Check for updates

Received: 25 October 2023 | Accepted: 25 February 2024

DOI: 10.1002/jeq2.20558

Journal of Environmental Quality

PERSPECTIVE

Special Section: Through the Lens of Phosphorus—Honoring the Legacy of Andrew Sharpley

Toward better targeting of mitigation measures for reducing phosphorus losses from land to water: Andrew Sharpley's legacy in Norway and Sweden

Jian Liu[1] | **Faruk Djodjic**[2] | **Barbro Ulén**[3] | **Helena Aronsson**[3] | **Marianne Bechmann**[1] | **Lars Bergström**[3] | **Tore Krogstad**[4] | **Katarina Kyllmar**[3]

[1]Department of Soil and Land Use, Norwegian Institute of Bioeconomy Research, Ås, Norway

[2]Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden

[3]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden

[4]Faculty of Environmental Science and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Correspondence

Jian Liu, Department of Soil and Land Use, Norwegian Institute of Bioeconomy Research, 1431, Ås, Norway.
Email: Jian.Liu@nibio.no

Faruk Djodjic, Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, 75007 Uppsala, Sweden.
Email: Faruk.Djodjic@slu.se

Assigned to Associate Editor Peter Kleinman.

Funding information

Norges Forskningsråd, Grant/Award Number: 336253; Svenska Forskningsrådet Formas, Grant/Award Number: 2019-00696

Abstract

Nordic agriculture faces big challenges to reduce phosphorus (P) loss from land to water for improving surface water quality. While understanding the processes controlling P loss and seeking for P mitigation measures, Norwegian and Swedish researchers have substantially benefited from and been inspired by Dr. Andrew Sharpley's career-long, high-standard P research. Here, we demonstrate how Sharpley and his research have helped the Nordic researchers to understand the role of cover crops in cold environmental conditions, best manure P management practices, and ditch processes. His work on critical source area (CSA) identification and site assessment tool development have also greatly inspired our thinking on the targeting of mitigation measures and the contextualizing tools for Nordic climate, landscape, and soils. While reflecting on Sharpley's legacy, we identify several needs for Norwegian and Swedish P research and management. These include (1) tackling the challenges caused by local/regional unevenness in livestock density and related manure management and farm P surpluses, (2) identifying CSAs of P loss with high erosion risk and high P surplus, (3) obtaining more high-resolution mapping of soils with low P sorption capacity both in the topsoil and subsoil, (4) improving cross-scale understanding of processes and mitigation measures and proper follow-up of applied mitigation measures, and (5) increasing collaborations of researchers with farmers and farmers' advisory groups and watershed groups by developing high-quality educational courses and extension materials. The needs should be addressed in the context of the challenges and opportunities created by climate change.

Abbreviations: AL, ammonium acetate-lactate extraction; CSA, critical source area; DPS, degree of phosphorus saturation.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2024 The Authors. *Journal of Environmental Quality* published by Wiley Periodicals LLC on behalf of American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

1 | INTERACTIONS DERIVED FROM COMMON INTERESTS

In both Norway and Sweden, the water quality of many lakes and other surface waters needs to be improved by reducing agricultural phosphorus (P) losses (HELCOM, 2018; Solheim et al., 2022; WISS, 2023). Like elsewhere, both countries have substantially benefited from and been inspired by Dr. Andrew Sharpley's global-wide legacy and impact on agricultural and environmental P research and management. Sharpley's impact dated back to his early work on soil P solubility (Sharpley et al., 1988) and P transport in runoff (Sharpley, 1980, 1985), which received close attention by Swedish and Norwegian researchers in the 1990s (Øgaard, 1996; Otabbong & Persson, 1991). Sharpley's systematic work on understanding of soil P forms and dynamics (Sharpley, 1995a; Sharpley et al., 2004), relating agronomic soil P status to environmental P losses (Sharpley, 1995b; Sharpley et al., 2013), identifying critical source areas (CSAs) (Sharpley et al., 2011), designing of P management strategies (Dodd & Sharpley, 2016; Sharpley et al., 2000), and development and application of P models and tools (Sharpley, 1990; Sharpley et al., 2003, 2017) has had a profound impact on our understanding of P processes in soil and runoff water, and of P mitigation efforts.

In addition to his published works, Sharpley has collaborated directly with Norwegian and Swedish researchers in several ways, including student supervision and staff training, and provided valuable inputs to many more activities. Due to his contributions, he was awarded an honorary doctorate at the Swedish University of Agricultural Sciences in 2011. In this paper, we aim to highlight a few areas where Sharpley and his work helped advance Norwegian and Swedish P research and management, as part of appreciation for his extraordinary work on P. Also, we intend to use the opportunity to summarize remaining research needs in the Nordic countries. Specifically, Section 2 highlights how Sharpley's work helped address some of the knowledge gaps in Norway and Sweden (also see Figure 1), Section 3 reflects on approaches and needs for collaboration and communication with farmers, and Section 4 summarizes remaining research needs in Norway and Sweden.

2 | SIGNIFICANT KNOWLEDGE AND TOOLS CREATED

Sharpley's work contributed to filling several gaps in Norwegian and Swedish P research and management. His direct contributions include understanding P behavior in cold environmental conditions, assessing best manure P management practices, developing a Norwegian version of P Index, and improving the representation of P transport in decision support tools. Indirectly, he has also considerably influenced Norwegian and Swedish P research through his impactful research, publications, and presentations.

Core Ideas

- Challenges in local/regional livestock density unevenness, manure management, and phosphorus (P) surplus should be tackled.
- Critical source areas of P loss with high erosion risk and high P surplus should be identified.
- High-resolution mapping of soils with low P sorption capacity both in the topsoil and subsoil is needed.
- Researchers should collaborate with farmers and farmers' advisory groups and watershed groups.
- Cross-scale understanding of processes and mitigation measures and follow-up of applied measures are needed.

2.1 | Cover crops in cold environmental conditions

Due to its high latitude, Nordic agriculture faces challenges in environmental nutrient management associated with short growing seasons. After harvest of annual crops, the soil is often left without vegetation for a long period. As a result, there is a high risk of erosion and nutrient leaching due to low plant cover and small uptake of nutrients by plants during autumn, winter, and spring. Although the time window is often quite narrow for crop growth and nutrient uptake after harvest of main crops, the use of cover crops was successfully introduced as a measure for reducing nitrogen leaching from crop rotations with annual crops and for reducing erosion and the loss of particle-bound P on high-slope fields (Aronsson et al., 2016). However, the fact that vegetation can become a source of dissolved P loss from land to water when plant cells are damaged by frost and release P (Sharpley, 1981) is also true for cover crops (Liu et al., 2019). These possible contradictory effects on nitrogen and P losses from fields need to be considered in the development of mitigation strategies on farms.

With the help of Sharpley and his colleagues (e.g., Peter Kleinman), Nordic researchers improved the quantification of cover crop effects on P losses in cold environmental conditions. Using packed soil boxes for surface runoff quantification and intact soil columns for leaching, Bechmann, Kleinman, et al. (2005) evaluated the effect of freeze-thaw on the fate of P from soils with an established annual ryegrass cover crop as compared to bare soils and manured soils.

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

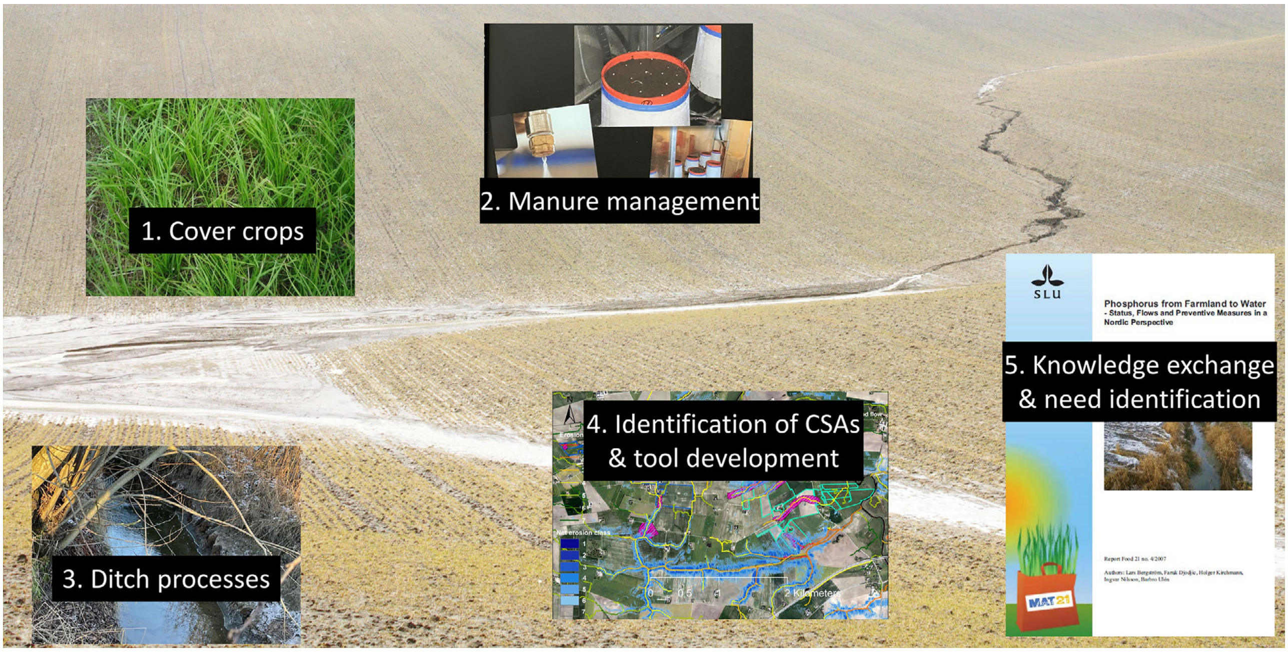

FIGURE 1 A diagram illustrating Sharpley's contributions to Norwegian and Swedish P research and management, which are explained in detail in Sections 2 and 3 (photos: NIBIO and SLU).

The study showed that the cover crop reduced particulate P together with dissolved P in surface runoff before freeze-thaw due to lesser soil erosion but increased dissolved P concentrations in runoff after freeze-thaw owing to the release of biomass P, as compared to manured or bare soils. There was no significant difference in total P leaching between columns with cover-cropped and non-cover-cropped soils. The study well demonstrated the multi-faceted, sometimes conflicting, effects of cover crops in cold production regions.

Although nutrient release from vegetation to water had been observed as early as 1720s (Hales, 1727) and reported in pioneer studies (Sharpley, 1981), the work of Bechmann, Kleinman, et al. (2005) re-sparked a Nordic-wide research interest to further assess cover crops and identify promising species with less P losses in cold conditions (see review of Liu et al., 2019). This included a Swedish PhD project with Sharpley as an assistant supervisor (Liu, 2013), in which eight different cover crops, including both annual and perennial species, were assessed through combined greenhouse and field growth experiments and laboratory rainfall simulations. The studies confirmed the release of P, mainly in the dissolved form, from all cover crops after freeze-thaw cycles (Liu et al., 2013). The tested cover crops differed in biomass production and P uptake, distribution of P between above-ground parts and roots, and resistance to frost over the winter (Liu et al., 2015), resulting in varying contributions to P leaching (Liu et al., 2014). Øgaard (2015) found that the minimum temperatures were important for the ranking of different plant species with respect to the risk of off-season P leaching. The studies suggest that cover crops use in cold agricultural regions needs special attention due to their agronomic and ecological effects, which are all climate dependent. The selection of cover crop species based on climate and soil conditions is thus important for utilizing their potential for improving water quality.

2.2 | Soil and placement considerations for manure

Manure management poses significant challenges from the perspective of water quality protection, particularly in livestock-intensive regions. Northern European studies have shown that manure applications have both incidental (Withers et al., 2003) and long-term effects (Liu et al., 2023) on P losses from land to water. In both Sweden and Norway, there is an elevated risk of nutrient losses when manure is applied on frozen and wet soils during the non-growing season, due to a large water surplus and inefficient nutrient use by crops. Therefore, regulations have been implemented since three decades ago to ban or restrict manure applications in late fall and winter (Liu et al., 2018), with regional adaptions for sensitive areas. Also, regulations were implemented to cap livestock densities in order to achieve a balance between manure production on farms and land area for spreading based on a maximum allowed manure P application rate. However, there was a lack of knowledge on the effects of manure placement on P losses from different types of soils.

With Sharpley's help, Liu et al. (2012) assessed the effects of manure broadcast versus incorporation on P leaching from

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

topsoils of a loamy sand and a clay loam and compared the manure treatments with a chemical fertilizer. The study was conducted using rainfall simulations on intact soil columns. Without any P additions, the loamy sand had significantly higher dissolved P and total P concentrations than the clay loam, owing to a higher soil test P value of the loamy sand resulting from long-term manure amendments to this soil. However, contrasting results were observed for the soils following the P applications. While both dissolved P and total P concentrations and loads remained unchanged in leachate from the loamy sand, they substantially increased in the clay loam, which was explained by the differing flow paths in the soils.

Phosphorus transport was most likely dominated by matrix flows in the loamy sand (Djodjic et al., 1999), which allowed efficient sorption of P into the soil during the leaching processes (McDowell et al., 2001a). As a result, the manure and fertilizer treatments had similarly, relatively small P losses. However, in the well-structured clay loam, P transport is known to be dominated by quickflow through large continuous voids (Djodjic et al., 1999), through which some of the added P most probably bypassed the sorption sites (McDowell et al., 2001a). In a previous study on a heavy clay soil with fertilizer P, P leaching losses were significantly reduced by incorporating the fertilizer into the soil (Djodjic, Bergström et al., 2002). When the manure was incorporated in the clay loam, it substantially reduced losses of all P forms as compared to the surface application to a level similar to the surface-application of chemical fertilizer but still much higher than without a P application and than any treatment to the loamy sand. These studies (Djodjic et al., 1999; Djodjic, Bergström et al., 2002; Liu et al., 2012) and many others outside the Nordic countries (e.g., Grant et al., 2019; Sharpley et al., 2001; Sims et al., 1998; van Es et al., 2004) stressed that soil types should be considered when assessing the risks of P losses and that manure and fertilizer P should be carefully incorporated into the soil in order to improve the contact between manure and soil and reduce the risk of P losses to waters.

2.3 | Phosphorus processes in sediments of drainage ditches

Drainage ditches are very commonly used in Norwegian and Swedish agriculture to carry water from cultivated fields, and most clay and silty soils have artificial subsurface drainage systems leading to open ditches or streams. The processes occurring in the tile drains and open ditches potentially affect the adsorption and release of P. The role of sediments as a source and sink of P was studied by Sharpley's group (McDowell et al., 2001b). Following this research, Norwegian researcher Krogstad conducted a more detailed study with Sharpley's group in forest and agricultural ditches, both in the field and the laboratory (Sharpley et al., 2007).

In the study of Sharpley et al. (2007), a fluvarium was used to test the sorption processes in detail and improve the understanding of the importance of both chemical and biological processes in the adsorption and release of P to soil and ditch sediment. A fluvarium is an artificial drainage system consisting of a 10-m open channel in which the slope and water supply can be varied and in which a few centimeters thick layer of sediment or soil is placed. Although the agricultural soil had higher P availability than the forest soil, P adsorption capacity was highest in the agricultural soil due to increased clay content from selective particle erosion and higher biological P uptake by microorganisms. Biological P uptake in manure-influenced sediments was as high as 42% of total P uptake, which showed that biological processes should be considered when evaluating the sorption capacity of ditch sediments on agricultural lands.

Although the study of Sharpley et al. (2007) was conducted in Maryland, the results were relevant for the Nordic countries, which faced similar challenges. The study suggested that information on how sediments respond was important for best management practices to reduce eutrophication. Best management practices may include increasing the residence time of water in ditches to promote biological P uptake, periodically removing particulates to maintain flow capacity for adequate drainage and establishing vegetated buffer zones along ditches to prevent P-rich particulates from entering the ditch.

2.4 | Identification of critical source areas

Studies have shown that the majority (~80%) of diffuse P losses originate from a small proportion of catchment areas (~20%), a situation known as the 80:20 rule (Sharpley et al., 2009). This led to widespread efforts to identify CSAs as a basis for targeting management strategies and conservation practices that more effectively mitigate P transfers from agricultural landscapes to surface waters (Sharpley et al., 2011). Building upon the concept of CSAs, P indices and other site assessment tools were developed around the world in the last 30 decades for assessing the risks of P losses and thereby better targeting of mitigation measures (Kleinman et al., 2017).

2.4.1 | Phosphorus index

The P index, originally developed in the United States, ranks source and transport factors controlling P loss at field and catchment scale, taking into account field and soil characteristics (e.g., slope, erosion risk, soil P status, and flow distance to receiving stream or ditch), varying responses of

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

P runoff to different manure and fertilizer application methods, and influences of soil cover (Lemunyon & Gilbert, 1993; Sharpley et al., 2003). When it is used in combination with nutrient management planning, it helps farmers to tailor their P management decisions using a site-specific approach so that farm-level P losses are reduced while complying with relevant mandatory and volunteering environmental policies (Sharpley et al., 2017).

Driven by a strong interest of the Norwegian water managers for P recommendations to farmers, the Pennsylvania P Index (Sharpley et al., 2003) was introduced and adapted to Norwegian conditions with the help of Sharpley (Bechmann, Krogstad et al., 2005). Similar to the Pennsylvania P Index, the Norwegian P Index is calculated based on weights for individual source factors (soil test P, fertilizer and manure P rate, fertilizer and manure application method, manure P availability, plant residue P, and P removal) and transport factors (soil erosion, flooding frequency, surface runoff class, contributing distance, modified connectivity, subsurface drainage, and soil type). Notably, the Norwegian P Index is based on erosion risks derived from maps of soil type, field slope, and climate variables, for which agricultural fields are classified into four classes with different levels of erosion risks. Moreover, P application rate is modified by crop P removal, and the tool includes P release from plant residues due to frost, flooding frequency, risk of leaching, and annual precipitation. In a test using data from six Norwegian catchments, the calculated P Index values correlated well with the average annual P losses from the agricultural areas within the catchments. The P Index is implemented in "Skifteplan," the most widely used fertilizer planning tool in Norwegian agriculture (Skifteplan, 2022). This means that farmers can have a P Index calculated for all fields on the farm to achieve optimal, environmentally friendly crop production.

In Sweden, a conditional P Index was also developed (Djodjic & Bergström, 2005; Ulén et al., 2011), where conditional rules were introduced to deal with the interplay of multiple factors. The significance of the subsoil P sorption capacity is considered high if slow matrix flow is the dominant transport pathway, but negligible if interaction between subsoil and percolating water is reduced due to quickflow through large continuous voids. A corresponding difference between a clay and a sandy soil was observed by Djodjic et al. (1999). The distribution of water percolating through soil profile into matrix flow and quickflow through continuous voids in the P Index is based on soil structure and soil saturated conductivity. However, this index did not gain broader use due to lack of available input data (Buczko & Kuchenbuch, 2007) and due to the belief that existing regulation of animal density and Swedish flat-rate P application (the maximum P application rate of 22 kg ha^{-1} $year^{-1}$) was already enough to avoid high P surpluses (Foged, 2011). Lack of relevant and reliable input data necessary for the trustworthy identification of CSAs remains an important issue.

2.4.2 | Other P assessment tools and approaches in Norway and Sweden

In parallel to the Norwegian P Index, a model tool called Agricat was developed in Norway for calculating soil and P losses from agricultural areas at the catchment scale (Kværnø et al., 2014). Agricat is greatly different from the P Index in that Agricat estimates annual P losses, whereas the P Index is an indicator of the risk of P loss. Agricat has a strong focus on estimating particle-bound P loss based on soil loss that is based on Norwegian erosion risk maps. In brief, erosion risk maps (https://kilden.nibio.no/) are used to present annual soil loss in surface runoff and subsurface drainage for "standard" autumn plowing (Kværnø et al., 2020). The soil loss is then estimated for actual fields based on tillage and crop factors and by withholding in a grass-coved buffer zone for surface runoff. The soil loss is finally multiplied by total P in the soil and a factor for accounting for the enrichment of soil P in the sediment, that is, enrichment factor developed by Sharpley (1980), to obtain the loss of particle-bound P. The soil total P is derived from soil P-AL values from farmers (P-AL is the standard soil P test method in Norway and Sweden, using ammonium acetate-lactate extraction (AL) developed by Egnér et al. [1960]), based on equations that differ among soil types (Kværnø et al., 2014). The final P loss is modified by any sedimentation pond located in the small stream.

In Sweden, a decision support system was developed as a tool for identification of CSAs at watershed scale, including the Maryland P Index as a first assessment step (Djodjic, Montas et al., 2002). Recently, higher focus has been put on high-resolution mapping of CSAs in Sweden due to increased availability of light detection and ranging data and better resolution of soil texture maps. For instance, CSAs for erosion and overland flow were identified through high-resolution erosion modeling (Djodjic & Markensten, 2019), whereas CSAs for losses of dissolved P were identified through national screening based on water quality monitoring data for 235 small catchments (<50 km^2), geology, and soil properties retrieved in the national soil survey (Djodjic et al., 2021, 2023).

Other approaches have also been developed for identifying CSAs in Sweden. Ulén (2006) suggested the degree of phosphorus saturation (DPS)-AL, based on molar ratio of P and the sum of iron (Fe) and aluminum (Al) extracted with AL (Egnér et al., 1960), as a simple and inexpensive Swedish risk assessment for losses of dissolved P. Within an agricultural catchment, DPS-AL of the soil profile was found to be correlated to water-extracted P (McDowell & Sharpley, 2001; Sharpley, 1982) and other source factors (Sharpley, 1995c) at field and farm scale (Ulén et al., 2011). The critical P source

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

areas represented up to 10% of all arable land in this catchment, which had a hummocky topography. Another approach in Sweden inspired by Sharpley was the development of a questionnaire to be used by agricultural advisors in discussion with farmers for identifying risk sources for P losses on the farm and possible corresponding mitigation measures (Kyllmar et al., 2013). The questionnaire conceptualized actual knowledge on P losses in the crop to stream continuum into an easy-to-use evaluation guide.

3 | COLLABORATION AND COMMUNICATION WITH FARMERS

We strongly support one of the core ideas promoted by Sharpley over the decades that researchers should ensure production and conservation tactics consider farming realities (Sharpley et al., 2015). Indeed, processes controlling P losses from land to water are often site-, soil-, and climate-specific, and thus so is the effectiveness of mitigation measures. Therefore, there are dual needs for P research and management in Norway and Sweden: (1) large quantities of soil P testing and field experiments, and (2) close collaborations between researchers and farmers and those who work closely with farmers, such as soil and nutrient advisory organizations and watershed groups.

In Sweden, a governmental advisory program was introduced in 2000, where farmers are offered free advisory support and education for improved nutrient management. This program also involves further education for staff engaged in advisory service for farmers, and it thereby constitutes an important link between research and practice. In 2018, the Swedish Authority for Water and Marine Management started the project LEVA (local engagement for water) based on a government mandate, where local catchment officers in 20 pilot areas in Sweden develop and support local actions and measurements against eutrophication. Catchment officers are the link between the farmers/landowners, the authorities (municipality or county), and different funding and consulting agencies (Swedish Agency for Marine & Water Management, 2021). The role of research in this context was to offer education to catchment managers and decision support through online platforms to make relevant modeling results easily available, as well as to offer farmers, catchment officers, and all other stakeholders a learning environment (https://arcg.is/1HC001) and an interactive tool to estimate the role of mitigation measures on nutrient losses (https://waterguide.online/nutrient-loss).

In Norway, the effects of mitigation measures are assessed by researchers (e.g., by using Agricat) through projects from regional authorities. These projects require access to farm information collected by the government. Some projects require cooperation with farmers to understand their actual farming practices and motivation and barriers for implementing measures.

Addressing both aforementioned needs will help to improve our understanding of soil and P transport processes and aid in designing most effective mitigation measures. One of the challenges in linking on-farm management to regional P mitigation models is the ownership of soil testing results and on-farm trials by the farmers and their advisors. There is no direct benefit to the individual farmer from sharing this information, but for the common well-being of protecting soil resources and water quality, this data would be of great benefit to the society. A mechanism should be developed to stimulate farmers' interests in research related to P and water quality, through for example, more educational courses and farm visits with improved risk maps.

Extension materials are very important as a media for researchers and nutrient management advisors to disseminate key research findings and recommendations to farmers and as a bridge to enhance the trust and collaborations between researchers and farmers. Due to its non-profit nature (strictly speaking, economically non-profit, but indeed ecologically profitable), the work of environmental P management is unfortunately not a top interest to most farmers. Phosphorus losses are very small in relation to P applied with fertilizers but still have significant ecological effects. Thus, it is even more important to deliver high-quality extension materials to farmers, which are adapted for them.

In the early 2000s, Sharpley brought our attention to the United States' "Innovative Solutions to Minimize P Losses from Agriculture" SERA-17 program (https://sera17.wordpress.ncsu.edu/). Over the years, we have learned from and exchanged information with many members of SERA-17 (Macrae et al., 2024) and adapted some of the relevant knowledge to the Nordic agriculture and benefit Nordic farmers. The information provided in the SERA-17 extension letters was, to a large extent, used as a basis for an inventory of Swedish research needs related to P losses from agriculture (Bergström et al., 2007). Subsequently, a large research program was started in 2008 by the Swedish Farmers' Foundation for Agricultural Research with the aim to develop and evaluate P mitigation measures directly applicable on farms. It involved 24 projects, and the outcome of the program was not only a broadened knowledge about measures for reduced P losses but also increased awareness and a constructive discussion climate between academia and the agricultural sector (Geranmayeh & Aronsson, 2015).

4 | REMAINING RESEARCH NEEDS IN NORWAY AND SWEDEN

Over the last four decades, both Norway and Sweden have made remarkable efforts in agricultural and environmental P research and management, for example, as summarized for Sweden by Bergström et al. (2015). However, big challenges remain for minimizing agricultural P losses. A decade ago,

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Sharpley et al. (2015) made a comprehensive summary of future research needs and directions for the global community of environmental P management, based on the 7th International Phosphorus Workshop held in Uppsala, Sweden, in 2013. Many of the research needs are still relevant to Nordic conditions and have been contextualized to Norway and Sweden by the authors in the present paper. Such needs include the following:

1. Tackling the challenges associated with regional/local unevenness in livestock density and related manure management and farm P surpluses: In both Sweden and Norway, spatially disconnected intensive arable and livestock production systems exacerbate the broken P cycle. In Sweden, livestock production and thereby farm P surpluses are located in the southern part of the country, whereas there is a P deficit in the central parts of the country (Akram et al., 2019). In Norway, very high livestock densities are found in the southwestern part of the country, leading to high manure pressure from slurry and very high soil P contents. In addition, high soil P contents also exist in the cereal-growing areas and regions with potatoes and vegetables, where only commercial fertilizers are used. Locally, high livestock density or uneven distribution of manure on single farms also contribute to increased soil P status over time and thereby increased risk of P loss. The regional and local differences in P balances, soil P status, and consequent risks of P loss should be better addressed through improved management.
2. Addressing the problems caused by deteriorated soil structure and poorly maintained drainage systems: A poor soil structure and lack of artificial subsurface drainage enhance fast flows by surface runoff and the risk of soil erosion. In Sweden and Norway, clay soils and silty soils are especially prone to rapid P erosion losses. Although the soils may be P deficient and have moderate erosion rates, runoff P concentrations may be high due to the enrichment of soil P on suspended particles (Sandström et al., 2020; Ulén et al., 2012; Villa et al., 2015). Moreover, areas with poorly maintained artificial sub-drainage systems are most likely CSAs. Damaged tile drains, in combination with soil cracks, enhance the quick transport of soil material from the soil surface into the drainage system and out to the stream. The drains can also be clogged, which prevents water to reach the stream and results in saturated soils and ponding surface water.
3. Producing more high-resolution maps of soils with low sorption capacity both in the topsoil and subsoil (Djodjic et al., 2021, 2023): When soils have similar flow paths, P loss greatly depends on the sorption-desorption characteristics of the soils. Greater P leaching losses have been found in soils with smaller P sorption capacities in the subsoils (Andersson et al., 2015). However, high-resolution soil maps documenting P sorption capacity are lacking in both Norway and Sweden.
4. Better identification of CSAs: In Norway, although soil loss is quantified for most cultivated land areas based on erosion risk maps (Kværnø et al., 2020), there has been a generally insufficient documentation of the P contents of eroded soil particles at generation, enrichment of soil P on suspended particles during transport, and the fate of P in streams, including P retention and bank erosion. In both Norway and Sweden, moreover, understanding is lacking regarding the distinction between natural background P loss and management-derived P loss. Improved understanding of these, together with those aspects discussed in points (1)–(3), should be integrated to the ongoing efforts in identifying CSAs.
5. Improving our cross-scale understanding of efficacy of conservation measures for reducing P losses from agricultural land to promote cost-effective mitigation programs in the future: Many conservation measures are effective at laboratory, plot, and field scales. At the catchment scale, however, the efforts to mitigate the P losses are complicated and even counteracted by climate change with increasingly extreme weather episodes. This has contributed to the lack of significant downward trends in agricultural catchment monitoring programs (Kyllmar et al., 2023; Sandström, 2022).
6. A proper follow-up of applied mitigation measures and a proper interpretation of the results: As the number of implemented countermeasures and amount of money spent on abatement programs increase, so does also the number of questions regarding the success of implemented measures in terms of improved water quality (Djodjic et al., 2022). However, a proper follow-up of applied mitigation measures is generally lacking in both Norway and Sweden. At a large scale, one should expect a lag time for the response of water quality improvement to implemented countermeasures. The recovery period for soil P generated by reduced P application was demonstrated to be three to four decades in a catchment in the south of Sweden (Ulén et al., 2015). Wastewater contributed to 10% of the catchment total P leaching in the receiving, partly culverted stream. Wastewater and other point sources of pollution prolonged the lag time for mitigating the loading of dissolved reactive P.

In our perspective, Dr. Sharpley's legacies on agricultural and environmental P research and management will continue to inspire Nordic P researchers and managers for a long time. Notably, one of his key legacies to the P community is raising the awareness of better targeting mitigation measures for reducing P losses (Dodd & Sharpley., 2016; Sharpley, 1995c; Sharpley et al., 2003, 2015). In Norway and Sweden, the challenges for reducing agricultural P losses are diverse and

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

complex due to the climate, landscape, and soils, as well as the need of subsidies for the relatively small-scale agricultural production. For these reasons, it is even more important for the countries to develop and implement locally meaningful, cost-effective mitigation measures. In the era of climate change with more and greater extreme weather episodes, such as drought, heavy rains, floods, and in some areas, winters with more frequent freezing–thawing of soil and vegetation, better targeting of mitigation measures is especially important. This means identifying appropriate measures and implementing them at the right places and right timing, based on scientific understanding of the drivers and processes controlling the P loss.

AUTHOR CONTRIBUTIONS

Jian Liu: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Faruk Djodjic**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Barbro Ulén**: Conceptualization; writing—original draft; writing—review and editing. **Helena Aronsson**: Conceptualization; writing—original draft; writing—review and editing. **Marianne Bechmann**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Lars Bergström**: Conceptualization; writing—original draft; writing—review and editing. **Tore Krogstad**: Conceptualization; writing—original draft; writing—review and editing. **Katarina Kyllmar**: Conceptualization; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

The funding was provided by the Research Council of Norway (Grant No. 336253) and the Swedish Research Council for Sustainable Development (FORMAS, Ref. No. 2019-00696).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Jian Liu https://orcid.org/0000-0003-4199-1296
Faruk Djodjic https://orcid.org/0000-0002-2172-242X

REFERENCES

Akram, U., Quttineh, N.-H., Wennergren, U., Tonderski, K., & Metson, G. S. (2019). Enhancing nutrient recycling from excreta to meet crop nutrient needs in Sweden—A spatial analysis. *Scientific Reports*, *9*, Article 10264. https://doi.org/10.1038/s41598-019-46706-7

Andersson, H., Bergström, L., Ulén, B., Djodjic, F., & Kirchmann, H. (2015). The role of subsoil as a source or sink for phosphorus leaching. *Journal of Environmental Quality*, *44*, 535–544. https://doi.org/10.2134/jeq2014.04.0186

Aronsson, H., Hansen, E. M., Thomsen, I. K., Liu, J., Øgaard, A. F., Känkänen, H., & Ulén, B. (2016). The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *Journal of Soil and Water Conservation*, *71*, 41–55. https://doi.org/10.2489/jswc.71.1.41

Bechmann, M., Krogstad, T., & Sharpley, A. (2005). A phosphorus index for Norway. *Acta Agriculturae Scandinavica B Soil Plant Science*, *55*(3), 205–213. https://doi.org/10.1080/09064710510029088

Bechmann, M. E., Kleinman, P. J. A., Sharpley, A. N., & Saporito, L. S. (2005). Freeze–thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. *Journal of Environmental Quality*, *34*, 2301–2309. https://doi.org/10.2134/jeq2004.0415

Bergström, L., Djodjic, F., Kirchmann, H., Nilsson, I., & Ulén, B. (2007). Phosphorus from farmland to water (Report Food 21, no. 4/2007). Swedish University of Agricultural Sciences.

Bergström, L., Kirchmann, H., Djodjic, F., Kyllmar, K., Ulén, B., Liu, J., Andersson, H., Aronsson, H., Börjesson, G., Kynkäänniemi, P., Svanbäck, A., & Villa, A. (2015). Turnover and losses of phosphorus in Swedish agricultural soils: Long-term changes, leaching trends, and mitigation measures. *Journal of Environmental Quality*, *44*, 512–523. https://doi.org/10.2134/jeq2014.04.0165

Buczko, U., & Kuchenbuch, R. O. (2007). Phosphorus indices as risk-assessment tools in the USA and Europe—A review. *Journal of Plant Nutrition and Soil Science*, *170*, 445–460. https://doi.org/10.1002/jpln.200725134

Djodjic, F., & Bergström, L. (2005). Conditional phosphorus index as an educational tool for risk assessment and phosphorus management. *Ambio*, *34*, 296–300. https://doi.org/10.1579/0044-7447-34.4.296

Djodjic, F., Bergström, L., Schmieder, F., Sandström, C., Agback, P., & Hu, Y. (2023). Soils potentially vulnerable to phosphorus losses: Speciation of inorganic and organic phosphorus and estimation of leaching losses. *Nutrient Cycling in Agroecosystems*, *127*, 225–245. https://doi.org/10.1007/s10705-023-10298-6

Djodjic, F., Bergström, L., & Ulén, B. (2002). Phosphorus losses from a structured clay soil in relation to tillage practices. *Soil Use Manage*, *18*, 79–83. https://doi.org/10.1079/sum2001104

Djodjic, F., Bergström, L., Ulén, B., & Shirmohammadi, A. (1999). Mode of transport of surface-applied phosphorus-33 through a clay and sandy soil. *Journal of Environmental Quality*, *28*, 1273–1282. https://doi.org/10.2134/jeq1999.00472425002800040031x

Djodjic, F., Bieroza, M., & Bergström, L. (2021). Land use, geology and soil properties control nutrient concentrations in headwater streams. *Science of the Total Environment*, *772*, 145108. https://doi.org/10.1016/j.scitotenv.2021.145108

Djodjic, F., Geranmayeh, P., Collentine, D., Markensten, H., & Futter, M. (2022). Cost effectiveness of nutrient retention in constructed wetlands at a landscape level. *Journal of Environmental Management*, *324*, 116325. https://doi.org/10.1016/j.jenvman.2022.116325

Djodjic, F., & Markensten, H. (2019). From single fields to river basins: Identification of critical source areas for erosion and phosphorus losses at high resolution. *Ambio*, *48*, 1129–1142. https://doi.org/10.1007/s13280-018-1134-8

Djodjic, F., Montas, H., Shirmohammadi, A., Bergström, L., & Ulén, B. (2002). A decision support system for phosphorus management at a watershed scale. *Journal of Environmental Quality*, *31*, 937–945. https://doi.org/10.2134/jeq2002.9370

Dodd, R. J., & Sharpley, A. N. (2016). Conservation practice effectiveness and adoption: Unintended consequences and implications for sustainable phosphorus management. *Nutrient Cycling in Agroecosystems*, *104*, 373–392. https://doi.org/10.1007/s10705-015-9748-8

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Egnér, H., Riehm, H., & Domingo, W. R. (1960). Untersuchungen über die chmische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Boden. II. Cheimische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. *Kungliga Lantbrukshögskolans Annaler*, *26*, 199–215.

Foged, H. (2011). *Phosphorus indices—Status, relevance and requirements for a wider use as efficient phosphorus management measures in Baltic Sea region*. BalticSea2020.

Geranmayeh, P., & Aronsson, H. (2015). *Phosphorus losses from agricultural land—Causes and effective countermeasures*. Swedish Farmers' Foundation for Agricultural Research. (In Swedish).

Grant, K. N., Macrae, M. L., Rezanezhad, F., & Lam, W. V. (2019). Nutrient leaching in soil affected by fertilizer application and frozen ground. *Vadose Zone Journal*, *18*, 1–13. https://doi.org/10.2136/vzj2018.08.0150

Hales, S. (1727). *Vegetable staticks, or, An account of some statical experiments on the sap in vegetables*. Innys & Woodward.

HELCOM. (2018). *Thematic assessment of eutrophication 2011–2016* (Proceedings No. 156). Baltic Sea Environment.

Kleinman, P. J. A., Sharpley, A. N., Buda, A. R., Easton, Z. M., Lory, J. A., Osmond, D. L., Radcliffe, D. E., Nelson, N. O., Veith, T. L., & Doody, D. G. (2017). The promise, practice, and state of planning tools to assess site vulnerability to runoff phosphorus loss. *Journal of Environmental Quality*, *46*, 1243–1249. https://doi.org/10.2134/jeq2017.10.0395

Kværnø, S. H., Barneveld, R., Heggem, E. S. F., Stratmann, M., & Søvde, N. E. (2020). Beskrivelse av erosjonsrisikokart—Metoder, forutsetninger og bruk. *NIBIO POP*, *6*(37), 12.

Kværnø, S. H., Turtumøygard, S., Grønsten, H. A., & Bechmann, M. (2014). *Modellverktøy for beregning av jord- og fosfortap fra jordbruksdominerte områder: Dokumentasjon av modellen Agricat 2* (Bioforsk Rapport vol. 9 nr. 108). http://hdl.handle.net/11250/2451511

Kyllmar, K., Andersson, S., Aurell, A., Djodjic, F., Stjernman Forsberg, L., Gustafsson, J., Heeb, A., & Ulén, B. (2013). Self-evaluation of P loss risks on the farm and identification of appropriate mitigation measures within the pilot project focus on phosphorus (Ekohydrologi 137). Swedish University of Agricultural Sciences. (In Swedish with summary and appendix in English).

Kyllmar, K., Bechmann, M., Blicher-Mathiesen, G., Fischer, F. K., Fölster, J., Iital, A., Lagzdiņš, A., Povilaitis, A., & Rankinen, K. (2023). Nitrogen and phosphorus losses in Nordic and Baltic agricultural monitoring catchments—Spatial and temporal variations in relation to natural conditions and mitigation programmes. *Catena*, *230*, 107205. https://doi.org/10.1016/j.catena.2023.107205

Lemunyon, J. L., & Gilbert, R. G. (1993). The concept and need for a phosphorus assessment tool. *Journal of Production Agriculture*, *6*, 483–486. https://doi.org/10.2134/jpa1993.0483

Liu, J. (2013). *Phosphorus leaching as influenced by animal manure and catch crops* [Doctoral thesis, Swedish University of Agricultural Sciences]. https://res.slu.se/id/publ/51895

Liu, J., Aronsson, H., Bergström, L., & Sharpley, A. N. (2012). Phosphorus leaching from loamy sand and clay loam topsoils after application of pig slurry. *SpringerPlus*, *1*, Article 53. https://doi.org/10.1186/2193-1801-1-53

Liu, J., Bechmann, M., Eggestad, H. O., & Øgaard, A. F. (2023). Twenty years of catchment monitoring highlights the predominant role of long-term phosphorus balances and soil phosphorus status in affecting phosphorus loss in livestock-intensive regions. *Science of the Total Environment*, *898*, 165470. https://doi.org/10.1016/j.scitotenv.2023.165470

Liu, J., Bergkvist, G., & Ulén, B. (2015). Biomass production and phosphorus retention by catch crops on clayey soils in southern and central Sweden. *Field Crops Research*, *171*, 130–137. https://doi.org/10.1016/j.fcr.2014.11.013

Liu, J., Khalaf, R., Ulén, B., & Bergkvist, G. (2013). Potential phosphorus release from catch crop shoots and roots after freezing-thawing. *Plant and Soil*, *371*, 543–557. https://doi.org/10.1007/s11104-013-1716-y

Liu, J., Kleinman, P. J. A., Aronsson, H., Flaten, D., McDowell, R. W., Bechmann, M., Beegle, D. B., Robinson, T. P., Bryant, R. B., Liu, H., Sharpley, A. N., & Veith, T. L. (2018). A review of regulations and guidelines related to winter manure application. *Ambio*, *47*, 657–670. https://doi.org/10.1007/s13280-018-1012-4

Liu, J., Macrae, M. L., Elliott, J. A., Baulch, H. M., Wilson, H. F., & Kleinman, P. J. A. (2019). Impacts of cover crops and crop residues on phosphorus losses in cold climates: A review. *Journal of Environmental Quality*, *48*, 850–868. https://doi.org/10.2134/jeq2019.03.0119

Liu, J., Ulén, B., Bergkvist, G., & Aronsson, H. (2014). Freezing-thawing effects on phosphorus leaching from catch crops. *Nutrient Cycling in Agroecosystems*, *99*, 17–30. https://doi.org/10.1007/s10705-014-9615-z

Macrae, M., Kleinman, P. J. A., Osmond, D., Shober, A., & Nelson, N. (2024). The importance of consensus science to understanding and managing phosphorus in the environment: SERA-17 and the legacy of Andrew Sharpley. *Journal of Environmental Quality*.

McDowell, R., & Sharpley, A. (2001). Approximating phosphorus release from soil to surface runoff and subsurface drainage. *Journal of Environmental Quality*, *30*, 508–520. https://doi.org/10.2134/jeq2001.302508x

McDowell, R. W., Sharpley, A. N., Condron, L. M., Haygarth, P. M., & Brookes, P. C. (2001a). Processes controlling soil phosphorus release to runoff and implications for agricultural management. *Nutrient Cycling in Agroecosystems*, *59*, 269–284. https://doi.org/10.1023/A:1014419206761

McDowell, R., Sharpley, A., & Folmar, G. (2001b). Phosphorus export from an agricultural watershed: Linking source and transport mechanisms. *Journal of Environmental Quality*, *30*, 1587–1595. https://doi.org/10.2134/jeq2001.3051587x

Øgaard, A. F. (1996). Effect of phosphorus fertilization on the concentration of total and algal-available phosphorus in different particle-size fractions in Norwegian agricultural soils. *Acta Agriculturae Scandinavica B Soil Plant Science*, *46*(1), 24–29. https://doi.org/10.1080/09064719609410943

Øgaard, A. F. (2015). Freezing and thawing effects on phosphorus release from grass and cover crop species. *Acta Agriculturae Scandinavica B Soil Plant Science*, *65*(6), 529–536. https://doi.org/10.1080/09064710.2015.1030444

Otabbong, E., & Persson, J. (1991). Relative agronomic merit of fused calcium phosphate—I. Phosphate dissolution and transformation in incubation experiment with four Swedish acid soils. *Fertilizer Research*, *29*, 173–185. https://doi.org/10.1007/BF01050364

Sandström, S. (2022). *Sources, composition and transport of fluvial sediment and attached phosphorus in agricultural catchments—A cross-scale analysis* [Doctoral thesis, Swedish University of Agricultural Sciences].

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Sandström, S., Futter, M. N., Kyllmar, K., Bishop, K., O'Connell, D. W., & Djodjic, F. (2020). Particulate phosphorus and suspended solids losses from small agricultural catchments: Links to stream and catchment characteristics. *Science of the Total Environment*, *711*, 134616. https://doi.org/10.1016/j.scitotenv.2019.134616

Sharpley, A., Foy, B., & Withers, P. (2000). Practical and innovative measures for the control of agricultural phosphorus losses to water: An overview. *Journal of Environmental Quality*, *29*, 1–9. https://doi.org/10.2134/jeq2000.00472425002900010001x

Sharpley, A., Kleinman, P., Baffaut, C., Beegle, D., Bolster, C., Collick, A., Easton, Z., Lory, J., Nelson, N., Osmond, D., Radcliffe, D., Veith, T., & Weld, J. (2017). Evaluation of phosphorus site assessment tools: Lessons from the USA. *Journal of Environmental Quality*, *46*, 1250–1256. https://doi.org/10.2134/jeq2016.11.0427

Sharpley, A., Krogstad, T., Kleinman, P. J. A., Haggard, B., Shigaki, F., & Saporito, L. S. (2007). Managing natural processes in drainage ditches for nonpoint source phosphorus control. *Journal of Soil and Water Conservation*, *62*, 197–206.

Sharpley, A. H. P. J., Buda, A., May, L., Spears, B., & Kleinman, P. (2013). Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *Journal of Environmental Quality*, *42*, 1308–1326. https://doi.org/10.2134/jeq2013.03.0098

Sharpley, A. N. (1980). The enrichment of soil phosphorus in runoff sediments. *Journal of Environmental Quality*, *9*, 521–526. https://doi.org/10.2134/jeq1980.00472425000900030039x

Sharpley, A. N. (1981). The contribution of phosphorus leached from crop canopy to losses in surface runoff. *Journal of Environmental Quality*, *10*, 160–165. https://doi.org/10.2134/jeq1981.00472425001000020007x

Sharpley, A. N. (1982). Prediction of water-extractable phosphorus content of soil following phosphorus addition. *Journal of Environmental Quality*, *11*, 166–171. https://doi.org/10.2134/jeq1982.00472425001100020004x

Sharpley, A. N. (1985). The selective erosion of plant nutrients in runoff. *Soil Science Society of America Journal*, *49*, 1527–1534. https://doi.org/10.2136/sssaj1985.03615995004900060039x

Sharpley, A. N. (1990). EPIC-erosion/productivity impact calculator: 1. Model documentation. *USDA Technical Bulletin*, *1759*, 235.

Sharpley, A. N. (1995a). Soil phosphorus dynamics: Agronomic and environmental impacts. *Ecological Engineering*, *5*(2–3), 261–279. https://doi.org/10.1016/0925-8574(95)00027-5

Sharpley, A. N. (1995b). Dependence of runoff phosphorus on extractable soil phosphorus. *Journal of Environmental Quality*, *24*, 920–926. https://doi.org/10.2134/jeq1995.00472425002400050020x

Sharpley, A. N. (1995c). Identifying sites vulnerable to phosphorus loss in agricultural runoff. *Journal of Environmental Quality*, *24*, 947–951. https://doi.org/10.2134/jeq1995.00472425002400050024x

Sharpley, A. N., Bergström, L., Aronsson, H., Bechmann, M., Bolster, C. H., Börling, K., Djodjic, F., Jarvie, H. P., Schoumans, O. F., Stamm, C., Tonderski, K. S., Ulén, B., Uusitalo, R., & Withers, P. J. (2015). Future agriculture with minimized phosphorus losses to waters: Research needs and direction. *Ambio*, *44*, 163–179. https://doi.org/10.1007/s13280-014-0612-x

Sharpley, A. N., Curtin, D., & Syers, J. K. (1988). Changes in water-extractability of soil inorganic phosphate induced by sodium saturation. *Soil Science Society of America Journal*, *52*, 637–640. https://doi.org/10.2136/sssaj1988.03615995005200030007x

Sharpley, A. N., Kleinman, P. J. A., Flaten, D. N., & Buda, A. R. (2011). Critical source area management of agricultural phosphorus: Experiences, challenges and opportunities. *Water Science & Technology*, *64*, 945–952. https://doi.org/10.2166/wst.2011.712

Sharpley, A. N., Kleinman, P. J. A., Jordan, P., Bergström, L., & Allen, A. L. (2009). Evaluating the success of phosphorus management from field to watershed. *Journal of Environmental Quality*, *38*, 1981–1988. https://doi.org/10.2134/jeq2008.0056

Sharpley, A. N., McDowell, R. W., & Kleinman, P. J. A. (2001). Phosphorus loss from land to water: Integrating agricultural and environmental management. *Plant and Soil*, *237*, 287–307. https://doi.org/10.1023/A:1013335814593

Sharpley, A. N., McDowell, R. W., & Kleinman, P. J. A. (2004). Amounts, forms, and solubility of phosphorus in soils receiving manure. *Soil Science Society of America Journal*, *68*, 2048–2057. https://doi.org/10.2136/sssaj2004.2048

Sharpley, A. N., Weld, J. L., Beegle, D. B., Kleinman, P. J. A., Gburek, W. J., Moore, P. A., & Mullins, G. (2003). Development of phosphorus indices for nutrient management planning strategies in the U.S. *Journal of Soil and Water Conservation*, *58*, 137–152.

Sims, J. T., Simard, R. R., & Joern, B. C. (1998). Phosphorus losses in agricultural drainage: Historical perspective and current research. *Journal of Environmental Quality*, *27*, 277–293. https://doi.org/10.2134/jeq1998.00472425002700020006x

Skifteplan. (2022). *Skifteplan fertilization program. Agromatic AS*. www.skifteplan.no

Solheim, A. L., Haande, S., Dillinger, B., Persson, J., Skjelbred, B., & Mjelde, M. (2022). Eutrofiering av norske innsjøer Tilstand og trender. NIVA RAPPORT 7744-2022.

Swedish Agency for Marine and Water Management. (2021). *Redovisning av regeringsuppdrag Pilotområden mot övergödning*. https://www.havochvatten.se/om-oss-kontakt-och-karriar/om-oss/regeringsuppdrag/regeringsuppdrag/pilotomraden-mot-overgodning-2018.html

Ulén, B. (2006). A simplified risk assessment for losses of dissolved reactive phosphorus through drainage pipes from agricultural soils. *Acta Agriculturae Scandinavica B Soil Plant Science*, *56*, 307–314. https://doi.org/10.1080/09064710500325889

Ulén, B., Bechmann, M., Øygarden, L., & Kyllmar, K. (2012). Soil erosion in Nordic countries—Future challenges and research needs. *Acta Agriculturae Scandinavica B Soil Plant Science*, *62*, 176–184. https://doi.org/10.1080/09064710.2012.712862

Ulén, B., Djodjic, F., Etana, A., Johansson, G., & Lindström, J. (2011). The need for an improved risk index for phosphorus losses to water from tile-drained agricultural land. *Journal of Hydrology*, *400*, 234–243. https://doi.org/10.1016/j.jhydrol.2011.01.038

Ulén, B., Johansson, G., Kyllmar, K., Forsberg, L. S., & Torstensson, T. (2015). Lagged response of nutrient leaching to reduce surpluses at the field and catchment scales. *Hydrological Processes*, *29*, 3020–3037. https://doi.org/10.1002/hyp.10411

van Es, H. M., Schindelbeck, R. R., & Jokela, W. E. (2004). Effect of manure application timing, crop, and soil type on phosphorus leaching. *Journal of Environmental Quality*, *33*, 1070–1080. https://doi.org/10.2134/jeq2004.1070a

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Villa, A., Djodjic, F., Bergström, L., & Kyllmar, K. (2015). Screening risk areas for sediment and phosphorus losses to improve placement of mitigation measures. *Ambio*, *44*, 612–623. https://doi.org/10.1007/s13280-015-0680-6

WISS. (2023). *Water information system Sweden*. https://ext-geoportal.lansstyrelsen.se/standard/?appid=1589fd5a099a4e309035beb900d12399

Withers, P. J. A., Ulén, B., Stamm, C., & Bechmann, M. (2003). Incidental phosphorus losses—Are they significant and can they be predicted? *Journal of Plant Nutrition and Soil Science*, *166*, 459–468. https://doi.org/10.1002/jpln.200321165

How to cite this article: Liu, J., Djodjic, F., Ulén, B., Aronsson, H., Bechmann, M., Bergström, L., Krogstad, T., & Kyllmar, K. (2024). Toward better targeting of mitigation measures for reducing phosphorus losses from land to water: Andrew Sharpley's legacy in Norway and Sweden. *Journal of Environmental Quality*, 1–11. https://doi.org/10.1002/jeq2.20558

15372537, 0, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/jeq2.20558 by Norwegian Institute Of Public Healt Invoice Receipt DFO, Wiley Online Library on [01/04/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License