Phosphorus in agricultural constructed wetland sediment is sparingly plant-available

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Abstract

Agricultural constructed wetlands (CWs) are intended to retain sediment and phosphorus (P) carried off with runoff and drainage water. The accumulated sediment, with sorbed P, is often advised to be recycled to agricultural land, but little is known about the fertiliser value of sediment-associated P. This study examined the effects on P sorption characteristics and P plant availability of mixing CW sediment into soil. Despite the total P content in the sediment was approximately equal and the NaOH-extractable P content was higher to those in catchment soil, in adsorption-desorption tests sediment P solubility decreased and affinity for P increased with increasing addition rate of CW sediment to soil. Already the lowest sediment addition rate (12.5% of dry weight) decreased the equilibrium P concentration (EPC_0') by 60% on average compared with unamended catchment soil. In a greenhouse pot experiment, ryegrass yield was largely unaffected by CW sediment application, but P uptake systematically decreased when the rate of sediment application to soil increased. When 12.5% dry weight of sediment was added, plant P uptake decreased by 6-50% in P-unfertilised pots and by 6-17% in P-fertilised pots (150 mg P kg^{-1}) compared with P uptake of ryegrass grown in unamended field soil. Our other results obtained suggested that the plant availability of P in CW sediments is very low due to high clay content and high concentrations of aluminium (Al) and iron (Fe) (hydr)oxides in the sediment. Thus if applied to agricultural fields in large quantities, dredged CW sediment may impair crop P supply.

1. Introduction

Constructed wetlands (CWs) have received much attention recently as a measure to intercept the load of suspended matter and nutrients from agricultural soils to watercourses. Efficiently working CWs can collect a large amount of particulate matter through sedimentation. In one example in Sweden, rapid sediment accumulation of 22 kg m^{-2} $year^{-1}$ has been recorded at the inlet of an agricultural CW (2.1 ha; CW area 2% of catchment area) that received waters from a catchment dominated by clay soils (*Johannesson* et al., 2011). An even higher sedimentation rate of 40-90 kg m^{-2} $year^{-1}$ has been reported by *Braskerud* et al. (2000) for small Norwegian wetlands (0.03-0.09 ha; CW area 0.03-0.06% of catchment area) receiving high loads of suspended particles. Settling of sediment matter near the inlet is a retention mechanism that requires continuous management to maintain the retention capacity.

In terms of maintenance work on CWs, accumulated sediment must be dredged out every few years to make space for further sedimentation and to prevent accumulated sediment from escaping downstream. Dredged sediment is often advised to be applied to surrounding fields, thereby recycling the sediment matter back to agriculture (*Harrington* and *McInnes*, 2009). Some studies, however, show strong P retention by CW sediment (*Zhang* et al., 2002; *Laakso* et al., 2017), suggesting a low value of sediment P for plant P supply. To our knowledge, no previous study has performed direct measurements of sediment P availability to terrestrial plants.

Sedimentation is thus the main mechanism for P removal from waters by CWs, but subsequent losses of dissolved P may follow as a result of changes in chemical equilibrium at the sediment-water interface and redox reactions (see *Liikanen* et al., 2004; *Tanner* et al., 2005; *Palmer-Felgate* et al., 2011). Desorption of P from CW sediment occurs if the dissolved P concentration in water drops below the previously established equilibrium P concentration (i.e. EPC_0) of aluminium (Al) and iron (Fe) (hydr)oxide surfaces (*Taylor* and *Kunishi*, 1971). Moreover, periods of anoxia can trigger sudden release of dissolved P, e.g. *Palmer-Felgate* et al. (2011) reported concentrations of up to 29.5 mg P L^{-1} in anoxic CW sediment pore water (although dissolved P concentration in overlying water remained an order of magnitude lower). If sulphate is present under reducing conditions, it can disrupt sediment Fe cycling by precipitation of sparingly soluble Fe(II) sulphide compounds that do not act as a major P sink (e.g. *Kleeberg,* 1997; *Lehtoranta* et al., 2015).

The above-mentioned changes in the sediment environment most likely cause re-distribution of P among the sorption components. In non-calcareous soils, fertiliser P surpluses accumulate as Al and Fe (hydr)oxide-bound fractions (e.g. *Kaila,* 1964; *Peltovuori* et al., 2002), and especially Al (hydr)oxides primarily control the P concentration in soil solution (*Hartikainen*, 1982). These same metal oxides also control the efficiency of sediments in retaining dissolved P (*Hartikainen*, 1979; *Olila* and *Reddy*, 1997; *Liikanen* et al., 2004). In a previous P fractionation study (*Laakso* et al., 2016), we showed that, compared with the parent soil, CW sediment was depleted in Al-bound P (NH_4F-extractable P) but enriched in Fe-associated P (NaOH-extractable P). Total P concentration of sediment did not differ from that in parent soil but clay-sized matter was enriched in sediment, which after drying also had higher reactive metal oxide content than parent soil. As a result, sediment P could be expected to be less plant-available than P in parent soil.

The objective of the present study was to examine P sorption-desorption characteristics and directly determine P availability to Italian ryegrass (*Lolium multiflorum* L.) when CW sediment is mixed with soil in different ratios. The sorption-desorption properties of the soil-sediment mixtures were evaluated by simple sorption tests that indicated how equilibrium P concentration (EPC_0’) of the soil was affected by sediment addition. Plant availability of P was tested in a 70-

day greenhouse pot experiment. The hypotheses tested were that (i) addition of CW sediment to soil increases P retention and decreases P solubility in the soil and (ii) CW sediment is depleted in plant-available P fractions and thus has limited value for plant P supply.

2. Materials and methods

2.1 Soil and sediment samples

Constructed wetlands at two agricultural sites in SW Finland, Ojainen and Liedonperä, were chosen for the study. These CWs were established in 2000 and 1995, respectively, in fine-textured mineral soils classified as Vertic Stagnosols (*IUSS Working Group WRB*, 2014). At the Ojainen site, the area of the CW is 370 m^2, comprising 0.23% of an upstream catchment area that consists of 100% agricultural land. At the Liedonperä site, the CW area is 4850 m^2 and it comprises 0.5% of a catchment with 50% agricultural land. The dominant soil texture in the Ojainen catchment is silty clay, while in the Liedonperä catchment it is silty clay loam. The agricultural land in both catchments is used for growing cereals and has a subsurface drainage system. The catchment area above the Ojainen CW is under a no-till cropping system, whereas a conventional crop rotation with autumn ploughing to about 20 cm depth is applied at Liedonperä.

The soils and the corresponding CW sediments were sampled in August 2012, followed by chemical analyses and laboratory testing during the following autumn and winter, and a greenhouse growth experiment in May-June 2013. Composite soil samples were taken from the fields surrounding both CWs on three transects that were set by eye to represent field areas from which most CW sediment would probably originate. The samples representing each transect consisted of three subsamples taken with a spade from the Ap horizon (0-20 cm depth) approximately every 30 m from the CW diagonally to the main slope.

The sediment samples were collected from open water areas with a water depth of about 1-1.5 m. The depth of the sediment profile sampled was 10 cm. Redox potential (Eh) of the fresh sediment was measured immediately after sampling, using a handheld Scientific Instruments IQ170 pH/Eh meter, and was found to be -21 mV and 5 mV at Ojainen and Liedonperä, respectively. All samples were stored at sampling moisture content at +5 °C in darkness.

2.2 Soil and sediment analyses

Measured properties of the soils and sediments are given in Table 1. Soil and sediment texture was determined by a pipette method (*Elonen*, 1971) and total carbon (C) was analysed with a LECO CN-analyser (TruSpec, Leco Corporation, St. Joseph, MI, USA). Soil test P (STP) concentration was determined by molybdate blue colorimetry after ammonium acetate (P_{Ac}, pH 4.65) extraction at a 1:10 soil-to-solution ratio for 1 hour (*Vuorinen* and *Mäkitie*, 1955). The results are expressed on the volumetric basis, i.e. mg P L^{-1} soil. Poorly ordered (hydr)oxides of Al (Al_{ox}) and Fe (Fe_{ox}) were analysed in fresh samples using the ammonium oxalate extraction method of *Schwertmann* (1964) followed by ICP-OES determination (Thermo Scientific iCAP 6300 Duo MFC, Waltham, USA). For more detailed descriptions of the soils and sediments, see *Laakso* et al. (2016).

((Table 1))

2.3 Incubation experiment

The Ojainen and Liedonperä soils were incubated with increasing amounts of their respective CW sediment (0% (control), 12.5%, 25%, 50% and 100% of sediment on a dry weight (d.w.)

basis), with triplicate samples of all mixtures. The mixtures (comprising in total 10 g dry matter) were set at 35% moisture content and kept at +21 °C for four weeks. On two occasions per week, the moisture content was checked and re-adjusted as necessary and the samples were stirred lightly.

After the 4-week incubation, 1 g (dry matter) subsamples were extracted with deionised water (P_w) and with a standard P solution containing 2 mg P L^{-1} at a soil-to-solution ratio of 1:60 (w:v) for 16 h. Following extraction, the suspensions were centrifuged and filtered through a 0.2-µm Nuclepore filter (Whatman, Maidstone, UK) and analysed for P according to *Murphy* and *Riley* (1962), with a Lachat (Milwaukee, WI) QC Autoanalyser. The amount of desorbed or adsorbed P (Q) was calculated as the difference between the initial concentration (I_0) and the equilibration concentration (I), multiplied by the solution-to-soil ratio (R):

$$Q = (I_0 - I) \times R \qquad (1)$$

The parameters Q and I were fitted to a linear equation:

$$Q = mI + b \qquad (2)$$

where *m* is slope and *b* is y-axis intercept, and an estimate for the equilibrium P concentration (EPC_0; the x-axis intercept) was derived. This simple two-point P adsorption test does not give accurate estimates of EPC_0 traditionally derived from multi-point Q/I-plots or the slope at the x-axis intercept, but indicates the P affinity of the soil-sediment mixtures and the direction of EPC_0 change.

To assess the amount of P bound to Al and Fe (hydr)oxides in the incubated samples, NaOH-extractable P was determined (as in the method of *Chang* and *Jackson*, 1957; *Olsen* and *Sommers*, 1982). In brief, the samples were extracted, using a soil-to-solution ratio of 1:50, with

0.1 M NaOH (for 16 h). The suspension was centrifuged (15 min, 3846 ×g) and dissolved humus was removed by precipitation with 0.5 M H_2SO_4 (*Hartikainen*, 1979).

For total P analysis, the soil and sediment samples were extracted in duplicate with the H_2SO_4-H_2O_2-HF method of *Bowman* (1988). The P concentrations of supernatants from extractions of total P and NaOH-P as well, were analysed by the method of *Murphy* and *Riley* (1962) using a spectrophotometer (Shimadzu UV-120-02, Kyoto, Japan).

2.4 Greenhouse experiment

2.4.1 Preliminary test

Field soil (Ap horizon) and sediment (0-10 cm) from the Liedonperä site were used as growth medium for Italian ryegrass (*Lolium multiflorum* L.) in a preliminary test, the purpose of which was to obtain information about the P supplying properties of the sediment. In the experiment, 100 g soil or 100 g sediment mixed with 200 g of quartz sand was used as the growing media in 500-mL pots for two cuts of ryegrass. Phosphorus (as KH_2PO_4) was applied to both mixtures at a rate of 90 mg kg^{-1}. Other nutrients were supplied in amounts that would not restrict plant growth (see the main experiment below). For the second cut, a supplementary dose of 270 mg P kg^{-1} (as $Ca(H_2PO_4)_2$), 100 mg N kg^{-1} (as NH_4NO_3) and 50 mg potassium (K) kg^{-1} (as KCl) was supplied.

2.4.2 Main growth experiment

For the main greenhouse experiment, the growth medium was composed of soil and sediment mixtures, in order to investigate how increasing sediment addition affected plant P uptake. The two soils and corresponding CW sediments were sieved (4 mm) moist, the moisture contents of all samples were determined and the growth medium was prepared on a dry weight basis.

Sediment addition rates to soil of 0% (control), 12.5%, 25% and 50% were tested. Total mass of each mixture was 100 g dry matter and triplicate samples were prepared for each mixture. The mixtures were allowed to equilibrate at +21 °C in the laboratory for five days at a moisture content of 35% (adjusted with deionised water).

Because the high clay content of the sediment could have resulted in an overly dense growth media at higher inclusion rates, causing adverse effects on aeration of the medium, 200 g of quartz sand (0.5-1.0 mm) rinsed with deionised water was applied to each mixture. Around two-thirds of each prepared growth medium was placed in a 500-mL pot and nutrient solutions were pipetted and mixed in. The remaining one-third of medium was then added, Italian ryegrass (*Lolium multiflorum* L.) seeds (0.35 g pot^{-1}) were sown and 60 g of quartz sand were applied on the surface of each pot in order to reduce evaporation. The moisture content was set at 35% with deionised water. The pots were then transferred to a greenhouse (+20 °C, daylight 6:00-22:00), placed in randomised order on a table and covered with perforated plastic film until germination (for 6 days).

Two P fertilisation levels were tested: 0 and 45 mg pot^{-1} (150 mg kg^{-1} as KH_2PO_4 solution). To supply other nutrients, the following elements were pipetted into the pots: 300 N mg kg^{-1} (as NH_4NO_3), 200 mg K kg^{-1} (as KCl), 66 mg sulphur (S) kg^{-1} and 50 mg magnesium (Mg) kg^{-1} (as $MgSO_4$). Total volume of nutrient solutions were 15 mL to P-unfertilised pots and 20 mL to P-fertilised pots.

The plants were watered with deionised water to the soil surface by hand every two or three days. Pots were placed into trays, and if leached, the water was poured back to soil surface. The moisture content of 35% was frequently checked by weighing few pots. Three cuts of ryegrass were taken. After the first and second cuts, supplementary doses of N (300 mg kg^{-1} as NH_4NO_3)

and K (200 mg kg^{-1} as KCl) were given in four different proportions (by pipetting 2 mL of 0.402 M NH_4NO_3 and 2 mL of 0.192 M KCl after 1, 6, 10 and 16 d of the first and second cuts) to ensure a sufficient supply for the following cut, but P was applied only at the beginning of the experiment.

Plant shoots were harvested by cutting at 2 cm above soil surface on three occasions: 30, 50 and 70 days after sowing. The shoots were placed in pre-weighed paper bags, dried at +60 °C for 5 days and weighed for dry matter yield. For nutrient analyses, the ryegrass shoots were milled in a hammer mill and ashed at 500 °C for 3 h. The residues were dissolved in 5 mL of 6 M HCl and evaporated to dryness on a sand bath. Cooled residues were flushed on paper filters (white ribbon; Schleicher & Schuell, Dassel, Germany) with hot 0.24 M HCl and filtered into 50 mL volumetric flasks. The filtrate was analysed for P, calcium (Ca), K and Mg using ICP-AES (Thermo Jarrel Ash, Franklin, MA).

Utilisation of P by ryegrass was calculated according to *Morel* and *Fardeau* (1990) as the percentage of fertiliser P taken up by the ryegrass in all three cuts. To obtain the final P utilisation value for added P, P uptake in the P-unfertilised control was subtracted.

2.5 Statistical analysis

Differences between means for the parameters analysed were tested with one-way analysis of variance (ANOVA) followed by post-hoc separation of means using Tukey’s test. Significance level was set at $p<0.05$. Statistical analyses were conducted with IBM SPSS Statistics 22.

3. Results and discussion

3.1 Phosphorus content and sorption characteristics of soil and sediment

For the two sites studied, the clay content and Al_{ox} and Fe_{ox} concentrations in the sediment exceeded those found in the soil (Table 1). The sum of Al_{ox} and Fe_{ox} was 30 and 55% higher in sediment than in soil at Ojainen and Liedonperä, respectively. Conversely, the sediments had clearly lower STP concentrations (11 mg P_{Ac} L^{-1} and 3 mg P_{Ac} L^{-1}) than the soils (24 mg P_{Ac} L^{-1} and 10 mg P_{Ac} L^{-1}) at Ojainen and Liedonperä, respectively. Concentration of NaOH-P, i.e. the sum of easily soluble P and P assumed to be bound to Al_{ox} and Fe_{ox}, was lower in soil than in sediment, the sediment having 49% ($p<0.001$) and 22% ($p=0.016$) more NaOH-P at Ojainen and Liedonperä, respectively. Consequently, on mixing soil and sediment, NaOH-P concentration increased as the share of sediment in the mixture increased (Table 2). Within each of the two sites, there were no differences in total P concentration between soil and sediment (Table 1).

((Table 2))

Compared with soil without sediment addition, the equilibrium P concentration (EPC_0') decreased steeply already at the lowest sediment addition rate (12.5%), by 62% for Ojainen samples and by 57% for Liedonperä samples (Fig. 1a). At 25% sediment addition, the corresponding decrease in EPC_0' was 76 and 81%, respectively. With the two highest sediment rates (50% and 100%) EPC_0' approached zero, indicating high-affinity sorption of P.

The curve showing the change in the estimated y-axis intercept (an indication of how much P might be released when the P concentration of the solution surrounding soil or sediment particles becomes very low) with increasing sediment proportion in the mixtures was a mirror image of the EPC_0' estimate curve (Fig. 1b). The change in y-axis intercept suggested declining desorption potential with increasing sediment rate. The slope of the plot, which indicates P buffering capacity at the point of EPC_0', showed an increasing trend for P buffering as the sediment addition rate increased (Fig. 1c), although less regular than for x- and y-intercepts.

((Figure 1))

Despite the approximately equal total P concentration in soil and the corresponding CW sediment and higher NaOH-extractable P concentration in sediment than in soil, mixing the sediment into soil clearly increased the tendency to retain P, while it also increased P buffering and depressed P solubility. The high NaOH-P content in the CW sediments was due to P enrichment in the Fe-associated fraction, as shown by the high concentrations of redox-sensitive P in these sediments (*Laakso* et al., 2016). Conversely, Al-associated P in the sediments was depleted, as suggested by our earlier P fractionation results (*Laakso* et al., 2016). The high tendency of the sediment matter to retain P is most likely due to low P saturation of Al (hydr)oxides, as this pool in non-calcareous soils mainly controls P solubility (*Hartikainen*, 1982). Depletion of readily soluble P takes place when soil matter is mobilised by runoff water and during settling in wetlands.

For the sediments used in the present study, accumulation of clay-sized particles was rather high, giving a clay content of 62 and 82% for Liedonperä and Ojainen sediment, respectively, compared with a parent soil clay content of 35% and 45%, respectively. Fine clay material itself has a high concentration of Al and Fe (hydr)oxides (*Sippola*, 1974, p. 201) and two processes can further increase the affinity of metal oxides for P. First, bottom sediments were initially at a low redox state that is conducive to dissolution of Fe(II), and introduction of oxygen into the anoxic sediment during dredging produces new Fe(III) (hydr)oxide surfaces (*Jensen* et al., 1995; *Palmer-Felgate* et al., 2011). Second, drying-induced breakdown of Al and Fe complexes with organic matter can increase reactive metal oxide concentrations (*Bartlett* and *James*, 1980; *Peltovuori* and *Soinne*, 2005). These newly formed Al and Fe (hydr)oxides have a high specific surface area and a high amount of reactive sites for P adsorption (*Jensen* et al., 1995; *Laakso* et al., 2017).

3.2 Ryegrass yields and P uptake in the growth experiment

In the preliminary study conducted with Liedonperä soil and sediment, ryegrass grew poorly (dry matter yield 0.5 g pot^{-1}; Fig. 2) in the growth medium comprising sediment only, even when P fertiliser was initially applied at a rate of 27 mg pot^{-1} (90 mg kg^{-1}). After an abundant supplementary dose of 81 mg P pot^{-1} (270 mg kg^{-1}) for the second cut, a substantial increase in growth was obtained, and dry matter yield (2.4 g pot^{-1}) was the same as in field soil fertilised with 27 mg P pot^{-1}. This shows that the first cut was suffering from P deficiency, even when P was applied at a rate of 27 mg pot^{-1}. Based on these pre-test results, it was concluded that quite high P application would be needed in the P-fertilised medium in the main growth experiment to ensure reasonable yield when using the highest sediment application rate. Thus it was decided to use a dose of 45 mg P pot^{-1} (150 mg kg^{-1} soil-sediment mixture) for the main growth experiment.

((Figure 2))

In the greenhouse experiment, ryegrass grown in Ojainen soil (which had the higher STP of the two soils) gave somewhat higher yield than ryegrass grown in Liedonperä soil (Fig. 3). For the Ojainen soil without P application, increasing sediment addition did not cause any significant yield decrease and even at the highest sediment addition rate of 50%, the sum of the three cuts showed only 10% lower yield (p=0.047) than recorded for pots without any sediment application. When P was applied at a rate of 45 mg pot^{-1}, sediment application actually seemed to increase the total yield somewhat, but the differences between the treatments were not statistically significant.

For the ryegrass grown in Liedonperä soil, the first cut showed a substantial decline in yield when sediment was present in the growth medium (Fig. 3). Compared with the yield in growth medium comprising soil only, the pots with 12.5 and 25% sediment had 45% and 44% lower first-cut yield, respectively, whereas a 78% yield decline was recorded when the sediment share was increased to 50% ($p<0.001$ in all cases). With the second and third cuts the differences levelled off and there was actually an overall tendency in both soil-sediment mixtures for a rise in yield during the last cut at all sediment addition rates, regardless of whether P fertiliser was applied or not. It is likely that the increase in dry matter yield as the experiment proceeded was because the root system was increasingly dense and able to utilise the whole soil volume for nutrient extraction (*Bradshaw* et al., 1960). Hence, the significant differences in the sum of yield observed for Liedonperä P-unfertilised mixtures (Fig. 3) stemmed from the hampered growth before the first cut. For the 50% Liedonperä sediment addition rate, total ryegrass yield was depressed by 30% ($p<0.001$) compared with that in soil only. As found for Ojainen soil-sediment mixtures, the Liedonperä mixtures that received P fertiliser also appeared to produce somewhat higher total yield with increasing share of sediment in the growth medium.

((Figure 3))

With increasing sediment addition rate and with successive cuts, there was a clear trend for decreasing P concentration in ryegrass (Table 3). For all cuts of ryegrass grown in the P-unfertilised Liedonperä soil-sediment mixtures, the P concentration remained below 1 mg g^{-1}, indicating a severe shortage of P. For the P-unfertilised Ojainen soil-sediment mixtures, the P concentration of ryegrass ranged from 0.6 to 1.5 mg g^{-1}, indicating at least latent P deficiency. With P fertilisation, the P concentration in the first and second cuts of ryegrass in other pots (excluding 50% sediment addition) was 1.9-3.4 mg g^{-1}, which seems to be adequate according to previous studies (adequate range 2.1-4.4 mg g^{-1} according to *Smith* et al. (1985) and 1.5-2.7 mg g^{-1} according to *Ylivainio* et al. (2008)).

The range of ryegrass P concentrations (0.5-3.4 mg g^{-1}) observed in the present study was somewhat wider than that reported in other Finnish P availability studies with ryegrass (1.0-1.7 mg g^{-1} in *Yli-Halla* (1991) and 0.9-2.7 mg g^{-1} in *Ylivainio* et al. (2008)). As a result, we observed visible symptoms of P deficiency in the shoots when the P concentration was below 1 mg g^{-1}, a limit for P deficiency suggested earlier by *Yli-Halla* (1991).

((Table 3))

Total P uptake (mg pot^{-1}) decreased in all soil-sediment mixtures with increasing sediment addition rate (Fig 4). This was observed also in pots receiving abundant P fertilisation (45 mg pot^{-1} or 150 mg kg^{-1}). The largest decrease (50%; $p<0.001$) in P uptake compared with the unamended control was recorded already at 12.5% sediment addition rate in Liedonperä soil, which was originally poorer in STP (but still with adequate P status), and was associated with low yield. On visual inspection, the plant shoots in these pots seemed to be suffering from P deficiency. In pots fertilised with P, the response to P uptake with 12.5% sediment addition was a decline of 6% compared with the control ($p=0.003$). The corresponding decrease in all other pots was on average 14%. With 50% sediment addition rate, the decrease in P uptake compared with the control was on average 50%, 31% and 37% in the first, second and third cut, respectively. In Ojainen growth mixtures with added P (45 mg pot^{-1}) and also Ojainen soil without P, the first cut had the highest P uptake at all sediment addition rates, followed by the second and third cuts, and P uptake of the cuts decreased in an almost linear fashion with increasing sediment addition rate (Fig. 4). In Liedonperä mixtures the opposite was observed, with the first cut having the lowest P uptake after 12.5% sediment addition, followed by significantly higher and almost equal P uptake in the second and third cuts.

((Figure 4))

By using a small soil volume (100 g soil/sediment diluted with 200 g quartz sand) and abundant N fertilisation, we obtained rather high P utilisation values. In Liedonperä soil-sediment mixtures, the highest value (39%) was reached in control, where no sediment was added, and the P utilisation rate decreased steadily with sediment addition rate to: 35% with 12.5% sediment addition, 29% with 25% sediment addition and 22% with 50% sediment addition. The corresponding P utilisation values for 0, 12.5, 25 and 50 % Ojainen soil-sediment mixtures were 37%, 32%, 34% and 28%. In a previous greenhouse study, *Morel* and *Fardeau* (1990) reported P utilisation values of 6-17% for *Lolium perenne* L. grown in 1 kg of P-poor soil (clay 24% on average) with 66 mg P kg^{-1} applied.

4. Conclusions

In this study, inclusion of CW sediment decreased plant-available P content in soil and impaired the P supply of ryegrass. Sediment had a high P sorption capacity, due to its high clay content and high concentrations of Al_{ox} and Fe_{ox}. Re-oxidation as a result of dredging sediment can further increase the oxide content and the affinity for P adsorption. In a greenhouse experiment, P uptake of ryegrass decreased with increasing rate of sediment addition to soil. Utilisation of applied P fertiliser (150 mg kg^{-1}) also decreased with increasing sediment addition rate and the lowest utilisation was recorded with the highest sediment addition rate tested (50%). Therefore returning dredged CW sediment to fields may impair the P supply to plants or even cause P deficiency at higher application rates.

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Table 1. Texture, pH$_w$, ammonium acetate buffer extractable P (P$_{Ac}$), total carbon (tot-C), total phosphorus (tot-P), acid ammonium oxalate-extractable aluminium (Al$_{ox}$) and iron (Fe$_{ox}$) and particle size distribution of the Ojainen and Liedonperä soils and sediments.

Name	Texture[a]	pH$_w$[b]	P$_{Ac}$[c] (mg L^{-1})	Tot-C (%)	Tot-P (mg kg^{-1})	Al$_{ox}$[d] (mmol kg^{-1})	Fe$_{ox}$[d] (mmol kg^{-1})	Particle size distribution (%)		
								Clay <0.002 mm	Silt 0.002-0.06 mm	Sand 0.06-2 mm
Soil										
Ojainen	Silty clay	6.7	24	2.8	1450±179	112±9	223±18	45	42	13
Liedonperä	Silty clay loam	6.7	10	1.7	993±137	93±3	191±13	35	50	15
Sediment										
Ojainen	Clay	7.3	11	3.6	1467±8	181±28	253±31	82	17	1
Liedonperä	Clay	6.8	3	1.3	972±17	124±11	315±48	62	30	8

[a] According to USDA texture classes.

[b] Measured in 1:5 H_2O, fresh samples.

[c] Soil P extractable by ammonium acetate buffer (pH 4.65).

[d] Extracted from fresh samples.

Table 2. NaOH-extractable P concentration of Ojainen and Liedonperä soil-sediment mixtures with 0%, 12.5%, 25%, 50% and 100% (by dry weight) sediment. Results are given as mean (n=3) ± standard error of mean (SEM).

Sediment addition rate (%) to soil	NaOH-P (mg kg^{-1})
Ojainen	
0 (control)	258±20 a
12.5%	320±90 ab
25%	369±15 bc
50%	419±6 c
sediment	508±8 d
Liedonperä	
0 (control)	147±6 a
12.5%	158±8 ab
25%	154±3 a
50%	156±1 ab
sediment	189±8 b

Values followed by different letters differ significantly ($p<0.05$, Tukey’s test). The two sites were tested separately.

Table 3. Phosphorus concentration (mg g^{-1}) in ryegrass cuts taken at 30, 50 and 70 days after sowing from plants grown in Ojainen and Liedonperä soil-sediment mixtures with 0%, 12.5%, 25% and 50% (m-% dry weight) sediment. Results are given as mean (n=3) ± SEM.

Sediment addition rate (%, dry matter)	P fertiliser 0			P fertiliser 45 mg pot^{-1}		
	1st cut	2nd cut	3rd cut	1st cut	2nd cut	3rd cut
	(mg g^{-1})					
Ojainen						
0 (control)	1.5±0.0 a	1.4±0.1 a	1.0±0.0 a	3.1±0.1 a	3.4±0.1 a	2.5±0.1 a
12.5%	1.2±0.0 b	1.4±0.1 a	0.8±0.0 b	2.9±0.0 b	3.3±0.1 a	1.9±0.0 b
25%	1.0±0.0 c	1.1±0.0 b	0.8±0.1 b	2.6±0.0 c	2.9±0.0 b	1.6±0.0 c
50%	0.8±0.0 d	0.9±0.0 b	0.6±0.0 c	2.1±0.0 d	2.3±0.1 c	1.2±0.1 d
Liedonperä						
0 (control)	0.6±0.0 ab	0.7±0.0 a	0.6±0.0 a	3.1±0.0 a	2.7±0.1 a	1.7±0.1 a
12.5%	0.5±0.0 a	0.7±0.0 ab	0.5±0.0 ab	2.7±0.1 b	2.3±0.1 b	1.3±0.0 b
25%	0.5±0.0 a	0.6±0.0 b	0.5±0.0 b	2.4±0.1 b	1.9±0.0 c	1.0±0.1 bc
50%	0.7±0.0 b	0.6±0.0 b	0.5±0.0 b	1.6±0.0 c	1.5±0.0 d	0.9±0.0 c

Values within columns followed by different letters differ significantly ($p<0.05$, Tukey’s test). The two sites were tested separately.

Fig 1 a) Equilibrium P concentration (EPC_0'), b) readily desorbable P (I=0) and c) slope as P buffering capacity in x-axis intercept (PBC_0) of Ojainen and Liedonperä soil-sediment mixtures with 0%, 12.5%, 25%, 50% and 100% (m-% dry weight) sediment. Results are given as mean.

Fig 2 Italian ryegrass (*Lolium multiflorum* L.) in the preliminary study grown in (left) field soil and (right) CW sediment from the Liedonperä site, both receiving P fertiliser at 27 mg P pot^{-1} (90 mg kg^{-1}). Photo: Janne Heikkinen.

Fig 3 Dry matter yield (g) of ryegrass in three cuts taken at 30, 50 and 70 days after sowing from plants grown in Ojainen and Liedonperä soil-sediment mixtures with 0%, 12.5%, 25% and 50% (m-% dry weight) sediment and with P fertilisation of 0 and 45 mg pot^{-1}. Results are given as mean (n=3) ± SEM. Bars followed by different letters differ significantly (p<0.05, Tukey's test).

Fig 4 Total P (mg pot^{-1}) uptake by ryegrass in three cuts taken at 30, 50 and 70 days after sowing from plants grown in Ojainen and Liedonperä soil-sediment mixtures with 0%, 12.5%, 25% and 50% (m-% dry weight) sediment and with P fertilisation of 0 and 45 mg pot^{-1}. Results are given as mean (n=3) ± SEM. Bars followed by different letters differ significantly (p<0.05, Tukey's test).

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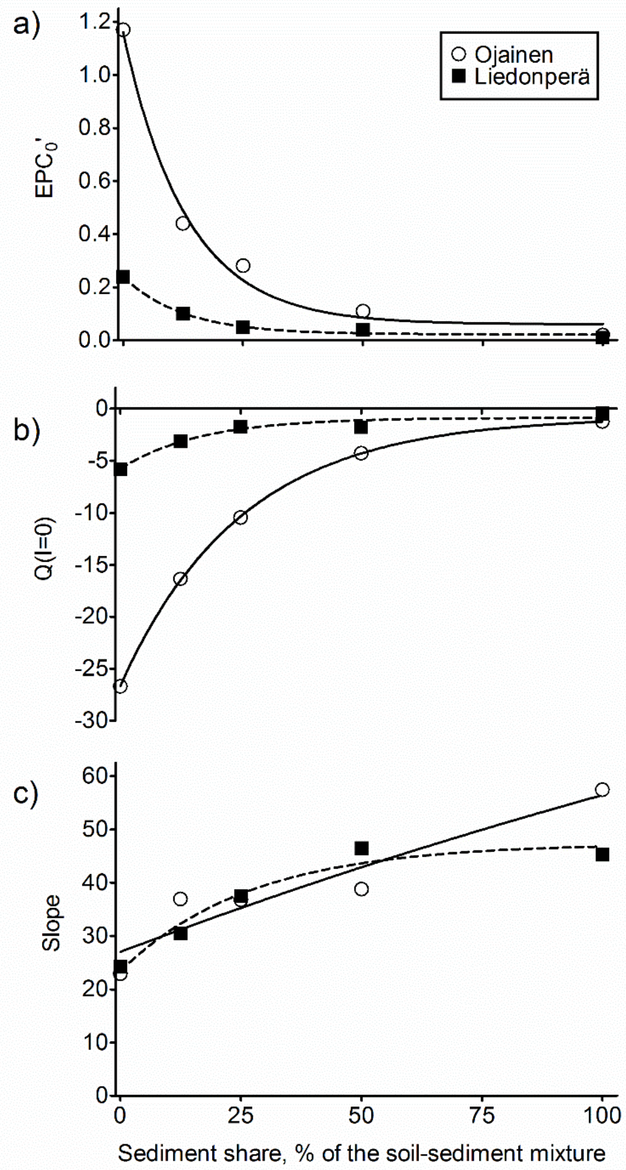
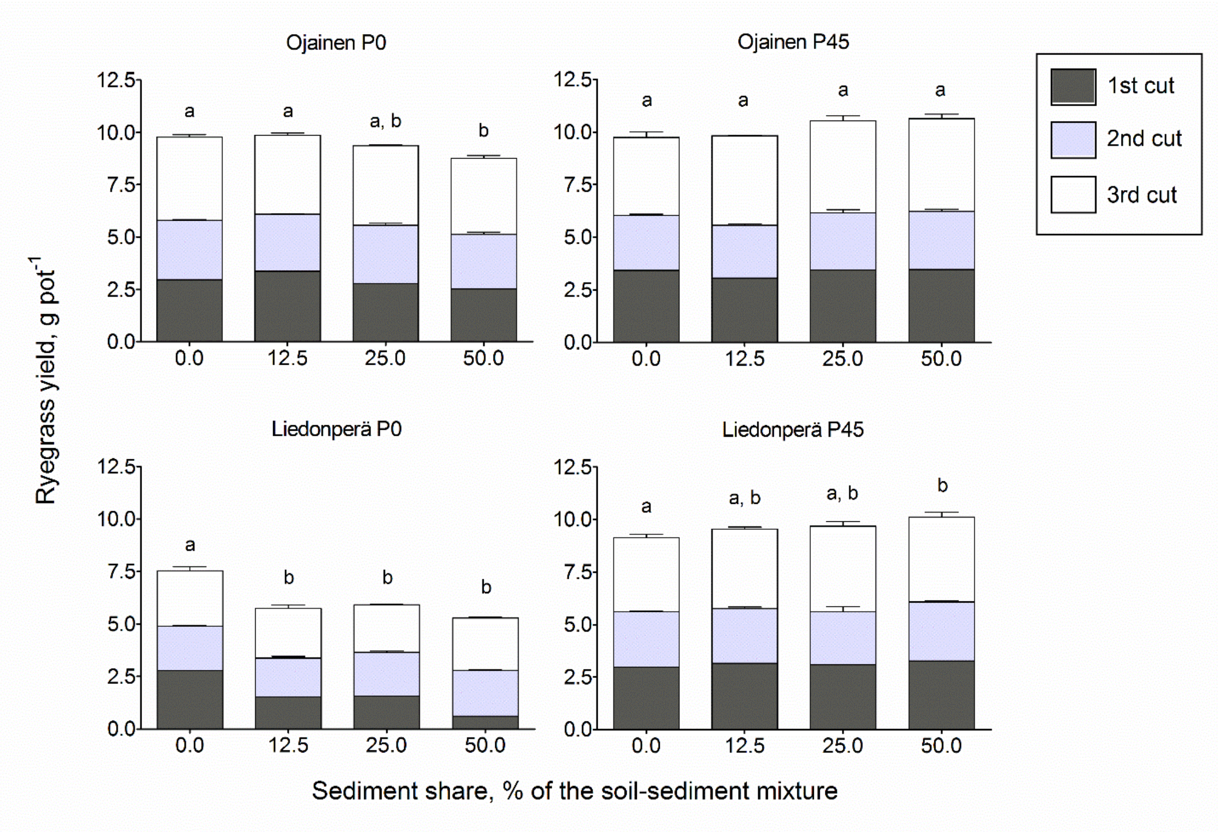
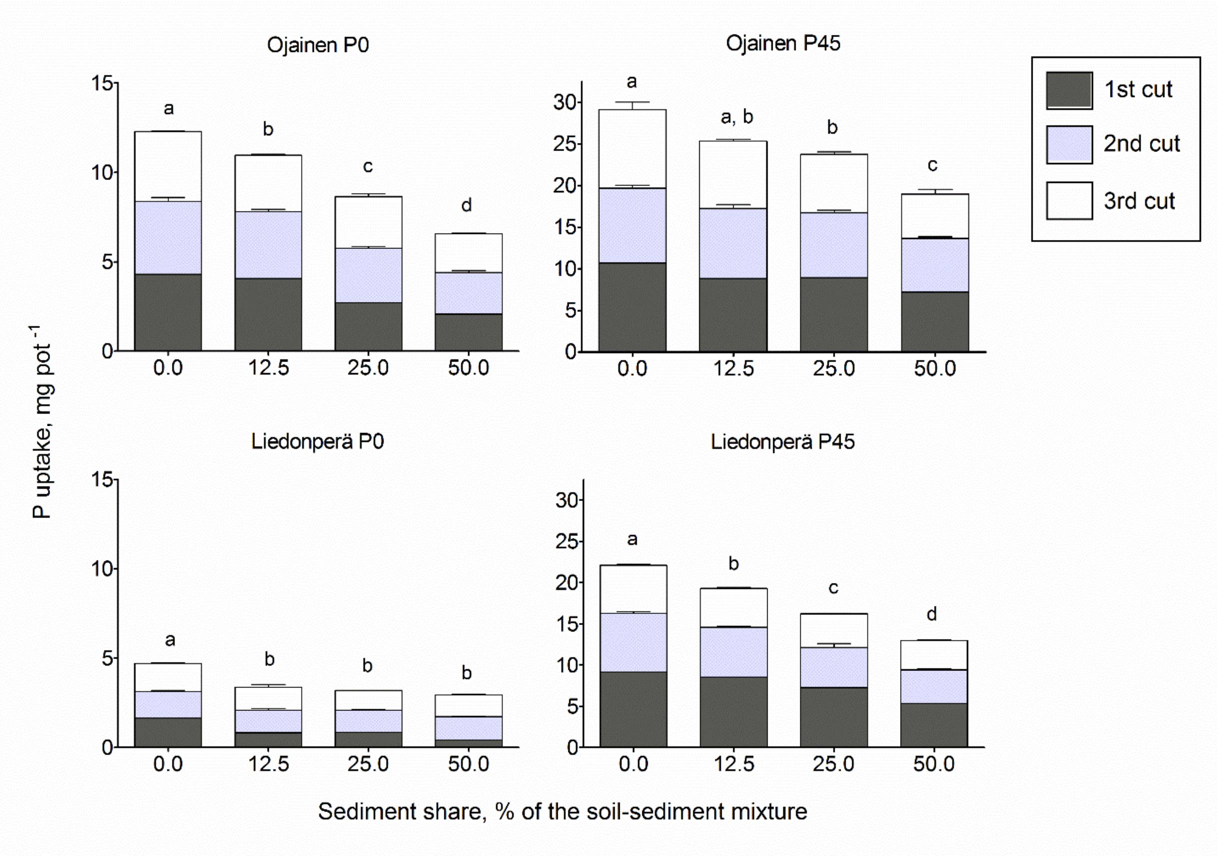

a)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
EPC_0'
○ Ojainen
■ Liedonperä
b)
0
-5
-10
-15
-20
-25
-30
Q(I=0)
c)
60
50
40
30
20
10
0
Slope
0
25
50
75
100
Sediment share, % of the soil-sediment mixture


10


Ojainen P0
Ojainen P45
Liedonperä P0
Liedonperä P45
1st cut
2nd cut
3rd cut
Ryegrass yield, g pot^{-1}
Sediment share, % of the soil-sediment mixture
12.5
10.0
7.5
5.0
2.5
0.0
0.0
12.5
25.0
50.0
a
a
a, b
b
a
a
a
a
a
b
b
b
a
a, b
a, b
b

479


Ojainen P0
Ojainen P45
Liedonperä P0
Liedonperä P45
1st cut
2nd cut
3rd cut
P uptake, mg pot^{-1}
Sediment share, % of the soil-sediment mixture
0.0
12.5
25.0
50.0
a
b
c
d
a, b
0
5
10
15
20
25
30