



A tool for easily predicting short-term phosphorus mobilization from flooded soils



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ABSTRACT

The construction and restoration of riparian (temporarily flooded) wetlands as water storage and flood protection areas plays a central role in climate-adaptive water management. In general, arable and ex-arable lands are used for this type of water storage. However, inundation may lead to problems, as excess phosphorus (P) stored in these soils may be released and result in the eutrophication of the overlying surface waters. Clearly, water and nature managers need to be able to determine for which areas temporary water storage would be a feasible option without causing eutrophication problems. Here, using a controlled experimental approach, a simple predictive tool for the P mobilization rates from soils upon short-term inundation has been developed. A large suite of soil characteristics and P mobilization rates were determined during flooding for different soil types (peat and sand), at two different depths to mimic topsoil removal (topsoils and soils from –30 to –60 cm below ground level), and at two temperatures to test seasonal influence (8 °C and 18 °C). Increasing the temperature from 8 to 18 °C almost tripled P mobilization rates, but the variation could not be linked to any of the soil characteristics measured – average Q_{10} (temperature coefficient) values were 2.8 (2.9 for peaty soils, 2.6 for sandy soils). Although P mobilization was related to P saturation of amorphous Fe, water-extractable P was found to be by far the best predictor for short-term P mobilization rates, explaining 86.9% of the variation. The predictive tool for P mobilization after short-term rewetting is simple, low-cost and widely applicable, and can support water managers during their decision-making processes concerning the optimal location for the construction of water storage areas, the restoration of riparian wetlands, and the combinational use of different ecosystem services.

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1. Introduction

To meet the challenges of population growth and climate change, landscapes are increasingly being designed for multi-functional use, combining ecosystem services to enhance land use efficiency. It is predicted that the frequency of severe flooding events in Europe will increase in the future due to the intensification of the global hydrological cycle resulting from climate change (Alfieri et al., 2015; IPCC, 2014). To deal with this, temporary water storage areas are essential during peak discharge periods to prevent flooding of urban areas. In addition, new riparian wetland areas are being developed to improve water retention and water

purification, to reduce greenhouse gas emissions, to increase nature restoration, and for recreational use. Such new areas for water storage, flood protection and/or riparian wetland restoration are frequently planned for both arable and formerly arable lands. As the extensive use of fertilizer and manure during farming generally have exceeded the output in primary production, large amounts of phosphorus (P) have accumulated in these soils (Barberis et al., 1996; Geurts et al., 2011; Pant and Reddy, 2003; Richardson, 1985; Smolders et al., 2008). Flooding of these P rich lands often causes eutrophication of the overlying water due to flood-induced mobilization of P resulting from oxygen (O_2) depletion in the soil (Lamers et al., 1998; Lamers et al., 2001; Loeb et al., 2007; Richardson, 1985). The nutrient release and the accumulation of reduced chemicals, such as ammonium and sulfide, leads to algal and cyanobacterial blooms, a die-off of target vegetation, a decrease in biodiversity, and an overall loss of wetland environmental quality (Conley et al.,

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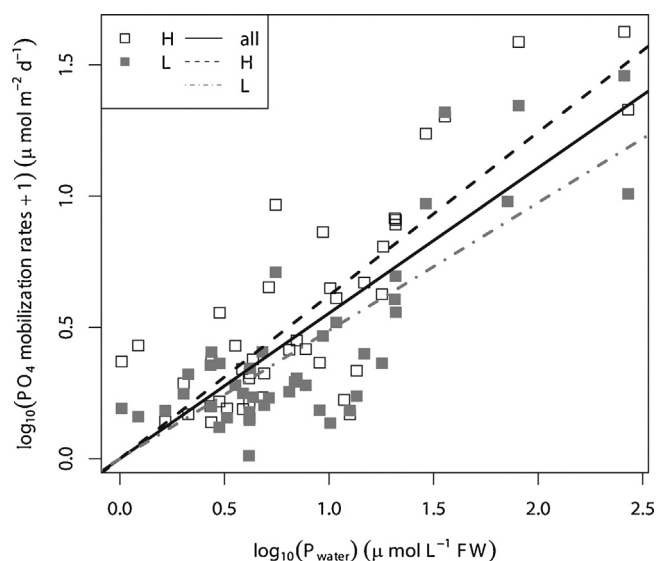


Fig. 1. Correlations between P mobilization rates and water-extractable P concentrations for all temperatures, and for high (18 °C; indicated H) and low temperatures (8 °C; indicated L) separately.

2009; Lamers et al., 2015; Pretty et al., 2003; Smolders et al., 2006). Clearly, these effects undermine the intended multi-functional land use.

For water security and environmental quality reasons, water managers need to be able to select temporary water storage areas wisely. However, currently there exists no simple investigative tool to aid in the selection of suitable locations, and an easy and cost-effective method to classify the potential P mobilization rates of different soils during short-term flooding events would be of great value so that lands with low P mobilization rates can be selected as areas for temporary water storage and retention and/or restoration of riparian wetlands.

It is well known that changes in iron (Fe) reduction rates (Mortimer, 1941; Ponnampertuma, 1984; Richardson, 1985), sulfate (SO_4^{2-}) reduction rates (Caraco et al., 1989; Lamers et al., 1998; Moore and Reddy, 1994), decomposition rates (Mclatchey and Reddy, 1998), and interactions among Fe, sulfur (S), P and O_2 (Cusell et al., 2013; Loeb et al., 2007; Smolders et al., 2006) strongly determine the actual P mobilization rates of soils upon inundation. In the present study, a suite of soil characteristics related to these mechanisms were determined for a large number of agricultural soils, in relation to their P mobilization rates to the overlying water. The aim was to find a reliable, simple indicator that could accurately predict P mobilization during temporary flooding for a wide range of soils.

As P mobilization may depend on organic matter content (Mclatchey and Reddy, 1998), different soils were used in this study to create a large range of soil organic matter contents. Since topsoil removal is an important measure when creating temporary storage basins, specifically to reduce P availability during flooding (Emsens et al., 2015; Van Dijk et al., 2004), deeper soil layers (–30 to –60 cm) were included to test P mobilization after topsoil removal. In addition, to test the influence of seasonal variation in temperature on P mobilization (Boers and Van Hese, 1988; Liikanen et al., 2002) two temperatures were used (8 °C and 18 °C).

In order to find a reliable, simple indicator that could accurately predict P mobilization during temporary flooding for a wide range of soils, this study needed to answer the following questions: (i) which soil characteristics can be used for the prediction of P mobilization rates during short-term flooding; (ii) does the predictability of P release differ for soils with different organic matter contents,

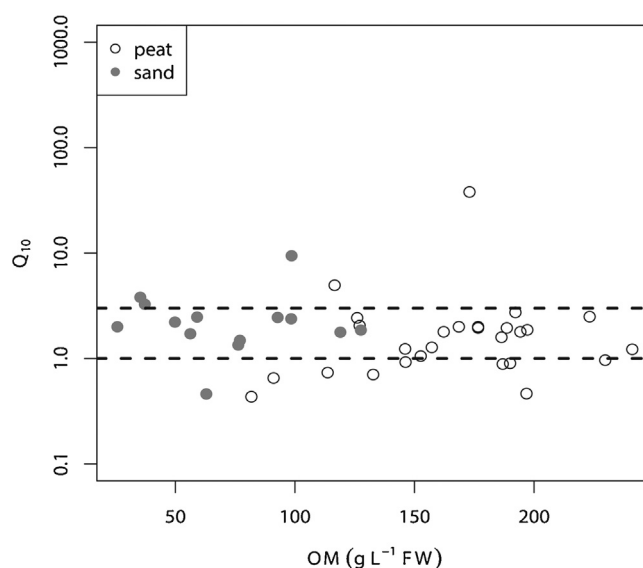


Fig. 2. Correlations between Q_{10} and organic matter contents. Most Q_{10} values stayed in the range of 1–3 indicated by the dashed lines. Note the logarithmic scale of the y-axis.

as well as for topsoil versus deeper soil; and (iii) how does temperature affect P mobilization rates.

2. Materials and methods

2.1. Fieldwork

Soil samples were collected using standard sharpened stainless steel cylinders (coring method) in October 2013 in the following areas (see Table A1 for all coordinates): Zuidplas (strongly decomposed peat; 51°59'N, 4°39'E; 5 locations), Burckmeer (strongly decomposed peat; 52°25'N, 4°59'E; 3 locations), Ilperveld (strongly decomposed peat; 52°26'N, 4°55'E; 4 locations), Wormer-Jisperveld (strongly decomposed peat; 52°31'N, 4°49'E; 4 locations), Stelkampsveld (sand; 52°06'N, 6°28'E; 2 locations) and Hallerlaak (sand; 52°04'N, 6°22'E; 5 locations) ($n=23$). At each of the 23 locations soils were sampled at 0 to –30 cm and –30 to –60 cm depth, with the deeper soil samples mimicking the situation after top-soil removal. The soil samples were put in plastic bags and kept at 4 °C until further analyses.

2.2. Soil analyses

Fresh soil samples were volume-weighed and subsequently dried (48 h, 60 °C) after which they were re-weighed to determine bulk density, and subsequently grinded with a mortar and pestle. Organic matter content was determined by loss on ignition (4 h, 550 °C). 200 mg of dry soil was digested in a microwave oven (MLS-1200 Mega, Milestone Inc., Sorisole, Italy) using 4 mL 65% HNO_3 and 1 mL 30% H_2O_2 to determine total sediment Fe and P concentrations. Digested solutions were then analyzed with inductively coupled plasma-optical emission spectrometry (ICP-OES; IRIS Intrepid II, Thermo Electron Corporation, Franklin, MA, USA). Water extracts were derived by incubating 17.5 g fresh soil in 50 mL Milli-Q for 2 h at 105 RPM, and Olsen P extracts (plant available phosphorus) were derived by incubating 3 g of dry soil in 60 mL NaHCO_3 for 0.5 h at 105 RPM (Olsen et al., 1954). Oxalate extracts were used to determine the concentrations of amorphous Fe and Fe-bound and aluminum- (Al-) bound P by incubating fresh soil material, corresponding to approximately 2.5 g dry weight in a 50 mL mixture of ammonium oxalate monohydrate and oxalic

Table 1

Model-averaged global regression coefficients and 95% of CIs from the model of P mobilization rates against soil characteristics showing Akaike weights (w) > 0.24; Coefficients are in bold where CIs do not overlap 0; Values of w represent the relative importance of the predictor variable based on summing weights of models where the given variable occurred; OM represents organic matter content; P_{water} represents water-extractable P.

| Terms | Coefficient | Standard error | Lower CI | Upper CI | w |
|--------------------------|--------------|----------------|--------------|--------------|------|
| P_{water} | 0.732 | 0.106 | 0.521 | 0.943 | 1 |
| Temp H | 0.170 | 0.370 | -0.566 | 0.907 | 0.93 |
| Temp L | 0.011 | 0.370 | -0.725 | 0.746 | |
| OM | -0.118 | 0.142 | -0.400 | 0.165 | 0.59 |
| Fe/ P_{total} | -0.094 | 0.145 | -0.382 | 0.194 | 0.50 |
| peat | 0.251 | 0.497 | -0.739 | 1.241 | 0.41 |
| sand | 0.173 | 0.416 | -0.655 | 1.001 | |
| S_{total} | 0.051 | 0.102 | -0.152 | 0.255 | 0.39 |
| Fe/ S_{total} | 0.044 | 0.182 | -0.318 | 0.406 | 0.36 |
| P_{total} | 0.030 | 0.127 | -0.223 | 0.284 | 0.33 |
| P_{olsen} | 0.040 | 0.117 | -0.194 | 0.273 | 0.33 |
| Fe/ P_{water} | -0.026 | 0.063 | -0.151 | 0.099 | 0.32 |
| Fe/ P_{oxalate} | -0.002 | 0.108 | -0.217 | 0.213 | 0.30 |
| Top layer | 0.132 | 0.393 | -0.649 | 0.913 | 0.25 |
| Deep layer | 0.139 | 0.388 | -0.633 | 0.912 | |

Table 2

Results from linear regression models of P mobilization rates in relation to water-extractable P and temperature, and water-extractable P only.

| Explanatory terms in model | R ² | P | AICc |
|----------------------------------|----------------|----------|---------|
| P_{water} + Temperature | 0.881 | 0.000*** | -14.517 |
| P_{water} | 0.869 | 0.000*** | -11.021 |

Table 3

Results from the linear regression analyses of water-extractable P concentrations on P mobilization rates; y represents P mobilization rates; x represents water-extractable P concentrations; All represents all incubations at both temperatures; H (high temperature) represents incubations at 18 °C; L (low temperature) represents incubations at 8 °C.

| Models | Formula | R ² | P |
|--------|---|----------------|----------|
| All | $\log_{10}(y + 1) = 0.554 * \log_{10}(x)$ | 0.869 | 0.000*** |
| H | $\log_{10}(y + 1) = 0.622 * \log_{10}(x)$ | 0.893 | 0.000*** |
| L | $\log_{10}(y + 1) = 0.488 * \log_{10}(x)$ | 0.865 | 0.000*** |

acid dehydrate in the dark for 2 h at 105 RPM (Houba et al., 1989). Extracts were collected in vacuum flasks using rhizons, after which the samples were decanted in 10 mL test tubes. The Olsen and oxalate extracts were diluted 5 and 4 times, respectively, before they were decanted in the test tubes. 0.1 mL of 65% HNO₃ was added to the test tubes (10 mL) containing the water extractions to avoid precipitation of redox sensitive compounds. Samples were kept in the dark at 4 °C until further chemical analyses.

2.3. Experimental set-up

At the start of the experiment 400 mL of each soil sample was placed in 1 L infusion bottles. Next, 600 mL of a standardized solution containing 1000 $\mu\text{mol L}^{-1}$ NaHCO₃, 1000 $\mu\text{mol L}^{-1}$ CaCl₂·2H₂O, 250 $\mu\text{mol L}^{-1}$ KCl and 500 $\mu\text{mol L}^{-1}$ MgSO₄·7H₂O were carefully added to all bottles. The open bottles were placed in the dark, either at 8 °C ('low temperature', L), or at 18 °C ('high temperature', H). The experiment comprised 122 infusion bottles in total (18 °C: 42 peat and 28 sand soils; 8 °C: 29 peat and 23 sand soils), and the incubation was for 6 weeks. During the experiment 20 mL surface water samples were collected twice weekly for the first three weeks and once every week for the last three weeks. After each sampling, 20 mL fresh surface water solution was added to compensate for the loss of the sampling volume for which was corrected in the calculation of P mobilization rates.

2.4. Analyses

Concentrations of PO₄ in the surface water were measured colorimetrically (Bran & Luebbe Autoanalyzer III, Norderstedt, Germany) using ammonium molybdate (Geurts et al., 2008). Total P, Fe, S were analyzed by ICP-OES (see above). At the end of the experiment, O₂ concentrations in the surface water were measured in all bottles with an optical oxygen probe (Hach LDO, Hach, Loveland, CO, U.S.A.).

2.5. Calculation of P release from sediments and Q₁₀

For the time span which showed a linear increase of surface water PO₄ concentration over time, P mobilization rates from soils into the overlying water were calculated by linear regression. The effect of increasing the temperature by 10 °C on biogeochemical rates, also known as the Q₁₀ temperature coefficient, was determined by dividing mobilization rates at 18 °C by those at 8 °C.

2.6. Statistical analyses

In order to meet the assumption that residuals fit a normal distribution, P mobilization rates (response variable) and most of all selected soil characteristics (predictor variables) were transformed by log₁₀(variable) or by log₁₀(variable + 1) (Bartlett, 1947) in cases where the lowest value of a variable was below one. For P mobilization rates, models with all possible subsets of all selected soil characteristics were fitted. Coefficients of each predictor variable across all considered models were averaged and their 95% confidence intervals (CIs) were calculated (Burnham and Anderson, 2002). An effect of predictor variable on the response variable was considered significant if CIs did not include zero. The relative importance (w) of each predictor variable was calculated by summing the weights of the Akaike information criterion (AICc: correction for small sample size) across all considered models, where a given predictor variable occurred (Burnham and Anderson, 2002), with 1 being the best predictor and 0 the worst. The influence of water-extractable P and temperature on P mobilization rates (both having a $w > 0.9$) was analyzed using linear regression models. All analyses were performed using the software program R (version 3.2.1; R development Core Team, 2015); model-averaged coefficients were tested by 'MuMIn' package (Bartoń, 2015). Q₁₀ values were considered to correlate significantly with soil characteristics when $P < 0.05$.

3. Results

As bulk densities of soils differ depending on their origin, the units $\mu\text{mol L}^{-1}$ or g L^{-1} soil fresh weight were used instead of $\mu\text{mol g}^{-1}$ or g g^{-1} soil dry weight for selected soil characteristics. P mobilization rates (see Table B1 for P mobilization rates and soil characteristics) were calculated by linear regression of surface water PO₄³⁻ concentrations at different times during short-term flooding, and expressed per unit soil surface.

3.1. Best predictors

P mobilization rates were best predicted by the combination of water-extractable P and temperature under aerobic surface water conditions (oxygen contents: $8.38 \pm 0.09 \text{ mg L}^{-1}$ and $9.52 \pm 0.10 \text{ mg L}^{-1}$ for 18 °C and 8 °C, respectively), with $w > 0.9$ for both variables (Table 1). Moreover, 88.1% of the variation in P mobilization rates could be explained by constructing a linear model using only these two variables, and a model including only water-extractable P was already able to explain 86.9% (Table 2). After water-extractable P and temperature, organic matter content and

Table A1
Coordinates of sampling locations in the Netherlands.

| Code | Latitude | Longitude | Area | Soil type |
|------|----------|-----------|-----------------------|-----------|
| 1 | 51°59'N | 4°40'E | Zuidplas | peat |
| 2 | 51°59'N | 4°37'E | | |
| 3 | 51°59'N | 4°38'E | | |
| 4 | 51°59'N | 4°38'E | | |
| 5 | 51°59'N | 4°39'E | | |
| 6 | 52°25'N | 4°59'E | Burkmeer | |
| 7 | 52°25'N | 4°59'E | | |
| 8 | 52°25'N | 4°59'E | | |
| 9 | 52°27'N | 4°55'E | Ilperveld | |
| 10 | 52°27'N | 4°55'E | | |
| 11 | 52°26'N | 4°55'E | | |
| 12 | 52°26'N | 4°56'E | | |
| 13 | 52°31'N | 4°48'E | Wormer- Jisperveld | |
| 14 | 52°31'N | 4°48'E | | |
| 15 | 52°31'N | 4°49'E | | |
| 16 | 52°31'N | 4°50'E | | |
| 17 | 52°07'N | 6°28'E | Stelkampsveld | sand |
| 18 | 52°06'N | 6°28'E | | |
| 19 | 52°04'N | 6°21'E | Hallerlaak | |
| 20 | 52°04'N | 6°21'E | | |
| 21 | 52°04'N | 6°22'E | | |
| 22 | 52°04'N | 6°22'E | | |
| 23 | 52°04'N | 6°22'E | | |

Fe/P_{total} ratios had the greatest effect on P mobilization rates, with *w* being 0.59 and 0.50, respectively. Finally, soil depth and soil type showed much lower *w* values than the four predictor variables (Table 1).

3.2. Effects of best predictors

P mobilization rates correlated linearly ($P < 0.001$) with water-extractable P concentrations at both temperatures (Fig. 1) (Table 3). At 18 °C 89.3% of the variation in P mobilization rates could be explained for all soils; at 8 °C 86.5% of the variation in P mobilization rates could be explained for all soils (Table 3).

3.3. Temperature effect

The Q_{10} of soil P mobilization rates did not correlate ($P > 0.05$) with any of the selected soil characteristics, including organic matter contents (Fig. 2). Results show that most Q_{10} values remained in the range of 1–3 and that Q_{10} of soil P mobilization rates were on average 2.8, 2.9 and 2.6 for all, peat and sand soils, respectively.

4. Discussion

4.1. Prediction of flooding-induced P mobilization

P mobilization rates in the present study varied between 0.010 and 1.280 mg P m⁻² d⁻¹. Of all selected soil characteristics, water-extractable P was the best predictor of P mobilization rates upon short-term flooding; 86.9% of the variation in P mobilization rates could be explained by this variable. Increasing the temperature from 8 to 18 °C almost tripled P mobilization rates, but the variation could not be linked to any of the soil characteristics measured. In contrast to water-extractable P, total P concentration in soils could not be used to accurately predict P mobilization rates. Based on P sorption and desorption characteristics, Hooda et al. (2000) similarly showed for clay and loam soils that next to Olsen P and P on Fe-coated paper, water-extractable P could predict P desorption. For a cluster of four areas differing in fertilization history, all with Spodosoil soil type, Pant and Reddy (2003) similarly showed that water-soluble P together with acid-extractable magnesium explained a large part of the variation in P desorption rates. Based on a large data set, the results show that water-extractable P can be

used as a general, widely applicable and low-cost predictor that can be used by water managers and other natural resource managers.

For underwater soils, Fe plays an important role in modulating P mobilization to the overlying water layer (Geurts et al., 2011; Jensen et al., 1992; Smolders et al., 2006, 2010), as oxidized Fe binds P at the soil-water interface (Einsele, 1938; Mortimer, 1941). For flooded soils, the same mechanism can be expected to play a role (Loeb et al., 2008). Under aerobic conditions, P is firmly bound by iron (III) oxides and hydroxides. After flooding, however, oxygen soon becomes depleted in the soil and Fe (III) is used as an alternative electron acceptor for the microbial oxidation of organic matter and reduced to the more mobile Fe (II) (Patrick and Khalid, 1974; Roy and Bickerton, 2014). P formerly bound to Fe (III) oxides and hydroxides becomes mobile and dissolves in the pore water (Loeb et al., 2007). Depending on whether the soil-water interface is aerobic or anaerobic, P may either be trapped in the interface due to the re-oxidation of Fe (II) to Fe (III) (Gunnars and Blomqvist, 1997) or be mobilized to the overlying water. Although the ratio between Fe and P in water or oxalate extracts showed much lower Akaike weights than P in water, extracts for the overall analysis of soils with water-extractable Fe:P > 5 all showed low P mobilization rates, below 0.067 mg m⁻² d⁻¹, even when water-extractable P reached 8 μmol L⁻¹ FW (data not shown). This is a strong indication that Fe plays an important role in P mobilization rates as long as the water layer is aerobic, similar to underwater soils (Geurts et al., 2011). This also means that if flooding water becomes anaerobic, for instance by the cover of floating-leaved plants (Van Kempen et al., 2012), or by the prolonged flooding of soils, resulting in oxygen depletion and increased microbial use of iron as an alternative electron acceptor (Lamers et al., 1998; Loeb et al., 2008; Zak and Gelbrecht, 2007), P mobilization rates may become much higher than those measured here because of the release of iron-bound (oxalate-extractable) P.

Next to Fe, S has also been shown to play a significant role in P mobilization from flooded soils. Under anaerobic conditions SO₄²⁻ is reduced to sulfide which has a much stronger affinity to Fe than P, leading to FeS_x precipitation (Lamers et al., 2002; Smolders et al., 2010; Sperber, 1958; Zak et al., 2006). Consequently, Fe becomes less available for binding P, which can lead to an additional release of P (Smolders et al., 2006). In this study, the inclusion of S-related variables did not add to predictability (Table 1). However, this may change after prolonged flooding of soils subjected to high SO₄²⁻ loads (Lamers et al., 1998).

4.2. Implications for wetland creation

The present study shows that it is indeed possible to predict potential P release rates from a wide range of agricultural and former agricultural lands under aerobic surface water conditions during short-term flooding through the simple measurement of water-extractable P. This provides a valuable predictive tool for the selection of suitable locations for temporary water storage and retention. The temperature sensitivity results also show that eutrophication risks can be expected to be much higher in summer than in winter. Topsoil removal is a commonly used measure in nature restoration to lower the P availability in the top layer, given that the soil exposed after topsoil removal usually contains much less P. This also reduces the risk of nutrient release upon inundation, which will prevent water eutrophication during flooding (Emsens et al., 2015; Lamers et al., 2006; Smolders et al., 2008). However, our results show that prior to topsoil removal it is important to determine P concentrations along the soil profile to establish whether this is necessary, and how much soil should be excavated.

Table B1Soil characteristics and P mobilization rates of peat and sand soils in the experiment. P_{water} represents water-extractable P; OM represents organic matter content.

| Code | Depth | P _{water} (μmol L ⁻¹ FW) | OM (g L ⁻¹ FW) | Fe/P _{total} (μmol μmol ⁻¹) | P _{olsen} (μmol L ⁻¹ FW) | Fe/P _{oxalate} (μmol μmol ⁻¹) | PO ₄ mobilization rates (μmol m ⁻² d ⁻¹) | |
|------|--------|--|---------------------------|--|--|--|--|-------|
| | | | | | | | 18 °C | 8 °C |
| 1 | top | 18.16 | 217.99 | 7.54 | 1159.54 | 10.89 | 5.42 | n.a. |
| | deeper | 9.02 | 223.27 | 9.72 | 736.94 | 18.30 | 1.32 | 0.53 |
| 2 | top | 35.80 | 229.75 | 3.03 | 2757.71 | 3.69 | 19.12 | 19.86 |
| | deeper | 5.56 | 176.63 | 4.92 | 980.99 | 5.72 | 8.27 | 4.14 |
| 3 | top | 5.15 | 116.67 | 10.10 | 2107.82 | 8.79 | 3.50 | 0.71 |
| | deeper | 4.19 | 146.31 | 15.92 | 967.56 | 12.21 | 1.12 | 1.21 |
| 4 | top | 3.569 | 197.12 | 6.04 | 1482.36 | 8.80 | 1.69 | 0.91 |
| | deeper | 4.33 | 188.67 | 6.63 | 1049.95 | 7.73 | 1.39 | 0.71 |
| 5 | top | 29.05 | 176.63 | 4.46 | 3055.34 | 3.29 | 16.29 | 8.37 |
| | deeper | 20.86 | 192.23 | 5.12 | 1684.54 | 4.43 | 7.13 | 2.61 |
| 6 | top | 71.43 | 249.15 | 3.46 | 1156.00 | 8.59 | n.d. | n.d. |
| | deeper | 80.67 | 162.25 | 3.54 | 298.60 | 15.33 | 37.68 | 21.13 |
| 7 | top | 6.86 | 215.12 | 8.97 | 1491.61 | 12.30 | n.d. | n.d. |
| | deeper | 6.45 | 168.56 | 10.53 | 304.00 | 20.97 | 1.60 | 0.80 |
| 8 | top | 2.02 | 241.07 | 7.99 | 426.05 | 21.77 | 0.94 | 0.77 |
| | deeper | 4.16 | 146.13 | 7.43 | 105.85 | 40.61 | 0.63 | 0.51 |
| 9 | top | 12.58 | 189.97 | 5.07 | 477.09 | 10.14 | 0.48 | 0.53 |
| | deeper | 1.02 | 126.11 | 15.22 | 78.31 | 35.60 | 1.34 | 0.55 |
| 10 | top | 2.74 | 186.87 | 5.27 | 275.18 | 20.77 | 1.36 | 1.54 |
| | deeper | 1.65 | 113.67 | 13.50 | 48.44 | 50.58 | 0.39 | 0.53 |
| 11 | top | 2.71 | 196.83 | 6.35 | 248.80 | 10.70 | 0.59 | 1.27 |
| | deeper | 2.12 | 81.79 | 3.45 | 30.59 | 30.14 | 0.48 | 1.10 |
| 12 | top | 3.25 | 157.32 | 8.18 | 72.30 | 35.45 | 0.55 | 0.43 |
| | deeper | 2.73 | 91.13 | 11.15 | 24.52 | 155.33 | 0.38 | 0.58 |
| 13 | top | 3.85 | 208.06 | 6.51 | 536.19 | 9.08 | 1.19 | n.a. |
| | deeper | 2.99 | 127.07 | 3.90 | 62.43 | 38.38 | 0.65 | 0.32 |
| 14 | top | 11.81 | 195.96 | 6.67 | 916.66 | 7.19 | 0.68 | n.a. |
| | deeper | 13.56 | 186.44 | 5.38 | 564.22 | 6.05 | 1.16 | 0.73 |
| 15 | top | 7.74 | 194.25 | 5.95 | 754.11 | 7.01 | 1.61 | 0.90 |
| | deeper | 3.88 | 132.69 | 9.96 | 90.76 | 15.73 | 0.55 | 0.77 |
| 16 | top | 4.14 | 173.01 | 7.77 | 700.23 | 9.65 | 1.02 | 0.03 |
| | deeper | 4.16 | 152.60 | 15.86 | 91.11 | 31.54 | 0.42 | 0.40 |
| 17 | top | 10.14 | 98.63 | 5.39 | 2027.72 | 6.93 | 3.46 | 0.37 |
| | deeper | 20.80 | 56.20 | 4.19 | 2305.54 | 2.86 | 6.79 | 3.96 |
| 18 | top | 4.80 | 62.92 | 7.59 | 3537.90 | 5.33 | 0.72 | 1.55 |
| | deeper | 3.00 | 25.80 | 31.17 | 1016.53 | 12.56 | 2.60 | 1.30 |
| 19 | top | 10.83 | 76.36 | 16.39 | 1907.76 | 5.86 | 3.09 | 2.30 |
| | deeper | 14.75 | 92.72 | 18.45 | 2077.57 | 5.87 | 3.68 | 1.51 |
| 20 | top | 17.91 | 59.10 | 17.99 | 2676.02 | 7.89 | 3.23 | 1.31 |
| | deeper | 9.35 | 37.30 | 18.79 | 1254.63 | 6.01 | 6.30 | 1.93 |
| 21 | top | 20.63 | 98.50 | 11.51 | 2413.87 | 5.01 | 7.24 | 3.05 |
| | deeper | 7.00 | 119.00 | 32.47 | 1291.99 | 13.98 | 1.82 | 1.02 |
| 22 | top | 258.15 | 77.04 | 1.06 | 4452.04 | 1.11 | 41.28 | 27.73 |
| | deeper | 269.46 | 49.85 | 0.75 | 4627.16 | 0.44 | 20.35 | 9.21 |
| 23 | top | 4.90 | 127.52 | 14.11 | 1134.34 | 16.20 | 1.11 | 0.60 |
| | deeper | 1.22 | 35.31 | 14.06 | 925.02 | 10.44 | 1.70 | 0.44 |

Note that n.a. means not available; n.d. means not determined because soil became buoyant.

5. Conclusions

- For a wide range of soils, water-extractable P is the best predictor of P mobilization rates during temporary flooding; 86.9% of the variation in P mobilization rates could be explained by this variable. In addition, Fe also plays an important role in the process of P mobilization during short-term flooding.
- Release rates were found to be temperature sensitive. The average Q₁₀ of soil P mobilization rates was 2.8, which can be included in predictions based on differences in seasonal hydrology, but its variation around the average could not be explained by any of the soil characteristics measured.
- Depth profiles provide information whether topsoil removal is a feasible or necessary option to prevent high P mobilization rates.
- Water-extractable P is shown to be a widely applicable, cost-effective and simple tool to predict P mobilization rates during short-term flooding, which can greatly assist water managers during their decision-making processes concerning the optimal location for the construction of water storage areas, the restoration of riparian wetlands, and the combinational use of different

ecosystem services in climate-adaptive water and nature management.

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Appendix A

See [Table A1](#).

Appendix B

See [Table B1](#).

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