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Achieving agricultural and environmental targets in a changing climate requires a whole-system based approach

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Abstract
Feeding the large future population is associated with severe environmental challenges to which climate change is adding further complications and stress to the global food supply system. The strategies to the challenges posed on ecosystem conservation and climate neutrality would be best achieved by integrating the most current scientific findings in 'best practice' policies and their implementation. This paper presents the outcomes from the fourth International Catchment Science Conference in Ireland, a three-day multi-actor conference, and calls for action to improve soil fertility, reduce GHG emissions, increase carbon sequestration, and reduce pollution loss to waters. It was concluded that an accountable management of the agricultural landscape requires a multi-actor, multidisciplinary and multi-scale approach with collaboration between the scientific community, policy makers and farmers. Importantly there should be a focus on linking research, technology, education, information, engagement and innovation. Following needed requirements were identified: (i) long-term monitoring, high-temporal and high-spatial resolution data collection, (ii) combining temporarily and spatially rich datasets, (iii) long-term planning horizons to be adopted by key institutional stakeholders, (iv) mitigation strategies to adapt to changing climate and agricultural practices, and (v) an adequate advisory support and training for farmers. Some progress has been achieved to a situation where it is possible to counter or mitigate some of the more urgent issues in the food systems under consideration in the review.

Keywords Water quality, Soil quality, Greenhouse gas, Mitigation measures, Socio-economy, Knowledge exchange

1 Introduction

The Food and Agriculture Organization of the United Nations (FAO) estimates that by 2050 we will need to produce 60% more food to feed a world population of 9.3 billion [1]. While such a target may be quantitatively feasible, there are large associated environmental challenges due to intensified agriculture contributing to enhanced soil degradation, global greenhouse gas (GHG) emissions, increased runoff and loss of agrochemicals to freshwaters. Climate change further compounds these processes and their impact [2]. Addressing these challenges requires a move away from traditional single-domain research towards a more complete systems science-based approach [3]. In November 2023 ca. 200 scientists, policy makers, regulators, advisors and farmers gathered over three days for the quadrennial International Catchment Science conference in Wexford, Republic of Ireland, to disseminate the latest science and discuss the challenges of achieving both agricultural and environmental goals. Water quality, soil-runoff and soil health/climate aspects are often reported in relative isolation, but the conference covered both. This paper therefore reports current knowledge and pathways in practice that answer the challenge of doing systems science in catchments (Fig. 1). The themes of the conference were: (i) Soil fertility and carbon management; (ii) Gaseous emissions and carbon sequestration; (iii) Land to water contaminant loss; (iv) Long-term, in-situ monitoring and catchment modelling of water quality and greenhouse gases; (v) Climate induced changes; (vi) Approaches for mitigation strategies, and; (vii) Socio-economy,

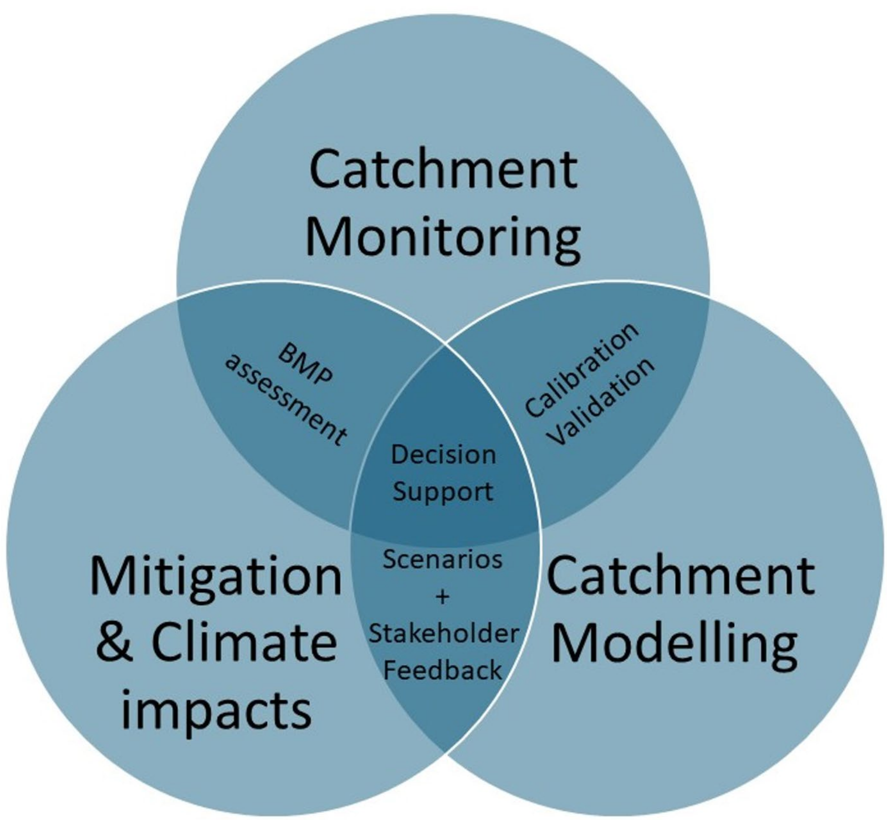

Fig. 1 Conceptual diagram of how the themes of this paper are linked together. This illustrates the synergies and benefits of a whole-system based approach

knowledge exchange and stakeholder engagement; each synthesised here with regard to how such multiple objectives may be achieved and assessed.

The concept of healthy soil is based on the ecological attributes of the soil [4] and soil fertility is one of the key indicators [5]. The FAO defines soil fertility as "the ability of a soil to sustain plant growth by providing essential plant nutrients and favourable chemical, physical, and biological characteristics as a habitat for plant growth" [6]. Sustainable maintenance of soil health aims to enhance long-term crop productivity by ensuring a balanced nutrient supply and improving the soil's physical and chemical properties. This approach not only reduces the loss of applied nutrients but also mitigates the associated negative impacts on the economy, environment and human health, such as high production costs, greenhouse gas emissions, eutrophication, and groundwater pollution [7–9]. Restoration and maintenance of soil health are key to achieving Sustainable Development Goals (SDGs 1, 2, 3, 6, 7, 13 and 15) of the United Nations' (UN) Agenda 2030 [10], while the European Union's (EU) *Soil Strategy for 2030* aims to achieve healthy soils in Europe by 2050 [9]. Globally, policies targeting sources of pollution in agriculture typically employ a mix of regulatory measures, financial incentives, and educational initiatives [11]. One of the main aims of managing agricultural sources of pollution is to enhance the dissemination of good agricultural management practices. Among these, effective nutrient management emerges as a critical area needed for global improvement. Yet, the uptake of nutrient management practices (NMP) among farmers remains limited, and even when implemented, adherence to recommended guidelines is often incomplete [12].

A major challenge for many European countries is the binding GHG emissions reduction Effort Sharing Regulation (EU 2018/842), adopted by the European Council. This is a particular challenge in highly agricultural countries. For example, Ireland's emission reduction target under the Effort Sharing Regulation is to reduce its GHG emissions by 42% by 2030, where the agricultural sector accounts for 38.4% of national GHG emissions [13]. To meet this emission reduction target, Ireland has been granted flexibilities under the Effort Sharing Regulation which include accounting for GHG removals from the Land Use, Land-Use Change and Forestry (LULUCF) sector of up to 26.6 Mt CO_2eq over the period 2021–2030. While this provides Ireland with an opportunity to meet national emission reduction targets through the LULUCF sector, there persists large uncertainties in the LULUCF emission reporting around net emissions and sequestration from grasslands (second largest GHG emitter from LULUCF at circa 2.48 Mt CO2eq in 2022). For example, the area of agricultural soils under drained peat was recently found to be 27–36% lower than previously reported [14]. These findings resulted in significant amendments to the national GHG inventory on drained peat soils from circa. 9.6 Mt CO_2eq to 3.6–4.7 Mt CO_2-equivalent. Therefore, there is an urgent necessity for long-term measurements from LULUCF for more accurate quantifications of the C sink potential of managed pastures.

Land-based climate mitigation measures have a cost-effective potential (up to $100/$tCO_{2eq}$) ranging from approximately 50% from forests and other ecosystems, 35% from agriculture, and 15% from demand-side measures [15]. The ongoing loss of ecosystem carbon (C), its sequestration potential, and related ecosystem services leave an unnecessary debt to future generations [2]. The major potential for carbon sequestration is in cropland soils [16], especially those with large yield gaps and/or large historic soil organic carbon losses [17]. In many European regions, agricultural adaptation options, even when focused on increasing yields, still have the potential to outweigh the negative direct effects of climate change on soil degradation [18]. The potential of land-based mitigation measures varies six-fold across the five regions assessed (0.75–4.8 $GtCO_{2eq}$ yr^{-1}), with the top 15 countries accounting for about 60% of the global potential, and larger countries generally having a higher potential [15].

Agricultural practices do not only have an impact on LULUCF-related GHG emissions but also pose other environmental challenges such as contaminant loss to water. Balancing food production and water quality requires fine-scale risk assessments to identify and target Critical Source Areas (CSAs) of nutrients and pollutants and their delivery pathways. To date, much research focus has been on understanding the delivery pathways and underlying transfer processes of nitrogen (N) [19], phosphorus (P) [20] and sediments [16, 21]. Progress has also been made on other agricultural pollutants such as pathogens [22], anti-microbial resistance genes (ARG) [23], pesticides [24, 25] and pharmaceuticals [26]. Over recent decades, a large body of research has focussed on better understanding the effect of Best Management Practices (BMPs) on the reduction of nutrient and pollutant losses to streams. Reliable identification of the CSAs, especially for erosion, overland flow and connected losses of P, but recently also of dissolved P, has been progressing, with notable advances at a national scale in Sweden [27, 28] and in Ireland [29, 30]. There is increasing recognition of the importance to better understand how detailed characterisation of CSAs can be used to target BMPs to improve their efficiency across field to catchment scales. An additional challenge will be to adapt national agri-environmental schemes from aiming at extensive coverage with equal cost compensation of environmental measures for farmers to result or value-based schemes promoting placement of cost-effective BMPs [31]. Detecting the effects of (targeted) small-scale BMPs on N and P losses at the catchment scale is difficult, due to catchment complexity and legacy effects [32, 33], as well as the continuous changes in land use (urbanisation, changes in population), weather variability and ongoing climate change [34, 35]. However, large-scale interventions targeting application rates, improvements in farmer knowledge and changes in application products, e.g. for pesticides, are easier to detect [25, 36, 37]. It is apparent that BMPs will need to be catchment-specific and target multiple stressors and pollution sources to achieve good ecological status of freshwaters [38].

Long-term hydro-chemical and gaseous emission monitoring in agricultural catchments is needed to assess the impacts of agriculture and climatic drivers on water quality and GHGs. It may further provide calibration and validation data for "black-box" numerical and process-based catchment models. The interrogation of long-term monitoring data has allowed for the detection of persistent and emerging pollutants, including their global and local drivers [39, 40]. Together with river flow data, hydro-chemical time-series can be used to estimate water constituent mass loads [41] and provide evidence for regulatory and policy purposes [33]. This type of monitoring, frequently based on monthly to daily grab or flow-proportional sampling of concurrent discharge and water quality parameters (e.g. temperature, pH, conductivity, turbidity, nutrients and suspended sediments), is typically carried out within observational catchments. When using in-situ automated sensors and analysers, the frequency of the sampling can be increased to sub-daily or even sub-hourly [42, 43], providing valuable information about monitoring uncertainties [44] and the processes underlying water quality and ecological patterns such as: mobilisation and delivery along different flow pathways [45, 46], concentration-discharge relationships [47–49], new analytical methods [46, 50], stream metabolism and nutrient uptake patterns [51]. Calibration and validation of process-based models also requires long-term time-series of discharge and water quality data, typically collected at lower than optimal sampling frequencies [52]. These models allow prediction of concentrations and mass loads for future climate and management scenarios but also enable hypotheses testing such as the effect of specific processes [53] and remediation measures on water quality [54]. As pollutant management decision support continues to evolve [55], data-driven numerical models exploring rich spatial and temporal datasets continue to be developed and improved, and are used to predict pollution risks [56–58], improve understanding of dominant stream processes [59, 60], and help shift farmer behaviour [61].

Climate change is likely to exacerbate land to water contaminant loss, causing further degradation of water quality in rivers. In combination with increasing water temperatures and extreme hydrological events and more variable flow regimes, this will further stress freshwater ecosystems [62, 63]. Climate change can cause both long-term subtle changes, that may change baseline conditions for water quality, and short-term offsets that can pose extreme pressures to water quality [36]. The link between changing weather patterns and water quality can be observed in the extreme hydrological events, and the continuation of climate change mainly affects societies through water availability and quality [64]. Extremes in the global hydrological cycle cause changes in the way critical nutrients N, P, and carbon (C) are transferred between land and rivers [65]. Hydrological extremes (including flooding, drought, wetting-drying) [66] affect how these nutrients are cycled, and these events are expected to increase in frequency and intensity in many regions due to climate change [67]. The nutrient transfer continuum (source, mobilisation, delivery, impact) provides a detailed and focussed approach to framing and understanding the nature of these processes [68] and in a climate change framework [69]. However, differences in local land management practices and catchment characteristics also need consideration [70]. Catchments with different intrinsic physical and chemical settings respond differently to climate change in terms of transfer processes [51]. Development of catchment integrated climate-chemical indicators was suggested to consider the hydro-biogeochemical sensitivity of catchment response to climate variations [71]. Some zones may require more focus. For example, riparian zones are the highly dynamic interfaces between terrestrial and aquatic ecosystems and can be considerably affected by climate change effects. They are particularly vulnerable due to their intermittent hydrological connectivity and highly dynamic water table, associated with their topographic position [72]. Sustainable agricultural systems must therefore be integral to any agenda to address climate change and variability, improve renewable fresh water supply and quality, restore degraded soils and ecosystems and advance food security [73].

Strengthening nutrient mitigation planning by building on informed spatial frameworks for source and transport is paramount. Soil nutrient testing to inform soil nutrient availability to crops, adjustment of fertiliser inputs and the assessment of nutrient loss threats are fundamental to water quality management and an important step to change the perspective and behaviour of stakeholders towards actions that address pollution. Agricultural soil P testing was found useful to protect water quality and provide recommendations for site-specific adjustment (e.g. P fixation) by including environmental parameters [74] or regional variations in geology [27]. Quaglia et al. [75] developed priority area mapping for pesticide pollution mitigation in Belgium. Hewett et al. [76]. demonstrated how actions to engineer catchment systems to sustainable levels can be built on understanding of catchment water cycles and the implementation of proactive interventions that provide and enhance multiple ecosystem services, questions whether traditional mitigation interventions are fit for purpose and proposes bespoke measures/treatment trains. A UK report [77] highlights the basis for moving on from traditional fixed width grass infiltration buffer zones towards site-specific packages of multi-functional buffers, related to structural elements (termed 3D buffers) from deep roots, surface cover to vegetation canopy. Transferable learning into socio-economic instruments for agricultural landscapes [78] can come from urban diffuse pollution mitigation in terms of runoff reduction [79] and rainfall harvesting [80]. As the concept of Nature-based Solutions (NbS) for pollution management gather pace in Europe and elsewhere [81], Waylen et al. [82]. sought to evaluate how in practice they differ from traditional 'restoration' to better answer current societal needs.

The policy framework under the EU legislation (e.g. Water Framework Directive), aiming to achieve "good status" for all water bodies by 2027, represents a top-down approach to water quality improvements and protection. Addressing such complex environmental issues involves the integration of socio-economic aspects with knowledge exchange and stakeholder engagement to help understand the interplay between human behaviour, policy frameworks, and environmental outcomes [83]. In examining the current landscape of socio-economic attitudes towards water quality improvements stemming from agricultural practices, it is evident that the complex interplay of perceptions and policy influences the direction and pace of advancements [84]. Perceptions and policies are influenced by a multitude of interacting factors, and changes in one can have ripple effects on the other. Understanding this complexity is essential for policymakers, researchers, and stakeholders involved in addressing environmental challenges like water quality improvements [85]. While there has been a growing recognition of the significance of agricultural activities in influencing water quality, challenges persist in translating this awareness into tangible policy actions and behavioural changes. Key issues include high levels of heterogeneity at farm level and divergent viewpoints among stakeholders. Furthermore, the potential economic repercussions on farmers and equity considerations for communities reliant on the wider agricultural industry remain an issue. "Bottom up" approaches through targeted interventions and community engagement, such as the European Innovative Partnerships (EIPs), will play an important role in future policy frameworks, stakeholder engagement, conflicting interests, and evolving perceptions [86]. In assessing the current state of knowledge exchange and stakeholder engagement, several challenges emerge alongside notable progress. While there has been increased acknowledgment of the crucial role of collaboration and information dissemination, significant hurdles persist. Communication gaps between researchers, policymakers, farmers, and local communities restrict the efficient sharing of insights and best practices [87]. Moreover, the diverse interests and priorities of stakeholders often hinder consensus-building, and any coordinated action is further hindered by a complex policy environment, with various and frequently divergent policy objectives. Despite initiatives aimed at fostering dialogue and partnership, such as the Agricultural Catchments

Programme (ACP) [88], the Agricultural Sustainability Support and Advisory Program [89] and the One Planet Choices strategy [83, 90], disparities in engagement levels and access to resources persist across regions and demographics. Addressing these challenges requires a concerted effort to bolster communication channels, enhance inclusivity in the decision-making processes, facilitate adoption of BMP by allowing long-term rather than short-term institutional planning [90] and tailor strategies to local contexts. Socio-economic research and knowledge transfer (KT) aspects highlight the need for “bottom-up” approaches and community engagement to be considered along with “top-down” legislative approaches outlined in international and national policy frameworks for water quality protection and improvement [91].

Building on this background, this paper summarises the key outputs and recommendations from the fourth International Catchment Science conference which featured 102 individual presentations (62 oral and 40 poster), two panel discussions and four themed field visits. The objectives were to voice involved stakeholder opinions and concerns, benchmark research findings, highlight knowledge gaps, and provide future directions for the intricate goal of reaching both agricultural and environmental goals under changing climate. All abstracts are available as Supplementary Information (SI).

2 Knowledge gaps and strategic directions

When providing strategic directions for progress within the intersection of agriculture, environmental sustainability and climate resilience, we need to identify knowledge gaps and recognise that there are also other limitations of existing approaches, and gaps in the implementation of mitigation strategies. For example, progress on sustainable agriculture was found to be hampered by disciplinary silos preventing the integration of scientific approaches. Researchers from different fields need to openly examine and question their own assumptions and limitations [92]. Greater use of scientific evidence is a key lever to steer policy toward sustainable goals, yet only a small fraction of such evidence gains salience, and while salient scientific evidence can spark informed debate, it doesn’t always point to a clear guidance for policy [93]. Moving toward sustainable agriculture means aligning social, economic, and environmental policies, and ensuring farmers are recognized and rewarded for managing agroecosystems and cultural landscapes that deliver vital ecosystem services [94].

2.1 Soil fertility, nutrient and carbon management

Current research in this theme was focused on: (i) the need for both agronomic and environmental goals for a healthy soil (structure and fertility); (ii) soil climate mitigation potential and strategic challenges; (iii) required improvements to on-farm nutrient management planning; (iv) the critical role of the riparian ecosystem for nutrient management; and (v) long-term management of N and P in catchments.

Some studies demonstrated the need for farm scale management plans, sensitive to temporal variations in weather and crop growth, for better soil health and fertility. For example, the relevance of soil physicochemical properties on C sequestration, and the significance of land use legacy and soil memory was demonstrated by Bol (SI). There is a gap in local and regional frameworks for land use practices. In a study of soils across four Irish catchments, Žurovec et al. (SI) showed an increase of P, potassium (K) and pH over a 12-year period, highlighting the need for on-farm nutrient management planning.

In Scotland, *Brook et al.*, (SI) observed a degradation of soil structure in winter due to intense rainfall, illustrating the need for farm level management to account for temporal variations in weather. In Finland, Mäkelä et al. (SI) explored boreal sandy loam soils to assess the possibility of reducing the nitrogen load and the volume of drainage water and its susceptibility to leaching, while still increasing yield. This was achieved by combining sub-irrigation with controlled drainage, as an improvement on conventional drainage systems. It was demonstrated by Lynch et al. (SI) how early sowing of catch crops can increase crop yield, and by Kinsella et al. (SI) that sustainable crop yields can be maintained by replacing chemical nitrogen fertilizer with dried poultry manure.

Other studies were focused on monitoring and identifying changes in concentrations of N, C and P, the quality of organic matter and the stoichiometry of dissolved C/N/P in riparian ecosystems from observatories in the UK, Sweden and Germany. These presentations primarily focused on identifying knowledge gaps in sustainable soil management and finding the most effective solutions. While little is known about the impact of soil structure on the availability and release of legacy soil P, Roche et al. (SI) showed that such knowledge may open possibilities to improve the mining of P reserves. Other possibilities in increasing N use efficiency in Irish grasslands were explored by accounting for key variables from soil, weather, climate and management through a modelling approach, for which a conceptual framework was provided by Bhowmik et al. (SI). The development of an assessment frameworks to investigate the potential socio-economic effects of soil degradation on the Scottish economy was further discussed by Baggaley et al. (SI). This would serve the multifunctional purpose of flood prevention, pollutant removal, drinking water availability, improve crop yields and carbon sequestration. An example of the importance of a multidisciplinary ecosystem approach for a better understanding of change processes in complex riparian ecosystems was described by Trojahn et al. (SI).

The panel session (with a variety of local stakeholders) discussed long-term soil nutrient management in catchments. This discussion reflected particularly on N and P use over the decades since the Irish ACP started. One panellist highlighted a disproportionate focus on N rather than P likely because of the strategic requirements around the EU legislation and the EU Nitrates Directive, and related derogation issues. There is no reasonable scientific basis for this, as P is also important for the island of Ireland, and many of the problems emerging (e.g. with water quality) are manifesting because of long term P inputs. One key example is Lough Neagh in Northern Ireland, where lake sediments store large amounts of P. This consequently leads to taking two to four decades to return the lake to "Good" ecological status, even without additional terrestrial inputs of P from agriculture and point sources [95]. These issues have been in consideration for decades (the two first International Phosphorus Workshops were held in Ireland; Wexford in 1995 and in Belfast in 1998) and we need to question whether sufficient progress has been made.

There is considerable room for improvement in soil fertility, nutrient and carbon management. Three areas required for improvement are identified: (i) on-farm nutrient management planning; (ii) knowledge of biogeochemical processes of the riparian zone; and (iii) knowledge of farmers' motivation/constraints.

Despite global efforts aimed at fostering responsible use of N and P and sustainable farming practices to safeguard water quality and mitigate greenhouse gas emissions, there is an evident need to refine on-farm nutrient management planning. The riparian ecosystem is a complex and critical interface between the terrestrial hinterland and the freshwater ecosystem, acting as gateways for the conveyance and modification of macronutrients. The complex nature of riparian zones requires the biogeochemical understanding across C, N and P processes, which is currently limited. Holistic studies are required into process connections across C, N, and P cycles and with additional element cycles mechanistically related to change (e.g., iron). A deeper understanding of farmers' motivations and constraints holds the key to informing decision-making processes, offering insights crucial for addressing looming water quality challenges. Additionally, the role of agricultural advisory services in this context cannot be overstated. Trusted agricultural advisors and access to social capital will significantly influence and guide farmers towards embracing sustainable farming practices [96]. By tackling these challenges head-on and refining spatially explicit nutrient management strategies, stakeholders can make meaningful contributions toward the overarching goal of sustainable agricultural production. Such a strategy requires consideration of the different spatial and temporal scales involved (Fig. 2).

One viewpoint was that we may need to adjust our perspective towards the source of the nutrient transfer continuum [68], away from delivery modifying mitigation options [97, 98] and focus on the harder question about longer-term reductions of 'new' N and P into the system, if we are to make meaningful long-term progress [37, 99].

2.2 Gaseous emissions and carbon sequestration

All presentations in this theme came from the island of Ireland, a testament to both the Irish expertise in this area and the need for data specific to a highly agricultural land mass with a wet and mild climate. Fealy and McCarthy (SI) described the creation of an open data platform, which aims to use standardised site descriptions, measurements and soil parameters across all sites, which users can interrogate for research purposes. The measurements need to span both different spatial and temporal scales. In Ireland, Murphy et al. (SI) showed that this is well underway, with the National Agricultural Soil Carbon Observatory's 28 eddy covariance towers measuring carbon dioxide fluxes from

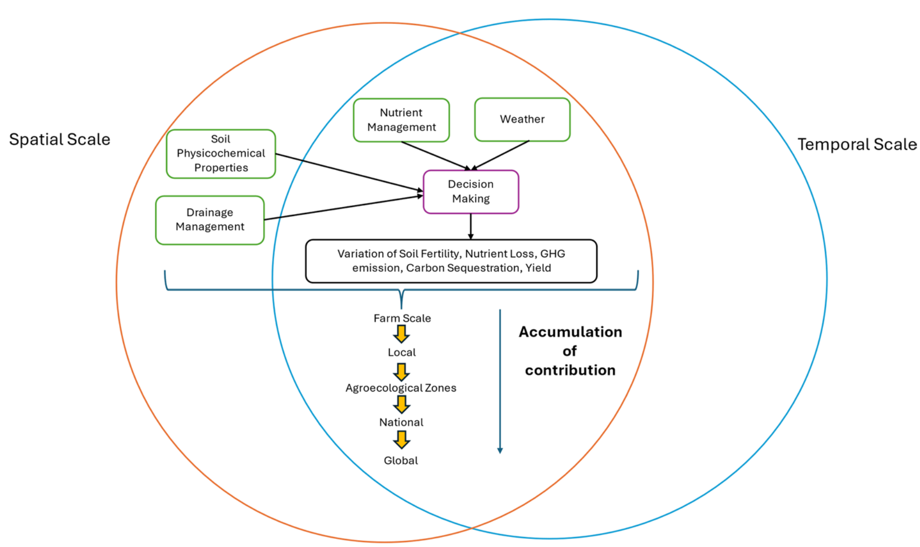

Fig. 2 Conceptual diagram of approach towards spatial and temporal management for sustainable agriculture

farms across the country (Fig. 3), as well as methane emissions from eight farms on peat soils and nitrous oxide emissions from two farms. Implementation of low emission practices on farms are needed to reach European targets. Humphreys et al. (SI) demonstrated an example of clover-based systems, only fertilised with slurry, which resulted in 16% lower nitrous oxide emissions compared to conventional grass-based synthetic fertiliser systems, without impacting on grass production or farm net margins. However, Morton et al. (SI) demonstrated another example highlighting the importance of weather and soil moisture conditions, in which low emissions slurry spreading equipment did not always result in lower ammonia emissions than slurry spread by splash plate, demonstrating the need for measures to be tailored to location and season. Additionally, Balaine et al. (SI) found that there was a substantial heterogeneity in the efficacy of GHG measures on Irish farms, with the largest emitters often seeing the greatest benefits, affecting farmer perception and uptake of a measure.

It is clear from current monitoring programmes that many countries will find meeting the European emissions reductions targets challenging. However, given the uncertainty around inventory values, it is also clear that figures need to be defined on a national scale for agricultural soils. In Ireland, 28 new benchmark sites are established to aid this. Given the large range of available GHG mitigation options, and the heterogeneity of their effects, there also needs to be a refinement of the emission factors of options for different land use specific contexts. Furthermore, a range of values needs to be presented for the mitigative effects rather than just averages, to present potential users of those options with more realistic expectations for their farm.

A *whole system approach*, integrating the impacts of proposed measures on, not only gaseous emissions and carbon sequestration, but also water quality, nutrient management, economic viability and societal needs is required to avoid pollution swapping whilst simultaneously producing sufficient food. However, this necessitates research

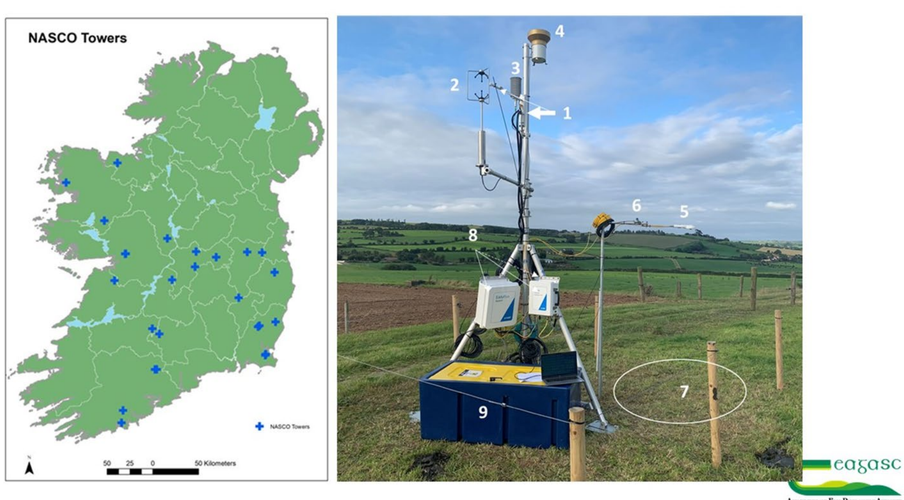

Fig. 3 Left: Map of eddy covariance tower locations that make up the National Agricultural Soil Carbon Observatory (NASCO). Tower locations are situated on different land-uses (grassland, cropland and peatland), managements (intensive and extensive systems) and soil types (mineral and peat). Right: Typical tower set up where (1) enclosed path CO_2/H_2O analyser, (2) 3D sonic anemometer, (3) humidity sensor, (4) rain gauge, (5) net radiometer, (6) quantum sensor, (7) soil moisture/temperature probes, (8) datalogger enclosures and (9) power - battery box. The figure exemplifies the extent of monitoring required to establish figures of GHG emission at the national scales for agricultural soils, here in Ireland

infrastructure to advance rapidly, with data compatibility and comparability, and open data platforms being key to enable researchers to amalgamate and interrogate data from a great variety of sources.

2.3 Land to water contaminant loss

There was a strong relationship found between the proportion of catchment land area above the agronomic optimum for soil test P, runoff risk and waterbody conditions [100]. Water quality improved when farm inputs were controlled and nutrient management planning directed at reducing soil P surpluses. Soil testing, coupled with the identification of areas with high runoff risk, proved to be a powerful tool to optimise nutrient management, target measures and reduce nutrient losses at a catchment scale. Targeting buffer strip design and location to intercept preferential flow pathways was demonstrated by Stutter et al. (SI) to improve their performance. The same is true for the location and design/size of constructed wetlands [101, 102]. However, Quinn et al. (SI) showed that alternative measures, such as in-ditch and in-field sediment traps, have a greater effect on sediment and total P reductions than adjustments to the buffer strip design. Conversely, Heerey et al.. (SI) showed that the installation of in-line leaky barriers to attenuate N and P losses from agricultural ditches had a limited effect. Novel pollutants, such as anti-microbial resistance genes (ARG), present a widespread threat to public health and Pagaling et al. (SI) stressed the need for a holistic 'One Health' approach, that recognises the linkages between human, environment and animal health, to address this problem. Residues of veterinary medicines in manure may be contributing to this problem, however our understanding of 'background' levels of ARGs in livestock-dominated catchments is limited and higher temporal and spatial resolution monitoring is needed to inform mitigation measures.

It is becoming clear that we need to move mitigation efforts further 'upstream' in the source-mobilisation-delivery-impact continuum. This means focussing on 'farm-gate' or 'system-based' interventions that address agronomic practices at larger scale. Cassidy (SI) stressed that these should prioritise source control through reduction of soil P surpluses to the agronomic optimum, and also through introduction of cover-crops to reduce nitrate leaching as proposed by Sheriff et al. (SI) and aim to balance nutrient surpluses at a watershed scale. Drohan et al. (SI) presented a 'manure-shed' approach, whereby areas that can absorb nutrients (sinks) are linked to livestock areas that produce nutrients (sources) in a targeted way, has been shown to achieve double-digit nutrient reductions, whilst maintaining profitability. Drohan et al. (SI) further showed that such targeted land reorganisation offers new economic opportunities for local fertiliser and biogas production and promotes circular economy. However, natural constraints related to physical landscape and climate may limit the extent to which this can be realised, such as in livestock dominated regions with limited arable potential [103].

To address nutrient surpluses at the required scale, it may be necessary to take a *whole system approach* upstream in the food chain, as large nutrient surpluses originate from the protein-rich diets and P additives used in the food industry [104–106]. Reducing dietary protein intake by 25% could help to reduce the area of land required for food production alongside the burden on sewage treatment systems [107].

Future work needs to focus on: (i) clarifying barriers to BMP implementation; (ii) KT strategies, particularly advisory support to farmers, to improve uptake of BMPs; and (iii) evaluation of BMPs for multiple contaminants to avoid pollution swapping. Cost evaluation is critical to offer realistic solutions that consider social, economic and biophysical aspects, informed by inter-disciplinary and trans-disciplinary science co-created with stakeholders. Balancing farmer implementation of BMPs and farming strategies will likely need to be coupled with society-wide P capture and recycling and society-wide dietary shifts if water quality goals are to be achieved.

2.4 Long-term, in-situ monitoring and catchment modelling of water quality and greenhouse gases

Both high-frequency and long-term data are required to: provide a process-based understanding of pollutants and interactions, provide insights into seasonality, facilitate trend analysis, explore and calibrate catchment-scale models, improve water quality forecasting, explore proxy monitoring, and demonstrate results of actions. However, Bieroza (SI) asked; is there a fear of missing out, where the question arises; what length of high-frequency water quality time series is needed? Several studies demonstrated the use of long-term data series, which increased in value the longer period the data spanned. For example, Mårtensson et al. (SI) showed that in Sweden, modelled data of standard leakage rates of N and P from arable land was compared with 25-years of monitored data. In another example by Petersen et al. (SI), Danish long-term (> 30 years) dataset of N losses found that the environmental impacts from agriculture can be reduced. Fisher et al. (SI) showed that in Norway, N losses from agriculture were estimated from long-term (30 years) data sets to evaluate the efficacy of mitigation measures. Water quality monitoring for 30-years has provided knowledge on hydrological regimes, agricultural management, sediment and nutrient losses from typical agricultural production areas in Norway. Ugstad et al. (SI) stressed that long-term monitoring is particularly important for assessing climate change impacts on nutrient and sediment losses from agriculture.

The importance of available high-frequency and long-term datasets for a range of catchment-scale model approaches was apparent. Several examples of models and model approaches for a better process-based understanding of the pollutant dynamics and pathways were presented. For example, in Denmark a large data set supported a newly developed machine learning TP-model. Kronvang et al. (SI) demonstrated that the model was a valuable tool both for calculating TP-loadings from ungauged areas to lakes and coastal waters, and for linking catchment pressures to stream ecological status. The SimplyP model [108] produced a good representation of hydrological, sediment, and P fluxes in a hydrological flashy Irish ACP catchment. However, it was stressed by Hawtree et al. (SI) that catchment-specific attributes and hydrological dynamics are important to consider. Two approaches for modelling N and P fluxes (the Materials Flow Analysis (MFA) [103] and the CRAFT model [109]) were used by Adams et al.. (SI) to assess scenarios of adopting land use change and mitigation measures in the trans-border Neagh-Bann catchment in the north of Ireland. The high-resolution data from the ACP (Fig. 4) allowed Negri et al. (SI) to test different model structures and elucidate the importance of different processes in model representation. That approach facilitated learning between models and data, when using probabilistic Bayesian Belief Network-based models (BBNs) of P concentrations and showed that knowledge of catchment processes and pathways was more important than the data frequency, at least when modelling monthly concentrations with the BBN approach [110]. The high-frequency data progressed the

Fig. 4 High-frequency water quality and hydrometric monitoring station within the Irish Agricultural Catchments Programme. This setup monitors concentrations of total reactive phosphorus, total phosphorus, total oxygenated nitrogen, total organic carbon and suspended sediments (derived from turbidity) together with electrical conductivity, temperature and river discharge (derived from river stage). All data is collected at a sub-hourly resolution since 2009. This shows that high-frequency monitoring requires a robust setup for long-term monitoring

BBN field through validation, which is commonly infrequent in these models [111]. A new method to model the impact of water and nutrient retention measures using SWAT + was demonstrated for a German catchment by Strauch et al. (SI). Eichenberger (SI) also used the SWAT + model to explore the impact of soil map resolution in a Swiss catchment. Long-term in-situ monitoring water quality data can be used for modelling of microbial water quality as described by Rusk et al. (SI). In another example by Thompson et al. (SI), it was shown that high-frequency monitoring of fluvial, gaseous and total C flux from peatland, will support the assessment of seasonality of dissolved and particulate organic C exports during the different stages of peatland restoration.

Virtanen (SI) showed that high-frequency and long-term data can also support models that enable water management simulations in the field, without time-consuming, expensive, field monitoring campaigns, or to use modelling as a first step in decision support to find the most effective ways to mitigate nutrient loads in agricultural catchments [54]. Quinn et al. (SI) used high-frequency data to model Nature-based Solutions, which can play a major part in improving water quality. Dash et al. (SI) demonstrated another approach that can assist policy makers in planning a sustainable management framework for maintaining the water quality and quantity in the best possible way is a remote sensing-based modelling, using readily available satellite imageries for mapping the distribution of different land use/land cover classes in a given period. Proxy measurements may be needed to overcome large costs in monitoring of some compounds. There are however questions about the implications of using e.g. turbidity from in-situ sensors as a proxy for TSS and TP. With high-frequency data, we can achieve a good description of temporal variation in the modelled output, but the results are still uncertain due to the proxy relationships [112].

Priorities for future research are: 1) to disentangle the effects of individual drivers and processes on water quality (for both hydrology, biogeochemistry and land management); ii) improving spatial and temporal representation of water quality patterns and processes by combining high-spatial and high-frequency data analysis and modelling; iii) effectively coupling models that are focused on different domains but are inherently linked (e.g. terrestrial, freshwater and marine models); iv) identifying proxies for difficult to determine water quality parameters using available measurements and "soft" qualitative data; v) improve model representation of instream processes and point pollution sources; vi) data-driven and process-based models for apportionment of point vs. diffuse, primary vs. secondary and current vs. legacy pollution sources; and vii) models that represent the uncertainty in both knowledge and data.

Some of these challenges are only possible to address by joint efforts from multi-disciplinary research and stakeholder groups, as evidenced by the conference presentations and discussions. There is also a challenge of maintaining long-term monitoring infrastructure and datasets that require sustainable funding sources.

2.5 Climate induced changes to soil and water pressures

Significant anthropogenic warming has been observed globally, with impacts on the physical and biological systems [113, 114]. Higher temperatures in soils can lead to shifts in abundance, community structure and activity of micro-organisms [115] and may harm beneficial micro-organisms [116]. Although enhanced microbial activity can accelerate decomposition and nutrient release, it may also increase nutrient and CO_2 uptake by microorganisms [117]. Dry conditions may slow down microbial growth, decrease nutrient needs, and limit CO_2 release [118]. When drought occurs, soil aggregates can disintegrate, the surface can crust, and the soil can become more water-repellent, harming its structure [119]. Wetter conditions and flooding cause soil erosion, nutrient loss, oxygen depletion and disruption of micro-organisms activity [119].

In the UK, where meteorological observations are also indicating signs of anthropogenic climate change, Murphy C et al. (SI) stressed that this would have a major impact on losses of nutrients to water bodies, with considerable seasonal and regional variability. There is, however, a lack of understanding on how climate change will impact on for example P losses from agricultural landscapes [120]. The transfer processes for P and the N losses associated with changing weather patterns are predicted to be different for different catchment typologies [121, 122]. The effect of more seasonality and more frequently occurring weather extremes, such as severe droughts and heavy rainfall events, was assessed by Meresa and Murphy (SI), by running water quality models using far-future scenarios (RCP4.5 and RCP8.5). Nitrate loss was modelled by Hermans et al. (SI) at the catchment scale using SWAT and P loss by Negri et al. (SI) and Adams K et al. (SI) using a probabilistic model based on a BBN approach. The BBN approach concurs with other process-based approaches [123] showing that ensemble-driven climate changes alone may not impact P concentrations significantly. Mellander et al. (SI) used far-future scenarios to estimate P transfer in hydrologically contrasting catchments, indicating a stability in P mobilisation but a large increase in P delivery by the end of the century [122]. More frequent rain events will hydrologically connect P mobilisation areas, and the concept of Critical Mobilisation Areas (CMAs) was recommended to target future mitigation strategies [122]. Ezzati et al.. (SI) stressed that the development of climate resilient mitigation measures, management decisions, and practices require consideration of seasonality and to be tailored to catchment characteristics [121]. On the other hand, evaluating the impact of changing climate on agricultural water resources and development of adaptation measures makes it necessary to develop metrics that capture potential evapotranspiration to monitor and assess future drought risk. While riparian zones have been recognised as being key “active zones” for nutrient cycling, Haygarth et al. (SI) stressed that certain riparian locations, may theoretically become hyperactive zones under future climate change scenarios. For example, Stutter et al. (SI) presented a study in which scientists from Scotland, England, Germany and Sweden focussed on a riparian project to assess whether nutrient loads and fluxes will be significantly altered by increasing temperatures, shifting water table dynamics and catchment morphology in riparian zones.

The impacts of changing weather patterns on water quality correlate to changes in discharge volume and are strongly controlled by rainfall and temperature [124–126]. The risks to water quality arising from changing rainfall patterns and varying annual temperature profiles pose serious direct and indirect challenges for water services infrastructures through (a) long-term alterations to current climate conditions, and (b) severe changes to intensity and frequency of extreme hydrological events [127]. The highest emissions scenario (RCP8.5) developed to force climate change projections foresee an increased frequency of summer draughts and heavy rainfall events in autumn and winter for large parts of Western Europe [128]. Meanwhile, the inadequacy of existing policy measures for climate adaptation and sustainable water resource management would further stress the provision of water of good environmental status and of high-quality drinking water, unless the pace and scale of implementing adaptation actions increase considerably to address the escalating climate risks across Europe [129].

Climate change also strongly affects farming by shifting growing seasons and reducing crop yields and quality. Rising temperatures are expected to lengthen the growing season and increase reliance on agrochemicals, while also prompting adjustments in crop rotation [130]. In addition, drought conditions may shift planting dates and drive the adoption of drought-tolerant species [131]. Droughts can also lead to shorter grazing periods and alternative feeds [132]. Wetter conditions and flooding can lead to the introduction of new flood tolerant species [133]. Flooding may change grazing patterns, restrict access to pastures, and increase the risk of livestock diseases [134].

Mitigation strategies for pollutant loss to water need consideration of both long-term subtle changes and short-term drastic events [35, 135]. Capturing such changes and events requires high spatial and temporal resolution monitoring of water quality. Climate resilient measures should also consider changes in seasonality [121], as a driver of changes in nutrient concentrations due to changes in hydrological flow pathways and associated biological processes [136], and site characteristics [125] which influence the resilience of catchments in the face of increased rainfall intensity [137]. There is a need to identify source/mobilisation areas and to understand the underlying transfer processes behind water quality impacts [122, 138]. There is a further need to identify the major drivers and controls of pollutant losses [139], analyse the complex link between drivers and climate-induced changes in the water cycle [140], and develop appropriate scales, guidelines and tools to efficiently equip water managers and policy makers [98]. Assessing the credibility of different climate model ensembles and development of more accurate and precise climate change scenarios that are applicable at a smaller scale corresponding to different catchment typologies and reflecting technological and socio-economic changes [141] would increase the efficacy of future projections. This would ensure socioeconomic benefit of water management [142] by allowing in-time implementation of mitigation measures and climate adaptation plans to prevent sudden losses of nutrients in the future.

2.6 Approaches for mitigation strategies

There was a strong emphasis on understanding and harnessing natural processes in pollution abatement (NbS) [143]. Emphasis was placed on the importance of effective measure selection for site context ('right measure') and placement ('right place') to increase mitigation efficiency, especially promoting treatment trains (e.g. in-field (source) linked with edge-of-field (pathway interruption)) and packages of measures in the field edge space [144, 145]. An example being the utilisation of a variety of runoff pathway specific and multiple benefit measures at field edges instead of default simple grass buffer zones [146]. Specific mitigation examples included riparian tree planting, effective against bank erosion and river to coastal P loading in Denmark, and constructed wetlands in Sweden being promoted (a concept of 'wet landscapes') for multiple water, air and biodiversity benefits, although it was noted that further guidance was required [147]. Farrow et al. (SI) demonstrated improvements in river and drinking water quality as the result of a scheme in which farmers were refunded all costs to alter their pesticide practices. Technical enhancements included additions of gypsum and subsoiling of grassland to mitigate soil P losses. Another example by Hallberg et al. (SI) was in-ditch remediation strategies (e.g. sediment traps and denitrification), noting potential conflicts in N and P retention. Cost-effectiveness assessment in Ireland brought a new angle to excluding livestock from sensitive areas, where resource losses (soil, nutrient) and pollution vastly outweighed fencing costs. Techniques for the retention and reuse of water and nutrients in small agricultural catchments showed promise and involved biochar and wood chip (including chipping woody debris from floods).

Decision support tools were shown to have a crucial role in selecting between mitigation measures based on farmed landscape factors. Examples were grounded in the principles of CSAs (superimposing runoff response zones with enriched source areas). Djojic et al. (SI) provided examples from Sweden and Stutter et al. (SI), from Ireland which both included user interfaces to access different styles of interactive GIS or question-based landscape risk frameworks. These serve multiple purposes of landscape planning and knowledge exchange on the concepts. However, appropriate guidance/training is required, and this should promote essential farm walkover assessments. A further example of a pesticide web tool showed potential for including monitoring data in online tools to target mitigation [90].

Mitigation strategies require innovative and collaborative adaptive management, as demonstrated by Adams et al. (SI) in the Scottish Eden catchment, where no one sector, or individual management option could achieve agricultural and environmental targets under a changing climate. A wide range of stakeholders are required in the design and implementation of mitigation strategies to address environmental issues and achieve wider stakeholder goals. This further requires both good communication between farmers, catchment programs, advisors, policymakers/regulators and research, and innovation (including monitoring, decision support and agronomic technologies) to support implementation. While farmers are willing to take some risks in mitigation management, externally funded demonstration catchments are important [148]. Effective demonstrators were considered as: (i) small to medium catchments, (ii) above one farm size (not too big and complex) and, (iii) uniting cultural and socio-economic groups. Knowledge should be exchanged internationally on success stories. Good collaborative working models also need 'space' to operate within regulation and funding drawing across areas (e.g. water quality, flooding and biodiversity) where outcomes are multifunctional and complimentary across policies.

Five stages for mitigation strategies were identified: *(i) Planning of mitigation*: this is needed to improve the mitigation efficacy. We need to develop methods that identify critical areas and complimentary series of linked treatments that perform well across multiple functions and ecosystem services (leveraging potential for multiple sector funding and private funding); *(ii) Understanding the impacts*: it is important to build better stressor-response relationships to disentangle and prioritise stressors and understand intervention impacts. We also should improve stakeholder understanding of why we are trying to protect aquatic and terrestrial ecosystems beyond legislative requirement by translating technical impacts to intrinsic and extrinsic values that people derive from ecosystems; *(iii) Promoting land-soil-water thinking*: land, and ownership of land, is essential for mitigation to protect the water environment [149]. Maintaining farm soil resources for economic (e.g. cropping) and environmental goals is recognised as persuasive towards positive actions amongst land managers. *(iv) Accounting for people and behaviours*: co-constructing mitigation strategies will help address social and economic barriers to mitigation measure uptake. Targets for improved socio-economic instruments towards new farming practices include working with farmers towards effective regulation and expanding societal contributions to premiums for environmental stewardship (e.g. through supermarkets); and *(v) Evaluating and ensuring effectiveness*: using monitoring to inform mitigation effectiveness, decision making and improved maintenance of measures, so outcomes persist. Moreover, it is important to communicate evaluation results to stakeholders, develop impact assessments and future effects predictions, and strengthen support for longer-term monitoring where justified.

Some examples of innovations in practice include: (i) the Duhallow Farming for Blue Dot Catchments EIP project, which worked closely with participant farmers in the Allow River catchment to implement interventions such as water bars diverting preferential flow from hard tracks into sedimentation ponds, as well as hedgerow establishment to intercept overland flow run-off; (ii) the EIP-AGRI Focus Group [150], recognizing barriers to uptake of mitigation strategies, this EU report examined digital innovations from researcher-farmer-industry perspectives towards improving decision support tools; (iii) a digital tool communicating the placement of CSAs to practitioners, for better placement and efficiency of mitigation [151]; (iv) 'interactive dashboards' displaying monitoring and interpretation *via* the EU WaterProtect project [152], which targets mitigation and informing local and policy stakeholders; and (v) the EU Waters of LIFE Integrated Project (IP) Framework of Measures for High Status Objective River Water Bodies and the Annex 1 for Agricultural Activities has an effectiveness score for measures (based on expert advisory and research material available at the time). The annex has the capacity to filter the measures by soil drainage type, effectiveness score, and "place" on the nutrient transfer continuum, making the measure very accessible to farmers, advisors, and researchers. Whilst such advances take this applied science forwards, recent assessments showed limited evidence for successful diffuse pollution mitigation outcomes in both the US [153] and Europe [154] highlighting the pressing need to bring technical and social innovation and 'right measure, right place' approaches into widespread practice.

2.7 Farmers' perspective

A farmer panel discussion gave insight into both the opportunities farmers have to implement measures to improve water quality and the associated barriers to overcome. As noted in Sect. 2.1, in Ireland there is room for improvement in soil fertility, nutrient and carbon management, and on-farm nutrient management. This combines well with farmers' opinion, who were positive to continue to improve nutrient balances at field level, which will benefit both farm economy and environment. Soil fertility tests as a basis for fertilisation plans and the optimisation of crop and grass growth, together with the local weather information for better timing of manure application, were measures mentioned as relevant in current production systems. It is highly useful having access to information on water quality monitored within their local catchments. One panellist mentioned the importance of having access to national data on production, financial and environmental metrics.

In three Sect. (2.3, 2.6 and 2.8) KT was brought up as an important component of reaching our environmental and agricultural goals. Also, the farmer panel stressed the importance of the agricultural advisor who not only contributes to knowledge exchange with each farmer but also facilitates sharing among farmers. A relationship with the farmer for several years ensures that changes in farm management happen over time. A hindrance to the farmer-advisor relationship is frequent change in advisors, too many clients and multiple administrative farm support schemes to follow for each advisor.

Measures related to investments reveal more planning for farmers to implement. For improved nutrient management, key investments are related to management of manure such as larger storage capacities, low emission spreading equipment and anaerobic digestion plants. For the planning and setting up of construction and infrastructure investments, the administrative and bureaucratic burden can be large and if a farm succession is due to come, further postponing in changes is common. The farmers again highlighted that support from advisors are important in decisions making in this area.

2.8 Socio-economy, knowledge exchange, stakeholder engagement and call for actions

Bottom-up solutions, stakeholder engagement and collaboration are increasingly a feature of initiatives for water quality protection. Kyllmar (SI) described a Swedish initiative with an ongoing novel collaborative exploration and creation of an active and continuously updated catalogue of the functionality and effect of measures, from a range of national and international research projects. While the focus is on water and nutrient retention, the catalogue also includes other ecosystem services, measures from field to stream and knowledge gaps. Experiences from landowners and users will further be included, with the aim of contributing to the Swedish national water management system. Piil et al. (SI) gave an example from Denmark, where the government has established four coastal water boards to inform the River Basin Management Plan (RBMP) for 2027. For the Hjarbæk water board, there was large variation in N-retention of groundwater and surface waters, with time lags in N responses exceeding 10 years. As presented by Piil et al. (SI), mitigation actions will be implemented through local engagement of stakeholders representing all sectors in the catchment and estuary to implement targeted agricultural/estuarine mitigation measures.

In Ireland, Ryan et al.. (SI) described that there has been a marked increase in collaborative and innovative approaches across the policy, research, enterprise and intermediary (advisory) actors that make up the innovation system for water quality improvement. Since the establishment of the Local Authority Waters Programme (LAWPRO) and the Agricultural Sustainability Support Advisory Programme (ASSAP) in 2018, 190 Priority Areas for Action (PAA) for water quality improvement have been identified in consultation with local communities. LAWPRO uses a catchment science approach to identify locations within PAAs with agricultural point or diffuse sources of N and P losses to water [155]. Meehan and Murphy (SI) explained how farmers in these locations are then visited by ASSAP water quality advisers who undertake farm assessments using biophysical research (e.g. drainage risk assessments) to identify specific risks at individual farm level to recommend targeted mitigation measures. Even though farmer engagement with ASSAP is voluntary, this one-to-one approach is achieving high levels of implementation of mitigation measures [156]. While the Irish EPA water quality report (2023) [155] notes a general decline in water quality, there was a positive impact of the targeting of measures in PAAs, compared to other areas. Related approach has been used in England as part of the Demonstration test Catchment Program [157, 158].

The likelihood of uptake of measures by farmers is an important consideration. Examples of barriers to uptake were the aging farmer population and land ownership challenges, along with the cost and practicality of implementing supplementary measures. Having consulted with stakeholders, Igoe (SI) found that the most appropriate mechanism for the provision of funding to farmers to implement water quality measures was *via* a Water EIP providing €60 million in funding over 5 years. Another study in Sweden stressed the importance of understanding legal rights and responsibilities to overcome barriers to the adoption of measures that benefit the environment and society. Collentine et al. (SI) presented that a high proportion of leased land in EU Member States (e.g. 40% in Sweden and 50% in Germany) presents a barrier to the implementation of land management measures that may reduce productivity or land availability (e.g. buffer zones or wetlands). The importance of farmers' perceptions of the benefits of specific measures was further emphasised. Mitigating the adverse impacts of excessive N use, the important role of innovation (including low emission slurry spreading), the percentage of slurry spread between January and April, and the percentage of N in feed concentrates were found by McCormack et al. (SI) to be highly significant drivers of N use efficiency on Irish dairy farms. In an investigation by Mulkerrins et al. (SI) of the consequences of regulatory changes for farmers, showed that some farmers have concerns that non-compliance by some will lead to stricter rules for all. Knowledge transfer will be key for achieving greater compliance. There is a need to build awareness of the benefits of measures to increase their adoption. For example, Mahony et al. (SI) found that there was a low willingness among farmers to adopt the use of anaerobic digestion for waste management and renewable energy production, despite its potential benefits. However, many farmers were positive about using catch crops, for reduction of N leaching on tillage farms, due to the awareness of positive impact on soil health and structure. Participatory approaches such as farmer discussion groups were suggested by Daly et al. (SI) to enhance greater adoption of catch crops by tillage farmers.

Socio-economic and psychology behavioural studies show that farmer perceptions of their capacity to undertake measures and influences from other farmers, advisors and media are key drivers of the intention to adopt water quality measures. Adoption of measures can be predicted by specific farm and farmer characteristics [159]. Additionally, the characteristics of measures (e.g. knowledge requirement, positive farmer norm, cost) can be used as predictors of adoption. Suggested behavioural interventions include for example discussion groups, where “trusted” advisers provide knowledge and where knowledge and experiences are shared, increasing the common knowledge, and helping to create positive norms around measures. In addition, the use of “champion” farmers and farm media is suggested by Ryan et al. (SI) to build positive norms around water quality mitigation on farms.

There are three main pathways to further develop: (i) Explore how to enhance knowledge exchange among local actors but also from local to international level and vice versa. A common knowledge base increases the possibilities for relevant and cost-effective mitigation measures to be implemented; (ii) Develop methods to support local collaboration within small catchments. Management of shared water resources includes not only the environment but also administrative, legal and production aspects; and (iii) Focus on Sustainable Development Goals and climate change adaption and mitigation, which include regulation of soil conditions, greenhouse gas emissions, biodiversity, drought and flood control besides nutrient management, water quality and production. With developments in EU policies (e.g. the EU Directive on Soil Monitoring and Resilience and the EU Nature Restoration Law) water management will require a broad view on sustainable agricultural production.

In Ireland, the need for a multi-actor water quality advisory campaign was recognized and in 2024 Teagasc, the Agriculture and Food Development Authority, launched the “Better Farming for Water” campaign. The aim is to support and speed up the adoption of action on all farms by supporting “8-Actions for Change”, which will involve better nutrient, farmyard and land management. A similar approach is established in Sweden where the agricultural advisory program ‘Focus on Nutrients’ supports farmers to adjust their field and farm management, for benefits to both farmer and environment. The program is financed by the Board of Agriculture and supported by the Federation of Swedish Farmers. In Northern Ireland, the Soil Nutrient Health Scheme (SNHS) has ambitiously set a target to test all or most of the 650,000 farmed fields over four years. Training in improved nutrient management will be provided to farmers who have received a suite of test results including nutrient status and runoff risk maps for each field, based on terrain analysis modelling [57]. The incentive for farmers to participate in the SNHS is eligibility for future government support for nature-sensitive farming upon submission of a Nutrient Management Plan for their farms. The hope is also that participation will enable better management of their nutrient resources (slurry and artificial fertilisers), ultimately improve yields whilst costing each farm the same or less than before. Similar KT initiatives are also implemented elsewhere to support and accelerate the adoption of management practices to improve water quality in farmed areas. For example, in New Zealand Our Land and Water recently published training modules (as well as tools and resources) for farm advisors to build capability in identifying the most effective mitigation actions for farm environment plans, communicating effectively, and helping farm businesses make decisions around land-use diversification.

Action for improvement of water quality requires full-scale and fully instrumented farms or small catchment scale demonstration sites. We need to set realistic targets and test mitigation options at the same site until it works. Nutrients can be lowered to a safe level for any climate. To demonstrate the efficacy of the measures, we need to allow for approximately five-years to design, build and create a network of demonstration sites and another ca. five-years to improve the water quality. Joint foci for action are:

- *Co-design*: Anybody can help to make it work. More people generate more ideas.
- *Soil health*: What is a healthy and productive soil?
- *Source*: What are the sources of pollutants put on the land?
- *Mobilisation*: How are pollutants mobilised and how does water move within the fields?
- *Connectivity and delivery*: Where does flow concentrate and enter drains and channels?
- *Pathway mitigation*: What are the BMPs and how can we make them work?
- *Knowledge exchange*: Multiple partners are required to design, build and evaluate together. Group learning builds confidence.

3 Conclusions

Within systems science, research from all aspects of systems is brought together with a goal to identify, explore and build knowledge of the systems complexity. The strategies to the challenges posed on ecosystem conservation and climate neutrality should be achieved by integrating scientific findings in policies and implementation. The scientific findings are, however, complex. For example, the problems with water quality and GHG are challenged by the spatial heterogeneity of soil, geology, climate and land use, and by the temporal heterogeneity of biophysical processes, land management and climate. Developing an accountable management of the agricultural landscape requires a multi-actor, multidisciplinary and multi-scale approach with collaboration between the scientific community, policy makers and farmers. There should be a focus on research, technology, education, information, engagement and innovation. Some key steps in this approach include:

- Long-term monitoring and both high-temporal and high-spatial resolution data collection is required to build a process-based understanding of water quality and GHG issues, and for modelling approaches. Both are needed to optimise management practices and develop nature-based solutions and other targeted and effective mitigation strategies that reduces sources.
- Combining temporarily and spatially rich datasets on research platforms, enabling integration of multiple sites, projects, schemes, models and strategies, is required for clarifying complex processes and for teasing out which measures are beneficial and where they are beneficial. This also facilitates discovering areas (both spatially and topically) requiring further research and mitigation measure development.
- Long-term planning horizons need to be adopted by key institutional stakeholders to allow investment and adoption of BMPs likely to deliver future catchment resilience. This further requires long-term funding and support available to those who are being asked to alter or enhance their current practices.
- Mitigation strategies need adaptation to changing climate condition, agricultural practices, and be tailored to catchment characteristics.
- While several measures (e.g. buffer zones, constructed wetlands) might be beneficial for multiple environmental targets (e.g. nutrient reduction, increased biodiversity, reduction of GHG), not all individual measures are beneficial for all targets.

Placement and design of individual measures need to be governed by the main target to achieve high cost-efficiency, whereas the broad spectra of environmental benefits can be achieved by combining individual measures at catchment scale (e.g. wetlands).

- Adequate advisory support and training for farmers is essential. Data provision, such as soil testing or CSA mapping provided to farmers through government-funded schemes, will improve impacts. In the busy farmed space, it is important that mitigation strategies can be demonstrated to work. This may require more bespoke soft engineered approaches to complement existing measures.

Abbreviations

ACP	Agricultural Catchments Programme
ARG	anti-microbial resistance genes
ASSAP	Agricultural Sustainability Support Advisory Programme
BMP	Best Management Practices
C	Carbon
CSA	Critical Source Areas
EIP	European Innovative Partnerships
EU	European Union
FAO	Food and Agriculture Organization
GHG	greenhouse gas
IP	Integrated Project
KT	Knowledge Transfer
LAWPRO	Local Authority Waters Programme
LULUCF	Land Use, Land-Use Change and Forestry
MFA	Materials Flow Analysis
N	nitrogen
NbS	Nature-based Solutions
NMP	nutrient management practices
P	phosphorus
PAA	Priority Areas for Action
RBMP	River Basin Management Plan
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goals
SI	Supplementary Information
SNHA	Soil Nutrient Health Scheme
SWAT	Soil and Water Assessment Tool
TP	total phosphorus
UK	United Kingdom
UN	United Nations
US	United States
WFD	Water Framework Directive

Supplementary Information

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Supplementary Material 1

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References

1. Food and Agriculture Organization of the United Nations (FAO). (2023). FAO Regional office for Europe and Central Asia. [online] www.fao.org. Available at: https://www.fao.org/europe/news/detail/towards-a-food-waste-free-future/en
2. Wang F, Harindintwali J-D, Wei K, et al. 2023 climate change: strategies for mitigation and adaptation. Innov Geoscience. 2023;1(1):100015.
3. Steffen W, Rockström J, Richardson K, et al. Trajectories of the Earth system in the anthropocene. PNAS. 2018;33:8252–9.
4. Chaudhari SK, Biswas PP, Kapil H. (2020). Soil Health and Fertility In: Mishra, B, editors The Soils of India. World Soils Book Series. Springer, Cham. 215–231. https://doi.org/10.1007/978-3-030-31082-0_11
5. Kibret K, Beyene S, Teklu Erkossa. (2023). Soil Fertility and Soil Health In: Beyene, S., Regassa, A., Mishra, B.B., Haile, M, editors The Soils of Ethiopia. World Soils Book Series. Springer, Cham.157–192.
6. Food and Agriculture Organization of the United Nations (FAO). (2024). Soil fertility. Global Soil Partnership. Food and Agriculture Organization of the United Nations. [online] www.fao.org. Available at: https://www.fao.org/global-soil-partnership/areas-of-work/soil-fertility/en/ [accessed on 02/10/2024].
7. Paramesh V, Kumar RM, Rajanna GA, Gowda S, Nath AJ, Madival Y, Jinger D, Bhat S, Toraskar S. (2023). Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. 7. https://doi.org/10.3389/fsufs.2023.1173258
8. Hou D. Sustainable soil management for food security. Soil Use Manag. 2023;39(1):1–7.
9. Bonsall B, Haverty D, Nzeteu C, Huiginn P, O'flaherty V. (2023). Advances in Sustainable Nutrient Recovery for the Management of Nitrogen-rich Residue Streams (REFERT). [online] Available at: https://www.epa.ie/publications/research/epa-research-2030-reports/Research_-Report-440.pdf
10. Lal R. United nations food systems summit: what is the role of soil health in putting the sustainable development goals on track? J Soil Water Conserv. 2021;76(6):A105–7.
11. Martínez-Dalmau J, Berbel J, Ordóñez-Fernández R. Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. Sustainability. 2021;13(10):5625.
12. Ulrich-Schad JD, De Jalón SG, Babin N, Pape A, Prokopy LS. Measuring and Understanding agricultural producers' adoption of nutrient best management practices. J Soil Water Conserv. 2017;72(5):506–18.
13. EPA. (2023). Ireland projected to fall well short of climate targets, says EPA: Environmental Protection Agency 2023 [updated 01/06/2023; cited 2024 06/03/2024]. Available from: https://www.epa.ie/news-releases/news-releases-2023/ireland-projected-to-fall-well-short-of-climate-targets-says-epa.php#:~:text=In%20April%202023%20the%20Effort,the%20EU%20later%20in%202023

14. Tuohy P, O'Sullivan L, Bracken C, Fenton O. Drainage status of grassland peat soils in ireland: Extent, efficacy and implications for GHG emissions and rewetting efforts. J Environ Manage. 2023;344:118391.
15. Roe S, Streck C, Beach R, Busch J, Chapman M, Daioglou V, Deppermann A, Doelman J, Emmet-Booth J, Engelmann J, Fricko O, Frischmann C, Funk J, Grassi G, Griscom B, Havlik P, Hanssen S, Humpenöder F, Landholm D, Lomax G, Lehmann J, Mesnildrey L, Nabuurs G, Popp A, Rivard C, Sanderman J, Sohngen B, Smith P, Stehfest E, Woolf D. Lawrence D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. Glob Change Biol. 2021, 27:6025–6058.
16. Wiltshire C, Meersmans J, Waine TW, et al. Evaluating erosion risk models in a Scottish catchment using organic carbon fingerprinting. J Soils Sediments. 2024;24:3132–47.
17. Amelung W, Bossio D, de Vries W, Kögel-Knabner I, Lehmann J, Amundson R, Bol R, Collins C, Lal R, Leifeld J, Minasny B, Pan G, Paustian K, Rumpel C, Sanderman J, van Groenigen JW, Mooney S, van Wesemael B, Wander M, Chabbi A. Towards a global-scale soil climate mitigation strategy. Nat Commun. 2020;11:5427.
18. Hamidov A, Helming K, Bellocchi G, Bojar W, et al. Impacts of climate change adaptation options on soil functions: A review of European case-studies. Land Degrad Dev. 2018;29:2378–89.
19. Bijay-Singh, Craswell ET. (2021) Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Appl Sci, 3, Article 518.
20. Haygarth PM, Jarvis SC. Transfer of phosphorus from agricultural soils. Adv Agron. 1999;66:195–249.
21. Sherriff SC, Rowan JS, Fenton O, Jordan P, Melland AR, Mellander P-E, Ó hUallacháin D. Storm event suspended sediment-discharge hysteresis and controls in three agricultural watersheds: implications for watershed scale sediment management. Environ Sci Technol. 2016;50:1769–78.
22. Pandey PK, Kass PH, Soupir ML, et al. Contamination of water resources by pathogenic bacteria. AMB Expr. 2014;4:51.
23. Zhang Z, Zhang Q, Wang T, et al. Assessment of global health risk of antibiotic resistance genes. Nat Commun. 2022;13:1553.
24. Atcheson K, Mellander P-E, Cassidy R, Cook S, Floyd S, McRoberts C, Morton PA, Jordan P. Quantifying MCPA load pathways at catchment scale using high Temporal resolution data. Water Res. 2022;220:118654.
25. Troldborg M, Gagkas Z, Vinten A, Lilly A, Glendell M. Probabilistic modelling of the inherent field-level pesticide pollution risk in a small drinking water catchment using Spatial bayesian belief networks. Hydrol Earth Syst Sci. 2022;26:1261–93.
26. Mooney D, Coxon C, Richards KG, Gill L, Mellander P-E, Danaher M. An analysis of the spatio-temporal occurrence of anthelmintic veterinary drug residues in groundwater. Sci Total Environ. 2021;769:144804.
27. Djodjic F, Bergström L, Schmieder F, Sandström C, Agback P, Hu Y. Soils potentially vulnerable to phosphorus losses: speciation of inorganic and organic phosphorus and Estimation of leaching losses. Nutr Cycl Agroecosystems. 2023;127:225–45.
28. Djodjic F, Markensten H. From single fields to river basins: identification of critical source areas for erosion and phosphorus losses at high resolution. Ambio. 2019;48:1129–42.
29. Thomas IA, Jordan P, Mellander PE, Fenton O, Shine O et al. (2016). Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution. Sci Total Environ 2016; 556: 276 – 90.
30. Service T, Cassidy R, Atcheson K, Farrow L, Harrison T, Jack P, Jordan. A national-scale high-resolution runoff risk and channel network mapping workflow for diffuse pollution management. J Environ Manage. 2024;368:122110.
31. McDowell R, Kleinman PJA, Haygarth P, McGrath JM, Smith D, Heathwaite L, Iho A, Schoumans O, et al. A review of the development and implementation of the critical source area concept: A reflection of Andrew sharpley's role in improving water quality. J Environ Qual n/a. 2024. https://doi.org/10.1002/jeq2.20551.
32. Bieroza M, Dupas R, Glendell M, McGrath G, Mellander PE. Hydrological and chemical controls on nutrient and contaminant loss to water in agricultural landscapes. Water (Switzerland). 2020;12. https://doi.org/10.3390/w12123379.
33. Bieroza MZ, Bol R, Glendell M. What is the deal with the green deal: will the new strategy help to improve European freshwater quality beyond the water framework directive? Sci Total Environ. 2021;791:148080.
34. Sandström S, Lannergård EE, Futter MN, Djodjic F. Water quality in a large complex catchment: significant effects of land use and soil type but limited ability to detect trends. J Environ Manage. 2024;349:119500.
35. Mellander P-E, Jordan P. Charting a perfect storm of water quality pressures. Sci Total Environ. 2021;787:147576.
36. Cassidy R, Jordan P, Farrow L, Floyd S, McRoberts C, Morton P, Doody D. Reducing MCPA herbicide pollution at catchment scale using an agri-environmental scheme. Sci Total Environ. 2022;838:156080.
37. Glendell M, Gagkas Z, Stutter M, Richards S, Lilly A, Vinten A, Coull M. A systems approach to modelling phosphorus pollution risk in Scottish rivers using a Spatial bayesian belief network helps targeting effective mitigation measures. Front Environ Sci. 2022;10. https://doi.org/10.3389/fenvs.2022.976933.
38. Glendell M, Palarea-Albaladejo J, Pohle I, Marrero S, McCreadie B, Cameron G, Stutter M. Modeling the ecological impact of phosphorus in catchments with multiple environmental stressors. J Environ Qual. 2019;48:1336–46.
39. Abbott BW, Gruau G, Zarnetske JP, Moatar F, Barbe L, Thomas Z, et al. Unexpected Spatial stability of water chemistry in headwater stream networks. Ecol Lett. 2018;21:296–308.
40. Aubert AH, Kirchner JW, Gascuel-Odoux C, Faucheux M, Gruau G, Merot P. Fractal water quality fluctuations spanning the periodic table in an intensively farmed watershed. Environ Sci Technol. 2014;48:930–7.
41. Kyllmar K, Bechmann M, Deelstra J, Iital A, Blicher-Mathiesen G, Jansons V, et al. Long-term monitoring of nutrient losses from agricultural catchments in the Nordic–Baltic region – A discussion of methods, uncertainties and future needs. Agric Ecosyst Environ. 2014;198:4–12.
42. Bieroza M, Acharya S, Benisch J, ter Borg RN, Hallberg L, Negri C et al. (2023). Advances in catchment science, hydrochemistry and aquatic ecology enabled by high-frequency water quality measurements. Environmental Science and Technology 2023: 1–32.
43. Rode M, Wade AJ, Cohen MJ, Hensley RT, Bowes MJ, Kirchner JW, et al. Sensors in the stream: the High-Frequency wave of the present. Environ Sci Technol. 2016;50:10297–307.
44. Cassidy R, Jordan P. Limitations of instantaneous water quality sampling in surface-water catchments: comparison with near-continuous phosphorus time-series data. J Hydrol. 2011;405:182–93.
45. Dupas R, Casquin A, Durand P, Viaud V. Landscape Spatial configuration influences phosphorus but not nitrate concentrations in agricultural headwater catchments. Hydrol Process 2023; 37.

46. Mellander P-E, Melland AR, Jordan P, Wall DP, Murphy PNC, Shortle G. Quantifying nutrient transfer pathways in agricultural catchments using high Temporal resolution data. Environ Sci Policy. 2012;24:44–57.
47. Haygarth PM, Turner BL, Fraser AI, Jarvis SC, Harrod TR, Nash D, Halliwell D, Page T, Beven K. Temporal variability in phosphorus transfers: classifying concentration-discharge event dynamics. Hydrol Earth Syst Sci. 2004;8:88–97.
48. Bieroza MZ, Heathwaite AL, Bechmann M, Kyllmar K, Jordan P. The concentration-discharge slope as a tool for water quality management. Sci Total Environ. 2018;630:738–49.
49. Knapp JLA, Li L, Musolff A. Hydrologic connectivity and source heterogeneity control concentration–discharge relationships. Hydrol Process 2022; 36.
50. Mellander P-E, Galloway J, Hawtree D, Jordan P. (2022). Phosphorus mobilization and delivery estimated from long-term high frequency water quality and discharge data. Frontiers in Water 2022; 4.
51. Jarvie HP, Sharpley AN, Kresse T, Hays PD, Williams RJ, King SM et al. Coupling High-Frequency stream metabolism and nutrient monitoring to explore biogeochemical controls on downstream nitrate delivery. Environ Sci Technol 2018.
52. Jackson-Blake LA, Sample JE, Wade AJ, Helliwell RC, Skeffington RA. Are our dynamic water quality models too complex? A comparison of a new parsimonious phosphorus model, SimplyP, and INCA-P. Water Resour Res 2017.
53. Jackson-Blake, Dunn SM, Helliwell RC, Skeffington RA, Stutter MI, Wade AJ. How well can we model stream phosphorus concentrations in agricultural catchments? Environ Model Softw. 2015;64:31–46.
54. Wynants M, Strömqvist J, Hallberg L, Livsey J, Lindström G, Bieroza M. How to achieve a 50% reduction in nutrient losses from agricultural catchments. Volume 12. Under Different Climate Trajectories? Earth's Future; 2024. 7.
55. Drohan PJ, Bechmann M, Buda A, Djodjic F, Doody D, Duncan JM, Iho A, Jordan P, Kleinman PJ, McDowell R, Mellander P-E. A global perspective on phosphorus management decision support in agriculture: lessons learned and future directions. J Environ Qual. 2019;48(5):1218–33.
56. Djodjic F, Elmquist H, Collentine D. Targeting critical source areas for phosphorus losses: evaluation with soil testing, farmers' assessment and modelling. Ambio. 2018;47:45–56.
57. Thomas IA, Mellander P-E, Murphy PNC, Fenton O, Shine O, Djodjic F, Dunlop P, Jordan P. A sub-field scale critical source area index for legacy phosphorus management using high resolution data. Agric Ecosyst Environ. 2016;233:238–52.
58. Morton PA, Cassidy R, Floyd S, Doody DG, McRoberts WC, Jordan P. (2021). Approaches to herbicide (MCPA) pollution mitigation in drinking water source catchments using enhanced space and time monitoring. Science of the Total Environment 755 (2021) 142827.
59. Heathwaite AL, Bieroza M. Fingerprinting hydrological and biogeochemical drivers of freshwater quality. Hydrological Processes; 2020.
60. Lannergård EE, Fölster J, Futter MN. Turbidity-discharge hysteresis in a meso-scale catchment: the importance of intermediate scale events. Hydrol Process 2021; 35.
61. Daxini A, Ryan M, O'Donoghue C, Barnes AP. Understanding farmers' intentions to follow a nutrient management plan using the theory of planned behaviour. Land Use Policy. 2019;85:428–37.
62. Murphy C, Kettle A, Meresa H, Golian S, Bruen M, O'Loughlin F, Mellander P-E. Climate change impacts on Irish river flows: high resolution scenarios and comparison with CORDEX and CMIP6 ensembles. Water Resour Manage. 2023. https://doi.org/10.1007/s11269-023-03458-4.
63. Woodward G, Perkins D, Brown L. Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philosophical Trans Royal Soc B: Biol Sci. 2010;365:2093–106.
64. UNESCO. (2022). The United Nations World Water Development Report 2022: groundwater: making the invisible visible. ISBN: 978-92-3-100507.
65. Ockenden MC, Hollaway MJ, Beven KJ, et al. Major agricultural changes required to mitigate phosphorus losses under climate change. Nat Commun. 2017;8:9.
66. Gordon H, Haygarth PM, Bardgett RD. Drying and rewetting effects soil microbial community composition and nutrient leaching. Soil Biol Biochem. 2008;40:302–11.
67. IPCC. Climate Change 2007 - Synthesis Report. 2007.
68. Haygarth PM, Condron LM, Heathwaite AL, Turner BL, Harris GP. The phosphorus transfer continuum: linking source to impact with an interdisciplinary and multi-scaled approach. Sci Total Environ. 2005;344:5–14.
69. Forber KJ, Withers PJA, Ockenden M, Haygarth PM. (2018). The Phosphorus Transfer Continuum: A Framework for Exploring Effects of Climate Change. Agricultural & Environmental Letters 3.
70. Ezzati G, Collins AL, Pulley S, Galloway J, Hawtree D, Mellander P-E. Impacts of changing weather patterns on the dynamics of water pollutants in agricultural catchments: insights from 11-year high Temporal resolution data analysis. J Hydrol. 2024;644:132122.
71. Mellander P-E, Jordan P, Bechmann M, Shore M, McDonald NT, Fovet O, Gascuel-Odoux C. Integrated climate-chemical indicators of diffuse pollution. Sci Rep. 2018;8(1):944.
72. Capon SJ, et al. Riparian ecosystems in the 21st century: hotspots for climate change adaptation? Ecosystems. 2013;16(3):359–81.
73. Lal R. Climate strategic soil management. Challenges 2014. 2014;5:43–74.
74. van Doorn M, van Rotterdam D, Ros G, Koopmans GF, Smolders E, de Vries W. The phosphorus saturation degree as a universal agronomic and environmental soil P test. Crit Rev Environ Sci Technol. 2024;54(5):385–404.
75. Quaglia G, Joris I, Broekx S, Desmet N, Koopmans K, Vandaele K, Seuntjens P. A Spatial approach to identify priority areas for pesticide pollution mitigation. J Environ Manage. 2019;246:583–93.
76. Hewett CJ, Wilkinson ME, Jonczyk J, Quinn PF. Catchment systems engineering: an holistic approach to catchment management. Wiley Interdisciplinary Reviews: Water. 2020;7(3):e1417.
77. Stutter M, Wilkinson M, Nisbet T. (2020) 3D buffer strips: Designed to deliver more for the environment. Bristol, UK Available at: https://www.gov.uk/government/publications/3d-buffer-strips-designed-to-deliver-more-for-the-environment
78. Stephenson K, Shabman L. Where did the agricultural nonpoint source trades go? Lessons from Virginia water quality trading programs. JAWRA J Am Water Resour Association. 2017;53(5):1178–94.
79. Battiata J, Collins K, Hirschman D, Hoffmann G. The runoff reduction method. J Contemp Water Res Educ. 2010;146(1):11–21.
80. Sample DJ, Liu J. Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture. J Clean Prod. 2014;75:174–94.

81. Nesshöver C, Assmuth T, Irvine KN, Rusch GM, Waylen KA, Delbaere B, Haase D, Jones-Walters L, Keune H, Kovacs E, Krauze K. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci Total Environ. 2017;579:1215–27.
82. Waylen K, Wilkinson ME, Blackstock KL, Bourke M. Nature-Based solutions and restoration are intertwined but not identical: highlighting implications for societies and ecosystems. Nature-Based Solutions; 2024. p. 100116.
83. Adams KJ, Macleod CAJ, Metzger MJ, Melville N, Helliwell RC, Pritchard J, Glendell M. Developing a bayesian network model for Understanding river catchment resilience under future change scenarios. Hydrol Earth Syst Sci. 2023;27:2205–25.
84. Ptak EN, Graversgaard M, Refsgaard JC, Dalgaard T. Nitrate management discourses in Poland and Denmark—Laggards or leaders. Water Qual Protection? Water. 2020;12(9):2371.
85. Montes deO, Munguia O, Pannell DJ, Llewellyn R. Understanding the adoption of innovations in agriculture: a review of selected conceptual models. Agronomy. 2021;11(1):139.
86. Eicken H, Danielsen F, Sam J-M, Fidel M, Johnson N, Poulsen MK, Lee OA, Spellman KV, Iversen L, Pulsifer P, Enghoff M. Connecting Top-Down and Bottom-Up approaches in environmental observing. Bioscience. 2021;71(5):467–83.
87. Adamsone-Fiskovica A, Grivins M. Knowledge production and communication in on-farm demonstrations: Puttinf farmer participatory research and extension into practice. J Agricultural Educ Ext. 2021;28(4):479–502.
88. Mellander P-E, Lynch B, Galloway J, Žurovec O, McCormack M, O'Neill M, Hawtree D, Burgess E. Benchmarking a decade of holistic agro-environmental studies within the agricultural catchments programme. Ir J Agricultural Food Res. 2022;IJAFR(1–17). https://doi.org/10.15212/ijafr-2020-0145.
89. van den Berg LM, Dingkuhn EL, Meehan N, O'Sullivan L. Investigating bottlenecks hampering the adoption of water quality-enhancing practices for sustainable land management in Ireland. J Environ Manage. 2023;345:118741.
90. Adams KJ, Metzger MJ, Helliwell R, Melville N, Pritchard J, Edwards K, Glendell M. Identifying and testing adaptive management options to increase river catchment system resilience using a bayesian network model. Discover Geoscience. 2024;2:62.
91. Viaggi D, Raggi M, Villanueva AJ, Kantelhardt J. Provision of public goods by agriculture and forestry: economics, policy and the way ahead. Land Use Policy. 2021;107:105273.
92. Fischer K, Vico G, Röcklinsberg H, Liljenström H, Bommarco R. Progress towards sustainable agriculture hampered by siloed scientific discourses. Nat Sustain. 2025;8:66–74.
93. Truffer O, Hofmann B, Lieberherr E. Salient and contested scientific evidence in debates over sustainable transformation: pesticide policymaking in Switzerland. Humanit Soc Sci Commun. 2025;12:1022.
94. Boix-Fayos C, de Vente J. Challenges and potential pathways towards sustainable agriculture within the European green deal. Agric Syst. 2023;207:103634.
95. Rippey B, McElarney Y, Thompson J, Allen M, Gallagher M, Douglas R. Recovery targets and timescales for Lough Neagh and other lakes. Water Res. 2022;222:p118858.
96. Rust, N. A., Ptak, E. N., Graversgaard, M., Iversen, S., Reed, M. S., de Vries, J.R., … Dalgaard, T. (2023). Social capital factors affecting uptake of sustainable soil management practices: a literature review. Emerald Open Research, 1(10).
97. Haygarth PM, Simon H, Betson M, Harris D, Hodgkinson R, Withers PJA. Mitigating diffuse phosphorus transfer from agriculture according to cost and efficiency. J Environ Qual. 2009;38:2012–22.
98. Cuttle SP, Newell-Price JP, Harris D, Chadwick DR, Shepherd MA, Anthony SGA, Macleod CJA, Haygarth PM, Chambers BJ. A method-centric 'User manual' for the mitigation of diffuse water pollution from agriculture. Soil Use Manag. 2016;32:162–71.
99. Haygarth PM, Rufino MC. Local solutions to global phosphorus imbalances. Nat Food. 2021;2:459–60.
100. Cassidy R, Thomas IA, Higgins A, Bailey JS, Jordan P. A carrying capacity framework for soil phosphorus and hydrological sensitivity from farm to catchment scales. Sci Total Environ. 2019;687:277–86.
101. Djodjic F, Geranmayeh P, Markensten H. Optimizing placement of constructed wetlands at landscape scale in order to reduce phosphorus losses. Ambio. 2020;49:1797–807.
102. Djodjic F, Geranmayeh P, Collentine D, Markensten H, Futter M. Cost effectiveness of nutrient retention in constructed wetlands at a landscape level. J Environ Manage. 2022;324:116325.
103. Rothwell SA, Doody DG, Johnston C, Forber KJ, Cencic O, Rechberger H, Withers PJA. (2020). Phosphorus stocks and flows in an intensive livestock dominated food system. Resources, Conservation and Recycling, 163, p.105065.
104. Pointke M, Albrecht EH, Geburt K, Gerken M, Traulsen I, Pawelzik E. A comparative analysis of plant-based milk alternatives part 1: composition, sensory, and nutritional value. Sustainability. 2022;14(13):7996.
105. Geburt K, Albrecht EH, Pointke M, Pawelzik E, Gerken M, Traulsen I. A comparative analysis of plant-based milk alternatives part 2: environmental impacts. Sustainability. 2022;14(14):8424.
106. Rombach M, Dean DL, Bitsch V. Got milk alternatives? Understanding key factors determining US consumers' willingness to pay for Plant-Based milk alternatives. Foods. 2023;12(6):1277.
107. Vallin A, Grimvall A, Sundblad E-L, Djodjic F. Changes in four societal drivers and their potential to reduce Swedish nutrient inputs into the sea. Report number: Swedish Agency for Marine and Water; 2016. Management report 2016:11.
108. Jackson-Blake LA, Sample JE, Wade AJ, Helliwell RC, Skeffington RA. Are our dynamic water quality models too complex? Acomparison of a new parsimonious phosphorus model,SimplyP, and INCA-P. Water Resour Res. 2017;53:5382–99.
109. Adams R, Quinn PF, Perks M, Barber NJ, Jonczyk J, Owen GJ. Simulating high frequency water quality monitoring data using a catchment runoff Attenuation flux tool (CRAFT). Sci Total Environ. 2016;572:1622–35.
110. Negri C, Schurch N, Wade AJ, Mellander P-E, Stutter M, Bowes M, Mzyece C, Glendell M. Transferability of a bayesian belief network across diverse agricultural catchments using high-frequency hydrochemistry and land management data. Sci Total Environ. 2024;949:174926.
111. Moe SJ, Carriger JF, Glendell M. Increased use of bayesian network models has improved environmental risk assessments. Integr Environ Assess Manag. 2021;17:53–61.
112. Lannergård EE, Sandström S, Widén Nilsson E, Lewan E, Futter MN. (2024). High Expectations and Open Questions: Using High-Frequency Proxy Data to Calibrate a Catchment-Scale Phosphorus Model. ACS ES&T Water 2024 4 (5), 2135–2143.
113. IPCC. 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B.

Averyt, M. Tignor and H.L. Miller, editors]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
114. Rosenzweig C, Karoly D, Vicarelli M et al. (2008). Attributing physical and biological impacts to anthropogenic climate change. Nature 453, 353–357 (2008).
115. Kim S-Y, Zhou X, Freeman C, Kang H. (2022). Changing thermal sensitivity of bacterial communities and soil enzymes in a bog peat in spring, summer and autumn. Applied Soil Ecology, 173, 2022, 104382.
116. Lombao A, Barreiro A, Fontúrbel MT, Martín A, Carballas T, Díaz-Raviña M. Effect of repeated soil heating at different temperatures on microbial activity in two burned soils. Sci Total Environ. 2021;799:149440.
117. Raza T, Qadir MF, Khan KS, Eash NS, Yousuf M, Chatterjee S, Manzoor R, ur Rehman S, Oetting JN. Unravelling the potential of microbes in decomposition of organic matter and release of carbon in the ecosystem. J Environ Manage. 2023;344:118529.
118. Allison SD. Microbial drought resistance May destabilize soil carbon. Trends Microbiol. 2023;31:8, 780–7.
119. Oishy MN, Shemonty NA, Fatema SI, Mahbub S, Mim EL, Raisa MBH, Anik AH. Unravelling the effects of climate change on the soil-plant-atmosphere interactions: A critical review. Soil Environ Health. 2025;3:00130.
120. Bol R, Gruau G, Mellander P-E, Dupas R, Bechmann M, Skarbøvik E, Bieroza M, Djodjic F, Glendell M, Jordan P, Van der Grift B, Rode M, Smolders E, Verbeeck M, Gu S, Klumpp E, Pohle I, Fresne M, Gascuel-Odoux C. Challenges of reducing water eutrophication from a phosphorus perspective in the agricultural landscapes of Northwest Europe. Front Mar Sci. 2018. https://doi.org/10.3389/fmars.2018.00276.
121. Ezzati G, Collins A, Pulley S, Galloway J, Hawtree J, Mellander P-E. Impacts of changing weather patterns on the dynamics of water pollutants in agricultural catchments: insights from historical data analysis. J Hydrol. 2024;644:132122.
122. Mellander P-E, Ezzati G, Murphy C, Jordan P, Pulley S, Collins AL. (2024). Far-future hydrology will change the phosphorus transfer continuum. Discover Geoscience, 2, 60 (2024).
123. Wade AJ, Skeffington RA, Couture R-M, Erlandsson Lampa M, Groot S, Halliday SJ, Harezlak V, Hejzlar J, Jackson-Blake LA, Lepistö A, Papastergiadou E, Riera JL, Rankinen K, Shahgedanova M, Trolle D, Whitehead PG, Psaltopoulos D, Skuras D. Land use change to reduce freshwater nitrogen and phosphorus will be effective even with projected climate change. Water. 2022;14:829.
124. Paul MP, Stamp J, Hamilton A, Coffey R, Johnson T. A review of potential climate change effects on U.S. Water Quality - Part I: sea level Rise, Flow, and temperature. J Am Water Resour Assoc. 2019;55(4):824–43.
125. Ezzati G, Kyllmar K, Barron J. Long-term water quality monitoring in agricultural catchments in sweden: impact of Climatic drivers on diffuse nutrient loads. Sci Total Environ. 2023;8864:160978.
126. Meresa H, Murphy C. (2023). Climate change impacts on the frequency, magnitude and duration of meteorological droughts for the Island of Ireland using SPI and SPEI. Internaitonal Journal of Climatology, JOC-23-0033.
127. DHPLG. (2019). Water quality and water services infrastructure, Climate Change Sectoral Adaptation Plan. Department of Housing, Planning and Local Government of Ireland. Available from https://www.gov.ie/pdf/?file=https://assets.gov.ie/204931/3bd18d19-432a-4435-bdbd-abe6fee4c407.pdf#page=null
128. EEA. (2021). Indicator Assessment: Meteorological and hydrological droughts in Europe. IND-105-en CLIM018. European Environment Agency 2021. Available from: https://www.eea.europa.eu/publications/europes-changing-climate-hazards-1/wet-and-dry-1/wet-and-dry-drought
129. EEA. (2024). Preparing society for climate risks in Europe – lessons and inspiration from Climate-ADAPT case studies. European Environment Agency 2024. Available from: https://www.eea.europa.eu/publications/preparing-society-for-climate-risks-in-europe
130. Zhao J, Yang X, Dai S, Lv S, Wang J. Increased utilization of lengthening growing season and warming temperatures by adjusting sowing dates and cultivar selection for spring maize in Northeast China. Eur J Agron. 2015;67:12–9.
131. Marklein A, Elias E, Nico P, Steenwerth K. Projected temperature increases May require shifts in the growing season of cool-season crops and the growing locations of warm-season crops. Sci Total Environ. 2020;746:40918.
132. Scasta JD, Lalman DL, Henderson L. Drought mitigation for grazing operations: matching the animal to the environment. Rangelands. 2016;38(4):204–10.
133. Furtak K, Wolińska A. The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – A review. CATENA. 2023;231:107378.
134. Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Secur. 2021;28:00488.
135. Morton PA, Hunter WR, Cassidy R, Doody D, Atcheson K, Jordan P. Muddying the waters: impacts of a bogflow on carbon transport and water quality. CATENA. 2024;238:107868.
136. Covino TP, Wlostowski AN, Gooseff MN, Wollheim WM, Bowden WB. The seasonality of in-stream nutrient concentrations and uptake in Arctic headwater streams in the Northern foothills of alaska's Brooks range. Volume 126. JGR Biogeoscineces; 2021. e2020JG005949.
137. Yuan Y, Koropeckyj-Cox L. SWAT model application for evaluating agricultural conservation practice effectiveness in reducing phosphorous loss from the Western lake Erie basin. J Environ Manage. 2022;302:114000. (Pt A).
138. Bieroza MZ, Hallberg L, Livsey J, Wynants M. (2024). Climate change accelerates water and biogeochemical cycles in temperate agricultural catchments. Sci Total Environ, p.175365.
139. Fu B, Horsburgh JS, Jakeman AJ, Gualtieri C, Arnold T, Marshall L, Green TR, Quinn NWT, Volk M et al. (2020_. Modelling water quality in wateersheds: from here to the next generation. Water Resour Res, 56, 11.
140. Gascuel-Odoux C, Fovet O, Faucheux M, Salmon-Monviola J, Strohmenger L. (2023). How to assess water quality change in temperate headwater catchments of Western Europe under climate change: examples and perspectives. Comptes Rendus Géoscience, 1–11.
141. Pedersen JST, Santos FD, van Vuuren D, Gupta J, Coelho RE, Aparício BA, Swart R. An assessment of the performance of scenarios against historical global emissions for IPCC reports. Glob Environ Change. 2021;66:102199.
142. EEA. Responding to climate change impacts on human health in europe: focus on floods, droughts and water quality. EEA report 3/2024. Luxembourg: Publications Office of the European Union; 2024.
143. Rizzo A, Sarti C, Nardini A, Conte G, Masi F, Pistocchi A. Nature-based solutions for nutrient pollution control in European agricultural regions: A literature review. Ecol Eng. 2023;186:106772.

144. Stutter M, Baggaley NJ, Davies J, Gagkas Z, Janes-Bassett V, Laudon H, Lilly A, Lupon A, Musolff A, Trojahn S, Haygarth PM. The riparian reactive interface: a climate-sensitive gatekeeper of global nutrient cycles. Front Environ Sci. 2023;11:1213175.
145. Stutter M, Baggaley N, Donnelly D, Lilly A, Mellander P-E, Wilkinson M, Ó hUallacháin D. (2023). Riparian mitigation measures selection tool. Available at: https://measure-selection-tool.hutton.ac.uk/
146. Stutter M, Wilkinson M. (2022). Can improved design concepts for riparian buffer measures and placement improve uptake and best practice in Scotland? CREW Project Code CRW2020_03. Scotland's Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/publications
147. Hambäck PA, Dawson L, Geranmayeh P, et al. Tradeoffs and synergies in wetland multifunctionality: A scaling issue. Sci Total Environ. 2023;862:160746.
148. Wilkinson ME, Quinn PF, Barber NJ, Jonczyk J. A framework for managing runoff and pollution in the rural landscape using a catchment systems engineering approach. Sci Total Environ. 2014;468:1245–54.
149. Hartmann T, Slavíková L, Wilkinson ME, editors. Spatial flood risk management: implementing catchment-based retention and resilience on private land. Edward Elgar Publishing; 2022.
150. EIP-AGRI Focus Group. (2022) Digital tools for sustainable nutrient management. Final Report, Sept 2022. Available at: https://ec.europa.eu/eip/agriculture/en/focus-groups/digital-tools-sustainable-nutrient-management.html
151. Djodjic F, Geranmayeh P, Markensten H, Widén-Nilsson E. (2023). Norrström. The right action in the right place – Support and data to reduce nutrient leaching losses from agricultural land. Published online Jun 2023. https://arcg.is/1HC001
152. Campling P, Joris I, Calliera M, Capri E, Marchis A, Kuczyńska A, Vereijken T, Burczyk P, Majewska Z, Juszkowska D, Przychodzka M, Belmans E, Borremans L, Dupon E, Pauwelyn E, Mellander P-E, Fennell C, Fenton O, Burgess E, Isla Puscas E, de Lopez M, Francès, Tudel G, Andersen E, Lajer Højber A, Suciu N. (2021). A multi-actor, participatory approach to identify policy and technical barriers to better farming practices that protect our drinking water sources. Science of the Total Environment, 755, 142971.
153. Tomczyk N, Naslund L, Cummins C, et al. Nonpoint source pollution measures in the clean water act have no detectable impact on decadal trends in nutrient concentrations in U.S. Inland waters. Ambio. 2023;52:1475–87.
154. Haase P, Bowler DE, Baker NJ, et al. The recovery of European freshwater biodiversity has come to a halt. Nature. 2023;620:582–8.
155. EPA. (2023b). Agriculture: Environmental Protection Agency 2023. Available from: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/ [accessed on 02/10/2024].
156. Cullen P, Ryan M, O'Donoghue C, Meehan N. Characteristics of water quality mitigation measures that lead to greater adoption on farms. J Environ Manage. 2024;58:120698.
157. Holden J, Haygarth PM, Dunn N, Harris J, Harris RC, Humble A, Jenkins A, MacDonald J, McGonigle DF, Meacham T, Orr HG, Pearson PL, Ross M, Sapiets A, Benton T. Water quality and UK agriculture: challenges and opportunities. Wiley Interdisciplinary Reviews-Water. 2017;4:16.
158. McGonigle DF, Burke SP, Collins AL, Gartner R, Haft MR, Harris RC, Haygarth PM, Hedges MC, Hiscock KM, Lovett AA. Developing demonstration test catchments as a platform for transdisciplinary land management research in England and Wales. Environ Science-Processes Impacts. 2014;16:1618–28.
159. O'Donoghue C, Ryan M, Sologon D, McLoughlin N, Daxini A, Daly K. 2024. A generalised behavioural model for greater adoption of Pro-Environmental farm measures. J Clean Prod 141631.

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