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Recycling of lake sediments as phosphorus fertilizer: Promising results from a greenhouse experiment with six different sediments

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ABSTRACT

Removing sediment from lakes is effective for restoration but involves high disposal costs. Repurposing these sediments as fertilizers could address phosphorus (P) shortages. Our study evaluated the fertilizing potential of sediments from Finnish lakes (Matjärvi, Kutajärvi, Kymijärvi, and Enonselkä) and two basins of Estonia's Lake Peipsi (Peipsi and Lämmijärv). We conducted a greenhouse experiment with ryegrass growing in sand, by applying to sand either 25 kg ha^{-1} of mineral P fertilizer or sediments with the same amount of bioavailable P according to their iron-bound P content, and using sand without any P fertilizer as a negative control. We also tested soil amendments like lime, biochar, or arbuscular mycorrhiza to enhance sediment-derived P availability. Results showed ryegrass biomass and P uptake in sediment treatments were 126 % and 133 % of those without added P. Sediments provided P and other macro- and micronutrients, enhancing plant growth. Organic matter contributed additional P, except for Enonselkä and Lämmijärv sediments. Contrary to our hypothesis, plant P uptake occurred even from sediments with high iron to P mass ratios, suggesting hypoxic conditions contributed to P solubilization. Biochar and lime amendments increased plant biomass, particularly in the Kymijärvi treatment, to 106 % of those without amendment, and decreased zinc (Zn) uptake, important for avoiding Zn contamination. These findings highlight the dual benefits of sediment removal for lake restoration and as a substitute for mineral P fertilizers. Further research is needed to explore the long-term effects of using lake sediments as fertilizers and identify optimal practices for enhancing nutrient availability under field conditions.

1. Introduction

Phosphorus (P) rock is one of the most critical natural resources, yet Europe depends on imports for about 86 % of its supply (Daneshgar et al., 2018). The nutrient needs of crops for P are increasingly being covered with inorganic fertilizers derived from

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non-renewable P rock deposits. However, 80 % of global P reserves are concentrated in just a few countries (Morocco and Western Sahara, China and USA) (Brownlie et al., 2023) making Europe highly vulnerable to supply risks and price volatility. The economically reasonably exploitable P rock stocks have been estimated to be used up in China and the USA in just 30 years, possibly leading to the worrisome situation where the cadmium-rich Moroccan stocks will be practically the sole P source for the whole world (Walan et al., 2014). The situation with P rock availability and price has only worsened since 2022 to the point where food security becomes jeopardized globally (Tammeorg et al., 2024).

Further, the anthropogenic (agricultural) part of the global P cycle is broken, with only about 16 % of the mined P ultimately consumed by humans (Daneshgar et al., 2018). Globally, P losses from agricultural soils through erosion and leaching, which cause eutrophication of water bodies, are estimated to be more than twice the amount of P entering the food system (Vaccari et al., 2019). Even if there was a way to improve farming practices to the point of zero P loss (abated external loading), the enormous P stocks (more than 3200 MtP; Raniro et al., 2025) already in the riparian and lake sediments (legacy P) would continue to release P to the overlying water column, a phenomenon known as internal P loading. Internal P loading is one of the reasons for the often-observed delay in response of lake water quality to reduced external nutrient supply (Jeppesen et al., 2005; Steinman and Spears, 2020).

Despite temporal environmental concerns, such as implications for the benthic invertebrates and sediment resuspension, sediment removal has often been shown to be an effective method from the perspective of combating the release of P in lakes in long-term (Cooke et al., 2016; Bormans et al., 2016; Lürling et al., 2020). Removal of legacy P was associated with a decline in water column nutrients (e.g., Van Wichelen et al., 2007; Härkönen et al., 2025), reduction of phytoplankton, and disappearance of cyanobacterial blooms (e.g., Björk et al., 2010). Moreover, there is an increasing number of studies demonstrating different benefits of sediment application in agricultural soils, such as increased water retention, organic matter content, nutrients, and crop yield (Canet et al., 2003; Leue and Lang, 2012; Renella, 2021; Brigham et al., 2021). Yet, there is lack of studies applying sediment as a P fertilizer that would be a more environmentally-friendly solution compared to using sediments as growing media due to lower leaching and risk of contamination (Haasler et al., 2024), which are currently restricting sediment application in agricultural production (e.g., EU Regulation 1009/2019). Hence, such studies would help also to develop regulations for recycling sediments that are currently available only for few countries (Renella, 2021).

Sediment P forms have different stability and availability (Ruban et al., 1999). Kiani et al. (2021, 2023) and Haasler et al. (2024) evidenced the iron-bound P fraction of sediments (Fe–P) as the source of P for crops in sediment applications. At the same time, this redox-sensitive P fraction is often the main source of sediment P release and associated water quality impairment in lakes (Nürnberg, 1988, 2024). Hence, there is a big potential for addressing water pollution and scarcity of mineral fertilizers simultaneously, provided that the sediments are not contaminated with heavy metals and other pollutants. Braga et al. (2025) have shown in their recent cost-benefit analysis that sediment reuse may result in savings of up to 68 % in the Jaguaribe River Basin (Brazilian semiarid region).

Nevertheless, recent studies focusing on the fertilizer value of sediment P from constructed wetlands in Finland demonstrated very low availability of P for plants due to the high concentrations of P-binding compounds (e.g., iron (hydr)oxides) in sediments (Laakso et al., 2017), suggesting that high iron to P (Fe/P) ratio could be one of the indicators for low P bioavailability (Kiani et al., 2023). Similarly, the Fe/P ratio was shown to determine P binding capacity in lake ecosystems (Jensen et al., 1992). Hence, the fertilizing ability of aquatic sediments may vary from sediment to sediment. None of the existing studies have yet tested simultaneously the availability of P to crops from sediments collected from different lakes in a consistent manner, while such studies would improve understanding how the sediment quality affects its ability to provide plant-available P.

Moreover, additional research is needed on improving the bioavailability of sediment P. Hypothetically, the solubilization of Fe–P compounds can be influenced by changing environmental conditions, e.g. changing pH or microbial activity. Soil pH can be increased and the release of P sorbed by ligand-exchange reactions can be promoted by adding lime (Simonsson et al., 2018). Some biochars have been demonstrated to affect microbial activity of growing media (Koide, 2017), affecting potentially P availability. Additionally, arbuscular mycorrhiza may increase P solubility through excretion of organic acids (Elbon and Whalen, 2015). Still, none of these additives have yet been systematically studied in combination with sediment application. The role of such amendments in sediment applications deserves attention also because of their potential impact on the mobility of heavy metals and other contaminants.

The current study aimed at elucidating the effect of lake sediments on ryegrass growth (yield and P uptake) in a greenhouse experiment using sediments from four lakes in southern Finland (Matjärvi, Kutajärvi, Enonselkä basin of Vesijärvi, Kymijärvi), and two basins of large shallow Lake Peipsi in Estonia. The variations in the sediment P release in these lakes were explained by the concentration of Fe–P in sediments (Tammeorg et al., 2020, 2022). Assuming that this is the main factor determining sediment P availability also for crops, in our experiment we amended soils with sediments containing similar amounts of bioavailable P according to their contents of Fe–P in sediments. By that, this is the first study where sediments of different lakes were tested as a P fertilizer (being applied in considerably lesser amount as it would have been done to improve soil structure, potentially with less negative implications for environment), addressing an important knowledge gap. We hypothesized that sediment Fe/P ratio can be one of the factors affecting sediment P availability for crops. In addition, we tested the potential of lime, biochar, and arbuscular mycorrhiza for affecting the bioavailability of sediment P and other elements for plants. Through the recovery of sediment P and addressing simultaneously the improvement of ecological conditions of lakes, our interdisciplinary study provides new knowledge vital for sustaining finite natural P resources for future generations and a practical solution for achieving both resource and environmental sustainability. Paying attention to the potential heavy metal contamination of sediments is a fundamental starting point for the evaluation of sediments for real world applications. While our findings are from a specific geographical area (Finland and Estonia), we claim the implications have potential for upscaling through addressing the issue of Fe–P complexes.

2. Materials and methods

2.1. Study area

The sediments used in the greenhouse experiment were selected to have distinct physicochemical properties and origin. The sediments were collected from eutrophic lakes of southern Finland, including Kymijärvi, Matjärvi, Kutajärvi and Enonselkä basin of Vesijärvi and two basins of Lake Peipsi in Estonia (Lake Peipsi and Lämmijärv; Supplementary Material, SM Fig. 1) (Tammeorg et al., 2020, 2022) at the locations of highest sediment TP concentrations (coordinates N, E 60°58.95′, 25°45.29′; 61°06.01′, 25°17.43′; 61°02.12′, 25°29.38′; 60°59.70′, 25°37.54′; 58° 55.29’, 27°13.8′; 58°20.00’, 27°30.00’, respectively). The sediments for the greenhouse experiment were collected with a grab sampler in October 2021, air-dried at 60 °C and ground to fine powder of a 0.2 mm particle size.

Sediment removal is potentially applicable to reduce eutrophication at all these lakes or some areas of the bigger lakes (Peipsi s.s. or Enonselkä basin of Vesijärvi). The nearby field areas (the highest proportion in the Matjärvi catchment; SM Table 1) enable potential to recycle the sediment as a P fertilizer. According to the recent data by Lemola et al. (2023), cropping in the agricultural field areas of the Vesijärvi watershed, where all studied Finnish lakes are situated, require P additions at a rate of 7.5–15 kg ha^{-1}, and this amount is not possible to cover with existing recyclable sources nearby (e.g. manure). Hence, the sediments from the lakes selected for the current study are relevant for the national efforts of covering the nutrient needs in sustainable way.

According to the previous studies, the contents of sediment TP and also Fe–P in Enonselkä and Kymijärvi were considerably higher than in other lakes (SM Table 2). The proportion of Fe–P in TP exceeded 40 % in the sediments of Enonselkä, Kymijärvi and Lämmijärv. The proportion of organic P in sediment TP (Org-P%) was highest in Matjärvi and lowest in Enonselkä. The changes in sediment Org-P % agreed with those of organic matter content (as loss-on-ignition, LOI). The Fe/P mass ratio in the sediments ranged from 10 in Kymijärvi to more than 30 in Matjärvi and Kutajärvi (SM Table 2). The contents of Ca, Cd and Ni were considerably higher, while the contents of Na, Al and Cr were lower in Estonian Lake Peipsi than in the Finnish lake sediments (SM Table 2). The elemental contents in the sediments across the Finnish lakes were highly variable. Matjärvi sediment had the highest contents of S, Al, Ca, Ni, Sr.

As contaminants may become an issue in recycling lake sediments as a fertilizer, the sediments used in the current experiment were screened for polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (according to the methods described below). The full list of analyzed contaminants (including heavy metals) is presented in SM Table 3. The threshold value to identify soil contamination according to the Finnish legislation was exceeded only by Zn for all lake sediments, and by Ni in Peipsi sediment (SM Table 3).

2.2. Experimental design and setup

The pot experiment was conducted in the greenhouses of Viikki campus (60°13’38.8452"N 25°1′4.7532"E), University of Helsinki. The experimental design followed an 8 × 4 full factorial randomized complete block design with different P fertilization and P mobilization (amendment) treatments. The first factor was P fertilization with eight levels: positive control with a mineral P fertilizer, negative control without any P fertilizer, and six different sediment treatments. The effects of P fertilization added in the treatments was tested by comparing the sediment and positive control treatments with the negative control. The second factor was the amendment of P mobilizing material with four levels: control without any amendment, arbuscular mycorrhiza, biochar, and lime. The effects of amendments were tested by comparison of the amended treatments with the non-amended treatment. All possible combinations of these two factors yielded a total of 32 treatments. All treatments included four replicates making altogether 128 pots (SM Fig. 2). All treatments were randomized within each replicate block. The buffer pots were placed on all sides of treatment pots.

The 3-L pots (with a soil layer height of 17 cm) used in the experiment had a piece of mesh fabric placed on the bottom of each pot to avoid loss of growing media. The pots were filled with 3400 g sand (commercial sand with a particle size of 0.1–0.6 mm, SPH FESCON, Finland) per each pot, resulting in the volume of 2.27 L (0.00227 m^3) and the bulk density 1497.8 kg m^{-3}. Next, lime ($CaCO_3$), arbuscular mycorrhiza and spruce biochar were added to selected pots at the rates of 10 t ha^{-1}, 625 kg ha^{-1}, 30 t ha^{-1}, respectively, to study their potential to improve sediment P bioavailability and reduce availability of heavy metals (through potential effects on pH, microbial activity or other mechanisms) compared with the non-amended treatment. The application rates were chosen to be highest locally relevant amounts not yet causing harmful effects (e.g. in regards of biochar, Kalu et al. (2021) and in regards of lime Nordkalk (2025)). The biochar was purchased from Carbofex Oy, which produces commercial biochar, by pyrolyzing spruce chips at 550 °C for 10–15 min in a continuous carbonizer (Tampere, Finland). It was dried and ground to 0.2 mm particle size and contained 21.4 g kg^{-1} ash and very small amounts of water-soluble plant nutrients, including only notable amounts (more than 0.1 g kg^{-1}) of K and Ca (1.3 and 0.56 g kg^{-1}, respectively). The granulated mycorrhiza used in the experiment was a mixed inoculum that includes both spores and plant roots as propagules.

Subsequently, the growing substrate was fertilized either with mineral P fertilizer (positive control) or the six different P-rich sediments by top-dressing. The positive control received 25 kg P ha^{-1} of mineral P as a mineral fertilizer (Yara, Finland; P 9 %, N 1 %), applied in the same manner as the sediments. In all sediment treatments, the same amount of bioavailable P (25 kg P ha^{-1}) was applied, using the Fe–P content in the sediments as basis for potentially bioavailable P form (Ruban et al., 1999). The applied quantities of each sediment were as follows: 38.31 g (29 t ha^{-1}) of Kymijärvi sediment, 35.84 g (27 t ha^{-1}) of Enonselkä sediment, 98.04 g (74 t ha^{-1}) of Matjärvi sediment, 123.46 g (93 t ha^{-1}) of Kutajärvi sediment, 64.10 g (48 t ha^{-1}) of Peipsi sediment, and 59.52 g (45 t ha^{-1}) of Lämmijärv sediment per pot.

All pots received nitrogen (N) and potassium (K) as crushed fertilizer granules as top-dressing at the rate of 200 kg ha^{-1} and

109 kg ha^{-1}, respectively. Half of these rates were added before sowing, while the remaining half was added after the second harvest. The micronutrients including magnesium (Mg), manganese (Mn), zinc (Zn), copper (Cu), sulphur (S), and boron (B) were added at the rates of 60 kg ha^{-1}, 10 kg ha^{-1}, 9.91 kg ha^{-1}, 10 kg ha^{-1}, 30 kg ha^{-1}, and 0.5 kg ha^{-1}, respectively at the setup of experiment. The application rates corresponded to the local fertilization recommendations (Viljavuuspalvelu Oy, 2000). The mineral fertilizers used in the experiment included: Yara Mila NK 2 (Yara, Finland; N 22 %, K 12 %, S 3 %, Mg 0.7 %, B 0.05 %), Magnesium nitrate: 16 % Mg, 11 % N, Manganese sulphate (MnSO4): 25 % Mn, 12 % S, Zinctrac (9 % Zn) Cutrac (10 % Cu). Seeds of Italian ryegrass (*Lolium multiflorium*) were sown at the rate of 0.33 g seeds pot^{-1} corresponding to 247 kg ha^{-1}. Applying six times of the normal seeding rate was used to ensure seeds germination. After seeding and watering with 50 ml of water, 100 g sand was placed on the top of sediment after seeding in order to avoid any sediment loss. Nine days after sowing, the number of plants growing in each pot was adjusted to 43 plants per pot, which is equivalent to 3225 plants m^{-2}.

The average temperature and relative humidity of the greenhouse throughout the experimental period from 24 November 2021 to 16 May 2022 were 18 °C and 59 %, respectively. The minimum and maximum temperatures were 15 °C and 17 °C, while the maximum and minimum humidity in the greenhouse were 80 % and 35 %, respectively. The average light intensity was 13 W m^{-2}, and the day length of about 6 h. A drip irrigation system was set up for all pots: the amount of tap water given to the plants was 30 ml day^{-1} for the first week of growth and adjusted to 40 ml day^{-1} for the remainder of experiment, ensuring consistent amount of water and nutrients to all pots.

2.3. Sampling and sample analyses

Four yields of ryegrass were harvested on the 12th January, 13th February, 20th March, and 16th May 2022 (corresponding to 43, 75, 110, and 167 days after sowing), respectively, by cutting at 2 cm above the soil surface and placed in paper bags. The plant samples were dried at 60 °C for 72 h, and the dry weight was recorded. Plants displayed no visible signs of P deficiency (no red leaf tips, or reddish/bluish antocyanic color changes in plants) throughout the experiment. The four yields were combined and ground with a hammer mill through a 1.0-mm sieve. The dry material was dry-ashed in a muffle furnace followed by dissolution of ash with 0.2 M HCl for determination of elemental composition (P, K, S, Ca, Mg, Na, Al, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Sr, and Zn) by inductively coupled plasma optical emission spectroscopy (ICP-OES; Thermo-Fisher iCAP3600 MFCDuo, Thermo Fisher Scientific, Cambridge, UK) as in Kalu et al. (2021). The total C and N contents of plant samples were determined by Dumas combustion with a Leco CN analyzer (CN828, Leco Corporation, St. Joseph, MI, USA). All chemical analyzes included quality checks with blanks and quality controls samples, as the standard procedure prescribes (in an order: initial blank, samples, reference samples and final blank; see Kalu et al., 2021 for the details).

At the end of experiment (after the last cut of ryegrass), the top 3 cm of the growing substrate was extracted and analyzed for the elemental composition (by ICP-OES) and P fractions. Additionally, the contents of easily soluble nutrients were analyzed commercially by the standard Finnish soil testing methods and ICP-OES. Easily soluble P, K, S, Ca, Mg, Na were extracted with the acid ammonium acetate, B with hot water, and Cu, Mn, Zn with acid ammonium acetate-EDTA (for procedures, see e.g. Kiani et al., 2023). The electrical conductivity and pH of the growing media samples collected at the end of the experiment were measured in a 1:2.5 (w/w) soil-to-water mixture as a part of the commercial soil fertility analyses.

Since Kymijärvi treatment gained lowest yields and benefited the most from amendment, the growing substrate containing Kymijärvi sediment was analyzed for the P fractions, following a protocol described by Ruban et al. (1999). The protocol results in five P forms according to their extractability: total P (TP), organic P (Org–P), inorganic P (In−P), P bound to Al and Fe (hydr)oxides (Fe–P), and P bound to Ca (Ca–P). To solubilize Fe and Ca for measuring the Fe–P and Ca–P fractions, respectively, 1 mol L^{-1} sodium hydroxide (NaOH) and 1 mol L^{-1} HCl were used, sequentially in the same aliquot (0.2 g of dried sample). With another aliquot, total P was extracted with 3.5 mol L^{-1} HCl. Using the third sediment aliquot, In–P was extracted by 1 mol L^{-1} HCl and the residual was treated at 450 °C to analyze OP (by colorimetry).

Six sediments used in the experiment were analyzed for the elemental composition (summarized in SM Table 2 and described in Section 2), using the same methods as described above for plant samples. Additionally, the sediments were analyzed for C and N content by Dumas combustion, as described above.

The screening of sediments in representative samples for contaminants, including heavy metals, PAHs, and PCBs was done commercially (results presented in SM Table 3). The concentrations of heavy metals were analyzed by ICP-OES. The concentrations of PAHs and PCBs were analyzed by gas chromatograph – mass spectrometer (Agilent GC 7890 MS 7000, Agilent GC 8890 MS 5977, Agilent Technologies, Santa Clara, CA, USA).

2.4. Calculations of indices and P budget

The plant uptakes of P and N (PU and NU, respectively) were calculated by multiplying the given plant nutrient content by the dry mass of plant biomass. Additionally, indexes fertilizer use efficiency were calculated as listed below in Eqs. (1)–(3).

Nutrient use efficiency (PUE for P, NUE for N), i.e. the amount of nutrient used by plants in relation to the amount of nutrient in the fertilizer or sediment applied to the soil:

$$Nutrient\ use\ efficiency(\%) = \frac{Nutrient\ uptake\ by\ plants}{Amount\ of\ nutrient\ applied\ to\ soil} \quad x \quad 100 \tag{1}$$

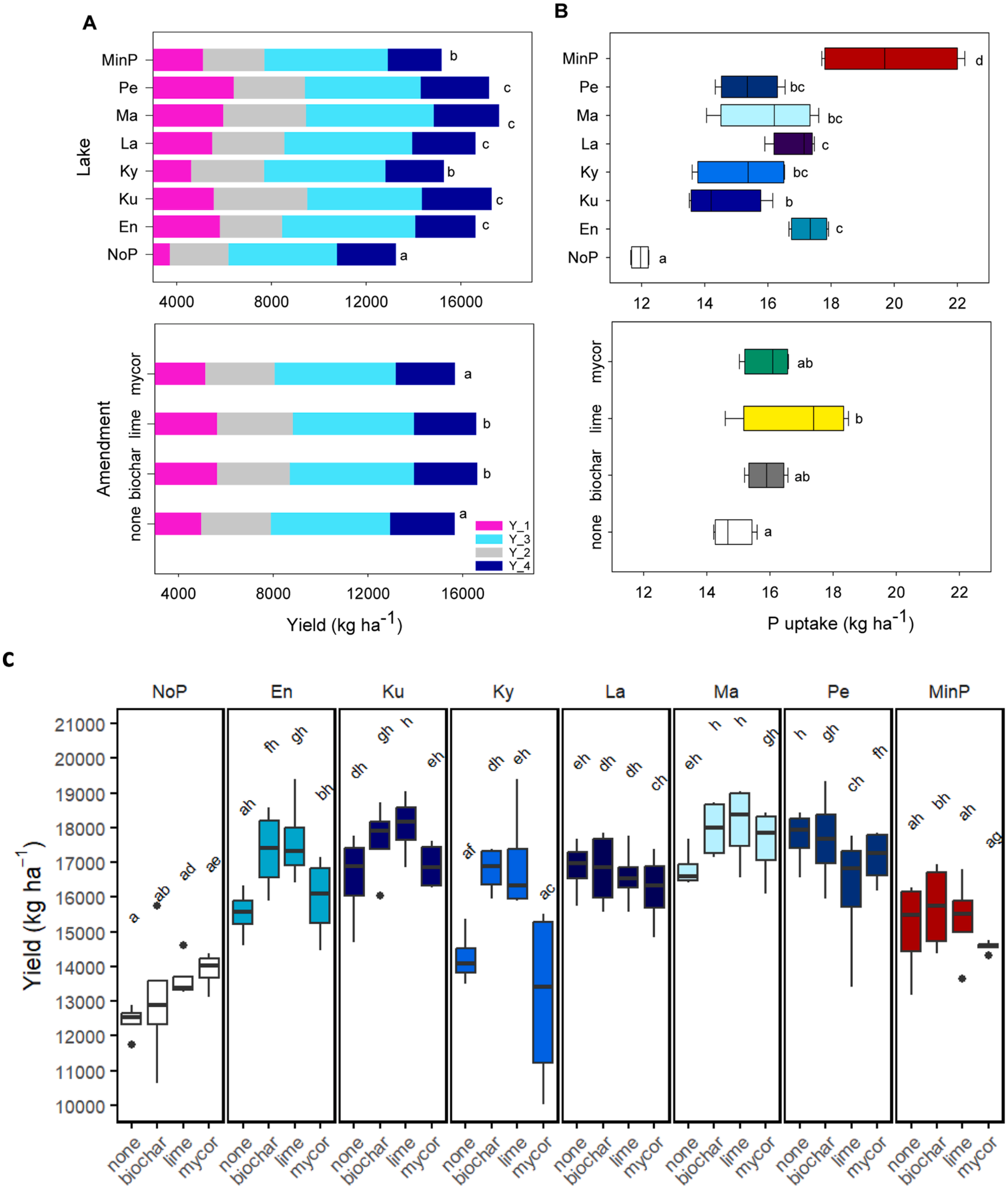


Fig. 1. Effect of sediments from eutrophic lakes and different soil amendments on (A) total yield (kg ha^{-1}) and (B) P uptakes (kg ha^{-1}) of ryegrass in the greenhouse experiment. The interaction of the factors was significant only for the yield (C). The line inside the box represents the median, the top and bottom of the box represent third (Q3) and first (Q1) quartiles respectively, top whisker is Q3 + 1.5 IQR and bottom whisker is Q1–1.5IQR.

Recovery efficiency of nutrient:

$$Nutrient\ recovery(\%) = \frac{Nutrient\ uptake(fertilized) - Nutrient\ uptake(unfertilized)}{Amount\ of\ nutrient\ applied\ to\ soil}\ x\ \ 100 \tag{2}$$

Finally, the mineral phosphorus replacement value (PFRV) was calculated as:

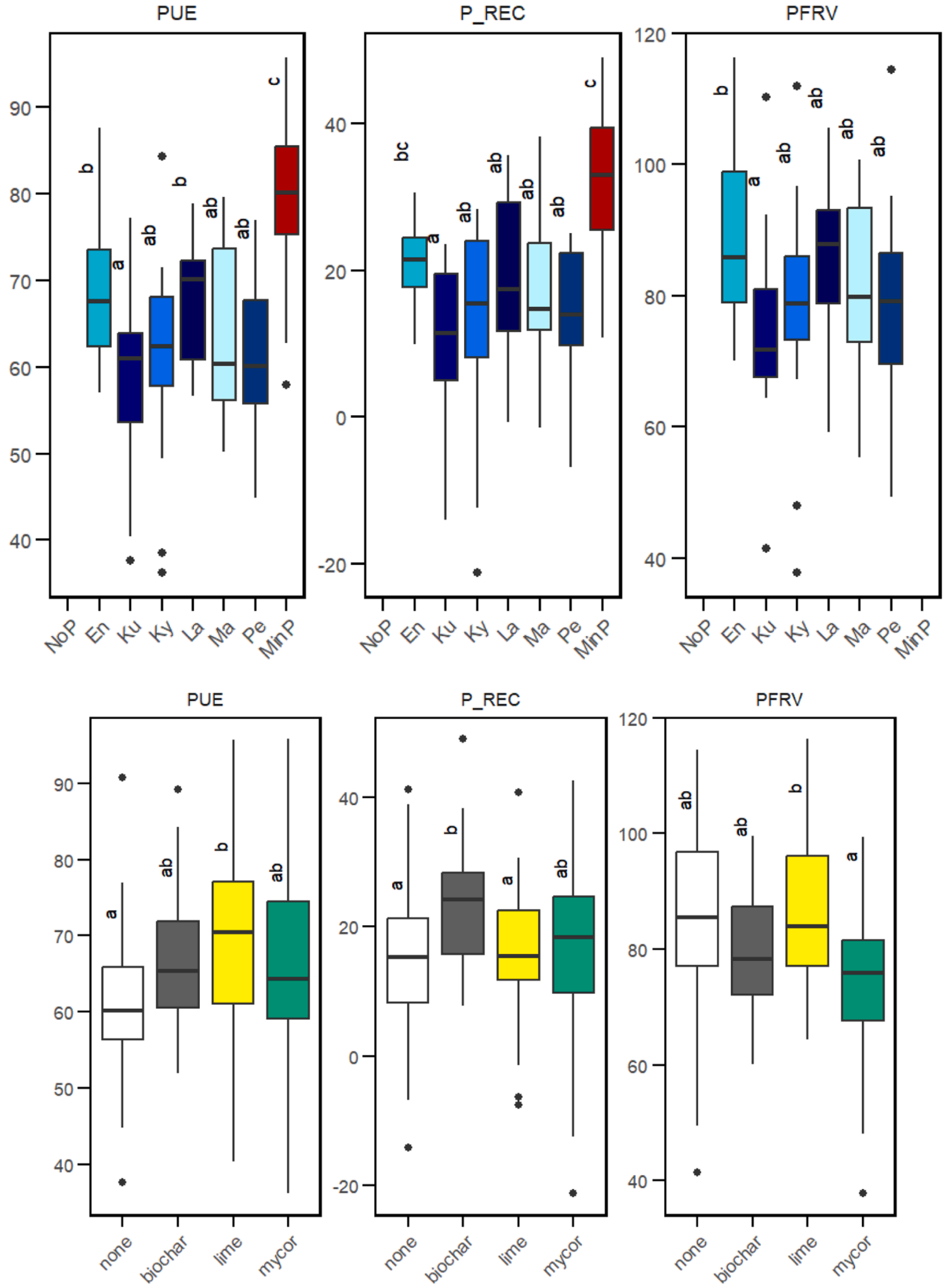


Fig. 2. P use efficiency, P recovery, and fertilizer recovery value in the sediment treatments and their amendments. The line inside the box represents the median, the top and bottom of the box represent third (Q3) and first (Q1) quartiles respectively, top whisker is Q3 + 1.5 IQR and bottom whisker is Q1–1.5IQR. Mean values followed by a different letter, are significantly different at $p < 0.05$. NoP: negative control; En: Enonselkä sediment; Ku: Kutajärvi sediment; Ky: Kymijärvi sediment; La: Lämmijärv sediment; Ma: Matjärvi sediment; Pe: Peipsi sediment; MinP: mineral P fertilizer (positive control); mycor: arbuscular mycorrhiza.

$$PFRV(\%) = \frac{PUE(alternative\ fertilizer)}{PUE(mineral\ fertilizer)} \quad x \quad 100 \tag{3}$$

The P balance for the growing media was calculated as the P input minus the P output (Xu et al., 2023):

$$\text{P balance (kg P ha}^{-1}) = \text{P input–P output} \tag{4}$$

where the P input is the amount of P applied in the fertilizer or sediment (kg P ha^{-1}) and P output is the removal of P in the harvested ryegrass, i.e. P uptake (kg P ha^{-1}). P that was applied to soil in the various amendments can be assumed to be negligible compared with the fertilizer P. P input as TP was variable; therefore, we also calculated the corresponding P application rate, and balance. The positive balance would suggest increased leaching potential.

2.5. Statistical analyses

Statistical analysis was performed using R v3.5.3 software. Using the Shapiro-Wilḱs test, normality of the data set was tested. The variables, including yields, P uptakes, plant nutrient contents were then analyzed by two-way ANOVA (P fertilizer and amendments as factors). One-way ANOVA was used to analyze growing media (fertility) and associated data (P balance). When a significant effect was detected in the ANOVA models ($p < 0.05$), Tukey HSD *post hoc* tests were run to compare the treatment means. Associations among different variables were studied with Pearson's correlation coefficients. When studying relations between sediment properties (including organic matter content) and yields (or plant P uptake), the mean values across sediment treatments were used (i.e., only non-amended treatments), because amendments caused variations masking the sediment effects.

3. Results and discussion

3.1. The effect of lake sediments on plant growth and P uptake

Both the cumulative dry-matter yields of biomass and the P uptake by crop in the sediment treatments (mean 16.8 t ha^{-1} and 15.9 kg P ha^{-1}) were significantly higher than in the negative control (13.3 t ha^{-1} and 12.0 kg P ha^{-1}, respectively). Average dry-matter yields varied from 15.3 t ha^{-1} in Kymijärvi sediment to 17.3 t ha^{-1} in Kutajärvi sediment (Fig. 1A). Moreover, the average yields in the Kutajärvi, Matjärvi and Peipsi treatments were significantly higher than in the positive control (mineral fertilizer, 15.2 t ha^{-1}). The biomass yields at the third harvest were the largest and contributed the most to the cumulative yields in all treatments. Average P uptakes in the sediment treatments varied from 14.5 kg P ha^{-1} in Kutajärvi to 17.3 kg P ha^{-1} in Enonselkä treatments, being lower than the average P uptake in the positive control (Fig. 1B). Variations in the P recovery and PFRV were similar to those of P uptake (Fig. 2), as indicated by significant positive correlation ($r = 0.852$, $p < 0.0001$, $n = 112$, and $r = 0.654$, $p < 0.0001$, $n = 96$, respectively). P recovery varied from 10 % to 21 % and PFRV varied from 75 % to 88 % in the different sediment treatments. P recovery in the mineral fertilizer treatment was 32 %.

The relatively high yields of ryegrass can be explained by the controlled growth conditions, where no stress was caused by temperature, light or moisture. In general, grass yields exceeding 16 t ha^{-1} have been reported in cutting and grazing trials under optimum environmental and soil fertility conditions (Jung et al., 1996), which is close also to the average values of silage in Finland in 2024 (14 t ha^{-1} as dry weight; LUKE, 2024). Kiani et al. (2021) reported yields of 18.1 t ha^{-1} for the grass growing on 75-cm thick sediment layer in the mesocosm study on day 131 of the experiment. Also, in our study, sediment additions improved the plant growth, as the average yields in the sediment treatments were 126 % of those in the negative control treatment without mineral P fertilizer. Moreover, the average yields in all sediment treatments were 110 % of the yields obtained with mineral P fertilizer. These findings suggest that sediments supply plants not only with P, but also with the other essential macro- and micronutrients, as reported also in the previous studies (Canet et al., 2003; Gmitrowicz-Iwan et al., 2023; Braga et al., 2024).

Larger input of TN than in negative and positive controls likely contributed to the increased yields in sediment treatments, as indicated by the significant positive correlation of yield with total nitrogen application rate (SM Fig. 3). We recorded the highest yields of ryegrass in Kutajärvi and Matjärvi treatments, which showed also the highest nitrogen use efficiency (NUE; SM Fig. 4). The affinity of ryegrass to nitrogen-rich conditions is well-established (Jung et al., 1996). Finally, the benefits of sediment application for the soil physical properties are widely reported (Canet et al., 2003; Kiani et al., 2023). Such benefits can be expected particularly if nutrient-poor sand is used as a growing media. In Matjärvi and Kutajärvi treatments, the proportion of sediment relative to the sand mass was the largest (2.9 % and 3.6 %, respectively, while the range for the rest of sediment treatments was from 1.1 % to 1.9 %), suggesting additional benefits to fertilization from sediment application.

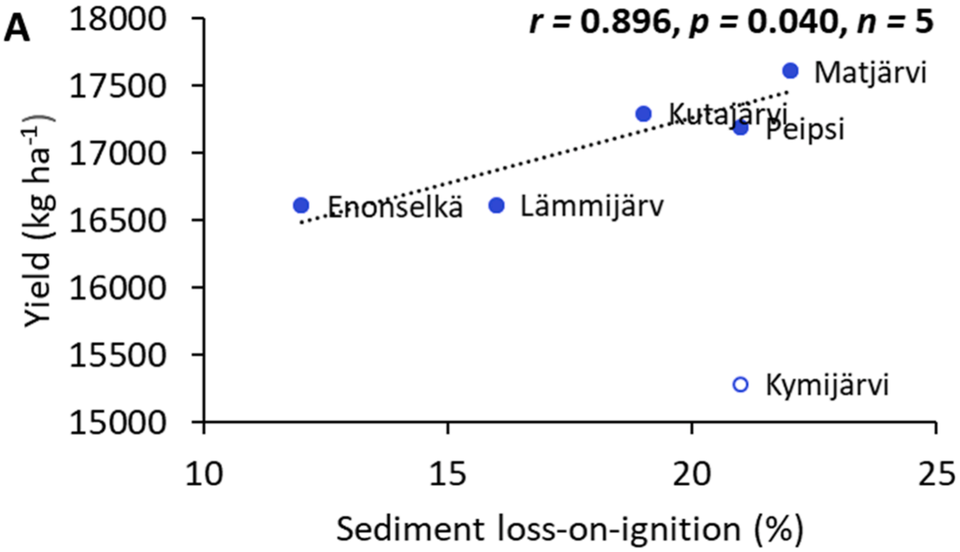
In the current study, the sediments were applied as P fertilizers, not as amendment materials, to reduce the potential negative environmental impacts (e.g., nutrient leaching). Further, the fertilizing ability of a given sediment was refined by adjusting its application rate according to the content of the Fe–P of the sediment, which was considered as the potentially bioavailable P form (Ruban et al., 1999). The magnitude of P uptake in the sediment treatments was on the average 133 % of that in the negative control treatment. Furthermore, the high values of both P recovery and PFRV indicated that the sediments functioned effectively as P fertilizers.

Similarly, Kiani et al. (2021) previously observed significant positive correlation between the P uptake by ryegrass and the Fe–P content of sediment in the mesocosm study. In addition, the Fe–P form was consumed and its contents in soil tended to decrease towards the end of long-term field experiment (Kiani et al., 2023). But more direct evidence about the effects of Fe–P to plant P uptake was provided recently by Haasler et al. (2024) who demonstrated Fe–P as an important contributor to the pool of bioavailable P for the crops, as the PUE in the treatment containing sediment was much higher compared with the treatment where Fe–P was removed. The PFRV in our study (average 81 %) was closest to that reported by Haasler et al. (2024); 67 %) for the treatment containing synthesized amorphous Fe–P.

Our results on the availability of Fe–P to plants suggest the occurrence of hypoxic (i.e. partially anoxic) conditions in the growing media. The bioavailability of Fe–P is redox dependent. In oxic conditions, P could co-precipitate or be strongly sorbed by ferric (hydr) oxides, reducing its availability for plants. In reduced environment, reductive dissolution of ferric iron to ferrous iron results in the release of associated P, making it plant available.

The redox potential of the growing media was not measured due to technical constrains. However, the hypoxic (partially anoxic) conditions are the most likely explanation for why P uptake was not correlated with the Fe/P mass ratio of sediments. In our study, the Fe/P mass ratio in all sediments was much higher than 15 that can be taken to indicate high P binding capacity of lake sediments in aerobic conditions (Jensen et al., 1992). Hence, our results support the view that hypoxic conditions contribute similarly to sediment Fe-P solubilization also in agroecosystems.

Hypoxic conditions in growing media are promoted by microbial decomposition of organic matter. In our study, yields positively correlated with the loss-on-ignition (LOI) of sediment ($r = 0.896$, $p = 0.04$, $n = 5$; Fig. 3A), when the lowest yield values in Kymijärvi



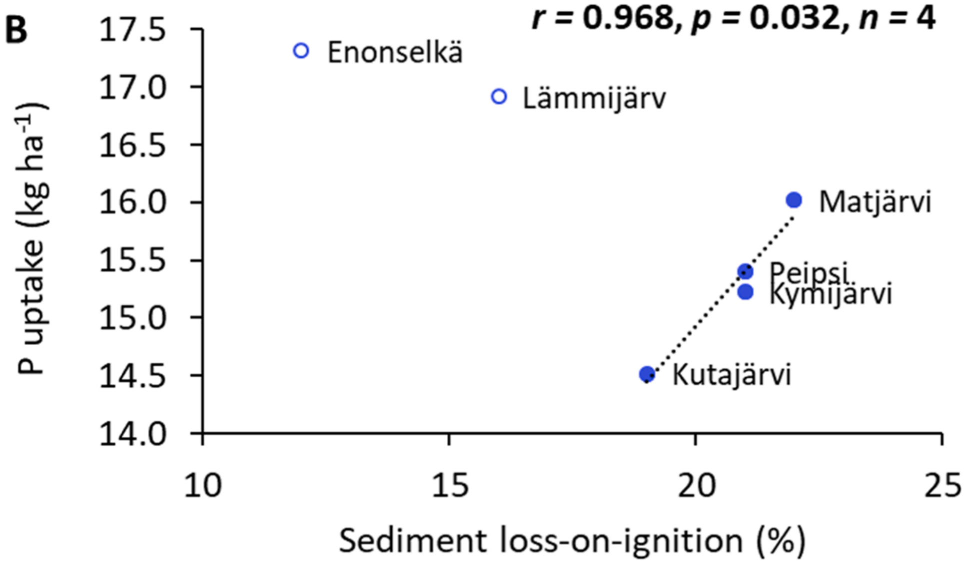


Fig. 3. Plant yield (A) and P uptake (B) as a function of sediment organic matter content (loss-on-ignition). Mean values of the plant yields and P uptake in the sediment treatments without any amendments were used in the plots.

treatment were excluded. Also, plant P uptake was correlated positively with LOI in the sediments having LOI > 16 % (Kymijärvi, Peipsi, Matjärvi and Kutajärvi; Fig. 3B), which suggests that organic matter was also a source of bioavailable P. In contrast, the yield-supporting role of organic matter decomposition in Kymijärvi is negligible, because Kymijärvi sediment was applied at very small amounts (29 t ha^{-1}) compared with sediments from other lakes. Moreover, the deviation of Enonselkä and Lämmijärv in the relationship between plant P uptake and LOI can be explained by the lowest content of Org–P in TP in these sediments (SM Table 2). In general, relatively low C/N ratios (about 10), such as those observed in the sediments in this experiment, suggest that mineralization of nutrients from the organic matter of sediments to plant available forms improve ryegrass growth (Gudasz et al., 2012). Also, the NUE values in most sediment treatments were higher than those in the mineral P fertilizer treatment, with the exception of Enonselkä treatment (SM Fig. 4).

3.2. *Effects of soil amendments on plant growth and P uptake*

Biomass yields were significantly higher in the treatments amended with lime and biochar (Fig. 1A), especially in Kymijärvi treatment (for biomass yield, the amendment × sediment interaction was significant at $p = 0.027$; Fig. 1C). The pH in lime-treated growing media (7.4) was significantly higher than in other amendments and corresponded to the “very high” fertility class (Table 1). Moreover, lime addition improved P uptake by plants, as the P uptake in lime treatment was significantly higher than in the treatment with no amendment. This is expected as pH is known to increase P desorption from Al and Fe (hydr)oxide surfaces to soil solution. However, no such effect was apparent for biochar, likely to typically negligible liming efficacy of wood biochars (Tammeorg, 2014).

At the end of experiment, comparison of the P fractions in the growing media with and without addition of Kymijärvi sediment indicated significant changes in the Org–P pool by amendments (Fig. 4). Both lime and biochar increased the Org–P pool, perhaps through an increase in the microbial activity, in a similar manner as reported in Kalu et al. (2024). Hence, the findings from Kymijärvi treatment suggest that addition of biochar and lime along with the applications of sediments from the lake improves plant growth, although the exact underlying mechanisms still warrant for more research.

Table 1

Chemical properties of the growing media in the 2021 greenhouse experiment. Data represent means of four replicates across eight growing medium treatments and means of eight replicates across four soil amendments. Mean values within each factor, followed by a different letter, are significantly different at $p < 0.05$.

Treatment	**EC**	**pH**	**Acid ammonium acetate extractable (g m^{-3} soil)**									
	dS m^{-1}		**P**	**K**	**S**	**Ca**	**Mg**	**Na**	**B**	**Cu**	**Mn**	**Zn**
Growing medium												
NoP	1.58 a	6.58 bc	4.42 b	22.4 ab	37 a	879 a	73 a	38 ab	0.201 a	1.24 a	1.71 a	0.915 a
E	2.39 ab	6.14 abc	4.86 bc	32.8 ab	66.6 cd	1178 a	95.7 ab	47.8 bc	0.236 ab	2.51 ab	8.89 ab	2.63 ab
Ku	3.4 abc	6.06 ab	2.43 a	48.7 bc	79.8 b-e	1395 a	123 bc	55.1 cd	0.346 bc	3.86 bc	12.8 ab	40.8 d
Ky	2.61 ab	5.91 ab	4.66 bc	36.7 ab	94 abc	986 a	78.2 ab	43.6 ab	0.24 ab	2.89 ab	10.1 b	7.47 bc
La	3.01 abc	7.15 c	6.04 cd	16 a	53.3 bc	1622 a	153 cd	47.7 bc	0.478 cd	2.56 ab	8.29 b	17.7 c
Ma	5.54 c	5.47 a	2.73 a	67.7 c	289 e	1148 a	106 abc	65.5 d	0.379 bc	5.88 c	26.8 ab	85.9 d
Pe	4.33 bc	6.91 bc	5.64 bcd	19.4 a	84.9 de	1443 a	195 d	47.6 bc	0.541 d	2.42 ab	8.92 b	15.8 c
MinP	2.43 ab	6.18 abc	6.47 d	21.7 ab	41.8 ab	852 a	64.8 a	35.2 a	0.189 a	1.61 ab	7.03 ab	1.78 a
Soil												
none	2.91 ab	5.97 a	4.31 a	40.6 b	126 a	485 a	64.7 a	44.4 a	0.243 a	2.93 a	11.4 a	25.8 a
biochar	1.98 a	6.29 a	4.09 a	30.9 ab	67.2 a	528 a	62 a	54.1 a	0.463 b	2.82 a	9.8 a	23.8 a
lime	3.36 ab	7.4 b	5.58 a	15.7 a	86 a	3274 b	249 b	48.2 a	0.309 ab	2.81 a	4.83 a	16 a
mycor	4.4 b	5.53 a	4.64 a	45.5 b	94.1 a	465 a	68.1 a	43.7 a	0.29 ab	2.92 a	16.3 a	20.9 a
Fertility												
very high		> 7.0	> 50	> 500	> 150	> 4000	–	–	> 2	> 20	> 1000	> 50
high		6.6– 7.0	33 –50	350 – 500	50 –150	2600 –	> 400	–	1.3 – 2.0	10 – 20	250–1000	20 – 50
good		6.2 – 6.6	20 –33	200 – 350	15 – 50	2000 –	200 –	60 >	0.9 – 1.3	5 – 10	75 – 250	6 – 20
satisfactory		5.8 – 6.2	12 –20	120 – 200	10 – 15	1400 –	120 –	45 – 60	0.6 – 0.9	2.7 – 5	25 – 75	2 – 6
passable		5.4 – 5.8	6 – 12	70 – 120	6 – 10	800 –	80 – 120	30 – 60	0.4 – 0.6	1.5 – 2.7	12 – 25	1.5 – 2
poor		5.0 – 5.4	3 – 6	40 – 70	3 – 6	400 –	50 – 80	15 – 30	0.2 – 0.4	1.0 – 1.5	6 – 12	1.0 – 1.5
very poor		< 5.0	< 3	< 40	< 3	< 400	< 50	< 15	< 0.2	< 1.0	< 6	< 1.0

Samples were collected at the end of the growing seasons. NoP: negative control; En: Enonselkä sediment; Ku: Kutajärvi sediment; Ky: Kymijärvi sediment; La: Lämmijärv sediment; Ma: Matjärvi sediment; Pe: Peipsi sediment; MinP: mineral P fertilizer (positive control); mycor: arbuscular mycorrhiza

[1] The Finnish classification for coarse mineral soils (Viljavuuspalvelu Oy, 2000).

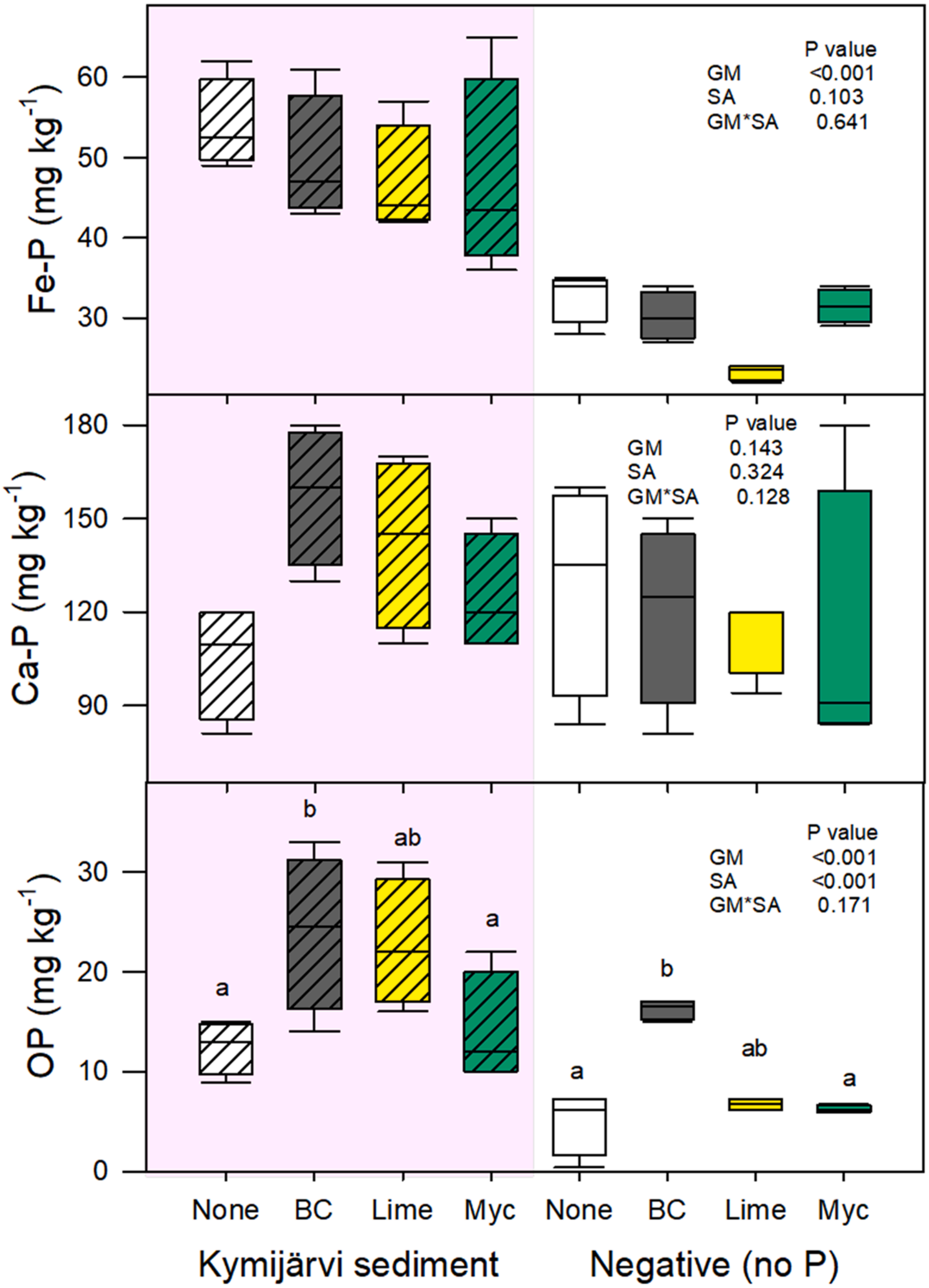


Fig. 4. Effect of different soil amendments (SA) on different P fractions (iron-bound P, Fe–P, calcium-bound P, Ca–P, and organic P, OP) in Kymijärvi sediment and negative (no P) treatment in the greenhouse experiment in 2022. The line inside the box represents the median, the top and bottom of the box represent third (Q3) and first (Q1) quartiles respectively, top whisker is Q3 + 1.5 IQR and bottom whisker is Q1–1.5IQR. Mean values followed by a different letter, are significantly different at $p < 0.05$. GM: growing medium. In this ANOVA analysis, GM includes only the difference between Kymijärvi sediment and the negative control treatment.

3.3. P balance in amended and non-amended sediment treatments and the potential for leaching

The positive P balance in the sediment treatments, with an average at 9.4 kg P ha^{-1}, indicates that the added amounts of P exceeded plant P uptake, and consequently increased the leaching potential of P. Moreover, the leaching potential of P was likely further increased by the accumulation of total P in the growing media of sediment treatments compared to the unfertilized negative control at the end of the experiment.

We applied 25 kg P ha^{-1} as Fe–P (considered bioavailable P) in the sediments. However, it contained 45–66 kg ha^{-1} of TP. The amount of P remaining in the growing media at the end of experiment was positively correlated with the amount of TP applied as sediments ($r = 0.626$, $p < 0.001$, $n = 28$; SM Fig. 5). The low contents of acid ammonium acetate extractable P in the growing media at the end of experiment (Table 1) suggests that the biggest share of P remaining in the growing media at the end of experiment was associated with the recalcitrant P forms, such as Ca–P and partially also Org–P. According to the soil fertility classification of Viljavuuspalvelu Oy (2000), such values of bioavailable P in coarse mineral soils characterize the fertility of growing media varying in a sediment-dependent way from "very poor" to "passable".

Moreover, the concentration of total phosphorus in the growing media correlated negatively with the concentration of bioavailable P at the end of experiment ($r = -0.534$, $p = 0.002$, $n = 31$, not shown). Hence, most of the bioavailable P was either taken up by plants or leached by the end of experiment. In lack of direct leaching measurements, we cannot assess the extent to which leaching may have occurred, but leaching would not be unexpected in a sandy growing media and experimental pots allowing free drainage of excess water. In general, this is further supported by: 1) positive P balance; 2) the fact that no differences were observed in the electrical conductivity of growing media at the end of experiment between the treatments (Table 1). Only Matjärvi sediment treatment with the highest value of the P balance (49 kg ha^{-1} at the highest TP application rate of 66 kg ha^{-1}) had also the highest electrical conductivity value, suggesting notable accumulation and increased leaching potential of P in the growing media.

3.4. *Effects of sediments and amendments on the availability of the elements other than P*

In general, the plant uptake rates of almost all studied elements (including B, Ca, Fe, Cu, K, Sr, Ni, Zn, S, Mg, Mn) in the sediment treatments were higher than in the negative control (Table 2). The concentrations of elements in plant biomass (SM Table 4) varied similarly to the uptake of elements by plants ($r > 0.780$, $p < 0.0001$, $n = 128$). The positive control displayed elevated uptake of Na and Sr, but also the uptake rates of elements including B, Ca, Fe, K, Mg, Mn and S were higher than in the negative control, while still in the range of those in other sediment treatments. In Kutajärvi sediment treatment, the uptake of Al was higher than in other sediments. Matjärvi sediment treatment showed the highest uptake of Zn, Sr, Co and S by plants. Also, the Zn and S content in the growing media at the end of experiment was still very high (Table 1). In addition, Matjärvi and Kutajärvi sediment treatments had the highest plant uptake of Fe and K. The highest uptake of Ni was observed in Matjärvi and Enonselkä sediment treatment. Application of sediments from the basins of Estonian Lake Peipsi, Peipsi and Lämmijärv resulted in the highest uptake of Mg (Peipsi) and Ca (Lämmijärv).

The varied geochemistry of sediments likely contributed to the differences in the elemental uptake by plant in the different treatments, such as clearly higher Ca, Mg concentrations in Estonian lakes than in Finnish lakes. Nevertheless, the variations in the elemental composition of Finnish lakes were notable as well, even if they were all located in the Vesijärvi watershed. Some elements (Co, Ni, Sr, Zn) can indicate human impacts rather than natural variations. Particularly high concentrations of such elements in Matjärvi can be explained partially by the high share of agricultural land in the catchment area.

If the sediment were already rich in some microelements (e.g. Zn), the application of additional fertilizer would not be desired, as overdosing of micronutrients can be harmful for plants and cause toxicity. The Zn contents in all sediments, particularly in Kymijärvi, Kutajärvi and Matjärvi, were high, exceeding the Finnish legislative threshold of 200 mg kg^{-1} for contaminated soil (Ministry of the Environment - MEF, Finland, 2007), indicating need for further analysis. The Zn uptake by plants was the highest in Matjärvi sediment treatment, being about 10 times higher than the lowest Zn uptake in Enonselkä sediment. The Zn content in the plant biomass fertilized with Matjärvi sediment was way above the maximum allowed content in feed for various domestic animal species in European Union (150 mg kg^{-1}; EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP), 2014).

Lime amendment was associated with increased plant uptake of Al, Ca and K. On the other hand, lime decreased the uptake of Zn and Mn by plants (Table 2). Biochar reduced the availability of B, Na, Zn, while increased the uptake of Ca, K and S. On the average, arbuscular mycorrhiza only increased the plant uptake of S, but did not affect the other elements. The notable effects of biochar, and especially that of lime, on the uptake of Zn were observed clearly in the sediments of Matjärvi and other Finnish lakes (SM Table 5). The Zn concentration in the plant biomass in Matjärvi sediment with no amendment was on the average 433 mg kg^{-1}, while it was significantly lower in the lime (120 mg kg^{-1}) and biochar (307 mg kg^{-1}) amendments. Hence, our results indicated a high potential of biochar and especially lime for the mitigation of metal toxicity risks, due to low solubility of Zn, Cu, Fe, Mn at high pH values (Riaz et al., 2020). Matjärvi was the only treatment, where sediment application to sand (negative control) lowered pH significantly (Table 1). Thus, also the benefits of lime amendments increasing the pH were especially evident.

Lime increased the Ca content in growing media, and Ca precipitation could bind part of potentially available for P to unavailable forms. However, this was not a concern, as lime generally improved P uptake by plants in overall. Moreover, lime improved the uptake of K by plants, and we can assume there were no inhibiting effects of increased Ca based on the reports about lime applications on acidic soils, similar to our study (Otieno et al., 2018). Han et al. (2019) observed significant increase in plant K uptake under lime application, with a simultaneous decrease in the soil exchangeable Al. Unexpectedly, lime addition slightly improved the availability of Al in our study without any obvious reason. Still, this did not inhibit plant K uptake, and Al concentrations in the plant tissues were far below the lower limit of values considered dangerous for livestock health (500–8000 mg kg^{-1}; Bahamonde et al., 2016). Plant K uptake in the biochar treatments was higher than in non-amended soil and not significantly different from that in the lime treatment, which indicated that K availability was improved by biochar. Wood-derived biochars typically increase the uptake of K as they increase soil K availability and are also sources of K themselves (Kalu et al., 2021; Kiani et al., 2023). Hence, the use of both biochar and lime is recommended in the sediment applications. When sediment elements are applied at generally recommended rates, there are no toxicity risks for the environment.

The effects of mycorrhiza amendment were evident only for the S uptake that was significantly higher compared with the non-

Table 2

Average elemental uptake in plants from four cuts of ryegrass in the greenhouse experiment. Data represent means of four replicates across eight growing medium (GM) treatments and four soil amendments (SA). Mean values within each factor, followed by a different letter, are significantly different at $p < 0.05$ (Tukey HSD). The interactions for Ca and Zn uptake are presented in SM Table 5.

Treatment	K	S	Ca	Mg	Na	Al	B	Cd	Co	Cr	Cu	Fe	Mn	Ni	Sr	Zn
	kg DW ha^{-1}					g DW ha^{-1}										
Growing medium (GM)																
NoP	284 a	27.1 a	70.9 a	29.4 a	8.9 ab	204 a	238 a	1.06	2.36 ab	4.79 a	67.9 a	557 a	3475 a	11.3 a	256 a	307 a
En	336 bc	40.4 bc	83.9 bc	39.6 cd	11.9 abc	206 a	275 ab	1.46	4 b	5.32 a	86.1 bc	753 b	5784c	26.2 de	315c	583 b
Ku	502 d	43.9c	78.2 ab	31.5 ab	8.4 a	314 b	292 b	1.51	3.43 ab	9.42 b	97.8c	972c	3991 ab	13.2 ab	303 bc	1963 d
Ky	323 bc	39.4 bc	86.7 bcd	36.1 bc	15.4 cd	199 a	275 ab	1.19	6.49c	4.68 a	90.2 bc	741 b	5758c	21.2 cd	308 bc	1731 d
La	349c	41.1c	108.1 f	42.2 de	13.5 cd	190 a	290 b	1.00	2.63 ab	4.96 a	86.5 bc	713 b	5054 bc	15.2 abc	268 ab	786 c
Ma	445 d	58.8 d	92.6cde	38.3 cd	12.4 bcd	229 a	284 ab	1.51	14.83 d	4.46 a	101.4c	1344c	4989 bc	32.9 e	371 d	5604 e
Pe	351c	43.2c	99.1 e	48.4 e	13 cd	193 a	301 b	0.91	2.04 a	5.14 a	92.2 bc	738 b	5481c	19.2 bcd	249 a	873c
MinP	300 ab	34.6 b	95 de	39.9 cd	16 d	218 a	295 b	1.05	3.32 b	6.83 ab	76.2 ab	698 b	4671 bc	15.5 bc	383 d	400 a
Soil amendment (SA)																
none	338 a	38.5 a	82.4 a	38.5 ab	13.6 b	210 a	299 b	1.45 b	6.23c	4.93 ab	85.5 a	923 a	5201 b	19.4 ab	314 b	1903c
biochar	374 b	42.3 b	89.3 b	36.1 a	9.8 a	182 a	244 a	1.72 ab	4.83 b	8.56c	89.3 a	804 a	5005 b	20.8 b	322 b	1523 b
lime	389 b	40.5 ab	102.3c	41.9 b	13.5 b	266 b	301 b	0.89 a	2.02 a	6.01 b	90.5 a	778 a	4030 a	15.3 a	282 a	793 a
mycor	345 a	42.9 b	83.2 a	36.2 a	12.8 b	220 a	282 b	0.79 a	6.47c	3.29 a	83.8 a	752 a	5365 b	21.9 b	308 b	1904c
P values																
GM	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.009	0.101	< 0.001	0.0002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
SA	< 0.001	0.008	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.009	< 0.001	< 0.001	0.254	0.424	< 0.001	< 0.001	< 0.001	< 0.001
GM * SA	0.253	0.157	0.009	0.104	0.969	0.991	0.904	0.435	0.990	0.894	0.726	0.903	0.960	0.990	0.077	< 0.001

NoP: negative control; En: Enonselkä sediment; Ku: Kutajärvi sediment; Ky: Kymijärvi sediment; La: Lämmijärv sediment; Ma: Matjärvi sediment; Pe: Peipsi sediment; MinP: mineral P fertilizer (positive control); mycor: arbuscular mycorrhiza.

amended treatments. Moreover, S uptake in the mycorrhiza treatment was similar to that in the biochar treatment. The positive effects of arbuscular mycorrhizal fungi on S uptake by plants are acknowledged and attributed to the increased percentage of root colonization and the magnitude of sulfonate mobilizing bacterial community (Gahan and Schmalenberger, 2014). Presumably, larger effects in terms of plant yields, P uptake and microelements would be achieved with the mycorrhiza application close to the seeds (or by coating seeds), but this would require confirmation by further studies including root colonisation data.

4. Conclusions

The six-month greenhouse experiment with the ryegrass grown in growing media comprised of unfertilized and fertilized sand, or sand added with six different lake sediments, has provided multiple novel insights on the lake sediment application in agriculture. All six sediments had a positive P fertilization effect, as plant P uptake increased. Also, plant biomass yields in the sediment treatments were higher than in the unfertilized and in most cases higher than in the mineral P fertilized controls. We evidenced that besides P, the sediments supply plants also with other essential macro- and micronutrients. As the amount of added Fe–P in the sediment applications was kept the same, the variations in the effect of different sediments on P availability for crops were explained by the amounts of organic matter or organic P. In general, liming and biochar amendments are promising for increasing the P uptake and use efficiency by plants. Further benefits of these amendments arise from the improved availability of macro- and micronutrients, but also from the reduced availability of any sediment contaminants (such as Zn) for plants. Still, each sediment has to be tested before application for the potential negative environmental risks. Based on the results of experiment, lake restoration by sediment removal may provide a useful tool for tackling important global and local challenges, including scarcity of P rock and environmental pollution associated with unsustainable use of P rock.

CRediT authorship contribution statement

Asko Simojoki: Writing – review & editing, Validation, Investigation, Formal analysis. **Sharifeh Nabavi:** Writing – review & editing, Data curation. **Priit Tammeorg:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Subin Kalu:** Writing – review & editing, Validation, Data curation. **Mina Kiani:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Olga Tammeorg:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2025.104638.

Data availability

Data will be made available on request.

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