Agricultural Water Management 333 (2026) 110645

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Can increasing farmers' awareness improve soil and water phosphorus status? Insights from a 'real-life' policy process

Julia Martin-Ortega [a,*], Cheng Wen [a], Pippa J. Chapman [b], Paula Novo [a], Alex Higgins [c], Phil Jordan [d], Rachel Cassidy [c]

[a] *Sustainability Research Institute, School of Earth and Environment and Sustainability, University of Leeds, Leeds, UK*
[b] *School of Geography, University of Leeds, Leeds, UK*
[c] *Agri-Environment Branch, Agri-Food and Biosciences Institute (AFBI), Belfast, UK*
[d] *School of Geography and Environmental Sciences, Ulster University, Coleraine, UK*

ARTICLE INFO

Keywords:
Diffuse water pollution
Awareness-focused approaches
Behaviour change
Best land management practices
Phosphorus
Soil

ABSTRACT

Addressing diffuse agricultural water pollution is central to ensuring food security while halting ecosystem degradation. Awareness-focused approaches attempting to prompt adoption of best farming practices to reduce negative impact on water quality are being increasingly implemented. This interdisciplinary study explores this awareness–behavioural change–water quality pathway *in full* and *over time.* We do so in the context of a 'real-life' active policy process, combining farmers' survey data one and four years after the inception of a government nutrient management programme in Northern Ireland, with soil and river water phosphorus analyses at the sub-catchment level. Our results suggest that increased awareness and changes in farm practices can be sustained over time, but whether they translate to reductions in soil and water phosphorus (thus completing the pathway in full), critically depends on the provision of tailored one-to-one advice. The recommendation that stems from this is that future agri-environment policies should include tailored and context specific advice in addition to the generic one. Our research also provides insights into the operationality of post-normal interdisciplinary science applied to wicked problems, illustrating the need to adjust methods and approaches in ways that produce robust science within the possibility of the policy context, even if this means accepting 'imperfect' experimental designs. Acknowledging that the particular changes observed in our case might be specific to Northern Ireland, two lessons are of broader relevance: 1) discussions on agricultural system transformation should include considerations on how to deliver tailored advice at scale; and 2) further disentanglement of the full impact pathway from increasing farmers awareness to mitigating enviromental impacts from agriculture requires the integration of social sciences from the outset of policy programmes' design, rather than being incorporated only as retrospective research.

1. Introduction

Ensuring global food security while halting ecosystem degradation is one of the most fundamental challenges faced by humanity. Agricultural diffuse pollution of waters is central to this challenge, with inefficient use of nutrients disrupting biogeochemical cycles, causing pollution of waterbodies and compromising aquatic biodiversity worldwide (Jwaideh et al., 2022; Li et al., 2022; Wang et al., 2024). These perturbations transgress planetary boundaries (Richardson et al., 2023) and are amplified in a changing climate (Van Vliet et al., 2023). Following generally unsuccessful attempts to address this problem through economic incentives and environmental regulations (Lintern et al., 2020; Boezeman et al., 2020; Pan et al., 2023), policy-makers around the world have turned to awareness-focused approaches. These approaches attempt to improve farmers' understanding of how agricultural practices affect soil and water quality, based on the assumption that greater awareness will encourage the adoption of improved nutrient management practices which, in turn, would lead to a reduction in nutrient losses and improvement in water quality. Examples of awareness-focused programs for reducing agriculture-related water pollution include the Catchment Sensitive Farming partnership scheme in England (Davey et al., 2020), the Agricultural Sustainability Support

* Corresponding author.
E-mail address: j.martinortega@leeds.ac.uk (J. Martin-Ortega).

https://doi.org/10.1016/j.agwat.2026.110645
Received 23 February 2026; Received in revised form 13 July 2026; Accepted 13 July 2026

and Advisory Programme in Ireland (Teagasc, 2021), and the participatory extension programmes (e.g. Forages for Reduced Nitrate Leaching) in New Zealand (Knook and Turner, 2020).

Critically though, existing evidence to support such expectations is still very limited and fragmented and covers only parts of the awareness-behavioural change-water quality pathway rather than the full pathway. There are studies that found that awareness and various other factors (e.g. social norms, perceived behaviour control, farming culture, and they way of presenting soil test results) lead to changes in farming practices (McCann and Easter, 1999; Blackstock et al., 2010; Ulrich-Schad et al., 2017; Okumah et al., 2018; Inman et al., 2018; Ma et al., 2023) but they do not examine whether that behavioural change ultimately leads to water quality improvements. Similarly, there are studies that investigate whether water quality has improved following implementation of a certain land management programme (Davey et al., 2020; McDowell et al., 2023) but they do not explore the effect of awareness in this process. An exception is Okumah et al. (2021a), who in a qualitative study, covered the full awareness-behavioural-water quality pathway, concluding that the reduction of pesticide concentrations in rivers following a targeted campaign in Wales (UK) could be attributed to increased farmer awareness. Such research, while valuable, only provides a snapshot in time.

This paper is the first in which the awareness-behavioural change-water quality pathway is explored *in full* and *over time* in a quantitative analysis, and in the context of a 'real-life' active policy process. We compare farmers' survey data one year and four years after the inception of a soil testing and awareness-raising voluntary programme implemented by the government of Northern Ireland (UK) in 2017–2018 within the Upper Bann (UB) river catchment. This was a pilot, voluntary scheme which provided free soil sampling and testing, as well as face-to-face training on soil nutrient management for farmers. Farmers' survey data on awareness and self-reported changes in adoption of land management practices are combined with analysis of soil and water quality data at the sub-catchment level, where phosphorus losses from agricultural land had contributed to water quality deterioration and failures. Specifically, we sought to answer the following questions: (1) has awareness-induced behavioural change (in the form of adoption of nutrient management practices) persisted over time? and (2) have soil and water phosphorus concentrations decreased over this period and, if so, can these improvements be associated with the behavioural changes?. These questions require an interdisciplinary research approach that acknowledges agricultural water diffuse pollution as a 'wicked' problem, i.e., somewhat intractable and entrenched in conflicting values and information, making them hugely challenging to research in their full complexity in ways that policy solutions can be established within a changing reality (Duckett et al., 2016). In this paper, we engage with and contribute to so-called post-normal science given the system's uncertainties and the active nature of the policy process. We reflect on the limitations and requirements of interdisciplinary research in such conditions. Beyond this academic contribution, our results also have implications for policy makers, particularly in informing the design of more targeted and effective agri-environment programmes in the future.

2. Methods

2.1. Case study

Northern Ireland is typical of a livestock-based, grassland-dominated agricultural system. At the time of the scheme implementation in 2018, the average farm size in Northern Ireland was 41.1 ha. 80% of farms were cattle and sheep farms, 10% were dairy farms (DAERA 2018a). As per 2024, 71% of rivers (including UB) and 76% of lakes in Northern Ireland failed to meet good ecological status under the Water Environment (Water Framework Directive) Regulations of Northern Ireland (DAERA, 2025). Low levels of nutrient management planning (NMP) had been identified as key causes of poor utilisation of available organic nutrients at farm level; both through a long-term and widespread decline in lime use (Holland et al., 2018), and low levels of soil testing. This results in sub-optimal grass yields, and a dependency on imports of chemical fertiliser and concentrate feed that maintain a national phosphorus surplus of about 11 kg/ha (Rothwell et al., 2020) that accumulates as a soil nutrient surplus, and that is then available for loss to water.

In 2017–2018, the Department of Agriculture, Environment and Rural Affairs (DAERA) initiated a soil sampling and farmer advisory programme under the EU Exceptional Adjustment Aid-funded Soil Sampling and Analysis Scheme in the UB catchment (220 km^2). The catchment was split into 12 headwater sub-catchments across an upland-to-lowland and extensive-to-intensive farm system gradient (Fig. 1). The programme was implemented as part of government efforts to address persistent water quality problems linked to agriculturally sourced nutrients, particularly phosphorus. The programme was voluntary, and incentive for participation included provision of free soil sampling and testing, advice and face-to-face training in NMP. The programme proved popular, with 513 farmers participating, out of a total of 622 farm businesses (i.e. 82.5%). Statistics of the participating farmers are not available due to data privacy.

Soil test results were sent directly to participants from the laboratory in a standardised tabular format, with crop-specific recommendations for pH (lime requirement) and fertiliser application, where farmers had provided detail on current and planned cropping during registration. It is important to note that recommendations were based on agronomic principles for intensive systems, where the soil analysis results are translated directly to nutrient and liming rates required to maximise yields for the selected crop (RB209, ADHB, 2023). They do not take into account farm stocking densities or any existing water quality criteria (except where land has an official environmental designation and receives no recommendation) as this information is not collected during registration nor are the locations of fields made available to the soil analysis company due to the confidentiality of farmers' data. The responsibility for further interpretation and action (e.g. change amount and type of fertiliser applied, or increased lime application) was on the farmer. Soil test results were supplemented by field-scale

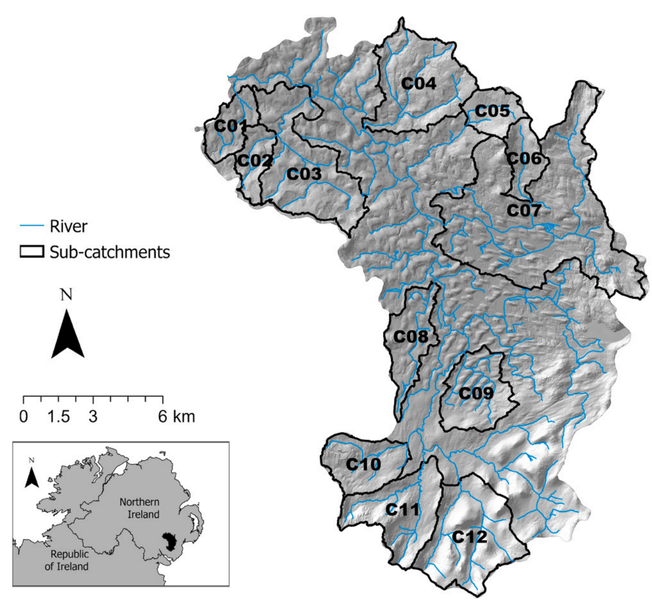

Fig. 1. Upper Bann River catchment with the sub-catchments under study in Northern Ireland. Seventy seven percent of land use is for agriculture, with 95% of this being grassland and only 5% arable (DAERA, 2024). Phosphorus is mainly applied to the land in fertiliser and slurry and is a major problem for water quality, so NMP is key to ensuring phosphorus is managed better on farms.

orthophotographic maps with colour-coded overlays based on the nutrient status (Olsen P, potassium (K) and pH, above, below and within the respective optimum ranges). Participants also received phosphorus runoff-risk maps which indicate areas with high potential for losing nutrients (primarily phosporus) during storm events from applied manures and fertilisers, or soil phosphorus excess. Besides receiving the soil test results and recommendations, farmers were offered generic training. Thirty-five percent of the total participants attended the face-to-face NMP training.

In addition, within three sub-catchments of the UB (C02, C05 and C04), one-to-one in person farm advice on nutrient management was provided in addition to the generic training (C02 and C05 by an AFBI farm advisor and C04 by a Rivers Trust advisor). This was mainly associated with the year of soil testing and followed up approximately annually thereafter along with ad-hoc responses to any queries individuals had over the year.

Through the provision of the soil testing results and the subsequent training on soil nutrient management, farmers were provided with recommendations for lime and fertiliser applications (to increase soil pH and apply only crop requirements of each nutrient) and guidance on fertiliser application (e.g. reducing amount applied or avoiding use of slurry in wet weather).

2.2. Measuring behavioural change over time

A survey to evaluate whether farmers had changed their soil management practices as a result of the programme was conducted one year (March – April 2019) and four years (December 2022 – January 2023) after the first soil sampling. The year-one survey was designed and collected by DAERA before the research team was engaged. The year-four questionnaire was designed by the research team, within the constraints of the previous design as to enable sufficient comparability across the two surveys. The questionnaires are available in the Appendix.

The year-one survey collected 148 questionnaires by post from the 513 farmers that had voluntarily participated in the scheme (29% response rate), and the year-four survey received a total of 90 valid responses (17.2% response rate). These are deemed typical response rates in the field (Pennings et al., 2002; Stedman et al., 2019). Due to data protection restrictions, the analysis of the surveys is based on averages across the catchment and not at the sub-catchment, field or individual farmer level.

The year-one survey used a one-page simple questionnaire to collect information about farmers' perceptions about the scheme (e.g. Do you expect crop yield increase with better knowledge of your soil?), their engagement with NMP and their actions after receiving soil testing results. The year-four survey questionnaire was an adaptation and extension of the previous one by refining the types of post-programme actions (e.g. disaggregating "changed the amount of fertiliser purchased" into "purchased more fertiliser" and "purchased less fertiliser") and adding questions about farmers' post-programme awareness of the link between soil health and water quality and characteristics of their farms. Any differences in questions are reported in the results (Table 1) and considered in the analysis. Descriptive statistics are used to compare results from the two surveys when possible. It should be noted that the year-one survey (implemented by DAERA) did not contain socio-demographic and economic characteristics, hence these are not available for comparison with the year-four survey data (which did collect such information). We do know that average farm size of our surveyed farmers (38.2 ha) is close to Northern Ireland's average (41 ha). Due to anonymity restrictions, it was also not possible to collect a panel dataset to reveal within-subject changes.

2.3. Measuring changes in soil pH and phosphorus and soluble reactive phosphorus in river water

At the time of the programme implementation in 2017–2018, soil samples were collected following standard protocols (a composite sample of 25–40 cores at 7.5 cm depth in grassland and 15 cm in arable across each field in a "W" formation) between November and February and sent to an accredited laboratory where they were tested for soil pH (in a 1:2.5 volume ratio of soil to water), Olsen P (in a 1:20 volume ratio of soil to sodium bicarbonate extractant), potassium (K), magnesium (Mg) and calcium (Ca) (in a 1:5 volume ratio of soil to ammonium acetate or ammonium nitrate extractant), and Loss-on-Ignition (LOI) as an indicator of soil organic matter content. The complete re-sampling of all soils in the catchment took place in 2022/23. Further, within twelve river sub-catchments in UB, water quality monitoring data covering phosphorus nutrient fractions at fortnightly sampling frequencies was available from 2016. Time series of soluble reactive phosphorus (SRP) concentration were extracted for the hydrological years aligned with and between the soil sampling campaigns. This facilitates comparisons between the diffuse pressure posed by excess phosphorus levels determined from the soil sampling scheme and in-stream phosphorus concentrations, and how both change over time. A soil phosphorus-water quality relationship was assumed here. It was assumed that catchment-scale area weighted mean Olsen P could be related to mean annual SRP concentrations from the fortnightly water sampling programme. This sampling design does not focus on specific diffuse processes such as storms events (i.e., Buda et al., 2009) and can be considered as being representative of quiescent river concentration conditions. However, Cassidy et al. (2019), Scott et al. (2024) and Cassidy et al. (2025) showed this soil P-river SRP relationship in small agricultural catchments in Northern Ireland with a range of area weighted mean and percentage above optimum soil phosphorus concentration relationships, indicating that different in-stream SRP levels may occur for a given Olsen P concentration. A further assumption used in this study, was that changes in soil Olsen P would be reflected in changes in quiescent, or low-flow SRP concentration state. We also assumed that changes in soil Olsen P, reflecting better phosphorus use efficiency or reduced phosphorus inputs, would translate rapidly to changes in river SRP concentration state. Indeed, Jordan et al. (2024) highlighted this transition between changes in phosphorus surplus and SRP concentration in 93 Northern Ireland rivers within 1-year, with Bailey (2016) showing a direct link between phosphorus surplus and Olsen P in soils. The very high hydrological connectivity in the Northern Ireland landscape, with extensive field drainage and reported drainage densities of 5 km km^{-2} (Service et al., 2024), is hypothesised to contribute to this responsiveness between change in available phosphorus (soil Olsen P) in soils and low-flow SRP concentrations.

Changes in soil chemistry between the two sampling periods were assessed through comparison of soil pH and Olsen P for those fields sampled on both occasions; a total of 6625 fields. For pH, an area-weighted mean value for each sub-catchment was calculated for both sample sets. Following Cassidy et al. (2019), the proportion of each sub-catchment with soil Olsen P concentrations above the upper boundary of the agronomic optimum for intensive grassland (Index 2+, 26 mg P/L) was calculated. A modified Mann-Kendall analysis (Patakamuri and O'Brien, 2021) was applied to identify trends in in-stream SRP concentration over the period October 2017 to October 2023.

A third assumption in this study was that upward shifts in soil pH to a minimum level would be reflective of liming as a fertiliser replacement to release recalcitrant soil phosphorus and that this in turn would reduce chemical phosphorus input. It was further assumed that this balance of released soil phosphorus would be recycled into offtake (grass, milk/meat) rather than be available for loss to runoff. Following Daxini et al. (2018) and Corbett et al. (2022) for Irish soils, it was assumed that the combination of reduced input of phosphorus in fertiliser and increased offtake of soil phosphorus into forage and other crops through better nutrient management would be reflected in reductions of SRP concentrations in catchment streams during baseflow conditions.

3. Results

3.1. Behavioural change over time

By providing free soil sampling and NMP training, the programme placed the emphasis on how to better manage phosphorus to reduce risks of losses from soil to watercourses. Through the preparation and use of NMP, farmers were expected to reflect on the process and benefits associated with targeting nutrient use efficiency and trigger changes in farm management practices (e.g., altering the type and amount of chemical fertiliser applied, or the application rates of slurry or farmyard manure to fields). Comparative results across the year-one and year-four surveys are presented in Table 1 and described next.

Awareness and perceptions. Farmers' engagement with NMP declined over the four year period (55% of farmers reported having a NMP one year after the programme compared to 37% four years later), and only about half of those who had initially expressed they were likely to carry out further soil sampling on their own following participation in the programme had done it four years later (44% compared to 89%). This decline of initial uptake once external support ceases is a common pattern in agri-environmental programmes more generally (Ruto and Garrod, 2009; Batáry et al., 2015; Beetstra et al., 2022) and has been observed in other schemes in Northern Ireland (Farrow et al., 2025). Despite this, the programme had a sustained impact on farmers' awareness and perceptions. For example, the proportion of farmers that recognised the link between healthy soils and good water quality was very similar in the year-one and year-four surveys (84% versus 83%, respectively). Interestingly, four years after the programme a higher percentage of farmers (68%) believed that water quality in their area would improve if the soil sampling programme involved enough farmers, compared to the year-one survey (53%), possibly aided by continued messaging on water quality issues in the farming media in Northern Ireland. The soil sampling programme also proved successful in meeting farmers' expectations regarding the economic benefits from better soil management. For example, 86% of farmers in the year-one survey expected a better crop yield with better knowledge of the soils on their farms. Then, in the year-four survey, 70% of farmers reported increased crop yield and 58% reported increased profitability of their farm business and linked this to better farm NMP. The statement "*applying fertiliser or slurry based on soil test results can save me money*" received the highest score in the year-four survey.

Changes in farming practices. Table 1 shows changes in farming practice year-one vs year-four. The extent to which changes in farming practice persisted in this period varied across different types of agricultural practices. Increasing the use of lime (as a crucial first step in engaging with NMP) was the most adopted practice in both surveys: 80% of farmers reported applying more lime one year after participating in the soil sampling programme; this figure remained high, at 67%, after four years. The percentage of farmers who had changed the amount of chemical fertiliser they purchased (either more or less) was also relatively similar between the surveys (66% and 57%, respectively). In contrast, 81% of farmers in the year-one survey reported changing the type of fertiliser purchased after receiving soil test results and recommendations from the programme, while this figure had decreased to 41% after four years. Furthermore, 26% of farmers reported importing slurry when they needed more than they had or exporting excess slurry one year after the soil sampling programme, while fewer farmers (7%–9%) had done so four years later. The year-four post-programme survey also asked if farmers had changed the timing of the application of slurry/manure to reduce potential for soil nutrient loss to the local water body after receiving soil test results and recommendations. Half of them reported doing so. As a point of comparison, less than 10% of farms in

Table 1
Changes in awareness, perceptions and behaviours over time. When not specified to the contrary, the question/variable was included in both surveys with equivalent phrasing.

Nutrient planning, soil sampling and training (%)	**1 year (N = 148, 29%)**	**4 years (N = 90, 17.2%)**	**P-value**
The farmer has adopted a nutrient management plan	55%	37%	0.01 *
1-year survey: Farmer reports to be more likely to carry out further soil sampling 4-year survey: Farmer reports to have carried out any further soil sampling?	89%	44%	
Perceived scheme benefits (%)			
Farmer thinks that if there were enough farmers taking part in soil sampling, water quality in the area would improve	53%	68%	0.04 *
1-year survey: Farmer expects a crop yield increase with better knowledge of their soil 4-year survey: Farmer thinks their involvement in the scheme has helped increased crop yields on their farm	84%	70%	
Farmer thinks involvement in the scheme has helped them increase the profitability of their business		58%	
1-year survey: Farmer recognises the link between good healthy soils and good water quality 4-year survey: Farmer thinks involvement in the scheme has increased their knowledge about the link between nutrient management on their farm and water quality	84%	83%	
Awareness (from "completely disagree": −2 to "completely agree": 2)			
Applying fertilizer or slurry based on soil test results can save me money		1.49	
There is higher risk of nutrient loss to the environment if I don't know the nutrient status of my soils		1.08	
Applying nutrients in excess of crop need does not increase yield		1.07	
There is a link between good healthy soil and good water quality in streams		1.06	
Applying fertiliser or slurry based on soil test results can help reduce water pollution in streams		1.01	
Behaviour changes following soil nutrient planning (%)	**1 year**	**4 years**	
Farmer has increased lime usage	80%	67%	<0.001 ***
1-year survey: Farmer changed the amount of fertiliser purchased (either more or less) 4-year survey: Farmer purchased more fertiliser/Purchased less fertiliser	66%	54%/4%	
Farmer changed the type of fertiliser purchased	81%	41%	<0.001 ***
1-year survey: Farmer imported or exported slurries 4-year survey: Farmer imported slurries/Exported slurries	26%	7%/2%	
Farmer changed timing of application of slurry/manure		47%	
Farmer increased application of slurry/manure to fields with low phosphorus index		33%	
Farmer reduced application of slurry/manure to fields with high phosphorus index		28%	

* = level of statistical significance.

Northern Ireland had an up-to-date soil analysis prior to the programme (DAERA, 2018b). This is substantially lower than the findings from the 4-year post-programme survey, which showed that 44% of farmers had conducted further soil sampling. In summary, it can be concluded that the programme did, in *general*, lead to sustained awareness and adoption of some best management practices over time, but with variation across different types of measures (i.e. those which are more accessible or easier to implement by farmers, such as lime application and changing the type/amount of fertiliser applied, are those which show to be more sustained).

3.2. Changes in soil pH and phosphorus and soluble reactive phosphorus in river water

Soil pH – Liming. Lime application to correct soil pH is an indicator of active NMP. It is usually the first, and a relatively low cost, step towards optimising phosphorus use efficiency without further phosphorus fertiliser applications, particularly in poorly draining and naturally acidic soils (Corbett et al., 2022), which are prevalent in Northern Ireland. In 2017–2018, 53.7% of the 6502 fields sampled within the UB catchment were below the optimum pH for maximum grass nutrient uptake (< pH 6 for mineral soil and < 5.3 for peat) and would have been issued with a lime application recommendation to raise soil pH (to a target of pH 6.2). By the time of the year-four survey (2022–2023), the proportion of fields requiring liming was 50.9%, indicating no *overall* significant improvement in soil pH over the 4-year period.

However, the picture is more nuanced when we look at the details per sub-catchment (Fig. 2). Eight sub-catchments showed a decrease in average (area-weighted) soil pH between soil sampling periods (indicative indeed of liming recommendations not being implemented, particularly for those catchments where the pH dropped below pH 6 in these predominantly mineral soils); out of which four were statistically significant decreases in soil pH (C03, C08, C11, C10 ($p < 0.05$ - *t*-test)) and one a strong tendency (C09 ($p < 0.1$)). In contrast, in five other sub-catchments, average soil pH was either maintained or increased; three significantly (C12, C05, C04) and one slightly (C02), indicative of liming recommendations being put into practice. In three of the catchments with an increase or maintenance in soil pH (C02, C05, C04),[1] farmers received additional one-to-one advisory support, beyond the generic advice and training available to all participating farmers. C12, on the other hand, is a revealing contrasting case. It is an upland catchment, which has traditionally been extensively farmed, with semi-natural grasslands, and at high water quality status (WFD status assessment, 2021). However, in recent years it has seen signs of agricultural intensification on some of the lower lying fields with liming used to bring semi-natural fields into production, as also shown in our pH results. C12 did not receive one-to-one tailored advice, so it would have received generic advice appropriate to intensive grassland systems that may have promoted lime applications, to the potential detriment of its semi-natural grassland and biodiversity.

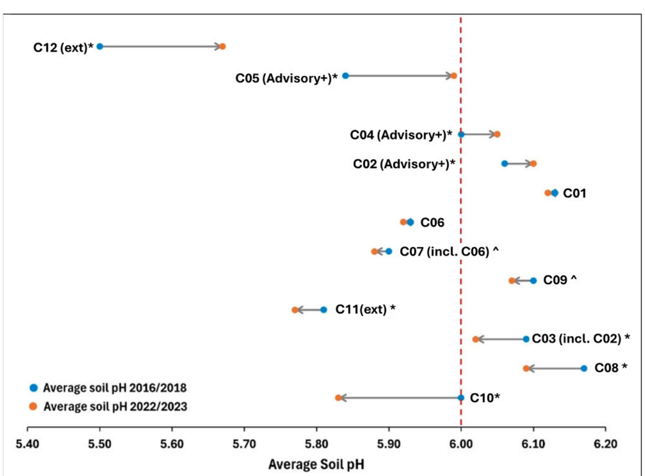

Fig. 2. Changes in Soil pH Before and After the Soil Sampling Programme. Direction of the arrows indicates whether the pH has increased or decreased. Sub-catchments are ranked according to the extent of pH improvement. The optimum pH for the predominantly mineral soils in the catchment is indicated by the red dashed line (pH 6), with farmers advised to target lime applications to pH 6.2. Statistically significant results ($p < 0.05$) are marked with *; results with a strong tendency ($p < 0.1$) are marked with ^. Catchments with additional farm engagement and advisory input are indicated with "Advisory+"; and extensively farmed upland catchments are indicated with "ext". Some sub-catchments are nested within each other (marked as "incl."). Data also available in tabular form in the Appendix Table A.1.

Soil Olsen P and river Soluble Reactive Phosphorus (SRP). At the start of the programme, 41.0% of the 6502 fields sampled were above the agronomic optimum for soil Olsen P, which negatively affects water quality (evidenced by strong positive correlations with river water SRP concentration) (Scott et al., 2024; Cassidy et al., 2019). At the time of the year-four survey, 47.0% of fields were above optimum for soil Olsen P (i.e., an *overall* deterioration, indicative of nutrient crop applications above crop requirements). Looking at the sub-catchment values, however, again reveals a more nuanced and interesting picture. Most sub-catchments indeed experienced an increase in soil Olsen P (Fig. 3) and in riverine SRP concentrations (Table 2). These increases were 4.9% and 6.6% in the more intensively farmed catchments – C03 and C08, respectively – with C03 also showing a significant increase (worsening) in river SRP concentration.[2] The increase in above optimum Olsen P in the less intensively farmed catchment C09 and the upland catchments C12, C11 and C10 was even greater, by over 10%. These catchments also saw increases in riverine SRP concentrations (two of which were significant (C12 and C10)). The results are different though for the three catchments that received one-to-one advice: two of them (C02 and C04) experienced improvements (reductions) in soil Olsen P (Fig. 3) and river SRP (Table 2), and the other one (C05), saw no significant deterioration in river SRP (Table 2).

In summary, for both soil and water phosphorus, only the sub-catchments where one-to-one tailored advice was given to the farmers in addition to the generic advice, have shown signs of improvement (or see no significant deterioration). Furthermore, the generic agronomic advice and nutrient recommendations could possibly have inadvertently led to intensification (and environmental deterioration) of one upland sub-catchment.

4. Discussion

4.1. The role of advice and increased awareness over time on improved soil and water quality

Our results suggest that following the awareness focused programme, farmers in this case generally display positive attitudes towards soil testing and NMP and have a good understanding of their value to crop yield and farm productivity, and the negative links between excess soil phosphorus and water quality. Despite farmers' engagement with NMP having somewhat receded over the four year period, their understanding and awareness seems to have consolidated over time.

This increased awareness is associated with adoption of good

[1] For those catchments where the average pH is above 6, it does not really matter if they fluctuate a bit so long as they are > =6. All soils in the catchment are naturally acidic, so the only thing keeping them at 6 or above is plentiful applications of lime and farmers checking this with soil sampling.

[2] UB06 showed a decrease in SRP concentration trend, which appeared from the time-series to be a sudden decline as would be noted with a point source mitigation, such as improvements to rural wastewater treatment systems.

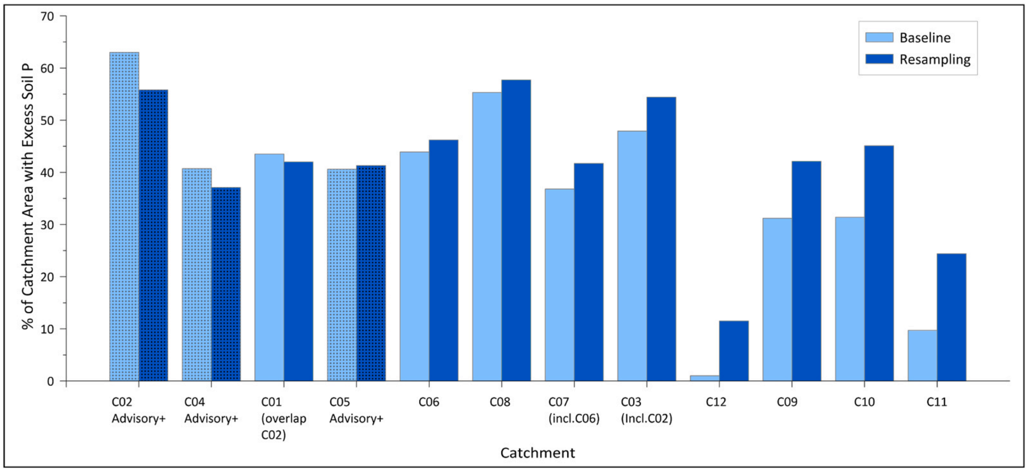

Fig. 3. Percentage of catchment area above optimum Soil Olsen P in the baseline soil sampling in 2017/18 and resampling in 2022/23. Dotted bars correspond to sub-catchments with additional one-to-one advice, which are also marked by "Advisory + ". Some sub-catchments are nested within each other (marked as "incl."). Data also available in tabular form in the Appendix Table A.2.

Table 2
Results of modified Mann-Kendall analysis of trends in SRP concentration timeseries from the initial baseline soil sampling (2017/18) to re-sampling (2022/23). Catchments with additional farm engagement and advisory input are indicated with "Advisory+"; and extensively farmed upland catchments are indicated with "ext". Some sub-catchments are nested within each other (marked as "incl."). Statistically significant results ($p < 0.05$) are marked with *; results with a strong tendency ($p < 0.1$) are marked with ˆ.

	Modified Mann-Kendall Corrected Zc	P-value
C01	0.16	0.874
C02 (Advisory +)	−2.44	0.015*
C03(Incl. C02)	2.17	0.030*
C08	−2.02	0.044*
C09	1.21	0.227
C12 (ext)	2.81	0.005*
C11 (ext)	1.34	0.181
C10	3.09	0.002*
C07 (incl. C06)	1.42	0.156
C05 (Advisory +)	1.86	0.062ˆ
C04 (Advisory +)	1.58	0.115
C06	4.60	0.000*

nutrient and soil management practices relevant to livestock farming (particularly those which are more accessible or easier to implement by farmers, such as lime application and changing the type/amount of fertiliser applied according to soil test results). Although there are inherent limitations in measuring self-reported behaviours via surveys like ours, this is still a widely used tool in farming research (Floress et al., 2018). This positive effect would be consistent with findings from the wider scope of previous research regarding the influence of awareness, advisory support, and non-monetary incentives (e.g. access to training) on farmers' willingness and preferences for adopting environment-friendly practices (Costedoat et al., 2016; Villanueva et al., 2016; Cortés-Capano et al., 2021; Schulze et al., 2023; Villanueva et al., 2026). However, this study provides extra contribution to the literature by focusing on farmers' actual behavioural change rather than their intention to change.

Our results suggest that whether sustained increases in awareness and changes in practices translate into actual improvements in soil and water phosphorus (thus completing the awareness-behavioural change-water quality pathway) critically depends on the nature of the advice that farmers received. One-to-one farm-specific advice supports farmers to change within the bounds of their business, increases the opportunity of experiential learning and the confidence in the advice given (Cotching et al., 2009; Okumah et al., 2021b) and, as suggested here, can consolidate the positive behaviour changes over time. Importantly, tailored advice can mitigate the risk of perverse productivity 'rebound effects' (Vivanco et al., 2022). Applied to our context, this risk would stem from soil testing recommendations generally being based strictly on agronomic principles for maximising crop yields rather than considering farm stocking densities and forage needs, or water protection. This means that soil test results in this programme may have inadvertently recommended – through the generic (non-tailored) advice - increasing phosphorus inputs on less intensive farms where grass production was sufficient for low stocking rates at lower soil phosphorus levels.

The case of the upland catchment C12 is particularly revealing in this respect. Without tailored advice, farmers in this catchment may have acted on generic advice that did not account for constraints imposed by the landscape or the higher environmental status of its waterbodies. A potential unintended consequence is that some farmers would, on review of their soil tests results, have observed the possibility of increasing productivity by increasing their phosphorus applications. This productivity rebound has been observed in other agricultural practices, such as the 'irrigation paradox' in areas of water scarcity, where improvements in irrigation technologies have led to overall increased water consumption, due to farmers switching from rain-fed crops to more profitable irrigated crops (Berbel et al., 2015).

Even if the soil and water phosphorus improvements shown here may be regarded as modest, it is important to consider that they happen against a backdrop of legacy soil phosphorus accumulation in Northern Ireland, where the balance between imports of phosphorus in fertiliser and feed concentrates, relative to exports in product sits at ~11 kg P ha^{-1} yr^{-1} (Rothwell et al., 2020).

While our study suggest that awareness focused approaches to mitigating phosphorus loss from agriculture can have sustained positive effects on soil and water over time, it also underscores the need for a deeper transformation of the agricultural system (Martin-Ortega et al., 2022). Soil testing needs to be seen as a first necessary step in addressing soil phosphorus excess, and it is critically needed because of the very low levels of evidence-driven decision making in farm systems. It is the most basic yet valuable measurement that can be made for a farm (and relatively inexpensive). But the extension from that essential measurement to guidance and recommendations made to farmers needs to be mediated by tailored advice. How to deliver that tailored advice across the board and at large scales needs to form part of the broader conversation on how we more fundamentally transform our agricultural systems for more sustainable food production.

Finally, we should note that in this paper we focus on the interplay between the awareness/behavioural aspects and the environmental effects over time, but not on the further disentangling of the relationship between awareness and behaviour. The analysis of drivers of such relationship (including socio-demographic and economic and farm characteristics), was not possible due to lack of such data collected in the year-one survey that was designed and administered by DAERA. This information was collected in year-four survey and is being explored in an in-depth modelling analysis in a separate forthcoming paper, which should allow the analysis of heterogenous responses amongst farmers. This will shed further light on the extent that, and mechanism by which, awareness triggers behavioural change, and support the design of more targeted and effective advisory strategies.

4.2. Reflections on interdisciplinary research of 'real-life' policy processes

We consider it important to also reflect on insights that this work delivers as a post-normal science contribution, i.e. as an interdisciplinary research piece operating in a 'real-life' active policy process, and what does this mean for similar policy processes and future research. The diverse data components available for this study, as well as its limitations, need to be considered in relation to: the wicked nature of the diffuse pollution problem (Duckett et al., 2016); the notorious difficulties in accurately surveying farmers (Tyllianakis et al., 2023); the near impossibility of isolating behavioural factors (Okumah et al., 2021a) from the complex combination of environmental factors affecting nutrient processes (Glendell et al., 2014); and the ethical restrictions of protected farmer data.

In wicked problems, complexities and uncertainties of bio-physical, psycho-social and economic processes overlay, while operating within a changing reality. If we are going to further our understanding of these kind of problems in ways that can provide useful information for policy makers, we need to work and operate differently, accepting that not every aspect of such complexity can be disentangled and yet, that connections across both realms (environmental and human) still need to be made. We would argue that some of the limitations of this study can be reframed as 'research realities' to which we simply need to adapt. For example, and in our case, we did not have information on the exact locations where changes in farm practices occurred within the sub-catchment and how these connect with specific trajectories of phosphorus in the soil and water (i.e. we do not know which individual farmers did what exactly where and how that relates to phosphorus circulation within the agricultural system). The only way to address such issues would be through an experimental design that allowed tracing the specific pathways that phosphorus could take from an individual field in the catchment. In practice, this could only be done at a scale and within the constraints of conditions so distant from how things operate in reality, that it would negate the very nature of trying to understand farmers genuine behaviours, and would render it policy irrelevant (e.g., engaging farmers in a micro-level study under 'lab' conditions alien to their actual working farm practice).

Identifying specific locations stumbles into another fundamental 'research reality': ethical constraints. Due to data protection agreements between the research institutions and the government (who hold the farmers data in real policy programmes), researchers are often not allowed to identify individual farmers. Even more, farmers often only agree to participate where they are guaranteed anonymity, requiring even more stringent individual privacy agreements. In our case this meant that farmers survey had to remain at the catchment level as at this scale needed to prevent individuals' identification under confidentiality agreements. Again, in an ideal 'lab-designed' study, this would not be a problem but is a reality when dealing with actual field data only accessible via protected governmental sources. This implies that all we can do is to approximate as much as possible the scales of the bio-physical work and the behavioural work to try to advance understanding, which is what we did here.

Another research reality in this case is the lack of baseline data on farmer attitudes and adoption of practices before the awareness programme began, or control sites where no awareness raising activities had taken place. We would argue, however, that thinking about this research in those terms (i.e. baselines and control sites), implies assuming that we could observe farmers who had absolutely no knowledge or previous level of exposure to the issue of fertiliser use and water quality and that we could attribute unequivocally any changes of behaviour identified in the post-treatment survey to *this* specific awareness program. This is highly unlikely or even impossible in the 'real-life' socio-political context. Farmers do not live in a bubble in which they would not have been, prior to this programme, exposed to at least some level of awareness, or in which they do not exchange information amongst themselves (particularly given the size and social dynamics of these catchments). We have in the past done research with control groups (Okumah et al., 2021a), but they can only yield relevant results when done qualitatively, so that the depth of how farmers' awareness relates or not to the interventions can be disentangled.

The singularities of researching a 'real-life' policy process would be applicable to similar policy processes. The programme already existed as a reality separate from any research. No farmers' baseline was done by the government at the time of starting the programme, no socio-demographic or other characteristics were initially collected, and no panel data were constructed. In essence we are operating in a reality where there is an on-going policy process which generates a field experiment lacking a full 'perfect' experimental design. Future research designs must adapt to make use of sources of data as they are possible to obtain them and researchers should relax some of the expectations of what can be achieved from the perspective of the individual disciplines involved (in this case, soil and water sciences and behavioural sciences) (Martin-Ortega et al., 2015; Albaladejo-García et al., 2026) and adopt 'opportunistic' research designs (King et al., 2023) that fit practical and ethical constraints in data collection. What can (and should) be done in the future in similar policy processes, in any case, is improve the conditions under which 'real-life' research can be deployed, for example, by embedding social sciences research in the policy programmes themselves (Martin-Ortega, 2023). In the same way that water and soil quality monitoring is in place in many policy programmes, mechanisms to measure social sciences variables should be procured.

5. Conclusions

This paper has explored the agricultural diffuse pollution awareness-behavioural change-water quality pathway *in full* and *over time.* We have done so by combining farmers' survey data one and four years after the inception of a nutrient management programme in Northern Ireland, with soil and river water phosphorus analyses at the sub-catchment level in a livestock dominated grassland-based system. Our results suggest that increased awareness and changes in farm practices can be sustained over time, but whether they translate into a reduction in soil and water phosphorus (thus completing the pathway in full), critically depends on the provision of tailored one-to-one advice. The recommendation that would stem straightforwardly from this is that future agri-environment policies should include tailored and context specific advice in addition to more generic advice. Besides consolidating good practices, tailored advice helps avoid 'rebound effects' of farming intensification that negatively impact waterbodies.

Operating within a 'real-life' active policy process, our research also provides insights into the operationality of post-normal interdisciplinary science applied to wicked problems. Our research illustrates particularly patently the need to engage with what is happening 'on the ground' and adjust methods and approaches in a way that produces robust science within the possibility of the policy context, even if this means that experimental designs are not 'perfect'. We would argue that this does not necessarily need to be conceived as a limitation, but as a 'research reality' we should embrace because policies will keep being designed, i.e. either we – as scientists - get on board and support improving them *on* *the move* or they will happen anyway without evidence-based support.

Combining these two contributions and while the particular changes of soil and water quality that we show might be specific to the Northern Irish context, two lessons are of broader relevance: 1) broader discussions on agricultural system transformation should include considerations on how to deliver tailored advice at scale; and 2) further disentanglement of the full impact pathway from increasing farmers awareness to mitigating enviormental impact from agriculture necessarily requires embedding social sciences from the design stage of the *policy* programmes *themselves*, rather than being incorporated only as retrospective research.

CRediT authorship contribution statement

Alex Higgins: Resources, Investigation. **Julia Martin-Ortega:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization, Writing – review & editing. **Cheng Wen:** Methodology, Investigation, Formal analysis, Data curation, Writting - original draft, Writing – review & editing. **Pippa J. Chapman:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Paula Novo:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Phil Jordan:** Methodology, Investigation, Writing – review & editing. **Rachel Cassidy:** Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received funding from the *Soil Nutrient Health Scheme* (SNHS) and the NAP/EFS E & I (Project 18/4/03) funded by the Department of Agriculture, Environment and Rural Affairs of Northern Ireland; the RePhoKUs project (*The role of phosphorus in the sustainability and resilience of the UK food system*) funded by BBSRC, ESRC, NERC and the Scottish Government under the UK Global Food Security Research Programme (Grant no. BB/R005842/1); and the *EU EAA Soil Sampling and Analysis* Scheme funded under the European Union Exceptional Adjustment Aid Scheme. Many thanks to staff from Soil Health Branch, DAERA and wider AFBI staff who contributed to programme and manage the SNHS, and who contributed to the review and implement the surveys. We also acknowledge the College of Agriculture, Food and Rural Enterprise (CAFRE) who developed and delivered the farmer training modules. The authors are grateful to the farmers who participated in this research.

This research received ethical approval from the Business, Earth & Environment, Social Sciences (AREA FREC) Research Ethics Committee of the University of Leeds [ID: AREA FREC 2022-0231-132]. Data were acquired under confidentiality agreements between AFBI with landowners and farmers and as such cannot be made publicly available.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2026.110645.

Data availability

The authors do not have permission to share data.

References

ADHB, 2023, Nutrient Management Guide (RB209). https://ahdb.org.uk/nutrient-management-guide-rb209.

Albaladejo-García, J.A., Medina-Vidal, M.D., Martin-Ortega, J., Alcon, F., 2026. Rapid economic impact assessment of nature-based solutions: illustration of a co-constructed approach. Environ. Impact Assess. Rev. 118, 108326.

Bailey, J.S., 2016. Phosphorus management for sustainable dairy production. Presented at the Step to Sustainable Livestock International Conference, Bristol, UK (2016). http://www.cabidigitallibrary.org/doi/pdf/10.5555/20163196180.

Batáry, P., Dicks, L.V., Kleijn, D., Sutherland, W.J., 2015. The role of agri-environment schemes in conservation and environmental management. Conserv. Biol. 29 (4), 1006–1016.

Beetstra, M.A., Wilson, R.S., Doidge, M., 2022. Conservation behavior over time: examining a Midwestern farmer sample. Land. Use Policy 115, 106002. https://doi.org/10.1016/j.landusepol.2022.106002.

Berbel, J., Gutiérrez-Martín, C., Rodríguez-Díaz, J.A., et al., 2015. Literature review on rebound effect of water saving measures and analysis of a Spanish case study. Water Resour. Manag. 29, 663–678. https://doi.org/10.1007/s11269-014-0839-0.

Blackstock, K.L., Ingram, J., Burton, R., Brown, K.M., Slee, B., 2010. Understanding and influencing behaviour change by farmers to improve water quality. Sci. Total. Environ. 408, 5631–5638. https://doi.org/10.1016/j.scitotenv.2009.04.029.

Boezeman, D., Wiering, M., Crabbé, A., 2020. Agricultural diffuse pollution and the EU water framework directive: problems and progress in governance. Water. https://doi.org/10.3390/w12092590.

Buda, A.R., Kleinman, P.J.A., Srinivasan, M.S., Bryant, R.B., Feyereisen, G.W., 2009. Effects of hydrology and field management on phosphorus transport in surface runoff. J. Environ. Qual. 38, 2273–2284.

Cassidy, R., Thomas, I.A., Higgins, A., Bailey, J.S., Jordan, P., 2019. A carrying capacity framework for soil phosphorus and hydrological sensitivity from farm to catchment scales. Sci. Total. Environ. 687, 277–286. https://doi.org/10.1016/j.scitotenv.2019.05.453.

Cassidy, R., Service, T., Atcheson, K., Farrow, L., Harrison, T., Higgins, A., Jack, P., Jordan, P., 2025. A unified and multi-scale source: pathway priority index for diffuse pollution management. Water Res., 123418 https://doi.org/10.1016/j.watres.2025.123418.

Corbett, D., Wall, D.P., Lynch, M.B., Tuohy, P., 2022. The influence of phosphorus application and varying soil pH on soil and herbage properties across a range of grassland soils with impeded drainage. J. Agric. Sci. 160 (6), 516–527. https://doi.org/10.1017/S0021859622000363.

Cortés-Capano, G., Hanley, N., Sheremet, O., Hausmann, A., Toivonen, T., Garibotto-Carton, G., Soutullo, A., Di Minin, E., 2021. Assessing landowners' preferences to inform voluntary private land conservation: the role of non-monetary incentives. Land. Use Policy 109, 105626. https://doi.org/10.1016/j.landusepol.2021.105626.

Costedoat, S., Koetse, M., Corbera, E., Ezzine-de-Blas, D., 2016. Cash only? Unveiling preferences for a PES contract through a choice experiment in Chiapas, Mexico. Land. Use Policy 58, 302–317. https://doi.org/10.1016/j.landusepol.2016.07.023.

Cotching, W.E., Sherriff, L., Kilpatrick, S., 2009. Integrating farm production and natural resource management in Tasmania, Australia. J. Agric. Educ. Ext. 15 (3), 287–300. https://doi.org/10.1080/13892240903069611.

DAERA, 2018a. Statistical Review of Northern Ireland Agriculture. https://www.daera-ni.gov.uk/publications/statistical-review-northern-ireland-agriculture-2018.

DAERA, 2018b. Sustainable Agricultural Land Management Strategy report. https://www.daera-ni.gov.uk/publications/sustainable-agricultural-land-management-strategy-report-and-executive-summary.

DAERA, 2024. Statistical Review of Northern Ireland Agriculture 2023, p.106 https://www.daera-ni.gov.uk/sites/default/files/publications/daera/24.25.095%20Stat%20Review%202023%20final.PDF.

DAERA, 2025, Northern Ireland Water Classification Statistics Report 2024, p. 42. https://www.daera-ni.gov.uk/sites/default/files/2025-02/NIEA%20-%20WMU%20-%20ICP%20-%20NI%20Water%20Classification%20Statistics%20Report%202024.pdf.

Davey, A.J.H., Bailey, L., Bewes, V., Mubaiwa, A., Hall, J., Burgess, C., Dunbar, M.J., Smith, P.D., Rambohul, J., 2020. Water quality benefits from an advice-led approach to reducing water pollution from agriculture in England. Agric. Ecosyst. Environ. 296, 106925. https://doi.org/10.1016/j.agee.2020.106925.

Daxini, A., O'Donoghue, C., Ryan, M., Buckley, C., Barnes, A.P., Daly, K., 2018. Which factors influence farmers' intentions to adopt nutrient management planning? J. Environ. Manag. 224, 350–360.

Duckett, D., Feliciano, D., Martin-Ortega, J., Munoz-Rojas, J., 2016. Tackling wicked environmental problems: the discourse and its influence on praxis in Scotland. Landsc. Urban. Plan. 154, 44–56. https://doi.org/10.1016/j.landurbplan.2016.03.015.

Farrow, L., Glass, C., Morton, P.A., McRoberts, W.C., Floyd, S., Burgess, D., Jordan, P., Cassidy, R., 2025. Charting water quality improvements and practice reversion with pesticide interventions at catchment scale. Sci. Total. Environ. 960, 178243.

Floress, K., Reimer, A., Thompson, A., Burbach, M., Knutson, C., Prokopy, L., Ribaudo, M., Ulrich-Schad, J., 2018. Measuring farmer conservation behaviors: challenges and best practices. Land. Use Policy 70, 414–418.

Glendell, M., Granger, S.J., Bol, R., Brazier, R.E., 2014. Quantifying the spatial variability of soil physical and chemical properties in relation to mitigation of diffuse water pollution. Geoderma 214, 25–41. https://doi.org/10.1016/j.geoderma.2013.10.008.

Holland, J.E., Bennett, A.E., Newton, A.C., White, P.J., McKenzie, B.M., George, T.S., Pakeman, R.J., Bailey, J.S., Fornara, D.A., Hayes, R.C., 2018. Liming impacts on soils, crops and biodiversity in the UK: a review. Sci. Total. Environ. 610 (611), 316–332.

Inman, A., Winter, M., Wheeler, R., et al., 2018. An exploration of individual, social and material factors influencing water pollution mitigation behaviours within the farming community. Land. Use Policy 70, 16–26. https://doi.org/10.1016/j.landusepol.2017.09.042.

Jordan, P., McElarney, Y., Cassidy, R., 2024. The farmgate phosphorus balance as a measure to achieve river and lake water quality targets. J. Environ. Manag. 372, 123427. https://doi.org/10.1016/j.jenvman.2024.123427.

Jwaideh, M.A., Sutanudjaja, E.H., Dalin, C., 2022. Global impacts of nitrogen and phosphorus fertiliser use for major crops on aquatic biodiversity. Int. J. Life Cycle Assess. 27, 1058–1080. https://doi.org/10.1007/s11367-022-02078-1.

King, P., Martin-Ortega, J., Armstrong, J., Ferré, M., Bark, R.H., 2023. Mainstreaming nature-based solutions: what role do Communities of Practice play in delivering a paradigm shift? Environ. Sci. Policy 144, 53–63. https://doi.org/10.1016/j.envsci.2023.03.003.

Knook, J., Turner, J.A., 2020. Reshaping a farming culture through participatory extension: An institutional logics perspective. J. Rural. Stud. 78, 411–425. https://doi.org/10.1016/j.jrurstud.2020.06.037.

Li, Y., Wang, M., Chen, X., Cui, S., Hofstra, N., Kroeze, C., Ma, L., Xu, W., Zhang, Q., Zhang, F., Strokal, M., 2022. Multi-pollutant assessment of river pollution from livestock production worldwide. Water Res. 209, 117906. https://doi.org/10.1016/j.watres.2021.117906.

Lintern, A., McPhillips, L., Winfrey, B., Duncan, J., Caitlin Grady, C., 2020. Environ. Sci. Technol. 54 (15), 9159–9174. https://doi.org/10.1021/acs.est.9b07511.

Ma, J., Gao, H., Cheng, C., Fang, Z., Zhou, Q., Zhou, H., 2023. What influences the behavior of farmers' participation in agricultural nonpoint source pollution control?—Evidence from a farmer survey in Huai'an, China. Agric. Water Manag. 281, 108248. https://doi.org/10.1016/j.agwat.2023.108248.

Martin-Ortega, J., et al., 2015. A transdisciplinary approach to the economic analysis of the European Water Framework Directive. Ecol. Econ. 116 (2015), 34–45.

Martin-Ortega, J., 2023. We cannot address global water challenges without social sciences. Nat. Water 1, 2–3. https://doi.org/10.1038/s44221-022-00013-0.

Martin-Ortega, J., Rothwell, S.A., Anderson, A., Okumah, M., Lyon, C., Sherry, E., Johnston, C., Withers, P.J.A., Doody, D.G., 2022. Are stakeholders ready to transform phosphorus use in food systems? A transdisciplinary study in a livestock intensive system. Environ. Sci. Policy 131, 177–187. https://doi.org/10.1016/j.envsci.2022.01.011.

McCann, L.M.J., Easter, K.W., 1999. Differences between farmer and agency attitudes regarding policies to reduce phosphorus pollution in the Minnesota river basin. Appl. Econ. Perspect. Policy 21, 189–207. https://doi.org/10.2307/1349980.

McDowell, R.W., Macintosh, K.A., Depree, C., 2023. Linking the uptake of best management practices on dairy farms to catchment water quality improvement over a 20-year period. Sci. Total. Environ. 895, 164963. https://doi.org/10.1016/j.scitotenv.2023.164963.

Okumah, M., Martin-Ortega, J., Novo, P., 2018. Effects of awareness on farmers' compliance with diffuse pollution mitigation measures: a conditional process modelling. Land. Use Policy 76, 36–45. https://doi.org/10.3390/land9050135.

Okumah, M., Chapman, P.J., Martin-Ortega, J., Novo, P., Ferréa, M., Jones, S., Pearson, P., Froggatt, T., 2021a. Do awareness-focussed approaches to mitigating diffuse pollution work? A case study using behavioural and water quality evidence. J. Environ. Manag. 287, 112242. https://doi.org/10.1016/j.jenvman.2021.112242.

Okumah, M., Martin-Ortega, J., Chapman, P.J., Novo, P., Cassidy, R., Lyon, C., Higgins, A., Doody, D., 2021b. The role of experiential learning in the adoption of best land management practices. Land. Use Policy 105, 105397. https://doi.org/10.1016/j.landusepol.2021.105397.

Pan, D., Chen, H., Zhang, N., Kong, F., 2023. Do livestock environmental regulations reduce water pollution in China? Ecol. Econ. 204, 107637. https://doi.org/10.1016/j.ecolecon.2022.107637.

Patakamuri, S., O'Brien, N., 2021. modifiedmk: Modified Versions of Mann Kendall and Spearman's Rho Trend Tests. R package version 1.6, http://github.com/patakamuri/modifiedmk.

Pennings, J.M.E., Irwin, S.H., Good, D.L., 2002. Surveying farmers: a case study. Rev. Agric. Econ. 24 (1), 266–277. http://www.jstor.org/stable/1349833.

Richardson, et al., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9, eadh2458. https://doi.org/10.1126/sciadv.adh2458.

Rothwell, S.A.D.G., Doody, C., Johnston, K.J., Forber, O., Cencic, H., Rechberger, P.J.A., Withers, 2020. Phosphorus stocks and flows in an intensive livestock dominated food system. Resour. Conserv. Recycl. 163, 105065. https://doi.org/10.1016/j.resconrec.2020.105065.

Ruto, E., Garrod, G., 2009. Investigating farmers' preferences for the design of agri-environment schemes: a choice experiment approach. J. Environ. Plan. Manag. 52 (5), 631–647.

Schulze, C., Zagórska, K., Häfner, K., Markiewicz, O., Czajkowski, M., Matzdorf, B., 2023. Using farmers' ex ante preferences to design agri-environmental contracts: a systematic review. J. Agric. Econ. 75, 44–83. https://doi.org/10.1111/1477-9552.12570.

Scott, A., Cassidy, R., Arnscheidt, J., Jordan, P., 2024. Soil phosphorus, hydrological risk and water quality carrying capacities in agricultural catchments. Catena 240, 107964. https://doi.org/10.1016/j.catena.2024.107964.

Service, T., Cassidy, R., Atcheson, K., Farrow, L., Harrison, T., Jack, P., Jordan, P., 2024. A national-scale high-resolution runoff risk and channel network mapping workflow for diffuse pollution management. J. Environ. Manag. 368, 122110. https://doi.org/10.1016/j.jenvman.2024.122110.

Stedman, R.C., Connelly, N.A., Heberlein, T.A., Decker, D.J., Allred, S.B., 2019. The End of the (Research) World As We Know It? Understanding and Coping With Declining Response Rates to Mail Surveys. Soc. Nat. Resour. 32 (10), 1139–1154. https://doi.org/10.1080/08941920.2019.1587127.

Teagasc, 2021. ASSAP Expert Review Final Report. Teagasc – Agriculture and Food Development Authority. https://teagasc.ie/wp-content/uploads/2025/05/ASSAP-Expert-Review-Final-Report-pdf-22-Nov-2021.pdf.

Tyllianakis, E., Martin-Ortega, J., Ziv, G., Chapman, P.J., Holden, J., Cardwell, M., Fyfe, D., 2023. A window into land managers' preferences for new forms of agri-environmental schemes: evidence from a post-Brexit analysis. Land. Use Policy 129, 106627. https://doi.org/10.1016/j.landusepol.2023.106627.

Ulrich-Schad, J.D., de Jalon, S.G., Babin, N., Pape, A., Prokopy, L.S., 2017. Measuring and understanding agricultural producers' adoption of nutrient best management practices. J. Soil. Water Conserv. 72, 506–518. https://doi.org/10.2489/jswc.72.5.506.

Van Vliet, M.T.H., Thorslund, J., Strokal, M., et al., 2023. Global river water quality under climate change and hydroclimatic extremes. Nat. Rev. Earth Environ. 4, 687–702. https://doi.org/10.1038/s43017-023-00472-3.

Villanueva, A.J., Rodríguez-Entrena, M., Arriaza, M., Gómez-Limón, J.A., 2016. Heterogeneity of farmers' preferences towards agri-environmental schemes across different agricultural subsystems. J. Environ. Plan. Manag. 60, 684–707. https://doi.org/10.1080/09640568.2016.1168289.

Villanueva, A.J., Perni, A., Barreiro-Hurle, J., 2026. Choice experiments on land managers' participation in environmental programs: a systematic review and meta-analysis of estimate validity. Am. J. Agric. Econ. https://doi.org/10.1002/ajae.70073.

Vivanco, D., Freire-González, J., Galvin, R., Santarius, T., Walnum, H.J., Makov, T., Sala, S., 2022. Rebound effect and sustainability science: a review. J. Ind. Ecol. 26, 1543–1563. https://doi.org/10.1111/jiec.13295.

Wang, M., Bodirsky, B.L., Rijneveld, R., Beier, F., Bak, M.P., Batool, M., et al., 2024. A triple increase in global river basins with water scarcity due to future pollution. Nat. Commun. 15, 880. https://doi.org/10.1038/s41467-024-44947-3.