derogation farms in ROI) soil should be tested using the prescribed national methodology.

There was a significant difference between the Corduff site and the other two sites. This could be explained by the effect of sampling depth, as textural analysis indicated overall similarity. As this catchment was wholly in ROI, soil was sampled to 10 cm depth, as per legislative requirements. Samples from the Blackwater catchment and its sub-catchment (TRACE soils) were sampled to 7.5 cm depth, as per UK legislative requirements. Therefore, the site factor (Corduff) could be considered to represent sampling depth. For the purposes of translating a sample from 10 cm depth between indices, a factor of 1 should be applied, whereas 0 should be applied when samples are obtained from 7.5 cm. Daly and Casey (2005) found a significant effect of sample depth on extractable P. Deeper sampling depth under the ROI regime tends towards lower estimates of P than more shallow depths which reflect accumulations near to the surface.

4.2 Comparison with Water Extractable Phosphorus

Although various soil tests have been correlated with P in runoff, drainflow, and leachate at various scales and using laboratory, field, and catchment techniques (Kurz et al., 2005; Watson et al., 2007; Cassidy et al. 2017; Roberts et al., 2017; Daly and Casey, 2005; Daly et al., 2002; Jordan et al., 2000), WEP is used herein as an independent measure of potential P solubility (McDowell et al., 2020; Hooda et al., 2000) against which the Morgan and Olsen tests can be compared. A greater relationship was observed between WEP and Morgan P than Olsen P, suggesting that Morgan P may better reflect the easily mobilised soluble P fraction of a given soil. Similarly, Horta and Torrent (2007) identified that P desorption was poorly predicted at low Olsen P values (<20 mg kg). Lumsden et al. (2016) found a strong relationship between the modified Morgan test and WEP (R^2=0.87), and further identified that additional research is required to elucidate the relationship and controlling factors for Olsen P-WEP relationships. Stutter and Richards (2018) similarly found Morgan P correlated more strongly with total dissolved P and dissolved reactive P in drainflow than Olsen P. However, WEP alone does not equate to environmental risk, independent of hydrologic connectivity. Connectivity is not considered with regards the either index system, which reflect limited chemical parameters. In a plot study ranging for Index 0 to 4 (NI system), Cassidy et al. (2016) observed no link between P index and water quality over 6 years. They observed that 'Soil Olsen P status alone does not indicate risk to water quality.' and additionally assessing other soil characteristics such as buffering capacity may improve the current index system as an environmental indicator. Roberts et al. (2017) presented one such framework for assessing risks of P transfer which incorporated not only P index (source), but mobilization and transport factors. It cannot be conclusively determined from the present study if either index system provides a more reliable indicator of environmental risk to water quality for island of Ireland and perhaps wider implementation of a more comprehensive risk assessment would support decision-making at farm and field-scale.

4.3 Comparison of Index Systems and Potential Consequences

While simple conversion between index systems can be implemented, caution is required as these conversions have not been validated against field trials (Mallarino, 1995). Consequently, 'optimal' indices in either system may not reflect equal capacity to fulfil plant nutritional requirements although each system has independently been developed to estimate fertilizer response (e.g., Schulte and Herlihy, 2007; Higgins et al., 2021). Essentially, the two agronomic soil tests extract different pools of the stored phosphorus and their ability to adequately reflect P availability to the growing plant or for loss to the environment depends on their suitability for specific soil types (Koopmans et al., 2006). The absolute values of P extracted via either approach do not in themselves indicate kg P ha^{-1} which will be taken up by the plant, but rather, are an indication of plant response to added P, which has been shown over many years of agronomic trials, resulting in the formulation of current fertilizer recommendations in both the UK and Ireland. These guidelines are reviewed and updated regularly in response to research findings (Higgins et al., 2021). The results of such trials provide the basis of qualitative indices. Furthermore, as new grass varieties become available variations in fertilizer response may occur. This latter point has been particularly examined with reference to nitrogen use efficiency (Lee et al., 2012). Continuous assessment, modification and revision of indices would allow application to be matched to requirements and limit opportunities for loss or under-application. Indeed, even within political jurisdictions a single prescribed soil test method may not adequately reflect P availability for various soil types, i.e., where hydrologic characteristics, pH, or iron and aluminium contents differ (Schroeder et al., 2004). The present study has examined only the grassland sampling procedures and index systems. Arable soils are sampled to greater depths and the ranges within the index systems also differ. Hence, the conclusions of this study should not be extended to arable (tillage) land.

The tendency of the Olsen P index to measure a higher percentage of soils with Olsen P Index of 3 or above (no further plant response to additional P fertilizer) means that system tends towards a more conservative approach to fertilizer allocation, i.e., it will propose that less additional fertilizer would be required to meet plant requirements than under the Morgan P Index system (ROI). This reflects depth of sampling as well as the strength of extraction (Daly and Casey, 2005), and the ranges set within the index system. Neither index is objectively 'correct' for all landscapes and soil types – they are fundamentally guidelines for agronomic advice which should be considered in conjunction with liming recommendations, considering the strong control of pH on P availability. The complexity of soil types and geology within the small land area in Ireland makes it very difficult to obtain a test that will be ideal for each soil type and field within the region. For example, the Olsen P test has been found to poorly indicate availability from basaltic soils along the north coast of NI (Bell et al., 2005). However, the implications of index systems which are oriented towards greater or lesser fertilizer applications should be considered. Estimates which suggest a lower index (indicating an under-supply of P from existing soil stores) may result in greater application of P relative to plant requirements or an under-estimation of environmental risk. In the former scenario, this may reduce the margins of profitability due to increased fertiliser inputs. In the latter scenario, greater loading of soil P may incur losses to waterbodies via runoff or leaching. Conversely, estimates of higher index may result in under-application of P relative to plant demands, potentially impairing yields, or over-estimation of environmental risk. This latter issue contributes to perceived failures of existing environmental measures. Potentially compounding the difference between the index systems is the choice of sampling depth; 10 cm in ROI and 7.5 cm in NI (for grassland). Daly and Casey (2005) observed significant difference in Morgan P with depth (decreasing P) in samples taken from 2, 5 and 10 cm, and a trend towards decreasing variance which increased with depth. This suggests that shallower sampling (as per NI regulations) will result in greater estimation of soil P content. From an agronomic perspective, shallow sampling may not be wholly representative of P reserves which are available for plant use, depending on root characteristics (Roberts et al., 2020; Gahoonia and Nielsen, 2004). However, in a grassland the majority of the root mass is within the top 7.5cm of the soil profile, and this forms the reasoning behind the shallower sampling depth (Wedderburn et al., 2010). Conversely, from an environmental risk perspective (assuming overland pathways are the primary route for P loss), the depth of interaction with water will strongly influence P losses. Previous research has indicated that samples taken from shallow depths (≤5 cm) exhibited greater variability in P due to localised effects such as dung and urine deposition (Daly and Casey, 2005) which may make it difficult to obtain a representative sample in the field.

If objectives under water quality legislation include reduction in nutrient sources, the choice of index system makes a difference as to the apparent success of individual catchments. Taking the Corduff catchment, for example, for which all 587 fields were sampled, under the Olsen P NI index system 9%, 41% and 50% would be classified as P deficient, optimal, and excessive, respectively. Conversely, under the Morgan P ROI system, it would be classified as 66%, 22% and 12% P deficient, optimal, and excessive, respectively. The implications of this are a greater perceived 'failure' to achieve low P balance under the NI system. The NI index could be therefore considered to be more stringent from an environmental perspective and perhaps less generous regarding P inputs from an agronomic perspective. In practice, P loss does not depend only on soil properties, but also on factors influencing water movement either via overland flow or leaching (Roberts et al., 2017). The choice of soil test used on the island of Ireland is dictated by an administrative border, not a difference in soil type, nor is it aligned with catchment boundaries. Hence, farmers with adjacent fields and farms including land on both sides of that border, are subject to different testing and index systems.

A further question pertinent to both index systems is whether they remain good indicators of grass requirements under present climate conditions, improved grass varieties and modern production systems that are currently preferred and which have driven increases in Irish and UK grassland productivity (Higgins et al., 2019). It could be questioned therefore whether the present ranges in both index systems accurately indicate deficiencies and requirements under the present production system. In both the UK and Ireland, fertilizer recommendations are reviewed and updated regularly by a committee of stakeholders involved in the production of the recommendations (Higgins et al.

2021) and are validated through a series of agronomic plot trials. Plant response to fertilizer remains the central basis for the current index systems in Ireland. Perhaps in future (given the current environmental pressures and legislation), plot trials should be devised to provide a dual examination of plant response combined with environmental risk. Evaluation of the availability and patterns of P release from different organic manure types would further attune fertiliser recommendations with plant requirements and risks to water.

4.4 Wider Implications

The present study has identified three sequential misalignments in the grassland P index systems used on the island of Ireland (ROI and NI); sampling depths, extraction methods, and index systems, and demonstrated the perceived characterisation of soils within a transboundary catchment dependent upon the choice of neighbouring systems.

Though both index systems are based in sound scientific knowledge, discrepancies in approaches lead to confusion in agronomic advice, best practices, policy, and particularly, in elucidating environmental risk and performance in cross-border catchments. The conversion approach described herein provides a means by which P values may be converted between systems. The issue of managing cross-border catchments is not restricted to Ireland; it is estimated that c. 60% of EU territory is represented by river basin districts which cross one or more national borders (EEA, 2012). In these instances, similar discrepancies in approach and challenges in management and understanding occur. It is not suggested here that identical soil tests or index systems be implemented across nations. Rather, that appropriate conversions be calculated for cross-border catchments so that consistent understanding on P availability and understanding can be derived.

The conversion approach has some limitations. Firstly, for the purposes of nutrient management at farm level it is essential that the correct STP method and index system are applied based on which country the farm/field is in. Use of a mathematical conversion does not satisfy legislative requirements. Secondly, when converting between index systems and the typical nutrient advice derived from them, it cannot be assumed that either approach is ‘better’ or empirically ‘correct.’ Factors such as hydrologic connectivity will influence the riskiness of a site to nutrient loss, and timing and application method play an important role in encouraging crop uptake. A valuable application of the P conversion equations and index comparisons is in the modelling of cross-border waterbodies. Despite advances in computing power and mathematical modelling of hydrologic systems, the efficacy of catchment models in cross-border regions has to date been constrained by the incompatibility of input data (Ly et al., 2019). Using the comparisons explored here allow a consistent estimation of critical source areas and P loads from different parts of a catchment to be derived, despite farm-level soil data which supplies either Olsen or Morgan P values.

5. CONCLUSIONS

In this paper a comparison of the STP using the requisite analytical methods for the Republic and Northern Ireland is presented. Relationship between STP methods was observed (R^2>0.8) and regression equations were derived by which translation between methods can be implemented, accounting for pH and site differences. Regarding the latter, this may reflect depth of sampling, which is different under ROI and NI regulations. The conversion equations presented herein have utility in evaluation of P reserves at catchment scale and facilitate modelling efforts to use equivalent data. The Morgan P method had a closer correlation with WEP than the Olsen method, which may provide a broad indication of environmental risk, but should not be considered independently of hydrologic or connectivity factors.

Classification of the three sampling areas indicated consistently greater perceived fertility and also environmental risk under the NI index system than the ROI system. This manifests in practice as lower recommended fertiliser application and perhaps over-estimation of environmental risk. Conversely, the ROI system may suggest greater P requirements which may lead to greater costs in terms of chemical P imports or an under-estimation of risk and failure to implement appropriate measures. Crucially, neither index system is presented herein as the optimal approach and further research is needed examining both test methods and index systems to refine recommendations.

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7. REFERENCES

Bell, A.A.W., Bailey, J.S., Smith, R.V. and Allen, M.M. 2005. Development of an alternative to the Olsen bicarbonate-extraction test for determining plant-available phosphorus in basaltic soils*. Soil Use and Management*. 21:330-336

Buckley, C., Howley, P. and Jordan, P., 2015. The role of differing farming motivations on the adoption of nutrient management practices. *International Journal of Agricultural Management*. 4(4): 152-162.

Campbell, J.M., Jordan, P. and Arnscheidt, J. 2015. Using high-resolution phosphorus data to investigate mitigation measures in headwater river catchments. *Hydrology and Earth System Sciences*. 19: 453-464

Cassidy, R., Doody, D.G. and Watson, C.J. 2017. Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils. *Science of the Total Environment*. 575(1): 474-484

Cassidy, R., Thomas, I.A., Higgins, A., Bailey, J.S. and Jordan, P. 2019. A carrying capacity framework for soil phosphorus and hydrological sensitivity from farm to catchment scales. *Science of the Total Environment.* 687: 277-286

Čerkasova, N., Umgiesser, G. and Ertürk, A. 2018. Development of a hydrology and water quality model for a large transboundary river watershed to investigate the impacts of climate change – A SWAT application. *Ecological Engineering*. 124: 99-115

Courtney, R. and Harrington, T. 2010. Assessment of plant-available phosphorus in a fine textured sodic substrate. *Ecological Engineering*. 36: 542-547

Daly, K., Mills, P., Coulter, B. and McGarrigle, M. 2002. Modelling phosphorus concentrations in Irish rivers using land use, soil type, and soil phosphorus data. *Journal of Environmental Quality*. 31: 590-599

Daly, K. and Casey, A. 2005. Environmental aspects of soil phosphorus testing. *Irish Journal of Agricultural and Food Research.* 44: 261-279

Daxini, A., O'Donoghue, C., Ryan, M., Buckley, C., Barnes, A.P. and Daly, K. 2018. Which factors influence farmers' intentions to adopt nutrient management planning? *Journal of Environmental Management.* 224: 350-360

DAERA (Department of Agriculture, Environment and Rural Affairs. The Nutrient Action Programme Regulation (Northern Ireland) 2019.

EEA (European Environment Agency). 2012. Territorial cohesion and water management in Europe: The spatial perspective. Technical Report. ISSN 1725-2237

Fan, B., Fenton, O., Daly, K., Ding, J., Chen, S. and Chen, Q. 2021. Alum split applications trengthened phosphorus fixation and phosphate sorption in high legacy phosphorus calcareous soil *Journal of Environmental Science*. 101: 87-97

Foy, R.H., Tunney, H., Carroll, M.J., Byrne, E., Gately, T., Bailey, J.S. and Lennox, S.D. 1997. A comparison of Olsen and Morgan soil phosphorus test results from the cross-border region of Ireland. *Irish Journal of Agricultural and Food Research*. 36: 185-193

Gahoonia, T.S. and Nielsen, N.E. 2004. Root traits as tools for creating phosphorus efficient crop varieties. *Plant and Soil*. 260: 47-57

Haygarth, P.M., Condron, L.M., Heathwaite, A.L., Turner, B.L. and Harris, G.P. 2005. The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach. *Science of the Total Environment*. 344:5-14

Higgins, S., Schellberg, J. and Bailey, J.S. 2019. Improving productivity and increasing the efficiency of soil nutrient management on grassland farms in the UK and Ireland using precision agriculture technology. *European Journal of Agronomy*. 106: 67-74

Higgins, S. Kadziuliene, Z. Mason, E. Vervuurt, W. Astover, A. Borchard, N. Jacobs, A. Laszio, P. Wall, D. Trinchera, G.A. Budai, A. Mano, R. Thorma, S. Rok, J.M. Sanchez, B. Hirte, J. Madenogiu, S. De Boever, M. D'Haene, K. Paz, A. 2021. Stocktake study and recommendations for harmonizing methodologies for fertilization guidelines. EJP Soil, European Joint Programme. Towards climate-smart sustainable management of agricultural soils. Deliverable 2.4.5 Final Report www.ejpsoil.eu

Horta, M. do C. and Torrent, J. 2007. The Olsen P method as an agronomic and environmental test for predicting phosphate release from acid soils. *Nutrient Cycling in Agroecosystems*. 77: 283-292

Jordan, C., McGuckin, S.O. and Smith, R.V. 2000. Increased predicted losses of phosphorus to surface waters from soils with high Olsen-P concentrations. *Soil Use and Management*. 16: 27-35

Kleinman, P.J.A., Sharpley, A.N., Wolf, A.M., Beegle, D.B. and Moore Jr., P.A. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. *Soil Science Society of America Journal*. 66(6): 2009-2015

Koopmans, G.F., Chardon, W.J., Dekker, P.H.M., Römkens, P.F.A.M. and Schoumans, O.F. 2006. Comparing different extraction methods for estimating phosphorus solubility in various soil types. *Soil Science*. 171(2): 103-116

Kurz, I., Coxon, C., Tunney, H. and Ryan, D. 2005. Effects of grassland management practices and environmental conditions on nutrient concentrations in overland flow. *Journal of Hydrology*. 304. 35-50

Lee, J.M., Matthew, C., Thom, E.R. and Chapman, D.F. 2012. Perennial ryegrass breeding in New Zealand: A dairy industry perspective. *Crop and Pasture Science*. 63: 107-127

Lumsdon, D.G., Shand, C.A., Wendler, R., Edwards, A.C., Sutter, M.I., Richards, S. and Sinclair, A.H. 2016. The relationship between water-soluble P and modified Morgan P: Results based on data and chemical modelling. *Soil Use and Management*. 32: 162-171

Ly, K., Metternicht, G. and <Marshall, L. 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. *Journal of Hydrology: Regional Studies*. 24: 100605

Mallarino, A.P. 1995. Comparison of Mehlich-3, Olsen, and Bray-P1 procedures for phosphorus in calcareous soils. 25th North Central Extension-Industry Soil Fertility Conference. Nov 15-16th, 1995, St Louis, MO.

McCracken, M. and Wolff, A.T. 2019. Updating the register of international river basins of the world. *International Journal of Water Resources Development*. 35(5)

McDowell, R., Dodd, R., Pletnyakov, P. and Noble, A. 2020. The ability to reduce soil legacy phosphorus at country scale. *Frontiers in Environmental Science*. 8(6): doi: 10.3389/fenvs.2020.00006

Mellander, P-E., Jordan, P., Bechmann, M., Fovet, O., Shore, M.M., McDonald, N.T. and Gascuel-Odoux, C. 2018. Integrated climate-chemical indicators of diffuse pollution from land to water. *Scientific Reports*. 8: 944

Morgan, M.F. 1941. Chemical soil diagnosis by the universal soil testing system. Connecticut Agricultural Experimental Station Bulletin 450. New Haven, Connecticut.

Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. 1954. Estimation of soil available phosphorus in soils by extraction with sodium bicarbonate. United States Department of Agriculture. Washington DC, circular No. 939. pp19

Plunkett, M., Murphy, P. and Wall, D.P. 2020. Teagasc Soil Fertility Report.

Poulton, P.R., Tunney, H. and Johnston, A.E. 1997. Comparison of Teagasc (Ireland) and MAFF (England and Wales) fertiliser P recommendations. In: Phosphorus Loss from Soil to Water. CAB International pp449-452

Roberts, W.M., Gonzalez-Jimenez, J.L., Doody, D.G., Jordan, P. and Daly, K. 2017. Assessing the risk of phosphorus transfer to high ecological status rivers: Integration of nutrient management with soil geochemical and hydrological conditions. *Science of the Total Environment*. 589: 25-35

Roberts, W.M., George, T.S., Stutter, M.I., Louro, A., Ali, M. and Haygarth, P.M. 2020. Phosphorus leaching from riparian soils with different management histories under three grass species. *Journal of Environmental Quality*. 49: 74-84

Rowell, D.L. 1994. Soil science: methods and applications. Longman, London

Schroeder, P.D., Radcliffe, D.E., Cabrera, M.L. and Belew, C.D. 2004. Relationship between soil test phosphorus and phosphorus in runoff. *Journal of Environmental Quality*. 33(4): 1452-1463

Schulte, R.P.O. and Herlihy, M. 2007. Quantifying responses to phosphorus in Irish grasslands: Interactions of soil and fertiliser with yield and P concentration. *European Journal of Agronomy*. 26(2): 144-153

Sharpley, A., Kleinman, P., Baffaut, C., Beegle, D., Bolster, C., Collick, A., Easton, Z., Lory, J., Nelson, N., Osmond, D., Radcliffe, D., Veith, T. and Weld, J. 2017. Evaluation of phosphorus site assessment tools: Lessons from USA. *Journal of Environmental Quality*. 46: 1250-1256

Shortle, G. and Jordan, P. 2017. Teagasc Agricultural Catchments Program Phase 2 Report. Teagasc Crops, Environment and Land Use Program, Johnstown Castle, Co. Wexford, Ireland.

StataCorp. 2017. *Stata Statistical Software: Release 15*. College Station, TX: StataCorp LLC.

Sutter, M. and Richards, S. 2018. A novel approach to evaluating relationships between soil test and runoff P at landscape scales by integrating farmer knowledge on soil drains. *Agriculture, Ecosystems and Environment*. 254: 179-190

Tóth, G., Guicharnaud, R-A., Tóth, B. and Hermann, T. 2014. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *European Journal of Agronomy.* 55: 42-52

Wall, D.P. and Plunkett, M. 2016. Major and micro-nutrient advice for productive agricultural crops. 4th Edition 2016. Teagasc, Oak Park, Co. Carlow

Watson, C.J., Smith, R.V. and Matthews, D.I. 2007. Increase in phosphorus losses from grassland in response to Olsen-P accumulation. *Journal of Environmental Quality*. 36(5): 1452-1460

Wedderburn, M.E., Crush, J.R., Pengelly, W.J. and Walcroft, J.L. 2010. Root growth patterns of perennial ryegrasses under well-watered and drought conditions. *New Zealand Journal of Agricultural Research*. 53(4): 377-388