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PERSPECTIVE

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# How will climate change influence phosphorus systems? An expert elicitation approach

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**Abstract**

Phosphorus (P) sustainability is a “wicked problem,” due to complex environmental and societal challenges. This will be further exacerbated by climate change, although interdisciplinary evidence on effects and adaptation are lacking. Our knowledge of how climate change may impact agricultural-systems P dynamics is challenged by our understanding of baseline versus managed system responses, complex biophysical and societal process interactions, and thresholds. This challenge was discussed at the 10th International P Workshop, gathering academia and industry experts. This perspective paper shows this community’s current state of knowledge and understanding on the impacts of climate change on P across soils, waters, and humans within agricultural systems. Participants discussed topic knowledge and data availability, and positioned their responses on a matrix with importance (relevance of the impact according to their understanding and knowledge) and confidence (about the data availability regarding that impact) as axes. The 320 statements were digitized and categorized into themes, reported here in the context of contemporary literature. While we do not address all topics across agriculture, our analysis highlights the community’s developing state of knowledge on connections between P systems and climate. Although the depth of topic-specific knowledge varied greatly, this analysis emphasizes that P must become more visible in climate change discourse and addressed by establishing transdisciplinary relationships. We recommend further data collection regarding circular economy and climate adaptation, and modeling and policy development to anticipate risks and support adaptive P management, including attention

**Abbreviations:** BMPs, best management practices; C, carbon; $CO_2$, carbon dioxide; ECRs, early-stage career researchers; GHGs, greenhouse gases; IPW, International Phosphorus Workshop; IPW10, 10th International Phosphorus Workshop; N, nitrogen; P, phosphorus; R&D, industry research and development.

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to thresholds and socioeconomic linkages, where consequences of inaction may be abrupt and widespread.

**Plain Language Summary**

Phosphorus (P) is an essential resource, but its management is difficult because of both environmental and societal challenges. Climate change could make this worse, yet little research has connected climate, P, and society. To address this gap, we brought together international experts from science, policy, and industry to explore how climate change might affect agricultural P in soils, waters, and human systems. Experts highlighted key concerns by rating the importance of each issue and data availability. From this discussion, we identified major themes, including the need for more data on P in circular economies, climate adaptation, and policy development. Our findings show that experts believe that P must become part of climate change discussions, since ignoring it could lead to sudden and widespread risks. Better research and cooperation across disciplines are needed to guide sustainable P management in a changing climate.

## 1 | INTRODUCTION

The potential impacts of climate change on the global phosphorus (P) cycle remain relatively underexplored in research and largely unaddressed in climate adaptation policy (Forber et al., 2018). Arguably, evidence on the impacts of climate change on P processes operating in the natural environment remains siloed to disciplines (Lucas et al., 2025; Stamm et al., 2022). This limits our understanding of important interactions between components of the environment required to effectively design and implement adaptation plans. Evidence points to climate change driving P losses from agricultural land and to watercourses because of altered hydrology (Ockenden et al., 2017), with P concentrations being less affected (Wade et al., 2022), and with high uncertainty related to future P loads under a changing climate (Wynants et al., 2024). Complex P-related outcomes have been shown as a consequence of rising temperatures and changing precipitation regimes, particularly more frequent extreme weather events, which may influence P availability and mobilization across both terrestrial and freshwater systems (Lucas et al., 2023; Mellander et al., 2022). At the same time, terrestrial ecosystems are experiencing shifts in nutrient cycling and plant community composition, while the effects of nutrient pollution on freshwater ecosystems are changing in response to climate change (Hou et al., 2018). Communities, especially in regions heavily reliant on P-intensive agriculture or facing water quality impairment due to nutrient pollution, are particularly exposed to the socioeconomic impacts of climate change (McNamara & Buggy, 2017). Understanding the complexity of interactions across components of the natural environment and their socioeconomic impacts requires transdisciplinary approaches (Forber et al., 2018).

There are multiple “critical unknowns” regarding the topic of climate change and P (Menge et al., 2023), including: the disconnect between modeling (long duration needs) and experimentation (shorter term, resource limited), a bias in study of average climate trends effects versus extremes affecting P, and underrepresentation of data from some parts of the globe. Lucas et al. (2023) show knowledge gaps in prediction of how multiple simultaneous climate change pressures will act on biogeochemical processes governing P losses to waters. Literature investigating P and climate change has developed only over the last two decades (Figure 1), and studies exploring aspects of soils, waterbodies, or socioeconomic issues in the realm of climate–P interactions are limited. Against a backdrop of insufficient formal literature crossing biophysical and human impacts, structured expert judgements can enrich understanding (Gulledge et al., 2009; Ó hUallacháin et al., 2025) and inform pathways to improve knowledge.

Recognizing the urgency of this issue, the 10th International Phosphorus Workshop (IPW10; Dundee, UK, August 2024) convened an international community that captured a unique transdisciplinary perspective on the topic of climate change and P. Breaking out of scientific siloes, we conducted a structured focus group with the primary aim of identifying pressing concerns across specialists in agronomy, ecology, hydrology, socioeconomics, environmental management, and policy. Our perspective from this several decade’s active International Phosphorus Workshop (IPW) community, mostly reflects natural sciences from the Northern Hemisphere.

Our commentary serves as a platform to benchmark current understanding and identify research priorities in (1) how climate change influences the P cycling and ecosystem interactions in natural and soil–crop–human systems (e.g., topics such as P losses from land to water), and (2) the role of research in shaping a climate-resilient future in the context of nutrient management. This perspective paper is not a review and therefore does not go into individual process details. Nevertheless, we show the topics raised, their interactions with climate, and the importance and confidence in the evidence, finally discussing emerging topics and the context of our approach. The paper is primarily aimed at researchers and practitioners in P and nutrient management aspects in agriculture and the food–water–energy nexus, where the convergence of these issues with climate change challenges practice and contemporary knowledge. Second, it informs the broader environmental science and policy community about how the P research community collectively views and responds to climate change challenges.

**Core Ideas**

- Experts gave views on future climate effects on P in soil, water, and human systems.
- Knowledge of P sources and forms under climate change is critical.
- Experts believe that P should play a bigger role in the climate change discourse.
- We highlight gaps in multi-aspect impacts of climate change for policy measures.

## 2 | METHODS

### 2.1 | Expert input

Primary data were derived from a focus group involving experts participating in the IPW10 during the structured workshop "Climate Effects on P Systems" (Figure 2) and reflect their state of knowledge and priorities. Focus groups and expert elicitation methods are often used in environmental science due to the complexity of problems faced (e.g., Adams et al., 2023; McDowell et al., 2021; Negri et al., 2024; Ó hUallacháin et al., 2025). Registered conference participants anonymously contributed to the workshop. Our methodology was explained and the future purpose of analysis toward a report or paper was declared. Experts were drawn from 19 countries and self-declared as early career researchers (PhD student or early-stage postdoctoral researchers), established to leading researchers, or other professions (Figure 3). The scientific pool was mainly engaged in biophysical research, including applied biogeochemistry, hydrology, and modeling, with fewer social scientists and economists; professionals worked with regulatory bodies, water companies, and consultancies; therefore, inputs reflect this expertise. Among IPW10's participants, 44 worked in a university, 42 at a research institute, 10 in agricultural organizations, six in regulatory bodies, and three in water or environmental consultancies. Six facilitators (authors Ezzati, Haygarth, Macrae, Mellander, Negri, Spears), with expertise in the academic and applied sciences of waters and soils, initiated and maintained conversations during sessions, answered queries during discussions, then later digitized statements and coded responses into groups (Section 2.2).

Participants were randomly assigned to one of three time slot groupings over three sequential blocks of 45 min, each time-block group repeating the same tasks (Figure 2a). Following an introductory debrief each time-block group ($n = 35$) subdivided between three topic-based activity stations focusing on impacts for (1) soils, (2) waterbodies, and (3) human systems. The stations comprised pre-drawn axes ($x$, moderate to critical importance; $y$, low to high confidence) onto A0 paper. Two facilitators per station ran the activity, capturing on flip charts discussion and rationale for participants positioning their input ("statements") onto the boards (Figure 2b), repeating the activity for the three time-block groups. Images of participant statements according to quadrant positions were captured on the day. Sessions commenced with general discussion of the topic bounds. However, interpretation was intentionally left free for all groups with facilitators giving minimum steer to move the discussion along within the core issue of climate change and P interactions. Hence, a consistent methodology was followed across these three given topic groups on the day, which allowed the experts freedom to react to the topic and provide the intended "window" on their and community understanding.

### 2.2 | Data processing

Post-it boards were divided into quadrants: (1) moderate importance, high confidence; (2) moderate importance, low confidence; (3) critical importance, high confidence; and (4) critical importance, low confidence (Figure 2b). Statements were photographed, digitized, and coded according to quadrant. Data within each topic were processed separately, combining time-block group for processing (i.e., no blocking effect as considered randomly assigned). Non-legible entries were discarded ($n < 5$). Statements for topics (1) and (2) were iteratively coded into thematic groups by the facilitators. Agreed themes were categorized by confidence/importance. For topics (1) and (2) analysis included a weighted (by number of statements) average "centroid" positioning onto the quadrants considered without uncertainty bounds. The approach

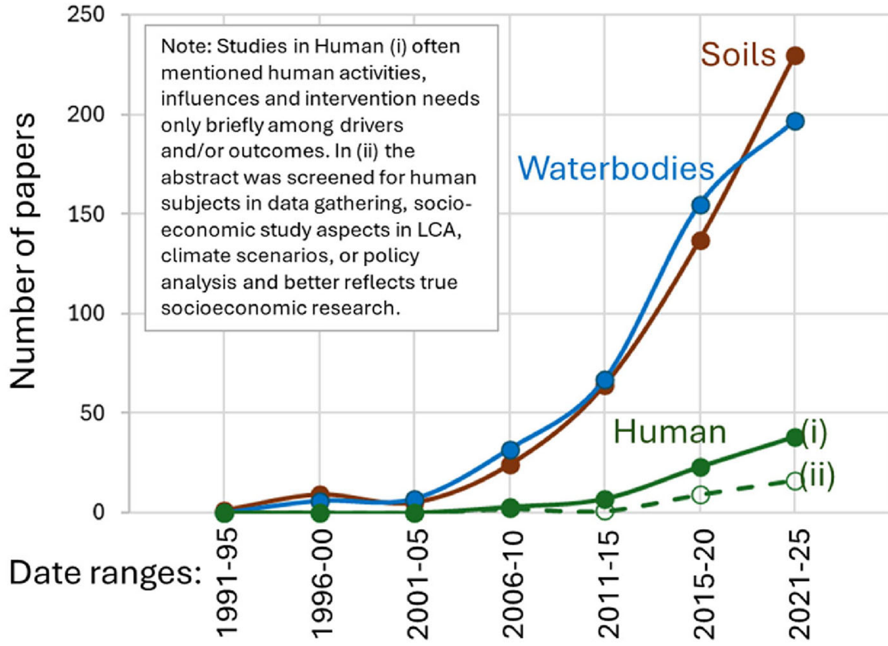


**FIGURE 1** Literature search results (within paper title, abstract, or keywords) for ISI publications on Web of Science using the bold search terms: **Phosphorus** AND "**Climate change**" AND sequentially either **Soil**, **Water*** (to capture waterbody-related terms), or **Human** (all terms selected as "topic"). See the inset note for the difference for "Human" between (i) raw and (ii) condensed results. Search date ranges commenced 1971–1975 but contained no results until the dates on the graph.

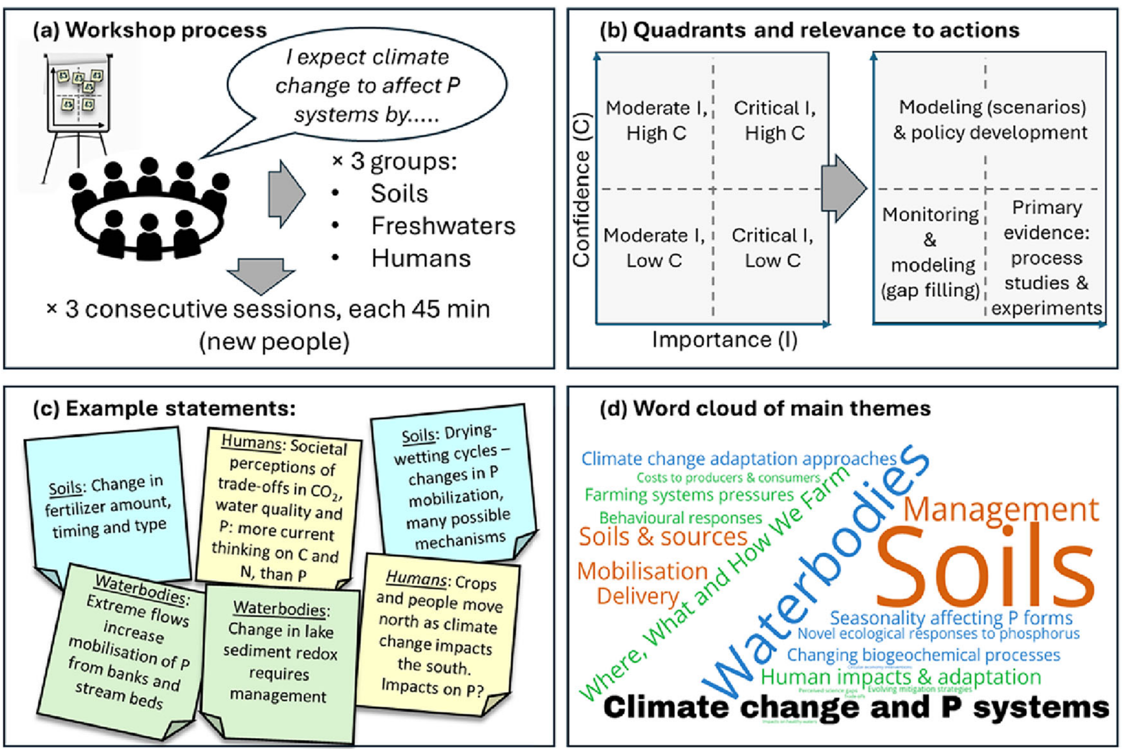


**FIGURE 2** Summary of the methods used in the study (a) general process, (b) detail of board quadrants given on the workshop day (left) and potential implications of positions for research recommendations (right), (c) example of some actual statements, and (d) illustrative word cloud of themes.

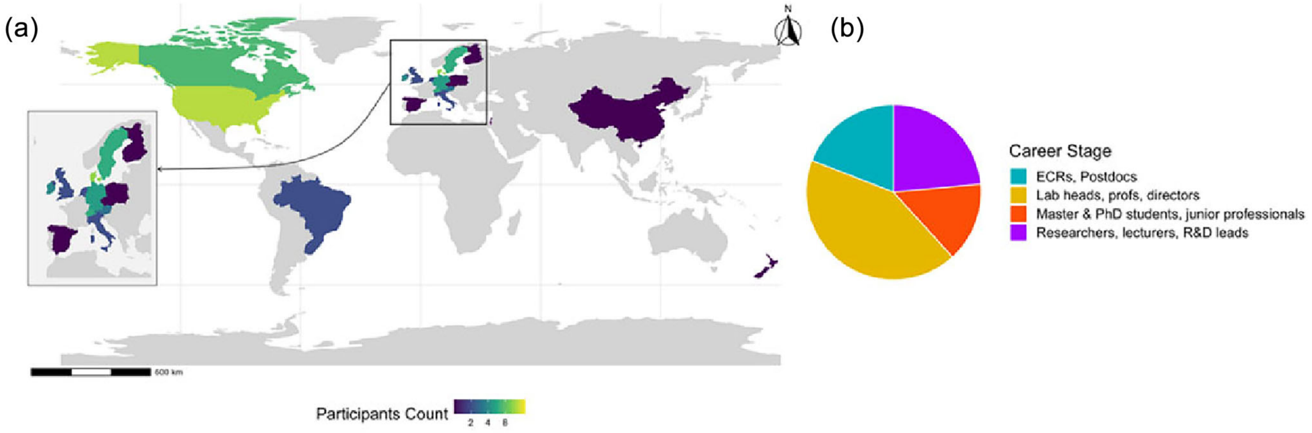


**FIGURE 3** (a) Map of the participants' home institutes' countries (spatial data by South [2017]). There were 103 participants at the 10th International Phosphorus Workshop (IPW10), and no participants from African institutes, but, when asked where they conducted research, locations covered all continents. (b) Career stage distributions of IPW10 participants (75 anonymous entries). ECRs, early-stage career researchers; R&D, those working in industry research and development.

differed for topic (3), whereby impacts were categorized not by theme but by ordering them based on whether the impact described was directly measurable (first order) or cascading from direct impacts of climate change, as described in Section 3.3.

## 3 | RESULTS AND DISCUSSION

Results are presented by topic, in order of themes (topics [1] and [2]) or impact levels (topic [3]). Themes are discussed here led by the participant statements and workshop discussion notes. We present these as the community perspectives across the raised topics supported by literature key references to add contemporary context, rather than as a traditional review article. Figure 4 gives a synthesis across all results, showing how the statements aligned with the importance-confidence matrix (Figure 2b). The statements in Figure 4 are grouped in subtopics, which reflect the header titles throughout Section 3. Figure 4 also shows statements grouped as "Other" (S4 and W6), which did not fit any grouping, although main points have been mentioned in the text.

Figure 5 highlights how experts collectively framed climate change and phosphorus interactions during the workshop. The resulting clusters do not represent predefined system components, but rather emergent groupings based on co-occurrence of concepts within discussions. For example, phosphorus availability and soil erosion clustered with hydrological and mobilization concepts, reflecting expert emphasis on climate-driven transport processes rather than static soil properties. Similarly, extreme events clustered more strongly with management-related terms than with climate drivers, indicating that participants primarily discussed extremes in the context of adaptation and operational response. Notably, some well-established causal relationships, such as those between fertilizer use and food security, were weakly connected or absent, highlighting potential disconnects in expert discourse and reinforcing the need for more integrated, cross-system approaches.

### 3.1 | Climate effects on phosphorus in soils

This topic had 98 statements, categorized by themes: (1) soils and P sources, (2) P mobilization, and (3) P source management. Initial discussion common to the three groups in the soils topic identified the P transfer continuum as the framework to structure input (Forber et al., 2018).

#### 3.1.1 | Soils and phosphorus sources

This theme was weighted highest in critical importance, but confidence levels varied (Figure 4). Statements addressed how climate change may affect soil P biogeochemistry. Phosphorus availability was recognized to influence compositions, diversity, and functions of microbial communities (Leff et al., 2015), and legacy P sources can cause large spatial variability (Lou et al., 2018). Changes in temperature, rainfall patterns, and carbon dioxide ($CO_2$) levels will influence microbes, their activity, and functions such as soil organic matter (SOM) decomposition, nutrient cycling, and support for plant growth (De Vries & Shade, 2013). Microbial activity and nutrient cycling may initially increase with warmer temperatures; however, extended or high temperatures can reduce community and functional diversity (Zhao et al., 2024). In equatorial regions, it was discussed that conditions may become too hot for some soil processes to occur (García-García et al., 2023).

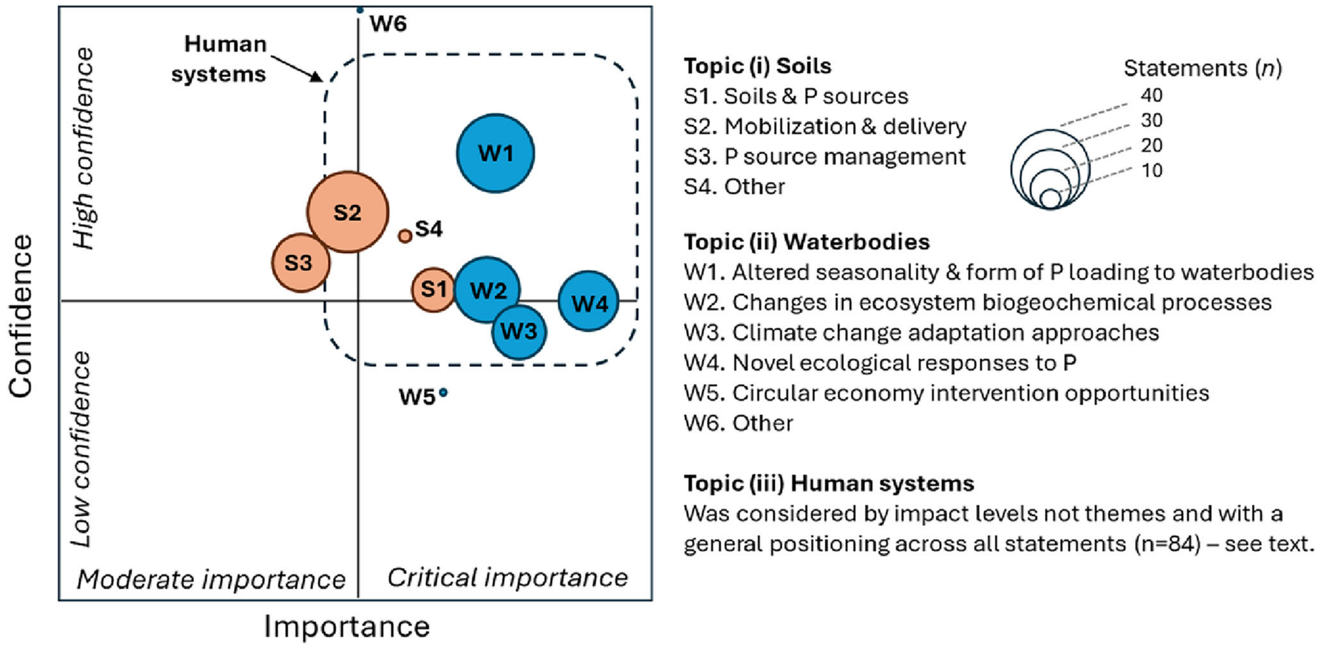


**FIGURE 4** Statement numbers and average positions by theme weighted by numbers and quadrants. Bubble centers indicate the centroid, with bubble diameter proportional to the total number of statements in that theme.

While warmer temperatures influence the demand for P in plants, leading to increased P and $CO_2$ uptake (Lucas et al., 2023), this may be countered by droughts, which alter microbial abundance, community structure and activity, and how microbes utilize and cycle P (De Silva et al., 2025). Drought in fertile land can reduce soil P availability by limiting biological activity, P mineralization, and nutrient cycling (Gao et al., 2024). Competing aspects of climate change were raised. Lower water availability during droughts limits plant uptake of P, increasing P availability, whereas microbially-driven P release from SOM during warming conditions becomes limited below critical soil moisture levels. Increased wildfires were raised as altering the P balance in soils by input of P-rich ash and high risk of postfire soil erosion (Gregory et al., 2015).

More frequent drying and rewetting cycles were discussed as enhancing soil microbial P turnover and more complex microbial activity, altering C:N:P ratios. Wetter soil conditions can alter the relative importance of different P species by enhancing the mineralization of organic P (Gordon et al., 2008; Weihrauch & Opp, 2018). However, under waterlogged conditions, mineralization may be reduced due to oxygen limitation.

### 3.1.2 | Mobilization and delivery

In this theme, statements scored relatively high confidence but varied in importance (Figure 4). Changing temperatures and rain patterns (e. g., warmer temperatures and intense rainstorms), associated altered drying/rewetting cycles (Blackwell et al., 2009), and fluctuating water tables (Bünemann et al., 2013) were discussed as influences on P mineralization and mobilization (Macleod et al., 2012). Changing rainfall patterns (and flood water for near-channel soils) alter soil water tables. Waterlogging, and appropriate temperatures for microbial respiration, may mobilize P by creating anoxic conditions that reduce iron, manganese, and co-precipitated P (Scalenghe et al., 2012). This effect may be mediated by the presence of $NO_3^-$, which serves as an alternative electron acceptor to oxygen and can delay reduction processes until $NO_3^-$ is depleted, and thereby altering the timing and magnitude of P release (Gu et al., 2025). Drier conditions and a lowering of the water table were noted to increase passage of atmospheric oxygen into deeper soil, enhancing decomposition processes and releasing subsoil P stores (Macrae et al., 2013). Changes in the frequency and timing of soil freezing/thawing and wetting/drying cycles impact sorption–desorption processes, as well as soil structure, both increasing P mobilization (Gregory et al., 2015; Pizzorni et al., 2024; Yevdokimov et al., 2016). Changing hydrology was discussed as increasing P transfers via soil erosion as well as leaching (Murphy et al., 2023; Sharpley et al., 2015). Under conditions of prolonged wetness, soils are hydrologically connected more quickly and over longer distances via runoff to rivers (Ezzati et al., 2025), and this has the potential to happen over an increasing number of seasons. At such times, future large rain events can mobilize more soluble and particulate P, lower soil P sequestration, and deplete legacy P. Wildfires also require consideration as these enhance soil erosion and

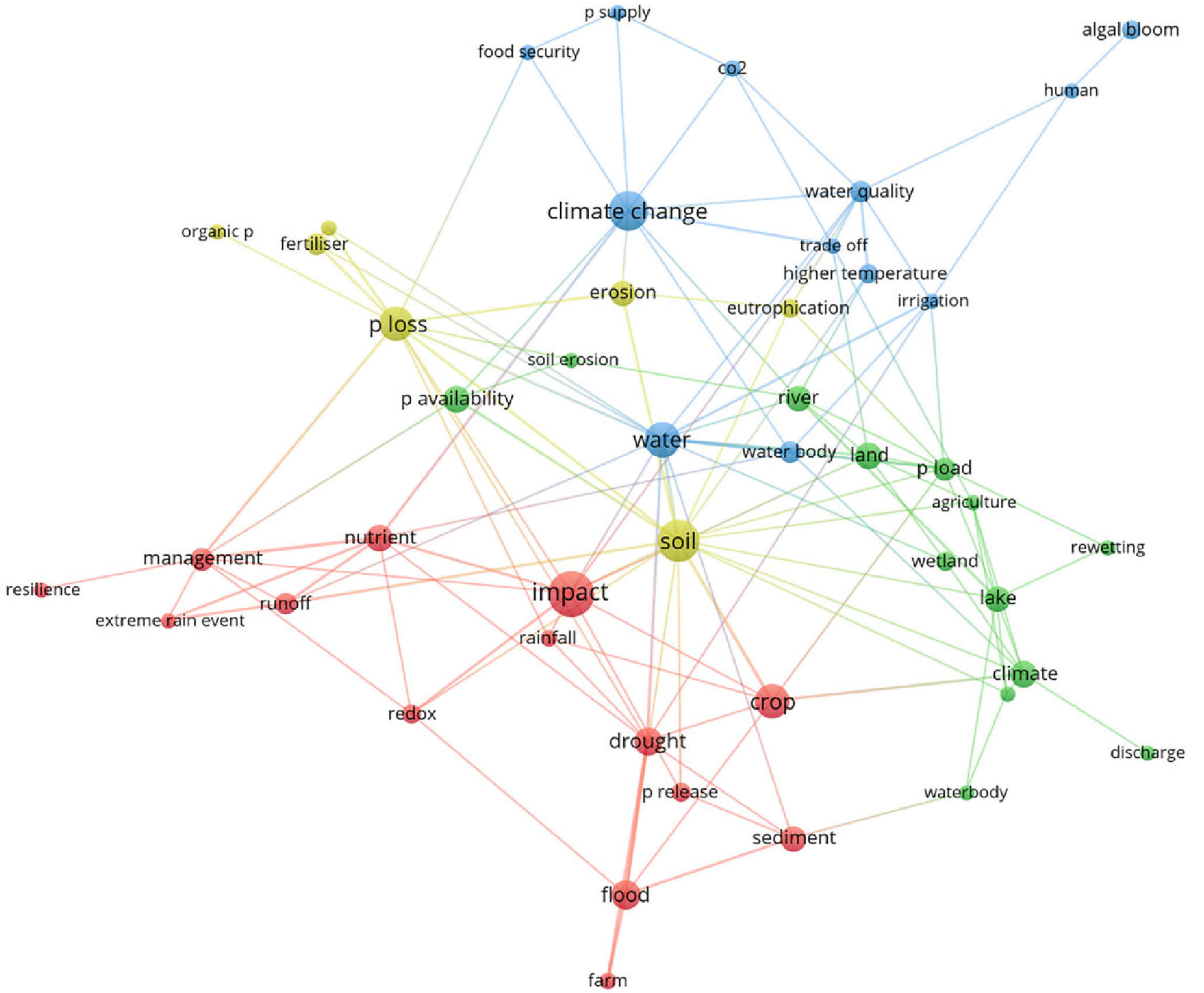


**FIGURE 5** Network visualization of keywords derived from expert statements across soils, waterbodies, and human systems using VosViewer. Nodes represent frequently occurring terms, node size reflects frequency of occurrence, and links indicate co-occurrence within the same expert statements. Colors denote statistically derived clusters of terms that were commonly discussed together. The network reflects patterns of expert discourse rather than mechanistic or causal relationships. Clusters therefore indicate how climate–phosphorus interactions were framed and connected by participants, revealing areas of strong integration as well as gaps in cross-domain linkage.

convert P into inorganic forms (Souza-Alonso et al., 2024). Fires further make soils hydrophobic, leading to reduced water infiltration and increased runoff.

### 3.1.3 | Phosphorus source management

Here, statements distributed in the quadrants toward moderate importance, higher confidence, with a few responses in the low confidence and critical importance quadrant (Figure 4). Climate change and farming practices impact various aspects of agricultural P management (Section 3.3.1), affecting P availability, soil stocks, and transfers (Lucas et al., 2023). Discussed adaptation strategies for managing climate stress on agricultural system included change in cropping, in inputs (fertilizer and other agrochemicals), and specific management changes to counter altered hydrology and soil P processes. Global shifts in cropping followed those in suitable agronomic conditions (soil moisture and temperature) leading to regional disfavoring of current crops; shifting crops types and timing; emerging new crops; arable to grassland conversions; and, at the macro-scale, change in global food production areas. Shifting crop types and timing could produce impacts such as altering P distributions in soils globally, bringing new soils to agronomic soil P minima at local scales, and changing P cycling and P transfers due to altered runoff. Altering crop rotations was considered to influence P uptake by varying the amount and timing of P removal (Bünemann et al., 2006), ultimately influencing soil P accumulation (Withers et al., 2014).

Many of these agronomic P-related changes were discussed in the context of required developments for resistance to hydrological extremes, crop physiological changes (e.g., rooting), and irrigation practices. Spring drought may change fertilizer efficiency and plant requirements as low soil moisture limits crop P acquisition, and the introduction of drought resistant crops will affect P uptake and fertilizer requirements (Lami et al., 2025).

Experts discussed changes in fertilizer inputs in terms of space and amount (because of cropping redistribution), timing matching altered growth phases with temperature or water stress, fertilizer form (manures vs. chemical), and application (liquid vs. granular), all with strong envisaged controls on soil–plant-runoff P processes, especially with shifting climate between extremes like flooding and drought. These changes will have direct P implications through shifts in global soils P distribution, with agronomic soil P levels rising locally, spatial changes in P cycling, and runoff losses, necessitating altering strategies for timing.

Management strategies raised were altering soil pH through liming, soil management targeting P availability, and leaching, developing best management practices (BMPs) with a focus on climate stressors and developing farm-local P resilience plans. Statements around inputs and cropping were generally considered moderate priority, while more statements addressing management for soil system resilience were rated critical priority. To counter climate change, it was expressed that P mitigation strategies and BMPs will need to work more effectively in the busy spaces of productive agriculture. Studies suggest that upscaling BMPs to whole catchments is most efficient (Giri et al., 2020). Resulting global change in where we grow crops, farm livestock, and adapting P management (Hultgren et al., 2025) was also a key discussion in Topic 3 (Section 3.3).

## 3.2 | Climate effects on phosphorus in waterbodies

The 138 statements returned by participants in this session were categorized into five themes: (1) altered seasonality and forms of P loading to waterbodies, (2) changes in ecosystem biogeochemical processes, (3) climate change adaptation approaches, (4) novel ecological responses to P, and (5) circular economy intervention opportunities.

### 3.2.1 | Altered seasonality and forms of phosphorus loading to waterbodies

Statements in this category scored highest in confidence and importance relative to other categories, placing within the high confidence and critical importance quadrants (Figure 4). The evidence-based responses highlighted a range of climate change-mediated effects on nutrient delivery from catchments to surface waters, including the effects of more extreme precipitation leading to increased transport to and through rivers. Such effects have been confirmed in meta-analyses of riverine water quality (Lin et al., 2021). However, availability of river high-flow data limits the accuracy of flood models (Dottori et al., 2013), impacting capacity to predict and prepare for extreme flood events and limiting reliable estimations of P loss.

Extreme rain events, small changes in rainfall, and/or potential evapotranspiration impact water balances and P transfers (Murphy et al., 2023). An increase in runoff and saturated soils will increase both soluble and particle-bound P delivery (Regan et al., 2014; Sharpley et al., 2015). In locations experiencing increased precipitation, P losses may increase through nutrient leaching and overland transport. However, P losses may be dampened by uptake by actively growing vegetation and canopy protecting erodible soils—hence future associated changing P fluxes are region and site specific and difficult to predict (Costa et al., 2023; Li et al., 2023). For point sources, an increase in storm overflow discharges may be expected due to more intense and frequent storms (Müller et al., 2020). Droughts and heatwaves, rainstorms and floods, and more gradual changes in temperature have all been confirmed to worsen surface water quality (van Vliet et al., 2023). An increase in nonpoint source delivery might increase P load while reduced baseflow might increase P concentration due to less dilution (Mellander et al., 2024; Shore et al., 2017). Droughts can also lead to drying and exposure of bed sediments in intermittent rivers and lakes, increasing P release rates during rewetting (Schreckinger et al., 2022). It should be noted that the net effect of multiple climate-driven changes (i.e., alterations in adapted farming systems) in nutrient delivery is most important at the lake basin-scale in some regions, due to compounding impacts of farming, hydrology, and climate in long-term accumulation of nutrients and/or quick response of lakes to changes in precipitation (Mutanda & Nhamo, 2024). Warming may also counteract the expected increase in nutrient delivery from increased precipitation through increased evapotranspiration (Kalcic et al., 2019). Nevertheless, an increase in P loading from land to lakes is generally expected to occur over the long-term (Jeppesen et al., 2009) because of climate-driven changes in agricultural practices (Robinson, 2024).

### 3.2.2 | Changes in ecosystem biogeochemical processes

Statements in this category scored high for importance but with varying levels of confidence, placing in the high importance/low confidence and high importance/high confidence quadrants (Figure 4). While catchment flow and water availability have become less predictable due to climate change (EEA, 2018), heavy precipitation and flooding can lead to reduced transit storage and residence time (Talbot et al., 2018), with highly flushed water bodies typically exhibiting reduced algal biomass accumulation (Yan et al., 2023). Warming-induced increases in lake stratification and deoxygenation may promote the release of redox-sensitive P from bed sediments to surface waters (Jansen et al., 2024). Changes in wetting/drying cycles is expected to alter key P transformation processes including organic P-mineralization, inorganic P solubilization, dissolved organic matter, dissolved oxygen concentration, and aquatic plant nutrient uptake (Sosiak, 2025; Venterink et al., 2002).

Regional shifts in primary production and denitrification are expected due to changes in N and P fluxes to waterbodies (Tivig et al., 2024). For example, reductive dissolution of iron-oxide may increase the release of P coupled with higher rates of denitrification (Huang et al., 2016), causing a shift toward lower N:P ratios. Higher temperatures also lead to longer anoxic conditions and increasing lake stratification, which cause oxygen depletion and eventual remobilization of P (Müller et al., 2020).

#### 3.2.3 | Climate change adaptation approaches

Statements in this theme scored high for importance but with varying levels of confidence, tending toward the high importance/low confidence (Figure 4). Comments under this theme focused on identifying trade-offs and opportunities for adapting to climate change effects in freshwater ecosystems.

Changes in design and placement of water monitoring and treatment technologies may be required to address changing P loading to inform management interventions (e.g., aeration treatment technologies in drinking water reservoirs). To develop data-driven approaches for efficient water resource management in a changing climate, research is needed on organic P turnover, sediment mineralization, and nutrient cycles (Stutter et al., 2023) and extreme event monitoring (Ezzati et al., 2023). It is also critical that adaptation measures be designed and assessed to provide clarity on efficacy and uncertainty to inform developing policies and planning on climate change adaptation (Zhang et al., 2024).

The demand for restoration may change so that more stringent P management may be required to off-set the effects of climate change. This is important where climate change stressors interact with or compound the effects of P in freshwaters leading to the need to revise water quality targets (Spears et al., 2021). Phosphorus management may become more prominent in the context of reducing anthropogenic methane emissions from waterbodies (i.e., eutrophication has been linked to increased methane emissions from lakes; Downing et al., 2021), presenting opportunities to embed P management in freshwaters in the context of climate change mitigation. Finally, conflicts related to resource availability (i.e., land and irrigation for agriculture, access to clean and safe water, and meeting food production demands) may be exacerbated leading to the need for new climate adaptation strategies (Jeppesen et al., 2017; Spears et al., 2022). A significant concern was that existing policy measures generally lack climate-resilient adaptation strategies for P.

#### 3.2.4 | Novel ecological responses to phosphorus

Statements in this theme scored the highest overall importance of all the topic input, evenly distributing across confidence levels (Figure 4), indicating a wide range of ecological responses to climate change. Extreme hydrological events may cause an increase in the prevalence of algal toxins, alter cyanobacteria communities and macrophyte density, change stratification, decrease biodiversity, release methane, and impact fisheries and aquaculture (Nwankwegu et al., 2019). These impacts will inevitably cascade to public health due to the emergence of invasive species (and higher concentrations of pathogens, vectors, and hosts), which will enhance disease transmission risks (Carr & Neary, 2009; Denóbile et al., 2023). Changes in phenology (i.e., the timing of seasonal life history events) of freshwater organisms are increasingly being associated with changes in weather patterns (Woods et al., 2022). Despite the extensive research in terrestrial and marine systems that have demonstrated the importance of phenology for biodiversity maintenance/conservation and the necessity of understanding the impact of climate change on phenology for preventing/mitigating biodiversity losses, freshwater phenology remains less established. In addition, the extent of direct impacts of climate change and interactions with P transport and transformation, which will shape future phenological shifts, is still not well understood.

#### 3.2.5 | Circular economy intervention opportunities

Statements in this theme scored with low confidence and mostly critical importance (Figure 4). This reflects uncertainty in the utility of some emerging approaches as described below. It is key for circular economy approaches that they conform to economies of scale. As ecosystems change in response to nutrient pollution and climate change, opportunities for P recovery have emerged. Most of these “Circular Economy” approaches are at early stages of technology readiness level, and this may reflect the low confidence in the responses on this category. A primary aim in this respect is the recovery and reuse of P from the environment for agricultural application. Additional benefits include harvesting algal and macrophyte biomass for biofuels, the creation of nature-based solutions bringing biodiversity and aesthetic gains, and the creation of jobs in the green economy sector (Sánchez-García et al., 2024).

Tammeorg et al. (2024) review circular economy approaches in lakes, including the removal of bed sediments from lakes for agricultural fertilization in Denmark (Haasler et al., 2023) and Estonia (Kiani et al., 2023). The removal of P-rich bottom waters from lakes (hypolimnetic withdrawal) also represents a potential circular economy approach (Silvonen et al., 2022). The treatment of nutrients in manure and sewage effluents has also received attention, including the use of microalgae (Kebede-Westhead et al., 2006) and chemical additives within circulating recapture systems (Altamira-Algarra et al., 2022) to enhance the efficiency of more traditional measures (e.g., constructed wetlands). In aquaculture, the recovery of nutrients is a key economic concern driving the "closed loop" or "recirculating system," and microalgae are utilized to recover nutrients prior to wastewater discharge (Ende et al., 2024). The climate change adaptation measures highlighted here are largely speculative as there are not any global conceptual approaches to decision-making for environmental managers. However, planning for climate change adaptation is required by many countries within their climate change national adaptation programs, requiring careful handling of uncertainty in future projections of both climate change stressors and the degree to which proposed adaptation measures will relieve the effects of those stressors on the environment. Nevertheless, some examples exist where climate change adaptation planning is ongoing for lakes with a focus on P management (e.g., in Loch Leven, UK; Lake Rorotua, New Zealand, and Lake Erhai, China; Spears et al., 2022).

## 3.3 | Climate change and phosphorus impacts on human systems

Eighty-four responses are grouped into different orders, as the impacts of climate change are anticipated to propagate as cascades through human and physical systems (Challinor et al., 2018; Lawrence et al., 2020). First-order impacts are those that are *direct* and observable. Second-order impacts are typically indirect impacts and are the consequences of the first-order changes (cascading impacts). In this section, we use "first order" to refer to the impacts of climate change on P in soils and water. We use "second order" to reflect changes to P management and mitigation. At the third order, we discuss the cascading consequences of first- and second-order impacts of climate change on P, but these are less directly related to P than the second-order impacts. Finally, we discuss participants' comments that reflect an understanding of the broader issue of climate change but do not relate to P specifically. About half of the transcribed statements were deemed high confidence (49 out of 84, across all orders) and the vast majority were marked as of critical priority (69 out of 84, across all orders). Given the lack of clear consensus about the placement of the impacts in the four quadrants, priority and certainty will not be discussed in this section.

### 3.3.1 | First- and second-order impacts of climate change on phosphorus in soils and waters

The first-order impacts on soil P and P in waterbodies interacting with climate conditions, described in Sections 3.1 and 3.2, collectively result in second-order impacts, such as impacts of changing P on crop growth, productivity, and yield via root structure, nutrient and water availability and uptake, disease resistance, and crop failure. Agricultural producers respond to changes in crop growth, productivity, and yield primarily via the implementation of existing management structures: switching to cultivars more suited to changing climatic conditions, altering rates of inputs such as fertilizer, water management strategies to enhance drainage or irrigation, and altering the timing of disease and weed management practices. Humans will change the way that water is managed on farms. For example, irrigation and water retention may increase due to a limited water supply under future climates, but artificial drainage may increase due to more extreme precipitation, both of which may have cascading impacts on P mobilization (Chrétien et al., 2016; King et al., 2015; Kleinman et al., 2015; Reinhardt et al., 2005). Strategies to manage first-order impacts (Section 3.1), can collectively be referred to as "autonomous adaptations" (Easterling et al., 2007; Smithers & Smit, 1997). Cascading from autonomous adaptations are purposeful adaptations, for example, there will be a need for efficient use of available P via mining of legacy P, or changes in fertilizer application strategies.

The changes in P delivery and seasonal timing of nutrient delivery to surface water and responses in waterbodies discussed in Sections 3.1 and 3.2 collectively contribute to changing water quality through increased likelihood of hypoxic events, alterations in phenology, and increases in the frequency and magnitude of algal blooms. Among participants, autonomous adaptations to second-order impacts of P in surface water were limited to drinking water treatment and water quality advisories. Challenges in managing toxic algal blooms and the treatment of drinking water supplies will increase (Taylor et al., 2023; Treuer et al., 2021), and there will be increased demand for new, purposeful adaptations (e.g., adaptations focusing on P recovery, Section 3.2.5).

### 3.3.2 | Third- and higher-order impacts of phosphorus management and mitigation in response to climate change

There will be changes in food production systems due to first- and second-order impacts, as well as due to adaptation to climate stressors. Cascading from these, third- and higher-order impacts identified by participants will lead to an overall transformation in the human system (e.g., changes in subnational and national policy, rural development, and the location of agricultural activity) because of changing climate conditions. Third-order impacts identified included the spatial migration of agricultural activity. It will be possible to grow food (or different crops) at higher latitudes in the future (Franke et al., 2022), but not traditional crops in regions with hotter and/or drier conditions, particularly where multiple stressors compound (Lesk et al., 2022). Respondents felt that this would lead to cascading impacts on P such as changing P distributions/fertilizer at the global scale. It was suggested that "the drying of agricultural lands that are currently fertile could lead to a massive movement of agricultural P" as cropping less fertile soils may require significant fertilizer application, and one participant commented "should we fertilize less fertile land bodies?". Nutrient management guidelines will need to shift to account for new crops and variable weather; although, it was noted that it is difficult to match crop P needs when soil conditions may shift between saturation and drought within any given year.

It was also noted that the geopolitical trade of P could change (cascading from crop migration), with potential changes to food security in response to the transport of P and food and fertilizer globally (Brownlie et al., 2023). Climate change will lead to increased costs to production systems ("Impacts on farmer profitability which increases regulation or decreases productivity") due to changing yields and higher production costs associated with fertilizers and nutrient and water management. Crop failure due to climate change can result in higher food costs in high-income and shortages in low-income areas (Jackson, 2025).

Further, the prioritization of environmental management could shift, where water quality will take the backseat in the face of water scarcity (Jones et al., 2024), and "current mitigation infrastructures/measures [related to P management] may become redundant and need to change." It was also felt that there would be "lower priority for P mitigation measures and more interest in P supply." This may have repercussions with respect to advances in water management adaptation efforts important for securing drinking water quality. Recreational water use will also be impacted by water quality, which will have economic repercussions in the tourism sector (Garcia-Hernandez et al., 2022).

### 3.3.3 | Broader societal implications

Discussions included comments that referenced societal implications of climate change that did not have a direct link to P. Participants were concerned that climate change will bring about issues regarding conflict, poverty, vulnerable communities, pests and diseases, population changes, societal and individual changes in behavior, climate change communication, greenhouse gases (GHGs), food security, and economy.

Participants believed that humans will shift to a more plant-based diet, primarily to mitigate GHGs emissions, not P losses. However, this shift may have the potential to modify P distributions globally by reducing the density of livestock and pasture relative to cropping systems, thereby modifying P supply and transport in these landscapes.

Increased conflict related to societal attitudes toward climate change—including science denial, resource competition, and mitigation, was also discussed. Participants were concerned that differing perspectives and legislation on mitigation and emissions might lead to conflict at borders ("How will changing behaviours lead to increased conflicts? i.e., impacts on adjacent lands"). As an example, the conflict in Ukraine has been linked to significant drawdown of soil P stocks in the country leading to reduced crop production capacity (Medinets et al., 2025). Whatever shape conflict will have, there was a consensus that vulnerable communities will be affected disproportionately, likely facing the greatest consequences of climate change ("The impacts of climate change will be felt first by the most vulnerable communities," "Access to adaptation and mitigation technology not consistent across the globe") (Bathiany et al., 2018).

Participants felt that current climate mitigation infrastructures and measures may need to change, both in relation to P under climate change (Section 3.3.2), and other climate-driven challenges. For example, the current capacity for stormwater management and treatment may need to shift in response to changes in storm frequency and magnitude. Similarly, farmers will have to consider their irrigation and nutrient management regimes more carefully. Some believe that climate will urge the public to invest in climate solutions and conservation, but others are concerned that resistance to mitigation will continue to be a major challenge in the future.

Phosphorus is not necessarily at the forefront of the climate discussion: "Lots of information on climate change but has it been translated to P?". This was perhaps the result of a larger knowledge gap in linking P with climate change (i.e., synergies, trade-offs, and modeling) in the literature. Participants noted areas of uncertainty on the impacts of climate change on P dynamics. Data from sustainable farms is available at a regional scale, but there is uncertainty on "how to scale up to the larger scale" to better project linkages with climate. Participants also commented on changing thresholds, tipping points and feedbacks, with evidence recently being reviewed for lakes, generally, but lacking for P in other systems (Hessen et al., 2024). Communication around nutrients and climate revolves mostly around carbon and nitrogen; however, experts stressed that P drives some of the feedbacks (Section 3.2). A question was raised asking whether society should be made aware of the impacts of climate change on P and whether society needs to know the P-specific climate implication or whether this is equivalent to overloading society with information. However, some thought this was important as P is related to food security and therefore important to society. The issue of communication will be felt by governing bodies, who will need further interdisciplinary advice as climate issues compound and become more complex (Glendell et al., 2025).

## 4 | CRITICAL DISCUSSION AND EMERGING CHALLENGES

Despite high levels of confidence in many areas of research results, experts underlined the need for better systems knowledge of the interlayered challenges for understanding and managing P under climate change. Many maturing datasets have potential for synthesis, modeling and policy development for managing altered soil P sources, mobilization and delivery (moderate priority), and P loading impacts in waterbodies under climate change (critical priority). Yet further primary data and model development were believed necessary to consider climate-driven P impacts with regard to human systems. Thus, this methodology has allowed a research community-level assessment across wide areas of this pressing issue. A limitation of this study was that participants' judgements of the impacts reflect their understanding of each topic, as well as where they primarily conduct their research. Responses were biased toward the global North, where most of the available data on P-climate interactions are gathered, leaving major uncertainties in tropical, arid, and high-latitude systems, generally reflecting the contemporary literature. Furthermore, emerging phenomena that are relevant to P management under climate change, including climate change–induced large scale processes (e.g., changes in aeolian dust transport of P and impacts of P limitation on carbon processes) were not reported during the workshop. This may reflect that they are yet to be fully developed in the academic discourse.

The influence of climate change on soil P processes and sources was considered critically important by experts, with varying levels of confidence. Shifting spatiotemporal patterns of agriculture were considered a key challenge associated with agricultural intensification as climate increasingly magnifies cropping constraints globally. This may necessitate new crops, altered fertilizer types, and timing. While existing management research may be translated to some of these new situations, there were challenges recognized in the underpinning soil P process knowledge, for example, altered soil P biogeochemical cycling under climate-altered soil temperature, water regimes, and runoff (Lucas et al., 2023; Mellander et al., 2025). Applying the underpinning technical knowledge can be advanced more effectively alongside greater availability of farm P management data (Helfenstein et al., 2024). Experts agreed that many agricultural management practices will change in response to climate change, but opinions differed on the magnitude of their importance (Figure 2b). This highlights the need for more modeling work to anticipate how management strategies (e.g., fertilizer timing, crop rotations, water retention measures, and crop redistribution) could mitigate climate-driven P losses across different climatic and soil contexts (Ockenden et al., 2017; Wynants et al., 2024). The need to learn from natural soil systems about P cycle resilience to climate change require investment in long-term environmental monitoring and experimentation to inform projections. In this context, process-based watershed models can already incorporate detailed, farmer-informed, management scenarios (e.g., Kalcic et al., 2016), and probabilistic models (e.g., Adams et al., 2023; Kneier et al., 2023) as well as agent-based models (e.g., De Keyser et al., 2025; Sommer et al., 2025) can also be used to include other stakeholders and their water and nutrient-related decisions.

Experts agreed on strong evidence for climate change to alter the timing, magnitude, and nutrient forms delivered to surface waters through more frequent extreme precipitation, droughts, and prolonged warm periods. The disrupted hydrological and nutrient cycles will intensify P losses and exacerbate eutrophication and harmful algal blooms through shifts in redox potential and hydrological regimes, triggering cascading impacts on biodiversity, aquaculture, and public health. However, the long-term nutrient dynamics, ecological freshwater responses, and catchments' behavior to the changing climate at a larger scale, are still poorly understood, highly site-specific, and variable. Research shows that tackling the challenge of climate change–induced risks on water bodies requires targeted catchment-specific mitigation strategies (Ezzati et al., 2024; Galloway et al., 2025), and care must be taken to consider sources of uncertainty when selecting measures following a robust statistical planning approach (Zhang et al., 2024). Primary data generation, associated funding, skills training, and methodological breakthroughs were considered challenges for climate-P impact adaptation in water bodies. Emerging circular economy approaches offer promising opportunities to recover and reuse P from aquatic systems, but experts agreed challenges remain for their development, with uncertain scalability, economic feasibility, and technological readiness (experts showed "uncertainty in the utility of some emerging approaches"—Section 3.2.5). Although the concept of circular economy to water science is relatively new (Morseletto et al., 2022), it is attracting more attention in water policy (Sauvé et al., 2021) as a promising approach to tackle water scarcity and insecurity (Lasseur et al., 2025), however, circular economy's role in climate adaptation must be further substantiated.

Despite uncertainties, technologies such as nutrient recovery, nutrient recycling, and food chain efficiency, have (at least partially) been demonstrated as effective climate-resilience building responses; so, as proposed by Elser and Haygarth (2021), *the wicked P problem* (Cordell, 2008), is now a governance issue. It is about economics, sociology, psychology, and political science, it is about systems and the need to shift our approaches and share our knowledge more widely. This is evidenced by the participants categorizing most human impacts as critical priority. Hence, the participants acknowledged that P challenges under climate change extend beyond their domain expertise, constituting a critical societal issue. While expertise on their specific P topics may vary, the experts showed that their collective research is driven by an urgent concern for the broader implications of the climate threat. Thus, the workshop shows that social science has been less integrated in strategies for future P management. This is common, for example, in conservation science (Bennett et al., 2017), and also likely due to the history of IPW which members are most often concentrating on P in soil, water, and at the soil–water interface. This resulted in limited statements on the governance, behavioral, and economic factors shaping P management practices, highlighting the need for future interdisciplinary studies, long-term monitoring, and real-world pilot programs, linking biophysical evidence with socioeconomic and institutional mechanisms for adaptive P management. Further, as P scarcity, water quality impairment, and resource security increase as public concerns, transdisciplinary modeling studies need to be applied to P under future climate scenarios (Bieroza et al., 2024; Negri et al., 2025). Future IPWs will endeavor to better reflect the needs for a stronger interdisciplinary approach, canvasing contributions across social scientists, economists, agronomists, policymakers, stakeholders , and decision-makers.

## AUTHOR CONTRIBUTIONS

**Camilla Negri**: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Golnaz Ezzati**: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Philip M. Haygarth**: Conceptualization; data curation; formal analysis; investigation; methodology; writing—review and editing. **Merrin L. Macrae**: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Per-Erik Mellander**: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Bryan M. Spears**: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Sara Trojahn**: Conceptualization; data curation; methodology; visualization; writing—original draft. **Johanna Wandel**: Formal analysis; investigation; methodology; writing—original draft. **Marc Stutter**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing—original draft; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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