Spatial and temporal variability in costs and effectiveness in phosphorus loss mitigation at farm scale: a scenario analysis

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Abstract

Current policy instruments under the EU Water Framework Directive (WFD) to mitigate phosphorus (P) loss require that P use on farms is managed through regulation of farm gate P balances. Regulation at farm scale does not account for spatial variability in nutrient use and soil fertility at field scale, affecting the costs and effectiveness of farm gate measures. This study simulated the implementation of a P loss mitigation measure coupled with improving soil fertility so that farm productivity would not be compromised. The measure was simulated at field scale and the costs and effectiveness assessed at farm scale. Effectiveness was expressed as the time taken for excessive soil P levels to decline to levels that matched off-takes and this varied temporally and spatially within and between farms ranging from 1 to 8 years. Sub-optimum soil fertility was corrected on all fields across both farms, with applications of other soil nutrients and lime to protect productivity. An increase in costs ranging from 1.5-116% was predicted in the first two years of the measure on both farms after-which savings of 15-31% were predicted for each subsequent year until the measure was effective in year 9. Despite initial cost increase, there was no statistically significant difference in costs over the time taken for the measure to be effective, when compared to baseline costs. Successful implementation of measures should consider the impact on farm costs and time taken for measures to environmentally effective. Adoption of measures could improve if demonstrating to farmers that costs will not vary significantly from current practice and in time may results in savings if measures are paired with correcting soil fertility and increasing yields. This ‘win-win’ approach could be used into the future to ensure successful implementation and uptake of measures within the farming community.

Keywords: Nutrient management, phosphorus, water quality, cost-effectiveness

1. Introduction

Agriculture is a major pressure on water quality, specifically phosphorus (P) loss from soil to surface and ground waters when applications exceed crop and animal demand (McDowell and Nash, 2012; Mockler et al., 2017). The growing demand for food worldwide and subsequent drive for intensification in agriculture will mean an increase in nutrient use on farms that needs to align with water quality targets set under the EU Water Framework Directive (WFD). This complex policy instrument is designed to protect all water bodies with specific aims to maintain high ecological status and achieve “good ecological status” across all waters within Europe (2000/60/IEC). This will be especially challenging in high ecological status catchments that may have very little capacity for intensification of agricultural production (White et al., 2014) as small inputs of nutrients and sediment can affect the entire ecosystem (Feeley et al., 2017; Ní Chatháin et al., 2013).

Integrated within the WFD, the Nitrate Directive focusses on the prevention of phosphorus and nitrogen losses from agriculture through implementation of a Nitrates Action Programme (NAP). Currently, this statutory instrument is designed to control the source pressure on water quality and relies predominantly on controlling P inputs. Measures such as, avoiding P applications on excessively fertilised soils can be effective (Cuttle et al., 2016) at controlling the source pressure, although, this does not provide for correcting nutrient deficiencies and poor soil fertility in other parts of the farm. Recent studies in intensive and extensively farmed catchments have identified a poor distribution of nutrients and suboptimal soil pH across farms that could adversely affect crop production and farm profitability (Roberts et al., 2017; Wall et al., 2013).

Excess and deficiencies in soil P levels are typically detected in detailed soil testing, and in Ireland the agronomic soil test for P is Morgan’s Extractable P (Morgan, 1941). For easier management and knowledge transfer at farm level Morgan's P values have been categorised as indices; 1 (0-3 mg L^{-1} deficient), 2 (low 3.1-5 mg L^{-1}), 3 (agronomic optimum 5.1-8 mg L^{-1}) and 4 (>8 mg L^{-1} excessive). In this system, Index 4 identifies excessively fertilised fields that could also act as a source of P loss to water and Index 3 represents the agronomic and environmental optimum value of plant available P in soil (8 mg L^{-1}) at which recommended P replaces P removed in products such as grass, silage, meat and milk (Wall et al., 2015). Maintaining fields at Index 3 allows farms to maintain a zero P balance at the farm-gate and is a requirement under the NAP in Ireland (S.I. no. 605 of 2017). For Index 1 and 2 fields, current agronomic advice provides for a 'build-up' amount of P to the target index, Index 3.

Efforts to balance P in soil through soil testing do not always ensure that other nutrients and trace elements will also correct to agronomic optimum values. Productive agricultural systems require other crop nutrients such as nitrogen (N) and potassium (K) in sufficient amounts to meet crop demand and animal health so that productivity goals are met. Maintaining soil pH at near-neutral values (e.g. 6.2 for grass production) improves nutrient availability for plant uptake and maintains healthy soil microbial community structures. Therefore, future measures to mitigate P losses need to ensure that other nutrients such as nitrogen (N) and potassium (K) and soil pH are maintained at optimum levels, so that soil quality and health within the farming system remains in balance. Considering the economic costs and opportunities of balancing other nutrients and soil pH across all fields on the farm will ensure that productivity is not compromised and agriculture remains sustainable, both economically and environmentally.

In terms of adoption, integrating water quality and soil fertility measures that are cost-effective are likely to be more successful and acceptable than regulating and limiting the use of P alone. This would require the adoption of an integrated nutrient management plan by farmers that would assist in optimizing soil fertility and reduce P losses to water. However, recent studies have reported that adoption of nutrient management planning in Ireland is low and perceived as costly (Buckley et al., 2015; Micha et al, 2018), mainly due to time required for soils to build-up from deficient to optimum levels with no immediate impacts on yields in the short term (Newell Price et al., 2011).

The overall objective of this study was to simulate the effects of applying a P loss mitigation measure that is integrated with field level soil fertility to assess if this approach can be cost-effective. The measure focuses on avoiding applications of P to excessively fertilised fields in Index 4, allowing them to decline to a target value (Index 3) that provides enough P for crop growth yet controls the source pressure on water quality. Within this measure, other nutrients (N and K) and soil pH will also be maintained at, or adjusted to, ideal levels to protect yields. In this study, this approach was simulated on two existing commercial farms in Ireland. Using these farms as case studies, baseline nutrient management data was collected and baseline costs assessed. The measure was simulated on a field by field basis using detailed soil information and land use data and deemed effective when all fields on the farm reverted to Index 3. The costs of the measure were examined by calculating costs associated with achieving ideal N, P, K values and soil pH conditions across each field. This study simulated a nutrient management measure for balancing P, at field scale, and examined the impact on costs for the farmers and time taken for this measure to become environmentally effective at farm scale.

2. Methodology

2.1 Study area and case study farms

2.1.1. The River Allow catchment

The study was conducted in the catchment of the River Allow in the South West of Ireland. The catchment is characterised was previously designated as a “high” ecological status catchment but has recently declined in status due to deteriorating water quality. The catchment covers an area of 82 km^2, with an average elevation at 113 m and average annual rainfall of 1304 mm. The main farming enterprises are dairy and livestock on predominantly poorly drained Surface Water Gleys with upland areas mapped as Humic Gleys.

Two farms in the catchment were selected as case studies and Figure 1 illustrates the location of each farm within the network of the Allow river. Farm B exists as two separate blocks while Farm A is located in one holding. Farm A is an extensive beef farm and Farm B, an intensive dairy farm existing in two blocks across the catchment. In Ireland, dairy farming is considered the most intensive farming system with the highest requirements in nutrients (Dillon et al., 2017). Higher stocking rates on dairy farms are often associated with higher losses of nutrients and greenhouse gases emissions compared to less intensive dry-stock farms (Gooday et al., 2017). Recent studies showed that the risk of nutrient losses is site specific and not always associated with the type and intensity of farm (Doody et al., 2014, 2012; Roberts et al., 2017) however, recent studies have shown that extensive farmers might not be aware about actual soil conditions due to lack of soil testing, and may overestimate or underestimate the nutrient application rate (Roberts et al., 2017).

A farm survey of current nutrient management on both farms was conducted during the winter of 2014/2015 and collected baseline nutrient use and land use data on a field-by-field basis across both farms. During the survey, soil samples were collected on a field-by-field basis, between November and January, coinciding with the “closed period” during which the application of slurry and fertilizers is restricted. Soil samples were taken to the standard agronomic depth of 10 cm in each field at approximately 2.3 ha scale and returned for laboratory analysis. Samples were air-dried and sieved to 2 mm prior to extraction for plant available nutrients P, K using Morgan's reagent (Morgan, 1941) followed by colorimetric analysis. Total P (TP) on all soil samples was determined using microwave digestion in hydrochloric and Nitric acid followed by ICP-OES analysis (Kingston and Haswell, 1997). Soil pH and lime requirement were determined on dried and sieved soils suspended in deionised water at a 1:2 soil to solution ratio, and measured using a Jenway pH meter with glass electrodes. Percentage organic matter (OM) was determined by loss on ignition using 5 g samples ignited for 4 hours in a Northerm muffle furnace at 400 ^{o}C.

The distribution of fields in each soil P Index on both farms, and their proximity to nearby rivers and streams in the catchment with associated water quality data were mapped in Arc GIS and shown in Figure 1. Field level nutrient use and soil data was used to calculate recommended rates of nutrients as organic and inorganic fertilizers, (N, P, K and lime) required for each field to meet crop demand based on land use and stocking rates. These rates were calculated using a decision support tool commonly used by farm advisory services and agricultural consultants for nutrient management planning, known as the Teagasc Farm Fertiliser Planner. This is an online platform that calculates nutrient balances and nutrient needs at field level based on soil tests results and current management practices.

2.1.2 Case-study farms

Farm A is a beef farms with a total area of 29.75 ha, consisting of 13 fields in one block, each used for producing silage (one cut) and grazing. The farm stocked 50 cattle > 2 years old with a stocking rate of 1.68 LU ha-^{1} and housed animals for 26 weeks in winter with annual slurry produced estimated at 338 tonnes.

Farm B is a dairy enterprise consisting of 17 fields in two blocks, with a total area of 65.44 ha, 100 dairy cows, 70 cattle 0 - 1 year old and 35 cattle 1 - 2 years old with a farm stocking rate of 2.44LU ha^{-1}. Animals were housed for 20 weeks and estimated annual production of animal waste was 140 t of farmyard manure (FYM) and 863 t of slurry. Land use across the farm was more varied than Farm A and ranged from grazing only, 1 cut silage + grazing, 2 cut silage + grazing and hay + grazing.

2.2 Modelling effectiveness: Soil P decline & improving soil fertility

An integrated nutrient management and P mitigation measure was simulated across each field on both farms. The effectiveness of this measure is assumed when high soil P levels (Index 4) declined to optimum values (8 mg L-1) in Index 3. This was assessed by modelling soil P decline and estimating the time needed for Index 4 fields to drop to the target Index 3. Soil P decline will occur when available P is removed by crops and not replaced by fertiliser. As excess available P is removed by the crop, the soil draws from its reserves of total P to replenish the available P pool. The time for this system to reach Index 3 depends on the rate at which available P declines and the initial available P values. As P can be replenished by reserves, the rate of decline is therefore a function of reserves in soil (TP) and the demand for P by the crop type (removal rates or P balance). In this simulation, Morgan's P, TP and land use data were applied to previously published models for Irish soils (Schulte et al., 2010; Wall et al., 2013) to calculate the time taken for Index 4 fields on both farms to decline to Index 3. The model applied is based on a scenario suitable for farms where some fields are at soil P Index 4 and used for animal and grassland production and calculates the time needed for soil at Index 4 to decline to concentration of 8 mg L^{-1} Morgan's P (upper boundary of soil P Index 3 concentration for grassland) as described by Equation 1 (Schulte et al., 2010).

$$Q = c^{-1} \times [ln\,(P_3) - ln(P_i)] \quad (1)$$

Where Q is the time required for soil P levels to decline to Morgan's P of 8 mg L^{-1}; P3 is the upper boundary of Index 3 for grassland (8 mg L^{-1}); and Pi is the initial concentration of bioavailable (Morgan's P) P in soil (mg L^{-1}).

The model expresses the rate of P decline as c, the exponential rate which depends significantly on the P balance ($P < 0.001$) and total soil P ($P < 0.001$) (Schulte et al., 2010; Wall et al., 2013), accounting for 63% of variation ($P < 0.001$) of c. Using field level total P values measured across both farms in this study and P removed by silage or grazing, c was calculated using the Equation 2.

$$c = -0.0586 + 8.25 \times \frac{P\ balance}{Total\ P} \quad (2)$$

In this simulation after fields at Index 4 declined to Index 3 a maintenance rate of P was simulated to maintain productivity. To improve soil fertility on the rest of the fields at Index 1 and 2, build up rates of P were simulated based on grassland stocking rates across both farms. In this simulation, slurry produced on the farm was redistributed to P deficient fields (Index 1 and 2) to build up to the target index, at Index 3 and thereafter, applications were simulated to maintain soil P concentration at Index 3.

As the target Index 3 was reached across P deficient and high soil P fields, overall soil fertility on both farms was improved to maintain yields by optimising N, P, K and lime requirement across both farms. In order to reduce cost, where possible, inorganic fertilisers were replaced with organic (i.e. cattle slurry and farmyard manure (FYM) produced on the farm). Where organic P was not sufficient, it was supplemented with inorganic P. The additional requirements were covered with inorganic compound fertilizer containing P (18-6-12) to supply soil with P where it was needed and CAN 27% where P was to be avoided. For fields where slurry did not cover K requirements, additional K was supplied on the fields in the form of 18-6-12 fertilizer and soil pH and lime requirement for each field was met with lime additions. Correcting soil pH not only improves uptake of nutrients by plants but also to releases up to 80 kg of N ha^{-1} yr^{-1} (Wall et al., 2013) and this was accounted for in the calculations of inorganic N fertilizers required and costs. For the estimation of the difference between the current and the proposed scenarios the following nutrient content in manures and slurries were assumed: FYM contains 1.35 Kg of N t-1, 1.2 kg of P and 6 kg of K t^{-1}, while cattle slurry contains 2 kg of N t^{-1}, 0.8 kg of P t^{-1} and 4.3 kg of K t^{-1}.

2.3 Calculation of potential cost of optimising nutrients use

The total farm costs were calculated for each year over the number of years it would take the measure to be effective, i.e. for Index 4 fields to decline to target Index 3. To determine the farm scale costs of applying organic fertilizers the study relied on price coefficients derived from estimated unit values (Table 1) (Teagasc, 2014). For the costs of applying inorganic fertilizers, direct fertilizer prices were extracted from the Irish Central Statistics Office (CSO, 2014). The cost of advisory services and cost of soil testing are standard costs from the Teagasc advisory price lists (Table 1).

On both case study farms, the total farm costs per year were calculated as follows:

$$Tc_i = ST_i + NMP_i + Fert_i + L_i + Sl_i + FYMC_i \qquad (3)$$

where TC_i is the total cost for year i and

ST is the estimated cost for soil testing, NMP is the estimated cost for having access to nutrient management advisory services Fert is the total inorganic fertilizer (kg) costs needed to maintain yields after slurry and FYM allocation and YGP is the value of the yield gap (tonnes) between years $i-1$ and i.

$$L = liming\ cost\ (€) = amount\ lime\ applied\ \times 19 \qquad (4)$$

$$Sl = slurry\ application\ costs\ (€) = t_{1a} \times 50 + t_{1s} \times 47.75 + [slurry\ produced - (slurry\ spread + slurry\ exported)] \times 9.27 \quad (6)$$

$$FYMC = FYM\ application\ costs\ (€) = t_{2l} \times 45 + t_{2s} \times 82.5 + [FYM\ produced - (FYM\ spread + FYM\ exported)] \times 10.36 \quad (7)$$

where t_{1a}, t_{1s} are the estimated time needed for slurry agitation and spreading in hours and t_{2l},t_{2s} are the estimated time needed for FYM loading and spreading in hours. To evaluate the cost-effectiveness of the measure the difference between the current and the proposed nutrient management was analysed for statistical significance using a paired sample t-test.

3. Results and Discussion

3.1 Baseline soil fertility and nutrient management practice

The baseline nutrient management recorded during the survey on both farms is presented in Table 2. On Farm A soil and nutrient management data indicated that the distribution of nutrients farms varied from field-to-field (Table 2). Based on soil test results, none of the fields in Farm A recorded nutrient and soil pH at ideal levels for good soil health and fertility. Eight fields had excessive soil P (> 8.0 mg L^{-1}), ranging from 9.6 mg L^{-1} to 28.1 mg L^{-1}, TP ranged from 701 to 2582 mg kg^{-1} and soil pH on all fields was below 6.2, the optimum pH for nutrient availability. Organic matter ranged from 10-21% and with the highest value recorded in Field 7. High organic matter soils have a limited capacity to store added P (Daly et al., 2001) and best practice and current advice for these soils is to limit applications to replacing P removed during the growing season (Gonzalez, 2018) and categorise them into Index 3. Organic soils present a high risk of P loss with no capacity to hold or build up P (Daly et al., 2001 Gonzalez et al., 2019; Gonzalez, 2019a), however, Field 7 on Farm A, received the same amounts of slurry and fertiliser as mineral soils on this farm. The survey revealed that all fields received the same amount of nutrients i.e. 8 t ha-1 of cattle slurry (7%) and approximately 185 kg ha^{-1} of 27-2.5-5 commercial fertilizer. Total available nutrients applied were 57 kg N ha^{-1} yr-1, 9 kg P ha^{-1} yr^{-1} and 38 kg K ha^{-1} yr^{-1}.

Soil fertility on Farm B also varied spatially. Excessive concentrations of available P were recorded on five fields while 9 fields were P deficient. Soil test P values ranged from 1.4 to 20.3 mg L^{-1}, TP ranged from 674 to 2100 mg kg^{-1}. Soil pH ranged from 5.6 to 6.7 7 indicating sub-optimal pH for nutrient availability and % OM ranged from 10-16 % across the farm. Phosphorus applications ranged from 0 kg ha^{-1} to 40 kg ha^{-1} in the form of compound fertiliser products (27-2.5-5). Slurry was unevenly distributed across the farm with 3 fields categorised as low (Index 2) and deficient (Index 1) received no slurry, while 5 fields at Index 4 received between 8-23 t ha-1 of cattle slurry. Similar to Farm A the application rates of the main nutrients (N and P) did not match crop requirements. Nitrogen application rates varied from field to field ranging from 0 kg ha^{-1} to 210 kg ha^{-1}, lower than recommended (225-237 kg ha^{-1}). The type of inorganic N fertilizers varied for each field, including compound fertilizers 27-2.5-5, 24-25-10, CAN 27% and 10-10-20. Cattle slurry (7%) was applied at rate of 7.78 t ha^{-1} on 12 fields, two fields received higher rates of slurry 23.34 t ha^{-1} (fields 8 and 9 at Index 4) while no slurry was added on three P deficient fields.

3.2 Effectiveness of a P loss mitigation measure

In this simulation, the effectiveness of the measure was expressed as the time taken for each field to reach the 8 mg L^{-1} the upper boundary value at Index 3. This allows for sufficient plant available P for crop growth, and as set in the current statutory instrument under Ireland's NAP to minimise environmental losses (S.I. no 605 of 2017). Modelled results are presented in Table 3 for both farms. For Farm A, this varied from 1 to 8 years, based on

Index 4 fields ranging from 9.9-28.1 mg L^{-1} and operating at field P balances of minus 30 kg ha^{-1} for silage production. For Farm B, the model predicted that it would take 1-3 years to reach 8 mg L^{-1} on Index 4 fields operating with a P soil balance -30 kg of P ha^{-1} with initial Morgan's P values between 9.8-13.5 mg L^{-1}. For fields used for grazing only, operating with a soil P balance -10 kg of P ha^{-1} at initial Morgan's P values of 12.7 and 20.3 mg L^{-1} it would take 7 years to decline to the target index (Table 3). The results presented in Table 3 demonstrate that the rate of soil P decline to the target index was more efficient on fields were initial soil P levels were lower and P-balance deficit, or off-takes, were higher. It is suggested that land use change from grazing only, to grazing plus silage, could accelerate the effectiveness of the measure and be included as a source control mitigation option.

These results in this study indicated that changes in Morgan's P were more pronounced in fields where initial soil P concentrations were highest, largely due to excess P in the available pool that is more easily desorbed and removed by a high crop demand for P e.g. silage production (Herlihy et al., 2004; Schulte et al., 2010; Wall et al., 2013). In contrast, some studies have shown that soil P build up and decline also depends on soil buffering capacity that is influenced by clay minerals and amount of Al and Fe in soil (Power et al., 2005, Daly et al., 2015) and these factors could be considered in future P models if collected at field level.

3.3 Improving soil fertility

For the measure to mitigate P loss and protect productivity and profitability on the farm, it required balancing other soil nutrients and soil pH with applications of lime, K, N and P on both farms. Year 1 of the measure represents new application rates for N, P, K and lime across both farms based on the surveyed data (Table 4). For Farm A the baseline application rate captured during the survey of 57 kg N ha^{-1} yr^{-1} on all fields was below agronomic crop requirements and the usually recommended amounts (125 kg N ha^{-1}). This was corrected in year 1 by calculating N applications (as CAN) along with distributing slurry across the farm, with values shown in Table 4. As soil P levels on this farm were in excess of the agronomic recommended levels, no applications of P were simulated in year 1, with the exception of 5 fields that recorded values in Index 2 and 3. At the time of survey, on Farm B, application rates of main nutrients (N and P) did not match crop requirements. Land use varied from grazing to two-cut silage + grazing and N rates were lower than recommended 225-237 kg ha^{-1} and as a number of fields on this farm also required build up amounts of P as well as allowing Index 4 fields to decline to optimum values, a combination of redistributing slurry, applying CAN and compound fertiliser (NPK), was simulated in Year 1 to balance both nutrients on this farm (Table 4). These applications varied temporally and spatially over the time taken for the measure to become effective on both farms. Soil pH was amended using lime applications to reach ideal or optimum values for grassland and improve nutrient availability on both farms. On Farm A, lime was recommended at a rate of 7.5 t ha^{-1} in the first year across all fields and on Farm B in year one, lime applications varied from 1 to 7.5 t ha^{-1}, ending with a maintenance rate of 1 t ha^{-1} on all fields to maintain pH 6.3 across the farm. Potassium is also an important major nutrient for crop growth and animal health and applications in year 1 were proposed to balance sub-optimal fields. On both farms, applications of lime, N, P and K varied for each year and each field, until the measure became effective. At farm scale, the redistribution of slurry and manure, fertiliser and lime products are presented in Table 5 showing the temporal variation in nutrient management and the estimated costs required across the timeline of the simulation.

3.4 Assessment of costs associated with implementation of the measure

The comparison of the costs associated with continuing current farm practices captured in the survey and implementing a P loss mitigation measure and improving soil fertility are included alongside the farm level nutrient management in Table 5 for both farms.

For Farm A soil nutrients and pH to would reach ideal values for agronomic and environmental sustainability in 9 years. Applying the measure significantly increased costs in the first year by more than 100% and continued to increase for the following two years. However, to offset this increase in costs, potential savings could be made on fertiliser costs from years 4 to 9, given that yields remain the same. When examined using a paired sample t-test results indicated no significant difference in costs across the nine years on this farm ($t = -0.80$; $P = 0.45$).

For Farm B, the time necessary to reach optimal or ideal nutrient and soil pH level across all fields would be realised after 8 years. Applying the measure increased costs by 33% in the first year, but from the second year onwards, cost reduced by up to 14.4% in year 8, given that the yields remain the same. Similar to Farm A, a paired sample t-test indicated no significant difference in costs for farm B across the 8 years of implementation of the measure ($t = 0.66$; $P = 0.53$).

This analysis showed that, in the long term, both farms would not incur additional costs, associated with adopting a P loss mitigation measure and balancing other soil nutrients and pH at field level. Increased cost were forecasted in the short term, particularly the first years of application, however, when compared over the time-line for P to decline, costs did not differ significantly. These results concur with previous studies (Haygarth et al, (2009) and Newel-Price et al. 2011) examining measures that avoid P applications on high P soils can be cost-effective, but only in the long term. The long-term benefit to soil fertility and water quality needs to be explained to farmers to ensure that this measure is adopted. Micha et al

(2018) reported that farmers perceived this measure to be costly, most likely because of the increased costs at the "start" which is likely to pose a challenge for policy makers to encourage farmers on marginal land to adopt similar measures in high status catchments.

The highest expenses for both farming system were estimated in Year 1 due to cost of advisory services and soil testing. During the last years of application, however, it is be expected that both farmers would potentially reduce costs, due to more efficient usage of nutrients from animal waste produced on the farm and subsequent decrease usage of inorganic N fertilizers and imported feed. Byrne et al (2008) in a study conducted in Northern Ireland also highlighted the initial increased costs that mainly arise from the fees of extensions services and suggested a "pilot" plan of free advisory services for the first years to overcome this caveat.

4. Conclusions and policy recommendations

Using two case study farms with different systems and intensity, we applied a scenario analysis to evaluate the costs and time taken for an integrated measure to be effective. In this measure, P applications were avoided on excessively fertilised fields and soil fertility (N, P, K, pH) was optimised across all fields. The measure was assumed effective when excessive soil P declined to a value where soil P can match the crop demand for P and the time taken for this to occur ranged from 1 to 8 years and varied from field-to-field based on land use, initial available P and total P reserves. Minimising the source pressure on local water quality are also likely to vary spatially which has implications for establishing water quality targets in catchments and the design of measures to achieve them.

A policy implication of this study is the significance of measuring costs and effectiveness in the long term. Effectiveness in this study took up to 9 years to be realised at field scale and informing farmers of the long term benefits of applying this measure, despite additional costs at the start, is key for the successful implementation and adoption of measures into the future. Information that provides a clear understanding of the causes of water pollution and the mechanism of mitigation, in combination with the long-term environmental/economic benefits, should be available to farmers.

In order to increase adoption and implementation of sustainable agricultural practices, policies need to be equally focused on farm profitability and environmental quality. Sustainability measures could include water quality protection coupled with agronomic measures to maintain productivity and are environmentally effective, providing a dual benefit to policy makers and farmers.

The recommendations arising from this work are as follows:

- Measures applied to soils will have lag times. The rate of soil P decline to environmentally sustainable levels will vary at field scale, which has implication for design of measures and monitoring effectiveness at farm, and catchment scale.
- Accelerated soil P decline could be achieved with changing land use from grazing only, to grazing plus silage.
- Despite higher costs in the first years of implementation, correcting deficiencies in P, N and K and balancing soil pH on all fields, and avoiding P applications on high soil P fields and high organic matter fields is proven cost-effective in the long term.
- Spatial variation in soil P showed that cost for soils testing and advisory services on a field-by-field basis is expensive in the first 2 years of implementing the measure. Providing financial relief for this initial phase of measures implementation would encourage farmers to adopt the measure in the future.

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Figure Caption

Figure 1. The location and setting of Farms A and B within the network of the River Allow showing field numbers, soil P Indices and local water quality status at EPA monitoring stations on the river network. Water quality and station data sourced from EPA GeoPortal (www.gis.epa.ie).