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Discussion

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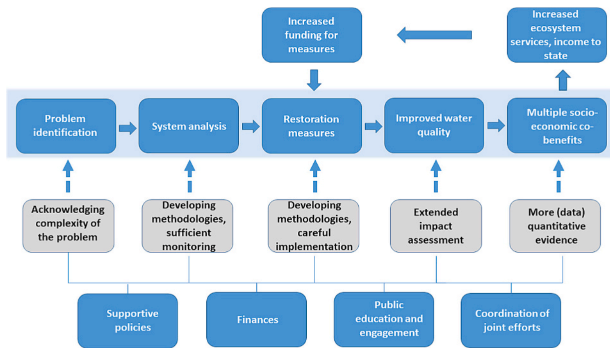
HIGHLIGHTS

- Managing lake's nutrient pollution is challenging.
- Sustainable lake restoration (SLR) is a solution.
- It improves lakes' ecological condtion and provides broader socio-economic co-benefits.
- We identified knowledge gaps and factors determining advance in SLR.
- Policy support is crucial for transformative change.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable lake restoration has been introduced recently as a strategy to address ecological, economic, and social challenges in nutrient management. The strategy would benefit at least 40 % of the world's lakes through addressing eutrophication, and the impact becomes even broader if we consider the complex nature of eutrophication (its linkage to multiple environmental problems). This approach involves: 1) demonstrating broader social and economic benefits, 2) integrating circular economies, and 3) directly engaging local communities in co-developing restoration goals, targets and monitoring. The current study explores opportunities to advance sustainable lake restoration using a well-established model that fosters interaction among restoration stakeholders. We assessed each model step for sustainability needs, identifying knowledge gaps and key factors for future success. We emphasize the need for a better understanding of the linkages between eutrophication and other environmental problems, proper monitoring programs to demonstrate broader restoration benefits, effective system analysis tools, sustainable nutrient recycling measures and accurate realization, and thorough documentation for life-cycle assessments. Achieving these goals requires significant policy and financing transformations, continuous engagement, and close collaboration among all stakeholders.

1. Introduction

Eutrophication remains the main cause of water quality impairment in lakes globally, affecting the provision of important ecosystem services for billions of people (Irvine et al., 2023). Over 40 % of the world's surface waters are impacted (UN report, 2024), implying ecological degradation through the proliferation of harmful algal blooms, high rates of biodiversity decline, increase in greenhouse gas emissions, and associated economic losses. More than 54 % of the 71 countries participating in the assessment reported that the ambient water quality indicator score in their lakes was less than high, while, in general, data for lakes is underrepresented relative to other water bodies (UN report, 2024). The US Environmental Protection Agency has categorized 50 % and 47 % of US freshwater lakes in poor condition with respect to phosphorus and nitrogen, respectively (Scholz et al., 2025). Landsat imagery data for water transparency (Secchi depth) indicated that about 37 % of lakes globally were eutrophic (the highest percentage of eutrophic lakes were in South America and Africa) and located mainly in areas with agricultural and urban-dominated drainage basins (Song et al., 2022). The extent of eutrophication is projected to double in response to climate change and population growth, leading to methane emissions from lakes and reservoirs exceeding 50 % of current fossil fuel emissions (Beaulieu et al., 2019). The substantial accumulation of nutrients in watersheds (legacy nutrients) will continue to damage ecological health in lakes for decades to come if left unmanaged (Carpenter, 2005).

Reuse and recycling, in combination with a circular economy, suggest an ongoing cycle of nutrient discharge and harvest, which is the best we can do at the moment in order to find a compromise between ecological, economic, and social challenges in nutrient management. Ultimately, the goal is to minimize and prevent the excess nutrients from leaking into the environment. The largest contributor to the global phosphorus (P) load into freshwater systems is the domestic sector (54 %), followed by agriculture (38 %) and industry (8 %) (Mekonnen and Hoekstra, 2018). Most nitrogen (N) loads come from diffuse agriculture sources (75 %), the domestic sector contributes 23 % of the total N load to freshwater, and the industrial sector 2 % (Mekonnen and Hoekstra, 2015). Of the domestic and industrial point sources globally, about half are being treated (Jones et al., 2021), although not necessarily effectively removing nutrients, and an increase by 10 %–70 % of the nutrient discharge from households to surface water is foreseen by 2050 (Van Puijenbroek et al., 2019). Whilst intercepting nutrients from point sources before they are discharged into the environment is technologically viable, in most developing countries, a strong increase in nutrient discharge from households to surface waters over the coming decades is expected (Van Puijenbroek et al., 2019). In addition, food demand has already risen dramatically over the last few decades and is predicted to rise further between 59 % and 98 % by 2050 (Elferink and Schierhorn, 2016). Consequently, nutrient transport from agricultural areas is expected to increase under business-as-usual scenarios, and mitigating these non-point nutrient sources creates severe challenges (e.g., food security issues; Luna Juncal et al., 2023). Hence, existing water quality management strategies have to account for ongoing high nutrient discharges from such areas.

On the other hand, because of the unsustainable use of P minerals, not only has the eutrophication of lakes intensified, but the availability and price of P fertilizer have also changed to the point where food security has become jeopardized globally (Brownlie et al., 2024). Also, rising P fertilizer prices will make alternative P sources economically feasible (Mew, 2016), and e.g., P-rich sediments may become included in a recycling P-chain. Undoubtedly, P recycling has to be intensified, not only to reduce environmental damage from surplus P leakage but also to reduce the dependency on high P-imports (Van Dijk et al., 2016). Hence, we need to revise the existing approaches to eutrophication management.

Recently, the lake restoration science community proposed a novel strategy called "sustainable lake restoration" (Tammeorg et al., 2024a), which aims at improving ecological conditions while delivering socio-economic co-benefits that extend beyond the scale of intervention. By managing nutrient pollution in lakes and their catchment areas sustainably, and addressing several interlinked environmental problems (Fig. 1), we can return to a safe operating space, i.e., the range within which human activities can occur without causing irreversible harm to the planet's life-support systems (Rockström et al., 2009, 2023a). This aligns well with many international policy initiatives (e.g., the UN Sustainable Development Goals (SDGs) & Decade on Restoration; European Green Deal & Biodiversity Strategy 2030). The essence of sustainable lake restoration was summarized much earlier by Moss (2007): "Lake restoration, in its most trivial form, may be simply a form of gardening to allay the symptoms of problems and create the illusion of a solution. Lake restoration in its most profound form involves an understanding of cultural significance, the workings of human societies, and forms an epitome for the solution of much greater, global problems." This suggests a significant role of information, technology, participation, institutions, policies, and finance, which were identified as the pillars of the concept of Integrated Lake Basin Management (ILEC, 2005). We further underline the need for the broad spectrum of the benefits of restoration (like circular economy, carbon neutrality). With this in mind, sustainable lake restoration includes three main elements that improve upon previous approaches.

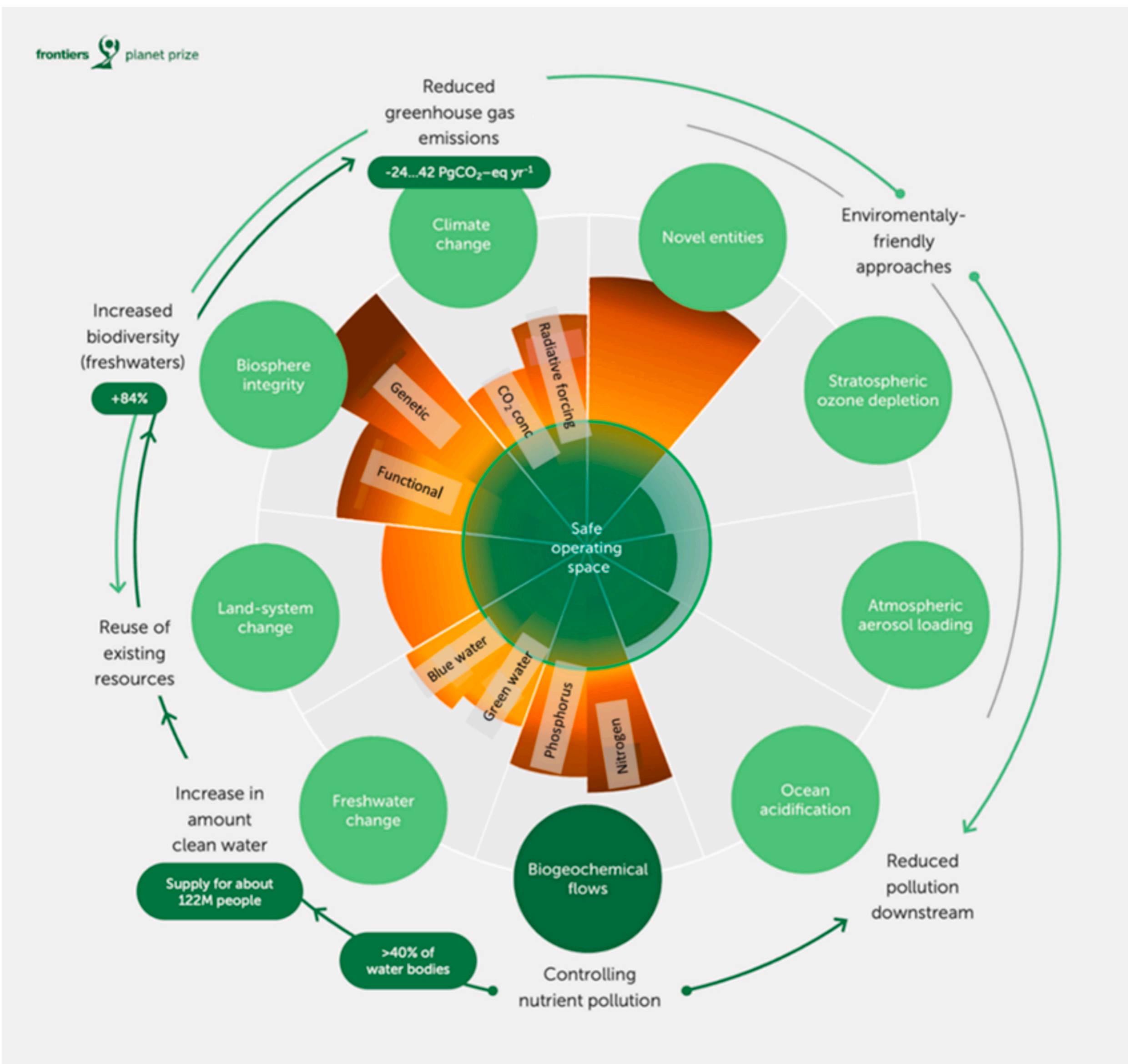

Fig. 1. Sustainable lake restoration is in line with a number of concepts and policy initiatives. For example, it brings us closer to living within a safe operating space (Planetary Boundary concept by Rockström et al., 2009; 2023). The most recent planetary boundaries framework update by Richardson et al. (2023) finds that six of the nine boundaries are transgressed (Earth is outside of the safe operating space for humanity). Tackling nutrient pollution in lakes in a sustainable manner has a big potential to change the situation, not only for phosphorus and nitrogen, but also for the interrelated issues (e.g., reduction of greenhouse gas emissions, increase in biodiversity). In the current graph, the recent update on the PB situation by Richardson et al. (2023) is provided, quantifying the impacts of sustainable lake restoration specifically for lakes (depicted as an outer sequence), using the statistics from the White Paper of WWQA (Irvine et al., 2023). The figure was edited by the Frontiers Planet Prize from Tammeorg (2024).

1) Providing evidence of the broader social and economic benefits that restoration delivers.
2) Creating circular economies as part of the restoration process, specifically aiming to recover legacy nutrients from the "system".
3) Involving the public directly in co-developing restoration targets and monitoring, to promote buy-in and acceptance, acknowledging their role in both causing and solving the problem, as outlined in the model of Cianci-Gaskill et al. (2024).

The current study aims to advance sustainable lake restoration, as defined by Tammeorg et al. (2024a). Tammeorg et al. (2024a) demonstrated a few emerging examples of sustainable lake restoration. As there has been little action since then, we further emphasize the need for progress (Fig. 2) to reduce potential gaps in the process with the example of idealized sustainable lake restoration, which is illustrated in Fig. 3. We build on the model by Lürling et al. (2016; Fig. 2), representing the sequence from identifying a water quality problem to the desired improved ecosystem services. Generally, the model is aligned with the similar models by, e.g., Harfoot et al. (2014), Steinman et al. (2015), Borja et al. (2016) through the integrated assessment and holistic approach. A simple design, flexibility, tailored to lake restoration and proven evidence of success (Lürling et al., 2024) of the sequence in Fig. 2 make it perfectly suitable for the current study.

Through the case-specific approach (system analysis), it can be applied globally. While we mainly concentrate on lake nutrient pollution here, the model can be easily adjusted to solve other case-specific problems (e.g., invasive species, hydrological alterations). For example, the benefits of increased macrophyte coverage for the lake ecosystem are well acknowledged (Poikane et al., 2018). Still, the treatment of invasive submerged species requires considerable funds worldwide, especially in the Global South, where many lakes have infestations or other macrophyte-associated problems (e.g., altered water balances; Hill, 2003). In such lakes, the removal of plant biomass, along with subsequent nutrient recycling, can be a solution (Tammeorg et al., 2024a). Rohr et al. (2023) demonstrated that the removal of the invasive *Ceratophyllum demersum* in lakes reduced infection by *Schistosoma* species (snail-transmitted flatworms) in children by capturing host snails on the recovered macrophyte biomass, improved access to water bodies, and provided cost-effective alternatives for livestock feed and crop production.

In the current study, we evaluate each step in the sequence in Fig. 2 for the further needs dictated by sustainability. These evaluation results are based on feedback from the participants of the international symposium on lake restoration, Lahti Lakes 2024 (authors of the current manuscript), regarding further steps towards sustainable lake restoration. Specifically, we flag the potential knowledge gaps for providing evidence of multiple socio-economic co-benefits of lake restoration and upscaling successful solutions (Fig. 2). Additionally, we identify major factors determining the future of sustainable lake restoration. Ultimately, the model will enable water managers to embed lake restoration across sustainable nutrient management for food security, by adapting to climate change, dealing with legacy pollution from past generations, and supporting conflict management in public discourse. We conclude with the policy recommendations, as policy support is crucial for transformative change.

2. Evaluating steps to further the sustainability of lake restoration from problem identification to multiple socio-economic co-benefits

2.1. Step 1: setting goals and problem identification

A key for sustainable lake restoration is that each lake restoration project starts with communities agreeing on a vision for what they want to restore in relation to water quality, biodiversity, and ecosystem services the lake can potentially provide, using e.g. surveys, which elicit individuals' stated preferences (Bateman et al., 2023). This enables lake managers to refine restoration goals, identify the problems preventing

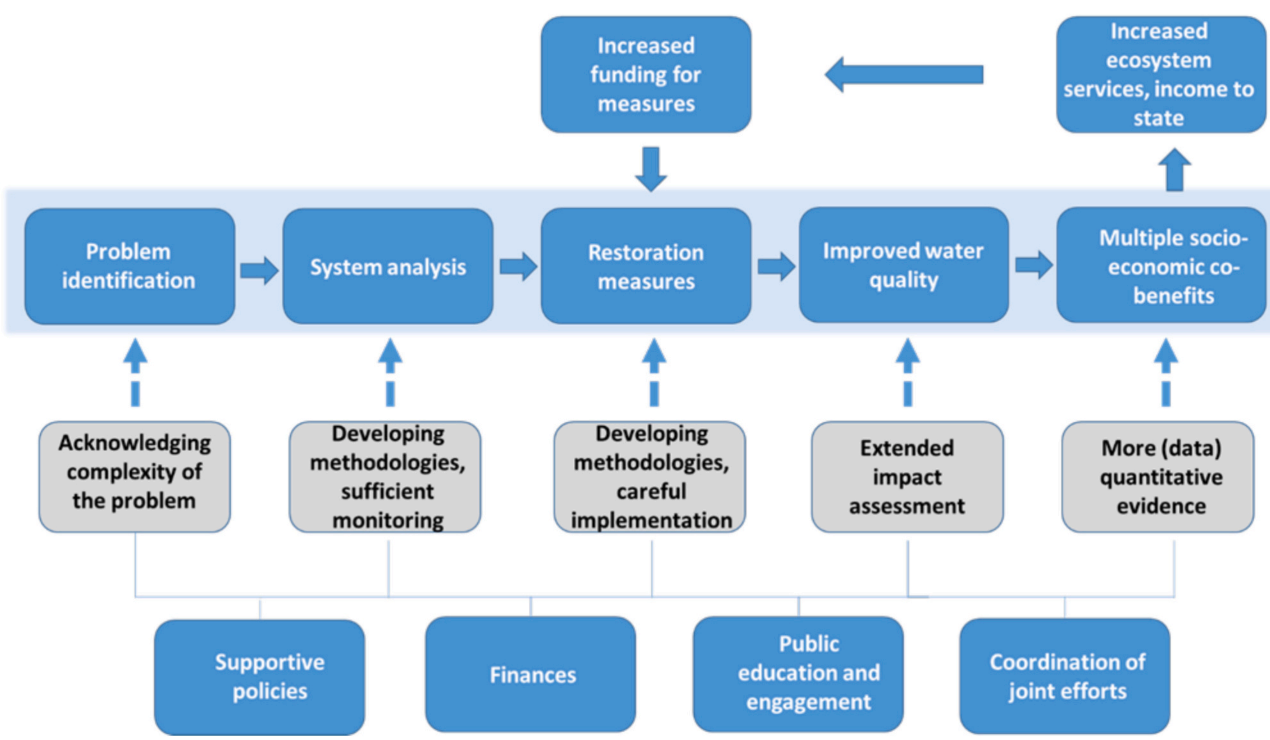

Fig. 2. Further opportunities for advancing sustainable lake restoration through eliminating knowledge gaps for the sequence from problem identification to multiple socio-economic benefits and increasing funding for restoration measures. Eliminating scientific knowledge gaps (in the grey area) would enable the improvement of methodologies for broader impact assessment and monitoring, and provide water managers with sustainable restoration tools. The sequence was introduced by Lürling et al. (2016; shaded part of the diagram). This requires changes in policies, financial schemes, engagement, and interactions of different actors.

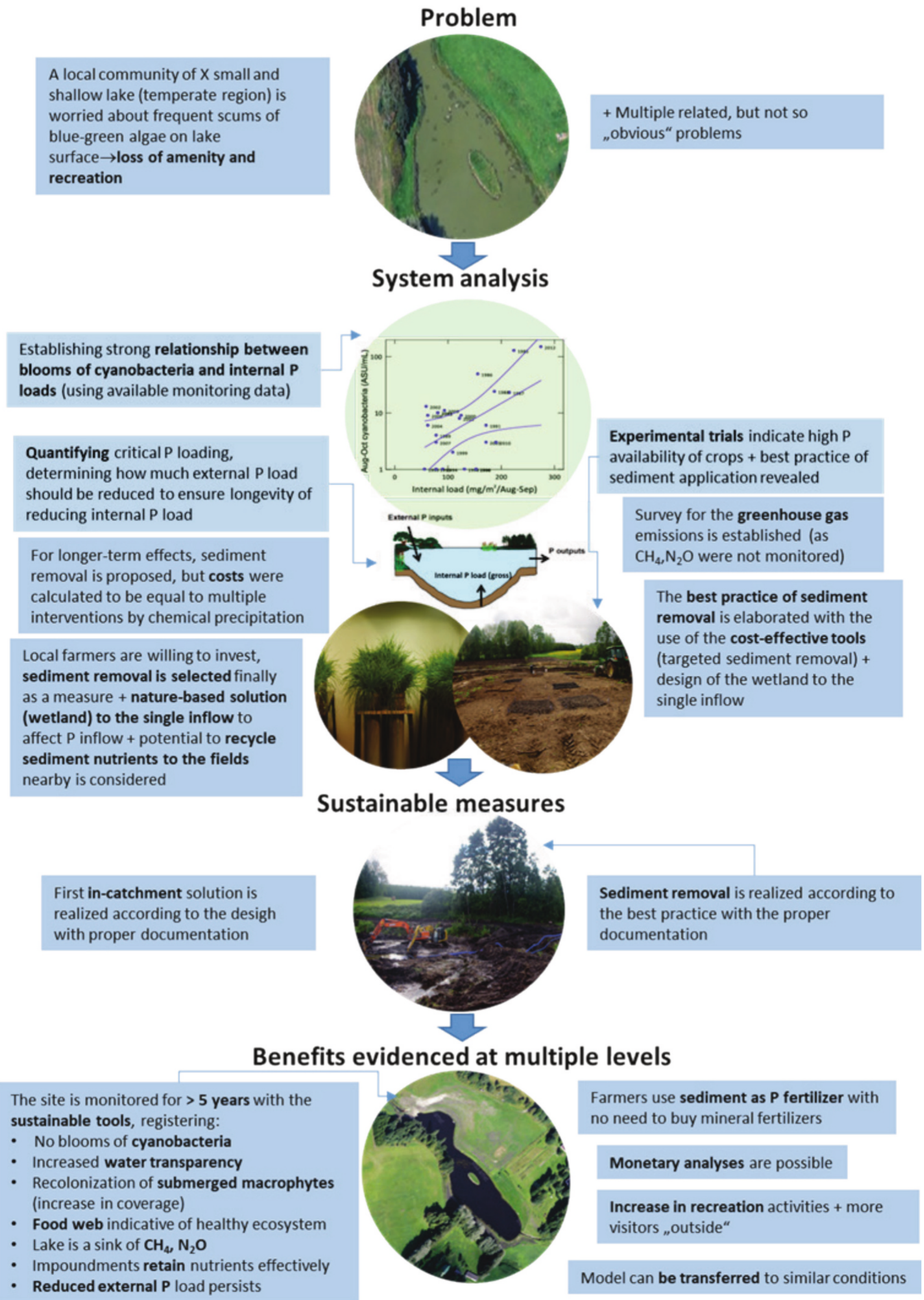

Fig. 3. An example of idealized sustainable lake restoration. All pictures are illustrative and used to illustrate key processes (indicated with arrows). Graphics from Nürnberg et al. (2019) are used to illustrate cyanobacteria as a function of internal phosphorus load.

them from being reached, justify actions, and design a restoration plan and monitoring program. The problem is usually a visible, easily detectable symptom of eutrophication (e.g., cyanobacterial blooms or fish kills), while the actual extent of the impact is considerably broader (Fig. 4). In addition to diminishing unpleasant (and potentially toxic) algal blooms and increasing water clarity, restoration measures may provide other positive changes for biodiversity and broader socio-economic benefits, including recreation, amenity, real-estate value, reduction in greenhouse gas emissions, and the potential to recycle nutrients (as P fertilizer). While documenting the wider impacts of restoration is aligned with the definition of sustainable lake restoration, the integration of broader success metrics requires a better understanding of their linkages with nutrient concentrations, consequent ecological structure, and greenhouse gas emissions. For example, there are still no field-scale studies explicitly demonstrating effects of lake restoration on greenhouse gas emissions, while there is evidence available at the lab (mesocosm) scale for both dredging and lanthanum modified bentonite with respect to reducing methane emissions (52 and 74 %, respectively; Nijman et al., 2022). To evaluate all benefits, it is important to design monitoring programs in a way that enables tracking success at multiple levels while keeping in mind the need to balance resources needed for monitoring with those required for actual restoration actions.

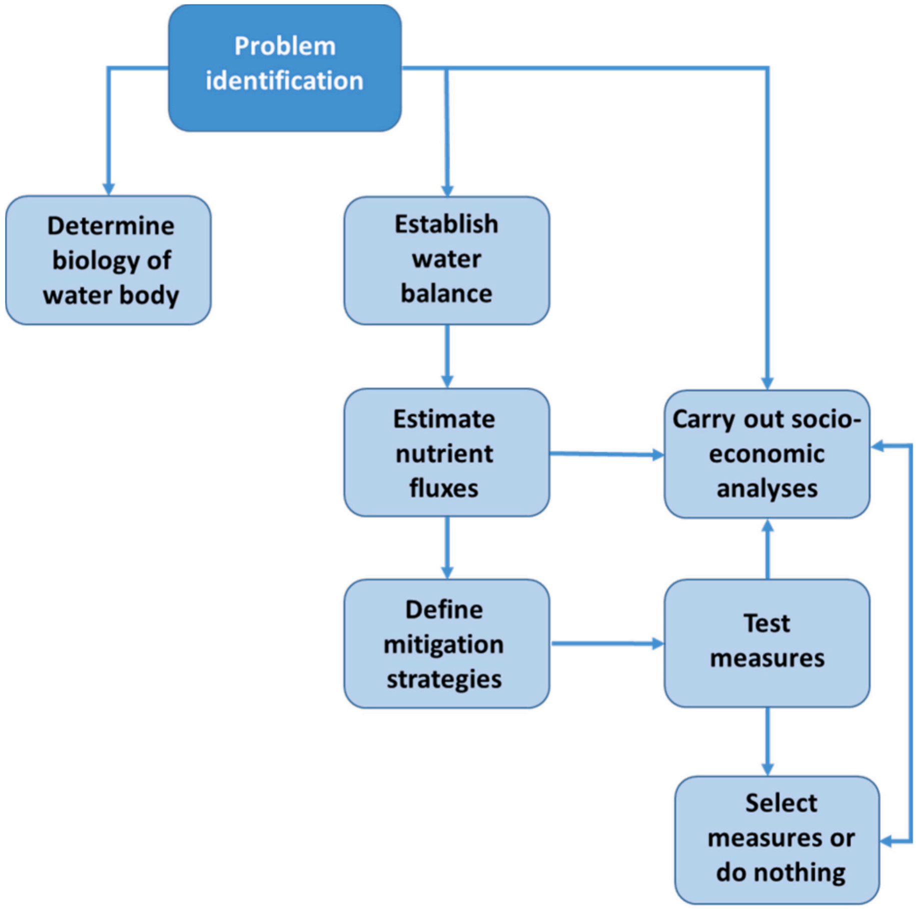

Fig. 4. System analysis as the key step to ensure improved water quality through appropriately selected restoration measures. The system analysis usually includes determination of water and nutrient budgets, the biological or response variable, and the costs and benefits of potential measures (modified from Lürling et al., 2016).

2.2. Step 2: system analysis

To ensure sustainable lake restoration, we need a thorough understanding of the operating mechanisms by using system analysis, which takes into account the specifics of each particular case. Specific targets for nutrient concentrations vary from lake to lake - characteristics and use of the water body, the severity of the problem, and all stressors involved (external, internal nutrient load, climate change), which can cause deviations from the general and often rigid legislatively derived regulations. Moreover, by using systems analysis we can select the appropriate measure(s) while simultaneously considering the potential drawbacks, harm to the environment, costs and potential for circularity, and public preferences in each particular case (Fig. 3). An example is illustrated in Fig. 3 that follows the step-by-step representation in Fig. 4, which is a guide for practitioners on conducting system analyses. System analysis would enable water managers, in the first place, to avoid numerous reasons for previous failures of lake restoration, reviewed most recently by Abell et al. (2022) and Poikane et al. (2024). However, the success of restoration is often limited by a lack of fundamental knowledge and insufficient monitoring at the system analysis stage.

As noted above, targets for nutrient concentrations and coupled biological water quality variables remain too unspecific. Criteria are often developed based on the P-algal biomass relationship across a broad gradient of lakes, and not the specific nutrient controls at an individual lake scale. Moreover, the relationship between algal biomass and nutrients (i.e., response and stressor variables) is not well understood, despite a considerable effort in the field. The need and extent of integrating N (especially in highly productive systems) is increasingly acknowledged (Maberly et al., 2020; Graeber et al., 2024). Further advances in theoretical and applied knowledge (e.g., a better understanding of which nutrients and other factors drive algal growth and shifts in community structure and composition) would help determine realistic nutrient management criteria for lake types/regions that do not have any regulatory targets and provide water managers with useful models (Sommer et al., 2012).

Consistency in analytical laboratory protocols and methodologies used in system analysis (e.g., methods to determine the contribution of different stressors, sediment phosphorus fractionation methods) is highly essential for guiding the need and type of restoration and for upscaling successful solutions. Internal P loading is one of the stressors that must be considered in regard to cyanobacterial blooms and how this process is impacted by climate change (Nürnberg, 2025), but definitions and, thus, also approaches to quantify internal P loading are inconsistent. Intercalibration and comparison of the different (available) methodologies would help identify potential problems and limitations, as well as standardize identification methods.

In-lake monitoring efforts used in a system analysis often fall short of representing nutrient transport processes at the full temporal scale, with low sampling frequency and resolution in both small and large lakes occurring due to limitations in funding and labor. Recent technological advances have provided significant opportunities to integrate cost-effective, affordable technologies like sonar (Kragh et al., 2017; Paranaíba et al., 2025), satellite observations (Politi et al., 2024), high-frequency sampling devices (Marcé et al., 2016), and molecular biological methods (Hering et al., 2018) to enhance data collection for system analysis. Still, many of these technologies have limited application in the Global South, where there remains a large need to build institutional and human capacity (UN report, 2024).

It should be noted that restoration always has a much higher cost compared to preventing eutrophication in non-impacted ecosystems (e.g. low lake water total phosphorus, TP concentrations; Fig. 5). This is in accordance with the hysteresis in the backward (also forward) shifts in stable states (e.g., shifts from eutrophic to mesotrophic conditions; Scheffer, 2009). Thus, primary preventative measures that delay the degradation of healthy systems (State 1) should have priority (minimal pollution) in sustainable management (Fig. 5). Secondary preventative measures avoid further damage to already impacted systems (State 2; higher lake water TP concentrations) avoiding 'collapse' and giving such lakes a window to recover. Stakeholders, including the local community, divers, anglers, swimmers, etc., often already notice State 2 before management authorities, with water managers generally taking action only later, after the lake has passed the stressor threshold (i.e., critical nutrient loading; Vollenweider, 1975) and the impact caused is relatively large or is noticeable. Then, managers use many curative interventions (stressor and/or impact-oriented) to rehabilitate an impacted system (State 3). Secondary measures should be preferred to the curative interventions, because this may prevent the further deterioration of lakes in a transitional (mesotrophic) state from exceeding the threshold. It is possible that secondary measures that can deliver needed benefits for multiple lakes are more feasible and cost-effective than investment in the restoration of a single degraded lake, perhaps serving only a small community. A system analysis, including a cost-benefit analysis, will give an underpinning for doing nothing when it becomes too difficult and/or expensive to restore a specific lake (Fig. 4), opening funds for more influential restoration.

2.3. Step 3: measures integrating nutrient recovery and their implementation

Measures that are used to reduce internal nutrient (primarily P but sometimes simultaneously N) load have different potential for sustainability. More sustained, long-term improvements can only be expected if the pool of releasable nutrients (P) can be reduced to the natural level. In shallow lakes, this can be done by sediment removal, and in deeper lakes by removing the nutrients from the hypolimnion. This is predicated upon further benefits arising from the recycling of nutrients for use as fertilizer. These measures still need further refinement to ensure they are environmentally friendly and to optimize their cost-effectiveness. The nutrient recycling opportunities and needed improvements for different restoration measures are summarized in the analysis by Tammeorg et al. (2024a). For example, concentrating sediment removal efforts on certain, hot-spot areas could reduce both environmental harm and help to reduce the cost of the treatment while maximizing P-harvest (Tammeorg et al., 2024b).

To establish circular economies, the reuse of recovered nutrients from sediment and hypolimnetic water needs further optimization to overcome constraints from, for instance, low bioavailability of sediment P, contamination by heavy metals and other pollutants, and to develop filter material with high P binding affinity for the further potential to be released for the plant uptake. Ready solutions have already been demonstrated by Kiani et al. (2023) and Haasler et al. (2024) in terms of good sediment P availability for crops, and for Pine Lake (Canada) in terms of the suitability of hypolimnion nutrient-rich water for the irrigation of golf courses (Nürnberg, 2007). Sediment reuse may result in savings of up to 68 % compared to conventional fertilization, which

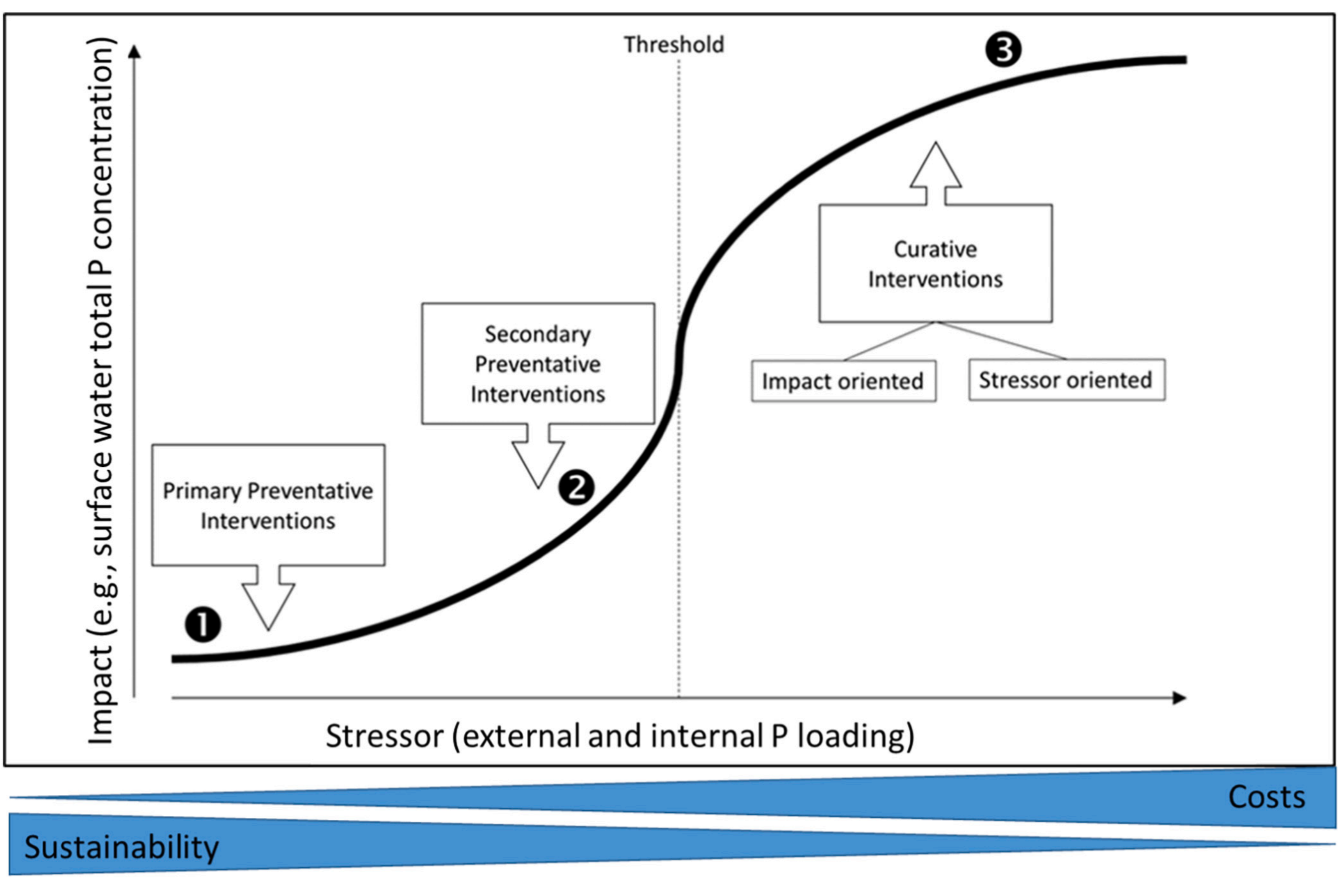

Fig. 5. Primary preventative measures that prevent healthy systems (State 1, oligotrophic lakes, i.e. lowest total phosphorus, P concentrations) to degrade (minimal pollution), secondary preventative measures that avoid further damage to already impacted systems (State 2, mesotrophic lakes) preventing 'collapse' giving them the window to recover, and finally different curative interventions (stressor and/or impact oriented) needed to rehabilitate a degraded system (State 3, eutrophic-hypertrophic). Costs and feasibility of the measures from 1 to 3 increase, rendering management less sustainable, as there is hysteresis in transitioning to stable states.

could additionally prevent about 12 Kt CO_2e emissions resulting from the substitution of mineral N fertilizers in the Jaguaribe River Basin (Brazilian semiarid region) alone (Braga et al., 2025). The synthetic N fertilizer supply chain was estimated to be responsible for the emissions of 1.13 Gt CO_2e in 2018, representing 10.6 % of agricultural emissions and 2.1 % of global GHG emissions (Menegat et al., 2022).

Where justified by the system analysis, chemical inactivation, e.g., by P-binders is applied, which renders nutrients biologically inaccessible for algae. It is important to use and develop binding agents that allow a recovery/easy reabsorption to ensure plant availability, such as the iron based mineral vivianite (Amjad et al., 2023), processed calcite-based materials (Pryputniewicz-Flis et al., 2021). Indeed, the establishment of a circular economy approach provides further avenues, but these need to be explored in an interdisciplinary way to provide water managers with economically viable solutions. The potential to integrate recycling of nutrients has to be considered at the system analysis stage with an adequate experimental setup (Fig. 3). In general, all in-lake measures (including those harvesting lake biomasses) should be improved to ensure sustainability in lake restoration. Specific measures that lack a solid theoretical foundation and have been consistently disproven (Lürling and Mucci, 2020) in case studies of peer-reviewed and grey-literature studies should be avoided (e.g., low-energy ultrasound and so-called "effective micro-organisms"). Innovation and implementation of specific measures should be grounded in a solid theoretical foundation and informed by key lessons learned from unsuccessful case studies, ensuring that new or improved measures build on evidence-based insights.

Reducing external nutrient loading also requires more sustainable approaches. Efforts must be made to develop in-catchment measures to enable better reuse of legacy nutrients in the catchment (McDowell and Haygarth, 2025). In many developed countries (for Europe, see e.g. Muntwyler et al., 2024) there is a huge nutrient surplus added to land (maximum values >2 kg ha^{-1} y^{-1}) due to manure being produced by cattle stock and overfertilization, which has led to nutrients (both N and P) moving through saturated (i.e., where the nutrient binding capacity is exceeded) soils. Besides a potential of the novel food technologies (e.g., "lab-milk" Mendly-Zambo et al., 2021), applying sustainable agricultural practices and landscape management by using buffer strips and smart fertilizer dosage or catch crops, an additional strategy would be entrapping a larger share of nutrients at lake inflow areas with the use of nature-based solutions (wetlands), allowing for the harvesting and recycling of these nutrients. For managing nutrient influx into lakes, conducting hot-spot analysis on nutrient pollution sources in streams and rivers passing through agricultural areas (Nallan et al., 2015) is a valuable method to pinpoint critical nutrient sources and suggest different land-use practices in favor of the aquatic ecosystems and biodiversity, with the support of proper models to test the scenarios. Similarly, it could be important to track the groundwater inputs that are often overlooked (Sol Lisboa et al., 2024). Small impoundments can be another infrastructure to trap nutrients before they reach downstream waters (Fernandes et al., 2025).

Timely, accurate, and transparent implementation of the measures selected by the system analysis are important. Delays between the initial system analysis and interventions may reduce effectiveness, as conditions may change by the time of implementation (changes in stressors; Mueller et al., 2015). Poor execution undermines treatment longevity and cost-effectiveness. Hence, implementing measures is as important as carefully planning them (Fig. 3). Furthermore, well-documented methodologies and real-time monitoring provide more accurate evaluations of the success of restoration efforts. For example, high-resolution and real-time oxygen monitoring enable adaptive management of lakes (Marcé et al., 2016) by aeration or hypolimnetic withdrawal.

2.4. *Step 4: measurement of success*

Comprehensive, before-during-after monitoring is essential to evaluate the success of lake restoration efforts (Cianci-Gaskill et al., 2024). Longer-term impact assessment enables us to consider changes in ecosystem components, such as biological communities that respond more slowly to the interventions and often require additional time to adjust to a new trophic state. Limiting impact assessments for restoration to one post-treatment year can lead to either under- or overvaluing the full impact of the interventions. Also, there is a bigger risk that the perception of the restoration's success will be affected by short-term (exceptional) events of increased nutrient inflow (Tammeorg et al., 2024b). The inverse is equally problematic. If the year of monitoring has low rainfall (and runoff), there may be a community perception of success, which is not only negated when precipitation returns to normal, but now alienates the community and results in their antipathy for future sustainable practices. Thus, a poorly evaluated restoration program not only risks being evaluated as a failure in the short term, but without follow-up studies, there is also a general lack of knowledge of the long-term effects. This includes limited potential for defining issues that cause restoration projects to fail or have only short-term, positive results, which in turn limits our ability to make future improvements. Thus, it is important that protocols ensuring monitoring activities during the post-restoration period are developed. Special attention should be paid to the frequency, spatial resolution and selection of the appropriate monitoring indicators (a possible list of metrics in Fig. 3). Remote sensing-based methods and/or autonomous measuring buoys can be particularly useful in overcoming the challenges of continuity of monitoring, while still needing further optimization (better comparability with in-situ data, linkage of optical or physico-chemical parameters with chemistry data, etc.) for better integration and effective implementation.

2.5. *Step 5: multiple socio-economic co-benefits*

Improved ecological conditions can lead to socio-economic co-benefits so that the investments in management will be paid back in the future in the form of improved ecosystem services (Fig. 3). Similarly, Rockström et al. (2023b) called for "new economic thinking" in management of the water resource ("a global common good") under the conditions of accelerated anthropogenic pressures and climate change. For example, strong "blue economies" (i.e., sustainable use of coastal water resources to promote associated economic growth and development preserving healthy ecosystems; Keen et al., 2018) can be established around protected or restored lakes, especially around large lakes as demonstrated by Sterner et al. (2020). However, we often lack quantitative evidence in terms of appropriate data and socio-economic analyses. In other words, we do not currently have sufficient evidence to be able to place a value on the successful outcomes of restoration on a socio-economic level (e.g., improved amenity value, sustainable slow-release fertilizers, reduced greenhouse gas emissions). Success criteria for monitoring need to be extended beyond water quality (Weyhenmeyer et al., 2024), ecological status, and biodiversity improvements. The frameworks or methodologies for evaluating these benefits in future projects should be elaborated to support policymakers and practitioners in incorporating socio-economic assessments into restoration planning and evaluation. Such methodologies are being developed (Carvalho et al., 2024; Schwerk et al., 2025). Monitoring programs should be adapted to be able to assess indicators of circular economy, green growth, and energy efficiency, as well as the cost-effectiveness of measures (i.e., life cycle assessment).

3. Key factors determining the future of sustainable lake restoration

Identifying supportive or hindering policies and incentives that impact both the feasibility and effectiveness of restoration efforts is crucial. This especially refers to land-use practices, but also applies to in-lake measures and possibilities for circular economy solutions in lake restoration. Where progress towards lake restoration is not achieved, it may be due to the lack of environmental governance structures that is needed to successfully oversee and influence policies on water quality and use. For example, in Europe, agricultural policies are not frequently associated with positive water quality outcomes, and the Water Framework Directive does not provide for the integration of other policy areas or provide additional policy instruments to address diffuse agricultural pollution (Boezeman et al., 2020). Also, essential inconsistencies exist among countries in the thresholds for nutrients, as comparison of the Nitrate and Water Framework directives revealed (Nikolaidis et al., 2025), and in their approach to sustainable phosphorus management more generally. In some countries, National Sustainable Phosphorus Plans have been developed (e.g. the UK Phosphorus Transformation Strategy, Cordell et al., 2022) or proposed (Baker et al., 2024). Integration of the full phosphorus value chain across national policy landscapes can be considered in such plans, including exposure to geopolitical supply chains of inorganic fertilizer, identifying local to national sources and sites for phosphorus recycling, identifying catchments and ecosystems where the benefits of reducing phosphorus pollution are greatest, and establishing an infrastructure development plan to enable greater recycling and reduced pollution (Brownlie et al., 2024). Specific actions can be targeted for major urban centers building on other sustainability initiatives (e.g. Net Zero Cities), for example, in the proposed development of Net Zero Phosphorus City Plans (Metson et al., 2022).

As environmental scientists, we advocate for a shift towards more sustainable, more natural land use management practices, i.e., sustainable agriculture and forestry that require less inorganic fertilizers, pesticide application, and less soil tillage (Demozzi et al., 2024), as well as shifts in human diets. Additionally, improving water storage capacity and managing artificial hydrological connectivity (ditching) between the landscape and water bodies can help enhance landscape nutrient retention and prevent further lake deterioration due to carbon and nutrient enrichment (Härkönen et al., 2023). Being realistic, the sought-after changes in nutrient losses (leaks in nutrient cycles) are not likely to occur in the near future. Thus, harvesting nutrients repeatedly or continuously from lakes to keep them in a desired state seems to be the best management practice we have until decision-makers prioritize actions facilitating longer-term solutions. A few examples of sustainable lake restoration by removal of nutrients with fish or plant biomass, hypolimnetic withdrawal, or sediment removal, enabling the subsequent recycling of nutrients, have been described in Tammeorg et al. (2024a).

Sustainability in lake restoration must be recognized in funding programs and schemes. The profitability of methods aiming at nutrient recovery needs to be developed (see step 3) and ways for the reimbursement of the costs of nutrient or biomass removal via their reuse need to be discovered. Additionally, higher investments should be allocated to the development, implementation and replication of circular lake restoration activities. For providing a more solid economic basis, the polluter-pays principle (or scheme of "payment for ecosystem services" discussed by Wiegand et al. (2023)) may be a powerful policy, especially because the capital expenses of methods aiming at nutrient recovery may often be higher compared to traditional in-lake measures. However, the need for repetition gradually decreases with reduced nutrient concentrations, consequently diminishing the operating expenses in the longer term. One emerging area in nature finance is the concept of 'nutrient markets' and 'nature markets', leading to off setting the impact of housing development and opening voluntary crediting schemes. These schemes have the potential to attract private investment in sustainable nutrient management measures and may be designed to limit the environmental impact of development, to encourage sustainable operations by businesses through disclosure initiatives, and, in some instances, may target a reduction in overall nutrient loading to sensitive ecosystems (Limb et al., 2024; Brownlie et al., 2014). One common complaint from the academic community of such schemes is the lack of robust Monitoring, Reporting and Validation (so called, 'MRV') processes to provide a secure market and that placement of off-setting measures may not be targeted towards high value protected ecosystems (e.g. for Biodiversity Net Gain in the UK; HMG POST Note 728, 2024). There is a clear need for scientific evidence to underpin the development of such schemes.

Demonstrating successful solutions through overcoming the knowledge gaps above (steps 1–5) and upscaling successful solutions is one of the objectives of the recently launched European Union funded projects in the Ocean Mission call. Further, the FERRO (Fostering European Lakes restoration, https://ferroproject.eu/) and FutureLakes (https://futurelakes.eu) projects, include demonstration sites integrating circular economy solutions (reuse and recovery of sediment P and lake biomass) into water quality management, providing sustainable lake restoration with several innovative new tools. The FutureLakes project will also establish business models incorporating the value of improved ecosystem services in restored areas. Two other sister projects, ProClean and EuropeLakes, will demonstrate the application and broader benefits of nature-based solutions in water quality management. By that, the projects aim to demonstrate financially viable (cost-effective) solutions to lake restoration – and this includes the need for removing and recycling nutrients (from sediments, algae, fish) to create a circular economy, as well as potentially new financing mechanisms (e.g., carbon credits for reducing emissions or increases in in-lake C storage). This would be the most promising way to support sustainable lake restoration and contribute, e.g., to the recently adopted European Water Resilience Strategy 2025. Strong "blue economies" can be established around protected or restored lakes, leading to future benefits similar to those around the coastal areas, supporting the call of Rockström et al. (2023b) for "new economic thinking" and an international governance framework for water as a common good. Hence, the benefits demonstrated by successful stories will help transform funding opportunities for wider application of restoration measures elsewhere (Fig. 2).

It is important to keep different actors (the public, policymakers, and other stakeholders) engaged and positive in what is often a very long process of restoration, with setbacks in some years. Effective lake management and community engagement rely heavily on proper education. Citizen science–based approaches with robust quality control and training can provide bottom-up support for regulatory monitoring and decision-making (Bishop et al., 2025). Hence, channeling public engagement into action is vital for demanding more policy action and finances for lake restoration. A detailed scheme (model) for public engagement in sustainable lake restoration was demonstrated by Cianci-Gaskill et al. (2024). In general, in many regions globally (including the Global South) local communities work alongside scientists and others in the restoration process and care for lake ecosystems. These communities consist of, e.g., fishers/ aqua culturalists, Indigenous Traditional Owners, and dedicated lake associations. Among European countries, Finland is one of the foremost countries of active community engagement in lake restoration. Specifically, Lake Vesijärvi is recognized as a flagship of sustainable lake restoration through a sound scientific understanding of the lake ecosystem functioning, effective policy and governance for lake management, and public-private finance partnerships to sustain lake monitoring and management programs over decades, and widespread local awareness of the social and economic benefits of restoration (EEA, 2024).

Improved collaboration between the social, political, and economic sectors can be achieved through creating joint platforms of lake restoration practitioners, stakeholders, and scientists. The Global Environment Facility has recently supported actions in this context through the uPcycle Lakes Project (https://www.upcyclelakes.org). Here, in collaboration with the World Water Quality Alliance (WWQA) Ecosystem Workstream (https://my.ltb.io/www/#/stack/ABRJR), a Global Community of Lake Restoration Practitioners has been established, which includes practitioners from over 70 countries and nearly 200 lakes globally (Poikane et al., 2024). In addition, in 2024 the WWQA completed a 12-month consultation with leading research institutes, UN Bodies, member states, and NGOs towards establishing a Global Coalition for Lakes. The Global Coalition will set the agenda on sustainable lake management across major international events and will work to address the four priority actions listed by the WWQA to support sustainable lake management globally: (1) improve monitoring and data; (2) embed lake restoration within national plans and policies, (3) establish green finance initiatives, (4) raise awareness across practitioners, the public, and policymakers.

Establishing a sustainable lake restoration information platform (system) will provide further opportunities to improve collaboration for transformative change in lake water quality management. The platform will integrate all current initiatives, enable monitoring and documenting the outcomes of sustainable solutions, key research developments, and lessons learned. The demonstration sites in the projects mentioned above would be a good starting point and could provide valuable input for the platform. Local platforms (at the country scale) could provide input for the bigger-scale coordinating platform.

We conclude the current analysis with several *key policy recommendations to advance sustainable lake restoration*:

1) We support the development of integrated, cross-sectoral policies for environmental protection, land use, and economic development, enabling reduced nutrient fluxes into lakes and increased possibilities for circular use of recovered nutrients.
2) We underscore a need for increasing investment in:
   a) the development of system analysis methodologies and restoration measures, particularly for nutrient recovery, to improve their effectiveness and cost-efficiency, reduce harm to the environment, and support the integration of circular economies.
   b) more comprehensive and longer-term monitoring, enabling adequate impact assessment and evidencing the broader benefits of lake restoration.
   c) public education and engagement, as the public is both one of the key beneficiaries and one of the main actors in sustainable lake restoration.

These investments will be paid back in the form of wide socio-economic co-benefits, extending beyond the scale of intervention.

3) We highlight a need to ensure the implementation of restoration measures selected by a system analysis in a timely and accurate manner, with proper documentation (transparency) of the implementation methods.
4) We advocate integrating circularity into nutrient management of lakes that requires a solid economic basis, and unlocking new ways of valuation, e.g., by using recovered nutrients in agriculture or gardening and by widening societal contributions.
5) We recommend the establishment of effective platforms (e.g., sustainable restoration information systems) to allow improved collaboration among lake restoration scientists, practitioners, and other stakeholders.

4. Conclusion

Managing nutrient pollution of lakes is increasingly challenging due to, e.g., climate change, need to ensure food security, and legacy nutrients, requiring urgent and joint actions including scientists, lake restoration managers, policymakers, and other stakeholders. Sustainable lake restoration aims to improve the ecological health of lakes while also delivering broader socio-economic co-benefits beyond the scale of intervention. The strategy initially relies on co-developing a vision with lake communities and agreeing on restoration goals that will deliver sustainable management. A full system analysis then enables the selection of cost-effective measures, both within the catchment and in-lake, considering any potential drawbacks or harm to the environment based on a complete life cycle assessment that includes the potential for circularity (e.g., nutrient reuse). To advance this form of sustainable lake restoration, we need comprehensive monitoring of the broad benefits, demonstrating the advantages of circular economies through nutrient recovery, and engaging with public co-design to support planning and implementation. This approach suggests significant policy and financing transformations, as well as overcoming multiple knowledge gaps identified by the scientific community. We have identified knowledge gaps essential for developing methodologies of system analysis, developing restoration measures that are more sustainable, and methodologies for evaluating broader restoration benefits that require a better understanding of the linkages between eutrophication and other processes (e.g., greenhouse gas fluxes, biodiversity indexes).

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No data was used for the research described in the article.

References

Abell, J.M., Özkundakci, D., Hamilton, D.P., Reeves, P., 2022. Restoring shallow lakes impaired by eutrophication: approaches, outcomes, and challenges. Crit. Rev. Environ. Sci. Technol. 52 (7), 1199–1246.

Amjad, S., Christensen, M.L., Reitzel, K., Qu, H., 2023. Vivianite for phosphorus recovery from digester supernatant in wastewater treatment plants. Chem. Eng. Technol. 46 (11), 2321–2329.

Baker, J., Schunk, N., Scholz, M., Merck, A., Muenich, R., Westerhoff, P., Elser, J., Duckworth, O., Gatiboni, L., Islam, M., Marshall, A., Sozzani, R., Mayer, B., 2024. Global-to-local dependencies in phosphorus mass flows and markets: pathways to improving system resiliency in response to exogenous shocks. Environ. Sci. Technol. https://doi.org/10.1021/acs.estlett.4c00208.

Bateman, I.J., Keeler, B., Olmstead, S.M., Whitehead, J., 2023. Perspectives on valuing water quality improvements using stated preference methods. Proc. Nation. Academy Sci. 120 (18), e2217456120.

Beaulieu, J.J., DelSontro, T., Downing, J.A., 2019. Eutrophication will increase methane emissions from lakes and impoundments during the 21st century. Nat. Commun. 10 (1), 1375.

Bishop, I., Boldrini, A., Clymans, W., Hall, C., Moorhouse, H., Parkinson, S., Loiselle, S., 2025. FreshWater watch: investigating the health of freshwater ecosystems, from the bottom up. Citizen Science: Theory Practice 10 (1).

Boezeman, D., Wiering, M., Crabbé, A., 2020. Agricultural diffuse pollution and the EU water framework directive: problems and progress in governance. Water 12 (9), 2590.

Borja, A., Elliott, M., Andersen, J.H., Berg, T., Carstensen, J., Halpern, B.S., Rodriguez-Ezpeleta, N., 2016. Overview of integrative assessment of marine systems: the ecosystem approach in practice. Front. Mar. Sci. 3, 20.

Braga, B.B., Brosinsky, A., Foerster, S., Oliveira, G., Medeiros, P.H., 2025. Reuse of sediments from surface reservoirs for agricultural production in the Brazilian semiarid region: extraction conditions, spatio-temporal variability, financial analysis and regulatory barriers. J. Soils Sediments 1–17.

Brownlie, W., May, L., McDonald, C., Roaf, S., Spears, B.M., 2014. Assessment of a novel development policy for the control of phosphorus losses from private sewage systems to the loch Leven catchment, Scotland, UK. Environ. Sci. Pol. 38, 207–216.

Brownlie, W.J., Alexander, P., Cordell, D., Maslin, M., Metson, G.S., Sutton, M.A., Spears, B.M., 2024. National phosphorus planning for food and environmental security. Current Opin. Biotech. 90, 103226.

Carpenter, S.R., 2005. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. Proceed. National. Academy Sci. 102, 10002–10005.

Carvalho L., Schwerk A., Matthews K., Blackstock K., Okruszko T., Anzaldua G.,…, Birk S., 2024 (latest version). New framework for monitoring systemic impacts of freshwater and wetland restoration actions. EU H2020 research and innovation project MERLIN deliverable 1.2. 75 pp.

Cianci-Gaskill, J.A., Klug, J.L., Merrell, K.C., Millar, E.E., Wain, D.J., Kramer, L., Yan, N. D., 2024. A lake management framework for global application: monitoring, restoring, and protecting lakes through community engagement. Lake Reservoir Manage. 40 (1), 66–92.

Cordell, D., Jacobs, B., Anderson, A., Camargo-Valero, M., Doody, D., Forber, K., Lyon, C., Mackay, E., Marshall, R., Martin-Ortega, J., May, L., Okumah, M., Rothwell, S., Shahvi, S., Sherry, E., Spears, B., Withers, P., 2022. UK phosphorus transformation strategy: towards a circular UK food system. RePhoKUs project. https://doi.org/10.5281/zenodo.7404622.

Demozzi, T., Oberč, B.P., López, A.P., Larbodière, L., Borges, M.A., Schnell, A.A., 2024. Sustainable Agriculture and Nature-Based Solutions.

EEA, 2024. Europe's state of water 2024: the need for improved water resilience. https://www.eea.europa.eu/en/analysis/publications/europes-state-of-water-2024.

Elferink, M., Schierhorn, F., 2016. Global demand for food is rising. Can we meet it. Harvard Business Rev. 7(04), 2016.

Fernandes, T., Shatwell, T., Schultze, M., Mi, C., Determann, M., Rinke, K., 2025. How efficient are pre-dams as reservoir guardians? A long-term study on nutrient retention. Water Res. 272, 122864.

Graeber, D., McCarthy, M.J., Shatwell, T., Borchardt, D., Jeppesen, E., Søndergaard, M., Davidson, T.A., 2024. Consistent stoichiometric long-term relationships between nutrients and chlorophyll-a across shallow lakes. Nat. Commun. 15 (1), 809.

Haasler, S., Kragh, T., Magid, J., Gunnarsen, K.C., Müller-Stöver, D., Klamt, A.M., Reitzel, K., 2024. Recycling of phosphorus from dredged lake sediment: importance of iron-bound phosphates for plant growth. Sust. Environ. 10 (1), 2362503.

Harfoot, M., Tittensor, D.P., Newbold, T., McInerny, G., Smith, M.J., Scharlemann, J.P., 2014. Integrated assessment models for ecologists: the present and the future. Glob. Ecol. Biogeogr. 23 (2), 124–143.

Härkönen, L.H., Lepistö, A., Sarkkola, S., Kortelainen, P., Räike, A., 2023. Reviewing peatland forestry: implications and mitigation measures for freshwater ecosystem browning. For. Ecol. Manag. 531, 120776.

Hering, D., Borja, A., Jones, J.I., Pont, D., Boets, P., Bouchez, A., Kelly, M., 2018. Implementation options for DNA-based identification into ecological status assessment under the European water framework directive. Water Res. 138, 192–205.

Hill, M.P., 2003. The impact and control of alien aquatic vegetation in south African aquatic ecosystems. Afr. J. Aquat. Sci. 28 (1), 19–24.

HMG, 2024. UK Parliament POST Note 728. Biodiversity Net Gain. POSTnote 728, J. Wentworth 2/11/2024. https://researchbriefings.files.parliament.uk/documents/POST-PN-0728/POST-PN-0728.pdf.

ILEC, 2005. Managing lakes and their basins for sustainable use: a report for lake basin managers and stakeholders. International Lake Environment Committee Foundation 146.

Irvine, K., Katsanou, K., Spears, B.M., Carvalho, L., Elelman, R., Free, G., …, Warner, S., 2023. Embedding lakes into the global sustainability agenda. United Nations Environment Programme (UNEP).
Jones, E.R., Van Vliet, M.T., Qadir, M., Bierkens, M.F., 2021. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth Syst. Sci. Dat. 13 (2), 237–254.
Juncal, M.J.L., Masino, P., Bertone, E., Stewart, R.A., 2023. Towards nutrient neutrality: a review of agricultural runoff mitigation strategies and the development of a decision-making framework. Sci. Total Environ. 874, 162408.
Keen, M.R., Schwarz, A.M., Wini-Simeon, L., 2018. Towards defining the blue economy: practical lessons from pacific ocean governance. Mar. Policy 88, 333–341.
Kiani, M., Zrim, J., Simojoki, A., Tammeorg, O., Penttinen, P., Markkanen, T., Tammeorg, P., 2023. Recycling eutrophic lake sediments into grass production: a four-year field experiment on agronomical and environmental implications. Sci. Total Environ. 870, 161881.
Kragh, T., Sand-Jensen, K., Petersen, K., Kristensen, E., 2017. Fast phosphorus loss by sediment resuspension in a re-established shallow lake on former agricultural fields. Ecol. Eng. 108, 2–9.
Limb, B.J., Quinn, J.C., Johnson, A., et al., 2024. The potential of carbon markets to accelerate green infrastructure based water quality trading. Commun. Earth Environ. 5, 185. https://doi.org/10.1038/s43247-024-01359-x.
Lisboa, M.S., Schneider, R.L., Rudstam, L.G., Walter, M.T., 2024. Groundwater inputs could be a significant but often overlooked source of phosphorus in lake ecosystems. Sci. Report. 14 (1), 16269.
Lürling, M., Mucci, M., 2020. Mitigating eutrophication nuisance: in-lake measures are becoming inevitable in eutrophic waters in the Netherlands. Hydrobiology 847 (21), 4447–4467.
Lürling, M., Mackay, E., Reitzel, K., Spears, B.M., 2016. Editorial–a critical perspective on geo-engineering for eutrophication management in lakes. Water Res. 97, 1–10.
Lürling, M., Mucci, M., Yasseri, S., Hofstra, S., Seelen, L.M., Waajen, G., 2024. Combined measures in Lake restoration–a powerful approach as exemplified from lake Groote Melanen (the Netherlands). Water Res. 263, 122193.
Maberly, S.C., Pitt, J.A., Davies, P.S., Carvalho, L., 2020. Nitrogen and phosphorus limitation and the management of small productive lakes. Inland Waters 10 (2), 159–172.
Marcé, R., George, G., Buscarinu, P., Deidda, M., Dunalska, J., de Eyto, E., Jennings, E., 2016. Automatic high frequency monitoring for improved lake and reservoir management. Environ. Sci. Technol. 50 (20), 10780–10794.
McDowell, R.W., Haygarth, P.M., 2025. Soil phosphorus stocks could prolong global reserves and improve water quality. Nature Food 1–5.
Mekonnen, M.M., Hoekstra, A.Y., 2015. Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water. Environ. Sci. Technol. 49 (21), 12860–12868.
Mekonnen, M.M., Hoekstra, A.Y., 2018. Global anthropogenic phosphorus loads to freshwater and associated grey water footprints and water pollution levels: a high-resolution global study. Water Resour. Res. 54 (1), 345–358.
Mendly-Zambo, Z., Powell, L.J., Newman, L.L., 2021. Dairy 3.0: cellular agriculture and the future of milk. Food, Cult. Soc. 24 (5), 675–693.
Menegat, S., Ledo, A., Tirado, R., 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Sci. Report. 12 (1), 1–13.
Metson, G.S., Brownlie, W.J., Spears, B.M., 2022. Towards net-zero phosphorus cities. npj Urban Sustain 2, 30. https://doi.org/10.1038/s42949-022-00076-8.
Mew, M.C., 2016. Phosphate rock costs, prices and resources interaction. Sci. Total Environ. 542, 1008–1012.
Moss, B., 2007. The art and science of lake restoration. Hydrobiology 581, 15–24.
Mueller, H., Hamilton, D.P., Doole, G.J., 2015. Response lags and environmental dynamics of restoration efforts for Lake Rotorua. New Zealand. Environ. Res. Letters 10 (7), 074003.
Muntwyler, A., Panagos, P., Pfister, S., Lugato, E., 2024. Assessing the phosphorus cycle in European agricultural soils: looking beyond current national phosphorus budgets. Sci. Total Environ. 906, 167143.
Nallan, S.A., Armstrong, L.J., Tripathy, A.K., Teluguntla, P., 2015. Hot spot analysis using NDVI data for impact assessment of watershed development. In: 2015 International Conference on Technologies for Sustainable Development (ICTSD). IEEE, pp. 1–5.
Nijman, T.P., Lemmens, M., Lurling, M., Kosten, S., Welte, C., Veraart, A.J., 2022. Phosphorus control and dredging decrease methane emissions from shallow lakes. Sci. Total Environ. 847, 157584.
Nikolaidis, N.P., Poikane, S., Bouraoui, F., Salas-Herrero, F., Free, G., Varkitzi, I., Kelly, M.G., 2025. Comparison of eutrophication assessment for the nitrates and water framework directives: impacts and opportunities for streamlined approaches. Ecol. Indic. 177, 113375.
Nürnberg, G.K., 2007. Lake responses to long-term hypolimnetic withdrawal treatments. Lake Reservoir Manage. 23 (4), 388–409.
Nürnberg, G.K., 2025. Lake Functioning: Internal Phosphorus Loading, Cyanobacteria, and Climate Change. CRC Press.
Nürnberg, G.K., Howell, T., Palmer, M., 2019. Long-term impact of Central Basin hypoxia and internal phosphorus loading on north shore water quality in Lake Erie. Inland Waters 9 (3), 362–373.
Paranaíba, J.R., Struik, Q., Rodriguez, M., Sobek, S., Kosten, S., 2025. Hydroacoustic surveys reveal high sediment carbon accumulation in an urban lake. J. Soils Sediments 1–9.
Poikane, S., Portielje, R., Denys, L., Elferts, D., Kelly, M., Kolada, A., Van den Berg, M.S., 2018. Macrophyte assessment in European lakes: diverse approaches but convergent views of 'good' ecological status. Ecol. Indic. 94, 185–197.
Poikane, S., Kelly, M.G., Free, G., Carvalho, L., Hamilton, D.P., Katsanou, K., Irvine, K., 2024. A global assessment of lake restoration in practice: new insights and future perspectives. Ecol. Indic. 158, 111330.
Politi, E., Cutler, M.E., Carvalho, L., Rowan, J.S., 2024. A global typological approach to classify lakes based on their eutrophication risk. Aquat. Sci. 86 (2), 52.
Pryputniewicz-Flis, D., Bańkowska-Sobczak, A., Burska, D., Idźkowski, J., Kozłowicz, G., Brenk, G., 2021. Non-invasive removal of phosphorus from lakes using processed calcite-based materials chemical Lake restoration: technologies. Innovations and Economic Perspectives. Springer 145–170.
Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9 (37).
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2).
Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Zhang, X., 2023a. Safe and just earth system boundaries. Nature 619 (7968), 102–111.
Rockström, J., Mazzucato, M., Andersen, L.S., Fahrländer, S.F., Gerten, D., 2023b. Why we need a new economics of water as a common good. Nature 615 (7954), 794–797.
Rohr, J.R., Sack, A., Bakhoum, S., Barrett, C.B., Lopez-Carr, D., Chamberlin, A.J., Wolfe, C., 2023. A planetary health innovation for disease, food and water challenges in Africa. Nature 619 (7971), 782–787.
Scheffer, M., 2009. Alternative stable states and regime shifts in ecosystems. Princ. Guide Ecol. 809, 395–406.
Scholz, M.J., Obenour, D.R., Morrison, E.S., Elser, J.J., 2025. A critical eutrophication–climate change link. Nature Sustainability 1–2.
Schwerk, A., Carvalho, L., Spears, B., Williamson, J., Pott, L., Kajner, P.,…, Birk, S., 2025. Manuscript and policy briefing evaluating success of large landscape-scale restoration. EU H2020 research and innovation project MERLIN Deliverable D1 (6), 135 pp.
Sommer, U., Adrian, R., De Senerpont Domis, L., Elser, J.J., Gaedke, U., Ibelings, B., Winder, M., 2012. Beyond the plankton ecology group (PEG) model: mechanisms driving plankton succession. Annu. Rev. Ecol. Evol. Syst. 43 (1), 429–448.
Song, K., Wang, Q., Liu, G., Jacinthe, P.A., Li, S., Tao, H., Fei, L., 2022. A unified model for high resolution mapping of global lake (> 1 ha) clarity using Landsat imagery data. Sci. Total Environ. 810, 151188.
Steinman, A.D., Isely, E.S., Thompson, K., 2015. Stormwater runoff to an impaired lake: impacts and solutions. Environ. Monit. Assess. 187, 1–14.
Sterner, R.W., Keeler, B., Polasky, S., Poudel, R., Rhude, K., Rogers, M., 2020. Ecosystem services of earth's largest freshwater lakes. Ecosyst. Serv. 41, 101046.
Tammeorg, O., 2024. Bringing the planet back to safe-operating space by controlling nutrient pollution to lakes. https://www.frontiersplanetprize.org/news.
Tammeorg, O., Chorus, I., Spears, B., Nõges, P., Nürnberg, G.K., Tammeorg, P., Lürling, M., 2024a. Sustainable lake restoration: from challenges to solutions. Wiley Interdiscip. Rev. Water 11 (2), e1689.
Tammeorg, O., Kiani, M., Nõges, P., Blank, K., Feldmann, T., Haberman, J., Tammeorg, P., 2024b. Management implications following the reconstruction of the small and shallow Lake Mustijärv (Estonia).
UN report, 2024. Progress on Ambient Water Quality. Mid-term status of SDG Indicator 6.3.2 and acceleration needs, with a special focus on Health. https://www.unwater.org/sites/default/files/2024-08/SDG6_Indicator_Report_632_Progress-on-Ambient-Water-Quality_2024_EN_0.pdf.
Van Dijk, K.C., Lesschen, J.P., Oenema, O., 2016. Phosphorus flows and balances of the European Union member states. Sci. Total Environ. 542, 1078–1093.
Van Puijenbroek, P.J.T.M., Beusen, A.H.W., Bouwman, A.F., 2019. Global nitrogen and phosphorus in urban waste water based on the shared socio-economic pathways. J. Environ. Manag. 231, 446–456.
Vollenweider, R.A., 1975. Input-output models: with special reference to the phosphorus loading concept in limnology. Schweiz. Z. Hydrol. 37 (1), 53–84.
Weyhenmeyer, G.A., Chukwuka, A.V., Anneville, O., Brookes, J., Carvalho, C.R., Cotner, J.B., Zhou, Y., 2024. Global lake health in the Anthropocene: societal implications and treatment strategies. Earth's Future 12 (4), e2023EF004387.
Wiegand, C., Hernandez, S., Le Moal, M., Gruau, G., 2023. Payment for ecosystem services: an efficient approach to reduce eutrophication? Water 15 (22), 3871.