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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 amorphic 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.

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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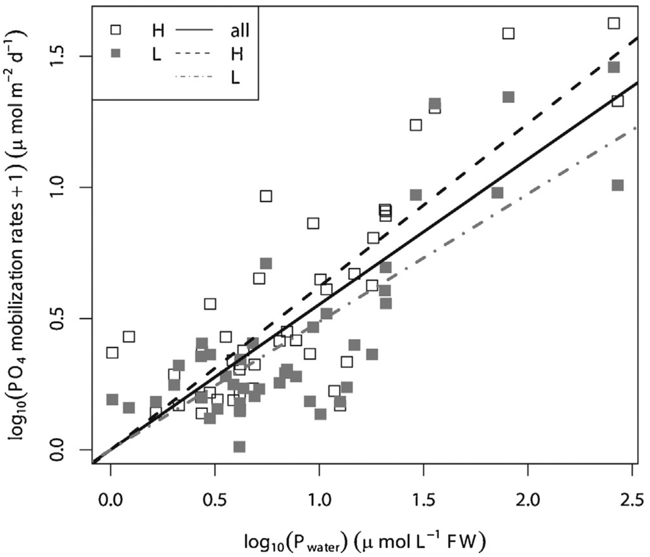

Fig. 1. Correlations between P mobilization rates and water-extractable P concentrations for all temperatures, and for high (18 °C; indicated H) and low temperatures (8 °C; indicated L) separately.

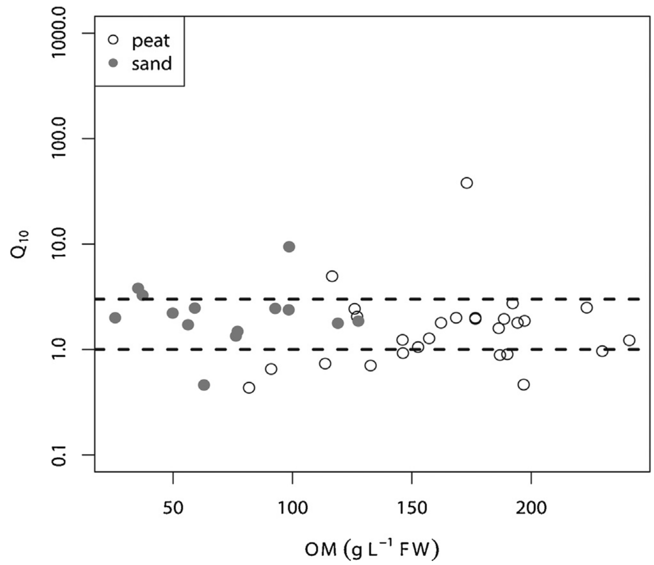

Fig. 2. Correlations between Q_{10} and organic matter contents. Most Q_{10} values stayed in the range of 1–3 indicated by the dashed lines. Note the logarithmic scale of the y-axis.

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; Ponnamperuma, 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, 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), Burkmeer (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