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OVERVIEW

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Sustainable lake restoration: From challenges to solutions

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Abstract

Sustainable management of lakes requires us to overcome ecological, economic, and social challenges. These challenges can be addressed by focusing on achieving ecological improvement within a multifaceted, co-beneficial context. In-lake restoration measures may promote more rapid ecosystem responses than is feasible with catchment measures alone, even if multiple interventions are needed. In particular, we identify restoration methods that support the overarching societal target of a circular economy through the use of nutrients, sediments, or biomass that are removed from a lake, in agriculture, as food, or for biogas production. In this emerging field of sustainable restoration techniques, we show examples, discuss benefits and pitfalls, and flag areas for further research and development. Each lake should be assessed individually to ensure that restoration approaches will effectively address lake-specific problems, do not harm the target lake or downstream ecosystems, are cost-effective, promote delivery of valuable ecosystem services, minimize conflicts in public interests, and eliminate the necessity for repeated interventions. Achieving optimal, sustainable results from lake restoration relies on multidisciplinary research and close interactions between environmental, social, political, and economic sectors.

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1 | INTRODUCTION

Unsustainable use of nitrogen (N) and phosphorus (P) has accelerated eutrophication of water bodies globally (Withers et al., 2014; Yuan et al., 2018). Eutrophication is one of the most common causes of water quality impairment in lakes (Birk et al., 2020; Chowdhury et al., 2017) and is often accompanied by cyanobacterial blooms (Figure 1), high turbidity, and excessive production of organic matter, leading to increased oxygen depletion. These effects can lead to loss of habitat, biodiversity, and amenity value and cause human health risks associated with harmful algal blooms. Oxygen depletion and high primary production-induced elevated pH can further exacerbate eutrophication by promoting the release of N, P, and associated metals (iron and manganese) from sediments, compromising water use for drinking and irrigation. In particular, deoxygenated, C- and N-enriched sediments can also release greenhouse gases (GHGs; Zheng et al., 2022), and these emissions increase with increasing eutrophication (Beaulieu et al., 2019) and particulate organic matter (Pickard et al., 2021).

Restoration is an important approach in lake water quality management. The most common restoration target for lakes is to improve their ecological state and ecosystem services for humans. The twentieth century brought some notable successes in freshwater restoration, in particular the introduction of advanced wastewater treatment technologies (e.g., Jeppesen et al., 2005). While lake restoration requires substantial financial investments, there is increasing evidence that these investments carry a high benefit to cost ratio (Bingham et al., 2015; Blignaut et al., 2014; Carvalho et al., 2021; Grizzetti et al., 2019). Besides social and economic benefits, water quality improvement may reduce the impact of other environmental problems, especially those related to climate change, such as GHG emissions (Ho & Goethals, 2019; Pickard et al., 2021). The global costs to society of eutrophication-driven methane emissions from lakes are projected to be $7.5–$81 trillion for 2015–2050 ($US), and local protective measures may have global benefits (Downing et al., 2021).

According to the latest European Environmental Agency Report (EEA, 2018), more than half of European freshwater bodies still do not meet the criteria of good ecological status set by the Water Framework Directive (WFD, 2000). Globally, the proportion of impaired water bodies (though the criteria differ from those in WFD) is smaller, but large-scale assessments are limited by a lack of monitoring data in low-income countries (UN, 2021). Carvalho et al. (2019) identified challenges in achieving WFD objectives, including insufficient monitoring, failure to meet nutrient load reduction targets, especially from diffuse sources, insufficient investment and integrative management, and a lack of political will. The apparent limited gains in lake recovery worldwide (EEA, 2018; UN, 2021), coupled with ominous forecasts of future pressures (especially climate change) have caused scientists to call for urgent action on preventing

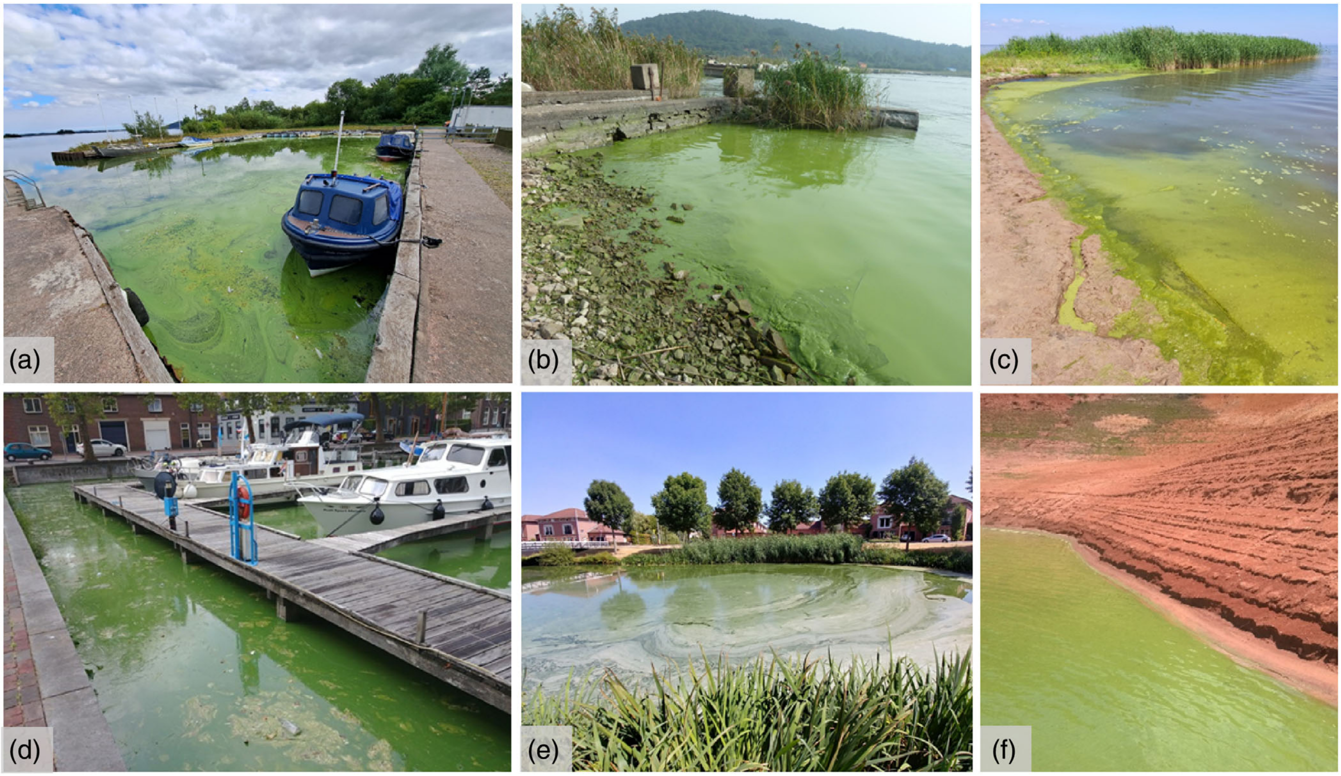

FIGURE 1 Cyanobacterial blooms as one of the most evident symptoms of eutrophication that impacts ecosystem services of lakes worldwide. Examples from (a) Loch Leven (Scotland), (b) Lake Taihu (China), (c) Lake Peipsi (Estonia), lakes in (d) Veghel and (e) Eindhoven (Netherlands), and (f) Funil Reservoir (Brazil). Photos by M. Lürling (a, d–f), H. Paerl (b), and O. Tammeorg (c).

future ecological degradation (Jenny et al., 2020; Spears, Lürling, & Hamilton, 2022). A framework for sustainable lake management that combines ecological, economic, and social interconnecting threads is required, as reflected in the UNEA sustainable lake management resolution (UNEP, 2022), the Integrated Lake Basin Management of International Lake Environment Committee (ILEC), and the World Water Quality Alliance Ecosystems Workstream (WWQA Ecosystems, 2023).

Here, we utilize the expertise of the lake restoration community to develop a framework designed to restore lake ecosystems through nutrient pollution reduction, while maximizing co-benefits. We examine the case of nutrient reduction as excessive nutrient inputs remain the most pervasive, current threat to lake water quality and lake ecosystem health globally. We propose a definition of "sustainable lake restoration" and define its opportunities based on the evidence of nutrient management approaches currently employed (Sections 1–3). Next, we develop a framework and highlight solutions to its implementation (Sections 4 and 5). Finally, we provide case studies of emerging approaches in the field of sustainable lake restoration, discussing their benefits and pitfalls, and flagging areas for further research and development (Section 6).

2 | DEFINITION OF SUSTAINABLE LAKE RESTORATION

The current use of the term "sustainable" can have multiple connotations when applied to lake restoration. First, sustainable lake restoration may aim to ensure that a single intervention delivers long-lasting effects and that future interventions are not required, so that the cost-effectiveness of the intervention is high (May et al., 2020; Suding & Gross, 2006). One example of this long-term efficacy is the shallow, urban Lake Alte Donau, Austria, where improvements in water quality following nutrient load reductions have persisted over 20 years (Dokulil et al., 2019). Second, the use of energy resources should be justified relative to the environmental benefits (Dondajewska et al., 2019; Gołdyn et al., 2014), and this will require environmental footprint assessments when planning restoration. This target can be achieved by using nature-based solutions and limiting the consumption of chemicals and energy by changing the power source of aeration to wind and photovoltaic panels (Dondajewska et al., 2019; Gołdyn et al., 2014). Third, sustainable approaches could include the use of recycled industrial side-stream materials (e.g., Kuster et al., 2023; Spears et al., 2013; Wang et al., 2013) or near-term water quality forecasting to reduce the operational hours of energy intensive physical infrastructure (e.g., aeration) in drinking water reservoirs (Carey et al., 2022). Finally, "sustainability" in lake restoration may refer to the co-benefits of successful ecological recovery. For example, the possible recapture and re-use of nutrients from depositional freshwater environments (e.g., as a fertilizer) has been underlined as an essential part of sustainable lake restoration (Horppila, 2019; Kiani et al., 2023), and frameworks to support the planning of "smart nutrient retention basins" have recently been proposed (van Wijk et al., 2022).

We integrate the concepts described above and define sustainable lake restoration as interventions that improve the ecological state in the target lake, while also delivering multiple environmental and socio-economic co-benefits extending beyond the scale of intervention. Such interventions will meet the needs of the present without compromising ecosystem structure and function, while enhancing the ability of future generations to meet their own needs (Brundtland Report, 1987; Kuhlman & Farrington, 2010). As such, they support the main principle of environmental sustainability; that is, to "keep wastes within assimilative capacities, harvest within regenerative capacities of renewable resources, and deplete non-renewables at the rate at which renewable substitutes are developed" (Goodland & Daly, 1996).

3 | CHALLENGES AND POTENTIAL FOR IN-LAKE RESTORATION MEASURES

Nutrient input reduction is the priority target for controlling and reversing eutrophication and its symptoms. Nevertheless, the lake recovery times can extend to decades due to processes both in the catchment (legacy nutrients in catchment soils; Basu et al., 2022; Jarvie et al., 2013; Kronvang et al., 2005; Sharpley et al., 2013) and within the waterbody (e.g., internal nutrient loading, biological changes; Abell et al., 2022; Scheffer et al.,1993; Steinman & Spears, 2020). Reducing nutrient losses from the catchment to water bodies can be particularly challenging when considering irreversible structural and land use changes in the cultivated landscapes, the rapidly growing global populations, an active and not always environmentally oriented agricultural sector, and political short-sightedness. Globally, about 80% of wastewaters are not treated (UN, 2021), and, in many cases, external nutrient load reduction has been lacking or is insufficient. Despite the highly effective performance of wastewater treatment in Europe, for example, diffuse agricultural loads have continued (EEA, 2018), and controlling these loads is a politically and economically contentious issue.

In-lake interventions may thus offer short-term respite, while longer-term, external loading reductions are implemented, and ecosystem responses are observed. This combined catchment and in-lake approach may be essential for maintaining societal and political commitments and interest, providing tangible environmental and socio-economic benefits at different scales from both short- and long-term investments (Figure 2). Similarly, the "ecotechnological immission concept" (Benndorf, 2008) suggests that internal measures can be economically relevant if it is not possible to reduce external pressures at reasonable cost, enabling cost-effectiveness in water pollution control.

While attractive for politicians and lake managers searching for quick and cheap, one-time in-lake interventions to improve water quality, the hope that a lake with ongoing high external nutrient loading will "sustain itself" with no future interventions is unrealistic. The speed at which a restored lake will return to turbid, eutrophic conditions depends on current external nutrient loading, which, in turn, is influenced by the political will of providing simultaneous investments in "smart" agriculture, supporting the reduction of point-source pollution, and prioritizing water quality problems (Carvalho et al., 2019, 2021). If external nutrient loading remains high, short-term in-lake restoration measures must likely be implemented repeatedly unless the decision is to accept lower water quality goals. Thus, the choice of strategy is determined by local conditions and should be clarified for specific cases by conducting a system analysis that includes both a limnological assessment and socio-economic considerations (Section 5).

4 | ASSESSING THE SUSTAINABILITY OF IN-LAKE MEASURES

We suggest that in planning a restoration strategy aimed at the reduction of internal loads, it is of paramount importance to analyze individual in-lake interventions with regard to sustainability. Several criteria could be used, including the effectiveness of removing nutrients associated with internal loads, costs, potential harm to the environment of the target lake or downstream systems, and support of a circular economy (see Section 4.4).

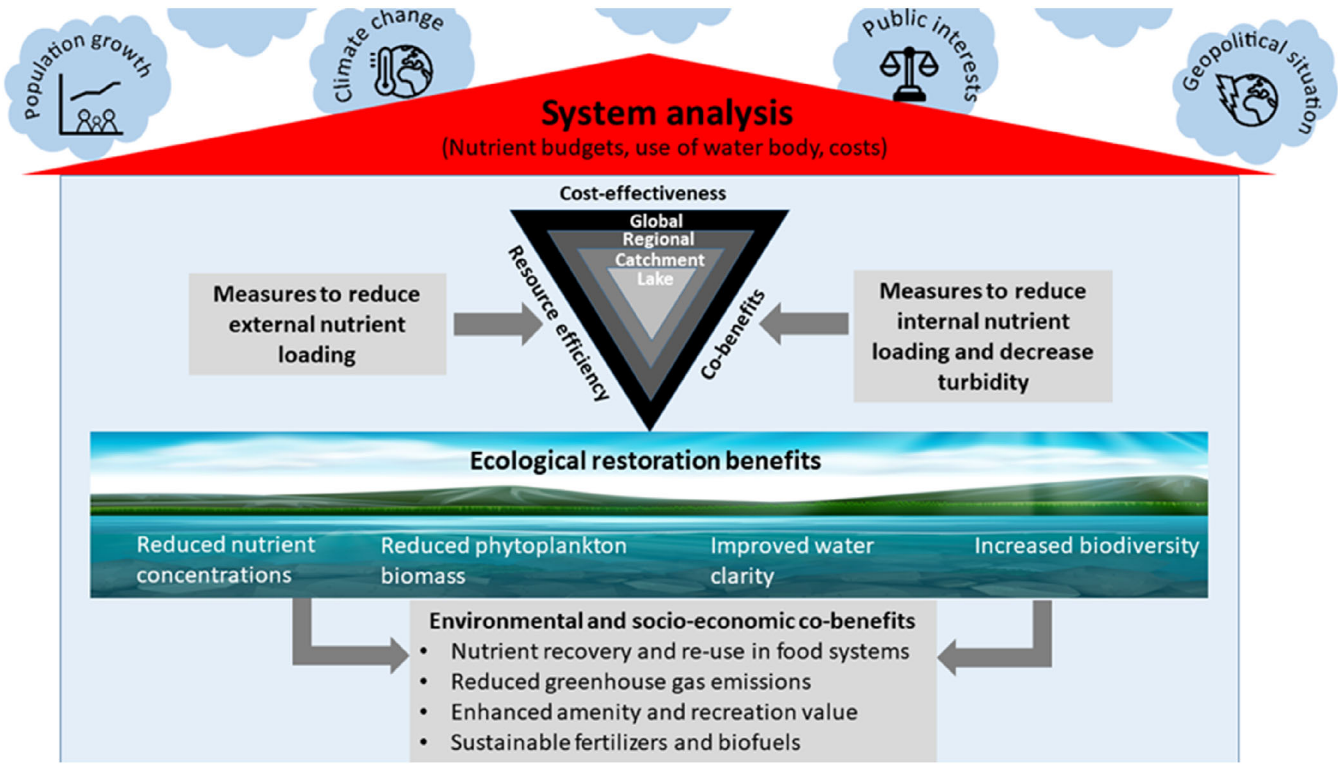

FIGURE 2 Sustainable lake restoration provides improved ecological state in the target lake, while also delivering multiple environmental and socio-economic co-benefits extending beyond the scale of intervention. The benefits of local, lake scale measures extend to catchment, regional, and global scales. Comprehensive system analysis identifying the most appropriate measures is the basis for effective restoration projects. Climate change, growing population, public preferences, and geopolitical situations affect the selection and cost-effectiveness of lake restoration.

Measures to mitigate internal nutrient loading (Table 1) can be grouped into physical, chemical, and biological interventions. Physical measures include sediment removal (dredging/excavation), hypolimnetic withdrawal, and aeration treatments (Lürling, Kang, et al., 2020; Lürling, Smolders, & Douglas, 2020). Some of these measures are based on the removal of nutrients from the ecosystem (e.g., sediment removal by dredging, hypolimnetic withdrawal), but many in-lake restoration methods, including aeration and chemical treatments (Beutel & Horne, 1999; Cooke et al., 2005; Copetti et al., 2016), aim to retain P in the bottom sediments.

In-lake measures to address P have variable effects on N. Aeration may facilitate N removal from the water column and/or sediments by promoting nitrification of ammonium to nitrate, which can then be removed via denitrification directly (Holmroos et al., 2016) or potentially, subsequent to assimilation and biomass remineralization. Thus, ammonium release from organic matter remineralization may be mitigated by denitrification. However, adding chemicals to control the internal P load (e.g., aluminum sulphate) may alter the N cycling, while enhancing N_2O emissions (Nogaro et al., 2013).

For the target of retrieving P as a potential fertilizer, P lost to sediments through the application of P inactivation techniques might appear counter-productive (Brownlie et al., 2022; Elser & Bennett, 2011; Neset & Cordell, 2012; Zamparas & Zacharias, 2014), while harvesting P might be viewed more sustainable. Harvest, however, requires dredging, hypolimnetic withdrawal, or the regular harvest of biota and their further processing; all these options come with increased energy costs.

4.1 | Optimal range of application conditions to meet effectiveness

Most of the methods in Table 1 have been proven effective provided that external nutrient loading was sufficiently low and the conditions for application (lake surface area, depth, water retention time, thermal regime, climatic region, extent and history of the impairment; details in Supplementary Material Table S1) were taken into account

TABLE 1 Assessing the sustainability of individual in-lake measures.

Method	Conditions influencing effectiveness	Costs	Environmental risk	Contribution to circular economy
Sediment removal	Potentially suitable for small and shallow lakes. Theoretically, it may be most effective as it removes a source of internal P and N loading from the lake ecosystem. Requires an appropriate method minimizing resuspension and ensuring sufficient depth of the treatment.	Very high, particularly if there is no sediment disposal site nearby. Requires expensive sediment analyses in the case of potential contamination with toxic substances, and—if toxics are found—expensive removal operations and treatment.	Effects for benthic invertebrates, macrophytes, fish, sediment resuspension, exposure of toxic compounds (if present in sediment), byproduct (sediments) in large amounts to be deposited, may potentially reduce N removal via denitrification; GHGs emissions when stored on land, nutrient leaching back if stored inappropriately.	Positive, removed sediment can be used as a fertilizer and for soil amelioraton unless contaminated by persistent substances, e.g., heavy metals, or a high content of P binding compounds.
Hypolimnetic withdrawal	In lakes where the hypolimnion comprises a considerable portion of the lake volume. Withdrawal should focus on periods with maximum nutrient accumulation in the hypolimnion. Requires that the water volume (inflow to waterbody) is sufficient for continuous removal. The method slowly removes nutrients from the ecosystem.	Low operational costs if gravity-based, higher costs if pumping is necessary.	Decrease in water level, potential weakening of stratification, downstream impact of withdrawn water rich in metals and nutrients, unpleasant odors.	Positive if water can be used, e.g., for irrigation, cooling offices in summer (reducing greenhouse gas emissions associated with cooling machines) or if the extracted nutrients can be recycled.
Aeration	Lakes and reservoirs with deep strata covering a large share of the sediment area. May control sediment P release at the sediment water interface by activating an iron-P trap under oxidizing conditions, depending on the presence of sulphide and the oxygen supply rate. Can facilitate N removal via coupled nitrification–denitrification.	High operational costs in the case of conventional electric aerators, low costs with wind or solar-powered aerators.	Risks of destratification, increase in the temperature of the hypolimnetic water with implications for fish, mineralization of organic material, and redox-sensitive P release.	None.
Binding P to minerals and clays (Al/Fe/Ca salts, lanthanum-modified bentonite)	Removes P from the water column to the sediment where it is no longer bioavailable. Effectiveness depends on the character of the P-binding agent and its	Moderate, but long-term costs can be high if repeated treatments prove necessary.	Ecotoxicity, occassionally altered N cycling. production and transport of treatment chemicals.	Few. Where it stimulates precipitation of vivianite, which is paramagnetic, there may be a potential for harvesting as a source of P.

TABLE 1 (Continued)

Method	Conditions influencing effectiveness	Costs	Environmental risk	Contribution to circular economy
	sensitivity to environmental conditions (pH, redox, sediment resuspension).			
Biomanipulation by removal of planktivorous and bottom feeding fish	Small to medium-sized lakes. Most successful in lakes in which the external nutrient load has been reduced to a level allowing a shift to a long-term clear state.	Relatively low (costs of cyprinid removal, piscivorous fish fry stocking and lake monitoring), but requires repetition.	Few negative impacts depending on fishing method, risk of overfishing if done also for commercial reasons, sometimes risk of dissatisfaction from recreational fishers due to reduced fish abundance.	Positive as fish can be used as food, for biogas production (e.g., fish wastes).
[a]Other biomass removal (e.g., aquatic macrophytes, cyanobacteria)	Lakes with mass occurence of nuisance macrophytes (e.g., dominant species are invasive) or removable phytoplankton.	Moderate depending on harvesting and transport cost.	Risk of endangered species, may increase algae blooms.	Biomass can be used for biogas production, fertilizer, or building material (e.g., reeds).

Note: In each case, the prerequisite for effectiveness is that internal nutrient loads contribute considerably to lake nutrient budgets, and their control is necessary for improving the lake's ecological state. These interventions are commonly used to address internal P loads but can also lead to simultaneous reductions of internal N loading. See Section 6 for examples of circular economy approaches.

[a]Biomass removal is not directly intended to reduce internal nutrient loads but may lead to reduction of nutrients in the water column.

based on an understanding of the underlying mechanisms (Bormans et al., 2016; Cooke et al., 2005; Lürling, Smolders, & Douglas, 2020).

For instance, sediment removal is best applied in small and shallow lakes (Cooke et al., 2005). In such lakes, even complete sediment removal is possible (Kiani et al., 2020). Insufficient thickness of the removed sediment and exposure of deep, nutrient-enriched sediment layers to the water column have often impaired effectiveness (Jing et al., 2019; Liu et al., 2015). Hypolimnetic withdrawal is suitable for lakes where the hypolimnion comprises a substantial share of the lake volume, and effectiveness may be optimized by coordinating the timing of withdrawal with maximum P concentration (Nürnberg, 2007, 2020a) that likely coincides also with that of maximum N concentration. For aeration, several studies have demonstrated limited success of lake water quality management, in part reflecting the proportionally large nutrient inputs from shallow, non-aerated areas (Horppila et al., 2017; Tammeorg et al., 2017), continued P release from sub-oxic sediments (Gächter & Wehrli, 1998), or limited ability of the sediment to bind additional P due to lack of binding sites (e.g., amount of Fe; Gächter & Müller, 2003). A simple predictive tool for assessing the potential success of aeration on P removal has been developed based on lake area, mean depth, and external P loading (Tammeorg et al., 2020).

For chemical treatments, aluminum (Al) salts are often used to immobilize P. Treatment longevity varies between 0 and 45 years (on average, 11 years), being longer in stratified lakes and shorter or even ineffective in shallow lakes impacted by sediment resuspension (Huser, Egemose, et al., 2016) or high pH (Nogaro et al., 2013). A decision tree by Huser, Egemose, et al. (2016) indicates Al dose, lake morphometry (ratio of mean depth to square root of the area), and watershed to lake area ratio (related to hydraulic residence time and internal P loads) to be the most important variables determining treatment longevity. Small Al doses applied at high frequency increase the P binding efficiency (Agstam-Norlin et al., 2020). Addition of small doses of iron salts and/or magnesium chloride repeated several times a year proved to be effective in removing P and N from the water column in shallow or artificially oxygenated thermally stratified lakes in Western Poland (Dondajewska et al., 2019, 2020). Iron salts bind P and adsorb it on Fe oxyhydroxides, while magnesium chloride binds both P and N to form insoluble struvite. Other chemical treatments include the application of a bentonite clay modified with lanthanum (e.g., Phoslock; Dithmer et al., 2015; Nürnberg, 2017; Spears et al., 2016), which binds phosphate rather than adsorbing it, and chemicals including zeolite and iron (Fe) products (Funes et al., 2018; Zamparas et al., 2020). While zeolite has poor phosphate adsorption capacity, because the cavities in this highly porous material are negatively charged, the negative charge improves their adsorption capacity for ammonium and metal ions (Lin et al., 2011; Wen et al., 2016). Zeolites may also promote nitrification (Miazga-Rodriguez et al., 2012). Each of these methods has its own specifics that must be considered. For example, management interventions involving iron amendments must consider the competing process of iron sulphide formation (Heinrich et al., 2022) and the potential of renewed P release under anoxia during the entire management period.

In addition to treatment longevity, ecosystem changes that could worsen water quality once the treatment ceases should be considered. For example, aeration or Fe additions could lead to enhanced storage of P adsorbed to sedimentary Fe oxyhydroxides, hence increasing the potential for internal P loading once the treatment is discontinued (Kowalczewska-Madura et al., 2020).

In shallow, subtropical lakes, fish manipulation combined with submerged macrophyte planting has improved water clarity and reduced nutrient concentrations (Liu et al., 2018). More effort to enhance bottom-up control of phytoplankton is needed in warm lakes as grazer control by zooplankton is less effective due to high predation of small fish (Jeppesen et al., 2020; Liu et al., 2018). While considerable research has been conducted on biomanipulation, the optimal range of application in different climate zones still needs to be clarified, and the extent to which biomanipulation can be successfully combined with physico-chemical methods warrants further study (Han et al., 2022; Jeppesen et al., 2012; Lürling, Kang, et al., 2020).

4.2 | Costs

Inappropriately selected measures inevitably lead to increased costs. For large lakes, external load reduction is often the only feasible measure that will contribute to decreased internal nutrient loads in the long term (Tammeorg et al., 2022) as most internal measures would be too expensive. The possible exception could be internal measures to harvest lake biomass (macrophytes, phytoplankton, or fish) for recycling nutrients that would compensate for high costs (see Section 6.1 for example of lakes Vesijärvi and Pyhäjärvi).

In general, biomanipulation methods are low-cost compared to most physical methods (Jeppesen et al., 2007). Hypolimnetic withdrawal is low-cost compared to other physical methods (Nürnberg, 2007, 2020a, 2020b), especially when using gravity-based syphoning. Such a treatment has been employed in Kortowskie Lake in Poland since 1956 (Dunalska et al., 2014) and in a small alpine Austrian lake since 1970 and still operates with little maintenance cost (Nürnberg, 2020a, 2020b). The typically high operating cost of aeration treatments (e.g., hypolimnetic aeration or oxygenation) can be reduced to almost zero by converting electrically powered aeration to wind or photovoltaic pulverizing oxygenation (Gołdyn et al., 2014; Osuch et al., 2021; Podsiadłowski et al., 2018). Nevertheless, it is important to note that the impact of wrongly selected measures will not be improved by using renewable energy. As costs for different interventions are strongly case-sensitive, they cannot be specified generally. Rather, their assessment is a key component of a system analysis (see Section 5) as is the evaluation of performance and longevity of the proposed measures.

4.3 | Environmental risk

Some restoration measures consume large amounts of energy, cause environmental problems downstream, or produce byproducts (e.g., dredged sediment rich in nutrients, organic pollutants, and toxic metals; withdrawn hypolimnetic water with nutrients in bioavailable form; Table 1). Best available practices should be followed to minimize the environmental risks. For instance, downstream water quality deterioration of sediment removal may be minimized by using cleaning screens, and the timing of interventions should be adjusted to minimize negative effects on biota. At all times, renewable energy sources should preferably be used, for example, as demonstrated by Lake Durowskie, where oxygenation is powered by wind energy (Gołdyn et al., 2014).

A further concern may be the production and transport of chemicals used for restoration. Instead of industrial production of nitrate, existing N sources can be reused to oxidize the sediment surface and thus suppress sediment P release (Dondajewska et al., 2019; Kozak et al., 2020). However, extreme caution must be exercised when adding excess N to eutrophic systems to avoid causing secondary problems, such as unintended proliferation of non-N-fixing, toxin-producing cyanobacterial taxa (Paerl et al., 2016). Environmental concerns regarding chemical treatments also include potential harmful effects on flora and fauna, and thus ecotoxicological tests are needed before broad application (Drewek et al., 2022; Lürling, Smolders, & Douglas, 2020; Rybak & Joniak, 2018). Nature-based interventions that maximize ecosystem services (Triest et al., 2016) could provide safer solutions in the context of environmental risks too (Dondajewska et al., 2019).

4.4 | Circular economy support

With P fertilizers produced from phosphate rock being a finite commodity, there is an urgent need to reduce P loss from the human food chain, preferably transforming it into a closed cycle (Dawson & Hilton, 2011; Jupp et al., 2021; Sharpley et al., 2018; Zou et al., 2022). Therefore, circularity at waste streams should have top priority, and internal restoration measures that enable removal of P from the lake ecosystem for their recovery and re-use (i.e., circular economy) should be prioritized. Similarly, the need for recovery and reuse of excess reactive N in the biosphere has been stressed in recent UN guidance document (UNECE; Sutton et al., 2022).

All measures focused on the removal of nutrients from lake ecosystems have a potential link to circular economy. There are a growing number of projects (e.g., RecaP) and studies searching for opportunities to recycle by-products of geoengineering (Zamparas et al., 2019, 2020). One of them is based on the paramagnetic properties of vivianite, which makes it potentially harvestable (e.g., ViviMag). Roy (2017) has summarized potential secondary products from which P may be recovered, and Tonini et al. (2019) estimated that the environmental and social costs of P recovery are lower than those for P production from mineral sources. Braga et al. (2019) projected that savings with sediment-based soil fertilization (N, P, and K) can amount to 28%. Sediments and biomass removed from lakes and its surroundings during restoration can be used for various purposes, depending on their characteristics. In this manner, the process of lake restoration gains value and reduces costs, supporting the general shift to green, circular economies worldwide. This shift is reflected, for example, in the adoption of the circular economy action plan (CEAP) of the European Commission in March 2020.

Several studies have demonstrated benefits of sediment application in agriculture, such as improved organic matter content and higher amount of plant-available water and nutrients, leading to improved crop yields (Brigham et al., 2021; Canet et al., 2003; Leue & Lang, 2012; Renella, 2021; see also Section 6.2) if the risk of contamination of soil with trace materials (Darmody & Diaz, 2017; Woodard, 1999) is controlled. In addition to nutrient recovery (see example in Section 6.3), hypolimnetic withdrawal may result in energy recovery. For example, deep water of Lake Ouderkerkerplas in Amsterdam is used to cool down a nearby office building resulting in a reduction of greenhouse gas emissions of 19.9 kton CO_2-eq year^{-1} (Van der Hoek, 2011). Fish biomass removed during biomanipulation can be used as food (see examples in Section 6.1) or feed, if it meets relevant quality standards, or as an energy source (e.g., fish wastes, Ward & Løes, 2011), which may need specific adaptation technologies depending on the temporal availability of resource. The biomass of emergent macrophytes (e.g., *Phragmites australis* and *Typha* spp.) can be increased in value to building and insulation material (Colbers et al., 2017) or used for energy (Komulainen et al., 2008), while submerged invasive species, such as *Elodea canadensis*, can be used for biogas production (Muñoz Escobar et al., 2011; see example in Section 6.4). By containing important compounds, such as proteins, lipids, carbohydrates, antioxidants, and pigments (Vega et al., 2020), cyanobacterial biomass as well as green macroalgae can potentially be used in biotechnology, medicine, pharmaceutical, and cosmetic industries (Khalifa et al., 2021; Michalak & Messyasz, 2021) as an energy source (Rittmann, 2008) or as biofertilizer (Chittora et al., 2020). However, complicated harvesting methods and the high water content in the collected biomass complicate drying and increase the costs (Chen et al., 2012, Chen et al., 2017; see example in Section 6.4). Specific adaptation of production technologies would be necessary to render such approaches cost efficient (Ward & Løes, 2011), though there is already evidence of success (e.g., Origin by Ocean).

5 | IMPLEMENTING THE FRAMEWORK OF SUSTAINABLE LAKE RESTORATION

5.1 | Importance of a site-specific assessment (system analysis)

Site-specific system analysis is the basis for sustainable lake restoration. First, it is necessary to identify the use of the water body, next, determine the severity of the problem (e.g., deviation from target conditions), and, finally, set targets for nutrient concentrations. Before restoration measures are applied, it is important to identify case-specific stressors that need to be mitigated for restoration to be successful (van Liere & Gulati, 1992; Figure 2). This can be achieved by constructing nutrient budgets that estimate the relative contribution of external and internal loads to the overall loading. Water budgets are needed, as nutrient dynamics are largely determined by hydrology and water body's retention (Nõges et al., 1998, 2003). The level of the required nutrient reduction is to be clarified. The complexity of the system analyses, for example, multitude of potential sources, different water types, biological characteristics (fish contribution), and the need for P budgets have been explained in Lürling et al. (2016). P input reductions have been the primary focus for freshwater eutrophication management, often because it is easier and cheaper to reduce in wastewater treatment systems than N (Carvalho et al., 2021; Golterman, 1975; Moss, 2010). Multiple models for P-based management (Janse et al., 2008; Hupfer et al., 2020; Nürnberg, 2009, 2020b; Vollenweider, 1968) were developed and are used in the system analysis. System analysis also includes determining the cost efficiency of potentially applicable measures and listing their success and failure rate to achieve maximum benefits at the lowest costs (including energy requirements) for each option under consideration. Decision trees were developed in some studies to ensure science-based choices among alternatives (e.g., Mehner et al., 2004; Pereira & Mulligan, 2023; Schauser et al., 2003; Waajen, 2017).

Currently, only some publications explain why specific restoration approaches were chosen (e.g., Nürnberg & LaZerte, 2016; Sarvala et al., 2020; Stroom & Kardinaal, 2016). Many lake restoration efforts have focused on a single restoration intervention, often with limited success (e.g., Gulati & Donk, 2002), and growing evidence suggests that combined measures may be more successful (e.g., Jeppesen et al., 2012; Lürling & Mucci, 2020; Waajen et al., 2016). This approach is particularly relevant for smaller lakes in which both in-lake and catchment interventions may be feasible. A smaller catchment often implies fewer stakeholders, possibly reducing the time needed to implement remediation measures that mitigate pressures, such as chronic, diffuse nutrient pollution and ecosystem alterations. A restored system may also increase resilience to stressors acting on scales beyond the catchment (e.g., on climate change-associated "pulse stressors," such as heatwaves and extreme precipitation events).

Sustainable lake restoration requires cost-efficiency analysis to avoid unnecessary costs for society. Cost-efficiency analysis requires data on the ecological and economic benefits of restoration measures (Tirkaso & Gren, 2022), as well as the increased value of ecosystem services provided by restored versus impaired lakes. These values may be viewed differently by different stakeholders (identified as trade-offs between ecosystems services by Janssen et al., 2021), and benefits may reach further than local communities (Reynaud & Lanzanova, 2017). These authors emphasize that lakes and their restoration effects are undervalued and that obtaining insight into the spatial distribution of benefits and beneficiaries is the main challenge when valuing lake restoration. Bateman et al. (2023) reviewed recent advances in valuing restoration in relation to innovation in stated preference survey methods (e.g., design and implementation of the surveys which elicit individuals' stated preferences).

Some studies concluded that mitigation of external nutrient loads would be the most cost effective way to maintain good water quality (e.g., Pexas et al., 2020; Withers & Jarvis, 1998; Wood et al., 2015). In some urban lakes, however, in-lake chemical treatments were determined to be more cost effective than catchment measures as the costs for reducing external loads sufficiently to improve water quality would be extreme (Huser, Futter, et al., 2016). In a recent study, aluminum treatment was identified as an optimal approach to reduce the internal P load in two Swedish lakes because this treatment combined the highest internal load reduction efficacy with the lowest cost (Sellergren et al., 2023). For Spring Lake (USA) however, Steinman (2019) concluded that, while alum reapplication may be the most cost-effective solution for aesthetics, it does not lead to ecosystem restoration in a holistic sense because the method creates a vicious cycle of enrichment and treatment and releases potential polluters from responsibility.

5.2 | Role of public interests in sustainable lake restoration

Determining restoration goals and the best practices to achieve these goals involves human perceptions, beliefs, and emotions (Schönach et al., 2018). Restoration activities are influenced by preferences, possibilities, and knowledge, which are context-dependent variables that can shift over time (Schönach et al., 2018). Achieving global water security by 2030 (UN Sustainable development goal 6) is projected to require capital expenditures of USD$1.7 trillion, which is three times more than is currently invested in water-related infrastructure (UN, 2021). Investments on this scale can be motivated by a growing appreciation of the value of water (Garrick et al., 2017). The prevention of water quality deterioration and restoration require involvement of decision makers, industry, water managers, lake owners, lake users (boaters, fishers, swimmers, etc.), tourist agencies, governments, and a united scientific community.

Recently, Abell et al. (2022) summarized the key factors determining the effectiveness of lake restoration at political and social levels:

1. Leadership by a dedicated water management agency.
2. Regulation to achieve nutrient load targets.
3. A political framework that supports a catchment-scale approach to management.
4. Presence of an active local restoration group.
5. Engagement with motivated local groups.
6. Reaction to a perceived environmental crisis.
7. Education to foster understanding of the issue.

As public interests can be numerous and sometimes contradictory, it is important to involve both, those contributing to poor water quality and those that benefit from good water quality, from the beginning of a restoration project. Here, it is also important to acknowledge that some recreational activities may benefit from measures, while others may be restricted, for example, angling for certain target species. When bringing diverse public interests together, the sharing of scientific and technical information is of great importance (Heikkila & Gerlak, 2005). This approach requires interactions between scientists, water managers, and interested parties (Jilbert et al., 2020). For safe human use of waterbodies, the World Health Organization advocates for using the development of site-specific water safety plans as a platform to bring these public interests together for the joint assessment of key pressures on water quality, development of the most effective control measures, and operational monitoring systems to ensure their continuous functioning (WHO, 2021; Rickert et al., 2016).

5.3 | Other factors to consider by system analysis

A growing world population, urbanization, agricultural intensification, and increasing global trade cause a number of pressures on lake ecosystems (e.g., fertilizers and pesticides from agricultural activities, traditional and emerging chemical pollutants from industrial discharges, water abstraction, invasive species introduction, and climate change; Spears, Lürling, & Hamilton, 2022; Figure 2). Here, we use examples of political situations and climate change to illustrate the consequences for lake restoration.

5.3.1 | Political consideration

The social and economic dimensions of sustainability are subject to rapid changes in policy and society. For example, the price of fossil fuels (important input for any large-scale nutrient removal from lakes) has fluctuated by more than 10-fold since 2020 (Tradingeconomics, 2022). Also, global events may make use of nutrients recovered from lakes more feasible since the alternatives, using natural P and industrial N sources, are becoming more expensive or include politically difficult trading situations (Brownlie et al., 2022). The price of mineral P fertilizers is prone to remarkable fluctuations, including nearly tripling of the P rock price from 2020 to 2022, reaching the highest price for a decade in March 2022 (Brownlie et al., 2023; Indexmundi, 2022). The reasons for the fluctuations are unclear but are thought to include geopolitical tensions (e.g., control of international trade and mineral access in disputed territories; Clayton, 2021; Dworkin, 2022; Karam, 2021), a constrained market (i.e., more than 70% of the global P rock originates from Morocco; Statista, 2022; Brownlie et al., 2022), and energy and transportation costs (Brownlie et al., 2023). The situation with P rock availability and price has worsened in 2022 with the Russian military aggression in Ukraine and the subsequent sanctions against Russia and Belarus to the point where food security becomes jeopardized globally (Faulconbridge, 2022; GRO Intelligence, 2022; Kaviti et al., 2022). Hill (2022) suggested that recent efforts to replace Russian energy with Algerian natural gas to Southern Europe may lead to a new wave of support for independence for the Western Sahara region, complicating access to mineral P reserves by Morocco in that region. This uncertainty would mean that phosphate prices will remain high in the coming years, especially in regions like the EU, for countries with a high dependency on P imports from Morocco and Russia. These issues have resulted in the scientific community calling for greater global coordination of P management, with focus on reducing losses to lakes and other ecosystems (Brownlie et al., 2021). Nitrogen fertilizer prices are also at record levels, affected by the Ukrainian crisis (Schnitkey et al., 2022), and depend on fossil fuels to perform the Haber–Bosch process (Rosa & Gabrielli, 2022). If the cost of fertilizers or energy associated with fertilizer production increases dramatically, then the value of nutrients recaptured from lakes and their catchments increases as well.

5.3.2 | Climate change

Climate change is one of the major challenges for sustainable lake restoration. Over recent decades, climate change effects include altered and more extreme temperature, precipitation, and wind regimes, heat waves, changes in ice cover, water column stability, water levels, and retention times in aquatic ecosystems (Nõges et al., 2016; Woolway et al., 2020). Higher evaporation rates for lakes and watersheds can also hamper restoration efforts (Meerhoff et al., 2022). In general, harmful algal blooms are predicted to be more likely, leading to adverse effects on the range of ecosystem services (Paerl et al., 2016). The most sensitive lakes to climate change in Europe are located in northern regions where lake temperature has increased to a range where cyanobacteria thrive (Richardson et al., 2018). Several models have been developed to predict the relative and interactive effects of climate change and nutrient enrichment on ecological quality (Richardson et al., 2018; Spears et al., 2021; Spears, Chapman, et al., 2022). In the UK, for example, the economic costs of algal blooms have been estimated to increase by 1.5–1.9 fold in the 2050s (Jones et al., 2020). Observed and projected impacts of climate chance emphasize the need to reduce algal bloom biomass by sufficiently stringent reduction of nutrients (Bonilla et al., 2023; Rigosi et al., 2014).

6 | POTENTIAL SUSTAINABLE LAKE RESTORATION AND CIRCULAR ECONOMY: RECENT CASE STUDIES

Given the growing concerns regarding water pollution, population growth, and scarcity of mineable P resources, there is a mounting need for ecological engineering approaches to develop nutrient recovery and recycling technologies, supporting both eutrophication control and food and energy security (Reitzel et al., 2019; Roy, 2017; Stamm et al., 2022; Vaccari et al., 2019). Below, we present examples of some case studies and the essential knowledge gaps that they reveal, directing future multidisciplinary research. By developing these emerging approaches, more accurate cost–benefit and feasibility analyses will become possible. In the examples 6.1–6.3, the restoration was focused primarily on the reduction of P in the water (thus, all effects are quantified for P), but potentially also N is removed (and recycled) with sediments and biomasses. For example, fish tissues contain a fair share of N (Tanner et al., 2000).

6.1 | Biomanipulation and use of fish as a food source (examples—Lake Vesijärvi and Lake Pyhäjärvi)

In Lake Pyhäjärvi (SW Finland; 155 km^2, mean depth 5.5 m, water residence time 3.2 years), intensive harvest of smelt (*Osmerus eperlanus*), roach (*Rutilus rutilus*), and ruffe (*Gymnocephalus cernua*), combined with commercial fishing of vendace (*Coregonus albula*) yielded a total catch of 20–50 kg ha^{-1} $year^{-1}$ during two periods (1995–1999 and 2000–2005). This fish harvest was estimated to remove an amount of P equivalent to 19 and 25% of the total external P load during the two periods, respectively (Ventelä et al., 2007), and to cancel out the effect of internal load (Nürnberg et al., 2012). Cyprinids removal is continued in Lake Pyhäjärvi at the same harvesting intensity (20 kg ha^{-1} $year^{-1}$).

A large-scale biomanipulation was carried out in the Enonselkä basin (32 km^2, mean depth 6.8 m, water residence time 5.6 years) of Lake Vesijärvi during 1989–1993. The mass removal of planktivorous and benthivorous fish such as roach, bleak (*Alburnus alburnus*), and common bream (*Abramis brama*) and stocking of predatory pikeperch (*Sander lucioperca* (L.)) led to a collapse of cyanobacteria biomass and decreased TP concentrations (Horppila et al., 1998). On average, ca. 73 kg ha^{-1} $year^{-1}$ fish was removed from Enonselkä basin during this period. Absence of changes in the zooplankton community suggested a stronger effect of fish removal on fish-mediated internal P loading and nutrient availability than on zooplankton grazing (Horppila et al., 1998). During the years 1993–2020, fish removal continued at 20 kg ha^{-1} $year^{-1}$ and maintained lower chlorophyll and total nutrient concentrations (Salonen et al., 2023). The amount of P removed with fish biomass corresponded to about 21%–27% of TP in the whole water mass in 1991–1993 and to about 6% in 1996–2020.

In both lakes, biomanipulation has been combined with commercial operation of formerly under-utilized cyprinid catches by the local food industry. Increasing catch proportions have ended up in food production, thus providing a link to the transition to a "blue" bioeconomy and implementation of the EU's Farm to Fork Strategy. Although cyprinids are not usually targeted in commercial and recreational fishing, they offer quality protein and fatty acids for human consumption (Taipale et al., 2022). The estimated ecologically sustainable catch potential for roach is around 19 million kg $year^{-1}$ in Finnish inland waters, and implementation of commercial biomanipulation is now planned for several lakes (Ruokonen et al., 2019). However, overfishing of target species must be avoided and sustainability secured by adequate fishery and ecosystem monitoring. There is a current lack of sustainability criteria for commercially intensive biomanipulation, but these criteria should be developed to avoid causing environmental harm to target or downstream ecosystems.

6.2 | Sediment excavation and sediment nutrient reuse in agriculture (examples—Lake Mustijärv and Lake Ormstrup)

The small (1 ha) and shallow (mean depth 2 m; Figure 3) Lake Mustijärv (central Estonia) is the first documented case of lake restoration using complete sediment removal linked with subsequent recycling of sediment nutrients in agriculture. Around 6.4 t TP and 33 t TN were removed with the total amount of the removed sediment estimated to 7500 m^3. However, in this case the success could not be fully documented as shortly after the sediment removal from the lake, the upstream riverbed was cleaned, causing exceptionally high external nutrient loading with unfavorable implications for lake water quality (Kiani et al., 2020). This certainly stresses a need for future lake restoration efforts to be coordinated better at the watershed scale. A subsequent mesocosm study demonstrated that the removed sediment was efficient growing media as it increased the growth and uptake of P by ryegrass. Particularly, the excavated sediment from Lake Mustijärv was an effective source of P, Cu, and Zn (Kiani et al., 2021). The high fertilizing ability of the excavated sediments was reaffirmed in a 4-year field experiment (2017–2020) conducted on the lakeshore (Kiani et al., 2023). In addition to P, the sediment provided a continuous supply of N to the plants, which was likely due to the mineralization of the sediment's organic matter (Kiani et al., 2023).

A similar approach to that used in Lake Mustijärv is currently being developed for small (12 ha), shallow (mean depth 3.2 m, maximum depth 5.5 m) Danish Lake Ormstrup. The high P concentrations (0.4–0.8 mg L^{-1} TP in surface water, up to 1.8 mg L^{-1} TP at 4 m depth in summer) are driven by internal P loading, while external P loads are low (Søndergaard et al., 2023). The high internal P loading leads to low TN:TP ratios (1.6–5 by weight) in summer. Sediment removal is considered an effective approach to reduce internal P loading in Lake Ormstrup, while creating a link to circularity (Haasler et al., 2023). A highly detailed and comprehensive limnological assessment is undertaken to evaluate the necessary depth of the sediment to be removed to induce positive shifts in lake ecosystem. Also dredging technology is being developed to minimize the environmental footprint. The recycling of dredged material in agriculture is a

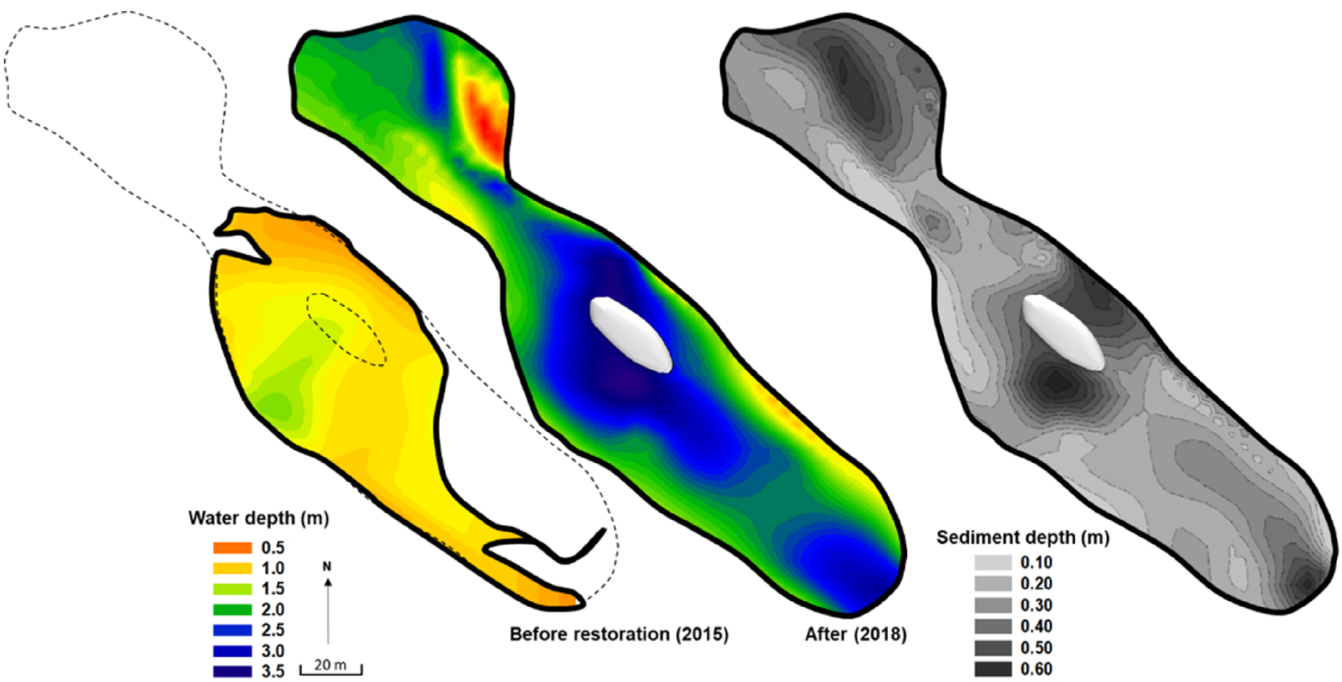

FIGURE 3 Changes in the morphometry of Lake Mustijärv (Estonia). High external loads recharged the sediment nutrient pool soon after sediment removal, partly due to intensive cleaning of an upstream streambed (from Kiani et al., 2020).

priority for the project, with pilot studies showing promising results on the P fertilizer potential of the Lake Ormstrup sediment.

In contrast, studies focusing on the fertilizer value of sediment P from constructed wetlands in Finland demonstrated very low availability of P for plants (Laakso et al., 2017), possibly due to the saturation of catchment soils with Fe, which adsorbed added P. Thus, the bioavailability of sediment P to terrestrial plants requires further research as does the understanding site-specific constraints (regarding also potential contamination and remediation opportunities), and should be included in a system analysis. Further evidence of sediment potential as fertilizers and progress in the remediation of contaminated sediments are necessary inputs for policy development as the legislation currently limits the application of sediments in agriculture (Renella, 2021).

6.3 | Hypolimnetic withdrawal and potential reuse of withdrawn nutrients (example—Lake Kymijärvi, Myllypohja basin)

A closed-circuit application of hypolimnetic withdrawal has been developed and tested in Myllypohja basin (0.9 km^2, mean depth 4.3 m, water residence time 0.6 years) of Kymijärvi (southern Finland; Silvonen et al., 2021) with the aim to mitigate negative environmental impacts and to potentially harvest P. Hypolimnetic water was pumped through a treatment unit consisting of a mixing well, in which the water was aerated and chemicals were added, and a sand filter (200 m^2), in which precipitated P was trapped. The water flowed from the treatment unit into a wetland (area 1.2 ha), from where it is released to the surface of the lake (Figure 4).

The mean retention of total P by the sand filters used in Kymijärvi was 60% and varied between 30% and 85%, depending on how long the filter had been in use, while the retention of dissolved P was 71%–95% (Silvonen et al., 2022). Nitrogen was not effectively captured by the sand filters. Within the filters, P was mostly bound to amorphous Fe(III), regardless of the treatment method used. The main mechanism of P capture was the formation of Fe hydroxy-phosphates during oxidation of Fe(II) (Silvonen et al., 2022). However, Fe blocked the sand filters, requiring frequent filter maintenance. Calculations based on Nürnberg (2007) suggested that a 10 L s^{-1} pumping rate during summer stratification (2 months) would decrease total P concentrations in the epilimnion from the current 35 μg L^{-1} to below 25 μg L^{-1} in ~25 years. With a 20 L s^{-1} pumping rate, the goal (25 μg L^{-1}) would be achieved in less than 15 years. The time span of 15–20 years is acceptable in comparison to decades of eutrophication. Also, with the external load reduced, this measure will not need to be permanently operated; once the restoration target of legacy P removal is met, operation can cease.

In the wetland located between the sand filter and the lake, P retention varied due to seasonal alterations in vegetation cover and biogeochemical cycling, but even with the lowest estimates of 33% P retention, the wetland added to the

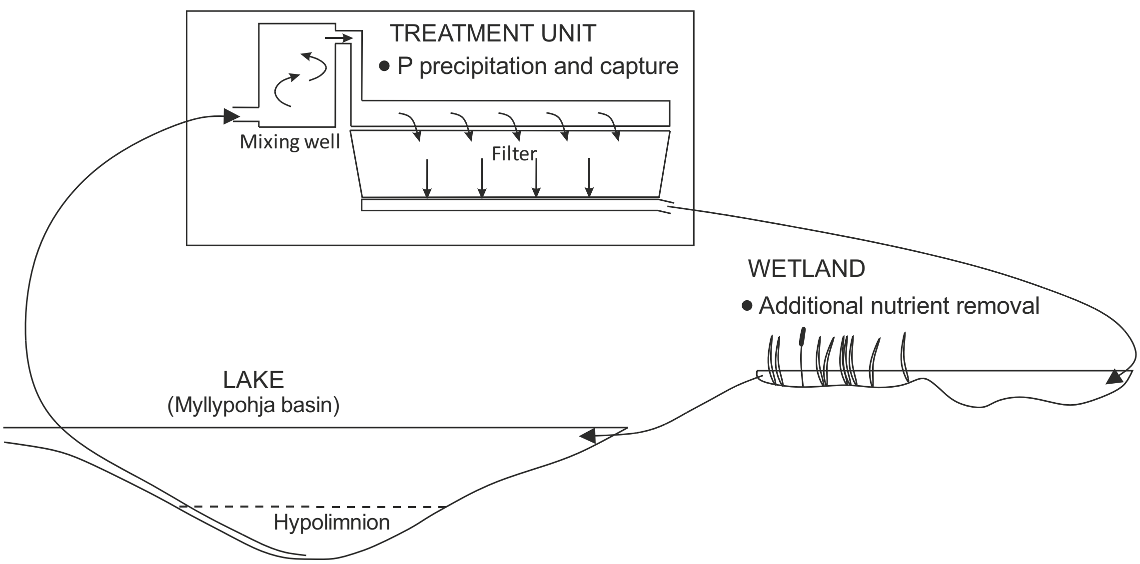

FIGURE 4 The structure of the closed-circuit hypolimnetic withdrawal in Lake Kymijärvi.

overall effectiveness of the closed-circuit hypolimnetic withdrawal (Silvonen et al., 2022). With the wetland and filters, "good" ecological status (as defined in WFD) should be achieved in <20 years with 10 L s^{-1} pumping rate and in <10 years with 20 L s^{-1} rate (Silvonen et al., 2022). The wetland is also expected to intensify N removal via denitrification (Martínez-Espinosa et al., 2021) and N retention via incorporation into biomass and organic matter burial in the sediments (Vymazal et al., 2020). When connected to a hypolimnetic withdrawal system, nutrient fluxes to the wetland were highest in mid and late summer when vegetation biomass is highest. The wetland also diminishes temperature differences between the lake and treated water, which reduces potential thermal instabilities in the receiving part of the lake.

The possibilities for P recycling of the filter precipitate are still unexplored but are hypothetically similar to those for sewage sludge. Pyrolysis is one of the methods potentially suitable for processing the precipitate and harvesting P for reuse, where thermochemical treatment of the sludge can decrease the mobility of inorganic contaminants (Frišták et al., 2018). Another method is dissolution of the dried chemical sludge with phosphoric acid where P and Fe are dissolved and can be separated for further processing and reuse (Rossi et al., 2018).

6.4 | Macrophyte and phytoplankton biomass removal and recycling (examples—Lake Vuotunki and Lake Taihu)

A Finnish case study (Lake Vuotunki; area 218 ha, mean depth 0.96 m) demonstrated the removal and subsequent cost-reducing exploitation of the invasive, submerged macrophyte Canadian waterweed (*Elodea canadensis)*, used in biogas production and soil amendment (Nilivaara et al., 2022). The species, also favored by eutrophication, originates from North America and is widespread globally. It may threaten endemic species and habitats by forming dense stands, displacing other native species, causing oxygen depletion, and hindering recreational activities on lakes (Josefsson, 2011; Sarvala et al., 2020). Nilivaara et al. (2022) found that waterweed biomass can produce a methane yield of up to 62% in the biogas process when mixed with grass. Waterweed may also have potential as an organic fertilizer due to high content of nutrients essential for plant growth. In Finland, Canadian waterweed biomass in invaded lakes is high (21.4–56.1 t dw ha^{-1}; Karjalainen et al., 2017). There is a risk of shifting the lake to a turbid, phytoplankton dominated state (e.g., Scheffer et al., 1993), even though the removed Canadian waterweed biomass (with the contents of N and P 28.5 g kg^{-1} dw and 2.1 g kg^{-1} dw, respectively) reduces lake water nutrients. However, only minor negative effects on water quality after Canadian waterweed removal have been reported (Nilivaara et al., 2022). Care must be also taken not to unintentionally introduce the species to other lakes, as Canadian waterweed can reproduce rapidly, even from shoot pieces.

Lake Taihu (China) is a large (2338 km^2), shallow (mean depth about 2 m), eutrophic lake prone to frequent cyanobacterial blooms (Xu et al., 2021). After a massive *Microcystis* spp. bloom in 2007 contaminated the drinking water supply of the nearby city of Wuxi (Qin et al., 2010), 1000 t of fresh cyanobacterial biomass were mechanically removed per day (Chen et al., 2012; Chen et al., 2017). Daily collection of the same amount of biomass from May to October would eliminate around 144 t of N and 9 t of P (Chen et al., 2017). This removal is, however, low compared to external nutrient loading (1–5 × 10^3 t P and 21–66 × 10^3 t N; Wang et al., 2019), and the internal load is twice the external load (Hampel et al., 2018). Although mechanical removal of cyanobacterial biomass is often used in China as an emergency response (e.g., to prevent health risks associated with cyanobacteria toxins; Chen et al., 2017), the lack of cost-effective techniques for its drying challenges subsequent re-use (Chen et al., 2006; Chen et al., 2012). Water quality may benefit from the concurrent removal of polychlorinated biphenyls (PCBs) and microcystins (0.5 and 900 kg annually, respectively), but these substances complicate further treatment, and potential technologies are under development to address this (e.g., use of bacterial strains; Dexter et al., 2018; Liu et al., 2022). Soil-based treatments are widely used but could pose environmental, ecological, and public health risks (e.g., microcystin leaching to groundwater, bioaccumulation in crops; Chen et al., 2012). Cao et al. (2018) did not describe a threat to human health (considering the estimated daily intake) of consuming rice fertilized with an appropriate amount of a cyanobacterial bloom as well as irrigated with lake water.

7 | CONCLUSION

Eutrophication remains a major cause of water quality impairment in lakes, leading to compromised ecosystem service delivery and affecting local economies and social stability. Nutrient load reduction to mitigate eutrophication (including cyanobacterial blooms) is the major priority of lake restoration, but reducing external nutrient loads at the catchment scale often requires changes at social, economic, and environmental levels. Internal restoration measures may promote more rapid ecosystem responses than may be feasible with external loading reductions alone, even if multiple interventions are needed. Such interventions may enhance socio-economic benefits of lake restoration. Internal restoration measures that remove nutrients, sediments, and biomass from lake ecosystems and reuse these nutrients in agriculture, food, or biogas production contribute to a circular economy and can be particularly useful in sustainable lake restoration. These measures/techniques require further research and development. Each lake should be assessed individually to ensure that restoration approaches will effectively address the lake-specific problem, do not harm the target lake or downstream ecosystems, are cost-effective, promote delivery of valuable ecosystem services, minimize conflicts in public interests, and reduce the necessity for repeated interventions. Thus, achieving optimal, sustainable results from lake restoration relies on multidisciplinary research and close interactions between environmental, social, political, and economic sectors.

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SUPPORTING INFORMATION

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