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Characterization of sediments for estimating potential P release after restoration of lake Søborg

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Abstract

The Danish state is planning to restore and reestablish the former lake Søborg, which was drained nearly 200 years ago for agricultural purposes. For this study soil samples up to 100 cm depth from two transects and two pits from across the project area were sampled.

P extractions with *aqua regia* and ammonium oxalate were carried out and soil properties like pH, bulk density, organic carbon and calcium carbonate content and iron and aluminum oxide concentrations were determined to characterize the sediment of lake Søborg.

Comparison of P concentrations from the different soil layers revealed that P contents were moderate to high, but did likely not change significantly since drainage. It is concluded that the P content originated from the sediments of the original lake and was initially influenced by the geological history of the area. Post-glacial rebound brought up limestone bearing marine sediments which acted as a P sink. Indicators of calcium carbonate associated marine sediments were also given through determined low bulk density, high organic carbon contents and a neutral to alkaline soil pH.

Al_{ox} showed moderate correlations, while Fe_{ox} showed strong correlations to P concentrations. A redox change induced Fe-P release is not expected after flooding since lake Søborg will be a shallow lake and most likely be well oxidized throughout the whole water column. An associated aerobic layer at the sediment surface will maintain iron (III) which in turn retains P in the solid phase.

Since there was no significant change in P concentrations in the approximately the last two hundred years since drainage, P fluxes will behave probably in a similar manner like when Søborg was still a lake and therefore no relevant P release is expected.

List of abbreviations

P	Phosphorus
Fe	Iron
Al	Aluminum
Ca	Calcium
Mg	Magnesium
Mn	Mangan
C	Carbon
C_{org}	Organic carbon
C_{inorg}	Inorganic carbon
P_{AR}	*Aqua regia* extractable phosphorus
P_{ox}	Ammonium oxalate extractable phosphorus
Fe_{ox}	Ammonium oxalate extractable iron oxides
Al_{ox}	Ammonium oxalate extractable aluminum oxides
N	North
E	East
$CaCl_2$	Calcium chloride
ÖNORM	Standardized methods of Austrian Standards International
CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
M	Molar
BD	Bulk density
ICP-OES	Inductively coupled plasma optical emission spectrometry
ANOVA	Analysis of variance
St. Dev.	Standard deviation
p	Probability value
DKK	Danish krones

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Statutory declaration

I hereby declare that I am the sole author of this work. No assistance other than that which is permitted has been used. Ideas and quotes taken directly or indirectly from other sources are identified as such. This written work has not yet been submitted in any part.

Vienna, May 5th 2019   Sami Simon Jabali

Acknowledgements

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1. Introduction

Draining water bodies and specifically lakes was practiced in Europe throughout the last centuries for the purpose of land reclamation and agricultural expansion. It is estimated that more than half of Europe's wetlands disappeared for those reasons (Zedler and Kercher, 2005; Moreno-Mateos et al., 2012). Especially shallow lakes in agricultural lowland regions of Europe were drained (Sand-Jensen, 2001). It is well known that land use change which mostly comes along with the above-mentioned conversion of ecosystems, is a major reason for biodiversity loss and reduced ecosystem functions (Halpern et al., 2008; Butchart et al., 2010). This circumstance is increasingly recognized by policy makers and authorities, thus the restoration and reestablishing of former lakes became more popular and practiced (Schönach et al., 2018). Besides lake's role as a habitat for flora and fauna increasing and conserving biodiversity (Biggs et al., 2017), also opportunities for recreational and touristic purposes (Fleming and Cook, 2008) or their potential in climate change mitigation (Erwin, 2009) are of higher interest in the society of today. Ecological restoration which aims at the recovery of an ecosystem which has been altered or damaged by human activity admires to bring back characteristics of an ecosystem which were existing before degradation or transformation of a site (Benayas et al., 2009). Planning and carrying out restoration projects, the responsible persons cannot only have the ideal outcome in mind, they also need to consider and assess possibilities of undesired outcomes or negative side effects that might occur during and after implementation (Buckley and Crone, 2008; Nilsson et al., 2016). To prevent these, pre-investigations and assessments have to be undertaken in advance (McDonald et al., 2016; Nilsson et al., 2016).

One of these issues and scenarios that needs to be considered when planning a restoration of a former lake is the process of internal loading and related nutrient release after flooding of an area (Kinsman-Costello et al., 2014). Sediments can either be sources or sinks of various nutrients (Boström et al., 1988). When lake sediments are being a source of nutrients to the lake water column, it is considered as the phenomenon of internal loading (Christophoridis and Fytianos, 2006; Søndergaard, 2007). Although the focus is most of the time on external nutrient inputs into water bodies, it has been proven that also nutrient rich lake sediments can supply the

overlying water body for decades (Søndergaard et al., 2003; Søndergaard, 2007; Yin and Kong, 2015) or that internal nutrient fluxes can temporarily balance or even exceed external nutrient input (Boström et al., 1985). Nutrient release to water columns after re-flooding of areas has been shown as well, thus demonstrating the influence and the need to investigate internal loadings (Aldous et al., 2005). The problem with high loads of nutrients being released to a water body is that it can lead to the process of eutrophication. Eutrophication describes a water body's enrichment and oversupply with nutrients (Rast and Thornton, 1996). This process has drastic influence on the biology of a lake. Eutrophic lakes are usually dominated by algae or cyanobacteria which in turn results in depletion of dissolved oxygen in the water column (Smith et al., 1999). Furthermore, cyanobacteria produce compounds that are toxic for humans and fauna in general (Bukowska et al., 2017). Smith (1998) names effects of eutrophication for lakes with reduced water clarity, elevated water pH, a shift in fauna and flora species and increased probability for fish mortality. All of these factors most likely contradict the vision of a desired lake that authorities have in mind when they plan to restore a lake. To examine the risk of eutrophication, there is one nutrient that should be paid special attention to, the chemical element phosphorus (P). Besides being essential for all living organisms, phosphorus is also usually in lakes the productivity limiting one of the nutrients, as well as algae growth limiting (Bormans et al., 2016). In nature P always appears in compounds, bound to different minerals or organic matter (Fink et al., 2016). Through biological, chemical or physical processes like weathering, mineralization and decay it gets set free in a soluble form as orthophosphate, which can be up taken by plants and microorganisms. Animal and plant decay is returned to the soil where the phosphorus is transformed to insoluble compounds again (Ruttenberg, 2001). Human activity however has strong influence on P fluxes in landscapes. P minerals are mined and transformed into fertilizer for application on agricultural fields (Tóth et al., 2014). Additional large quantities of phosphorus are added to soils in the form of animal manure (Hahn et al., 2012). The responsible persons who plan to restore and recreate a lake on a former agricultural site should be aware of that fertilization could have resulted in a P surplus in the soil, which might be partly released after the lake has been re-established (Fischer et al., 2017). Besides the P content, it needs to be considered that flooding of sediments can have an influence on chemistry and properties of soils. It is well known that flooding can lead

to a change in redox potential and can influence the soil pH which in turn has influence on P release or retention (Ponnamperuma, 1972; Jalali and Hemati Matin, 2015).

Also in Denmark restoration of wetlands became an important topic. Over the last decades 50 shallow lakes were restored and reestablished in Danish territories. Those sites were mostly located on agricultural fields and used to be natural shallow lakes before they were drained for agricultural purposes (Hansen, 2008). One of the future restoration projects of the Danish state and its ministry of Environment and Food (Miljø- og Fødevareministeriet) is the planned reestablishment of the former lake Søborg, located in the northeast of the island of Zealand in the Gribskov commune. Lake Søborg used to be one the largest lakes on Zealand until it was drained and the land used for agricultural purposes for nearly two centuries (Riis, 2014). Visions and reasons for this nearly 100 mio. DKK costly restoration project are named with positive effects for the nature, biodiversity and climate (Miljø- og Fødevareministeriet, 2018). The cultural landscape around the lake is supposed to be conserved and a recreational area shall be created with possibilities of outdoor activities and tourism in general (Riis, 2014; Miljø- og Fødevareministeriet, 2018). To meet those goals and to create the desired lake, pre-assessments have to be undertaken to prevent undesired outcomes or negative side-effects for humans and nature (Steinman and Ogdahl, 2011). Especially since the land and area was used in the meantime for intensive agricultural purposes and thereby also potentially fertilized there is the possibility of the mentioned risk of P surplus in the soil (MacDonald et al., 2011).

A challenge that pre-investigations of P contents in soil face is the fact that the mineral P is part of diverse surface structures and is present in different pools and fractions (Filippelli, 2002). Since different P extraction methods extract directly or indirectly from the different fractions and there is no universal soil P test, a lot of different methods are applied in different countries and for different research questions (Psenner et al., 1988; Tandy et al., 2011; Jordan-Meille et al., 2012; Moody et al., 2013; Schnug and De Kok, 2016). For the aim of giving a prediction of potential P release from sediments to lake water, P concentrations chemical sequential extractions have been widely used (Lijklema, 1993; Seo and Canale, 1999; Søndergaard et al., 2003; Roy et al., 2017). Besides quantifying P pools, sorbents and binding minerals play a major role in the question of P mobilization (Cui et al., 2018; Wang et al., 2019). Iron- (Fe) and

aluminum- (Al) oxides are two of the main P binders in soils (Lijklema, 1980). Therefore, a quantification of available Fe- and Al-oxides can help to give a prediction of how much of the P will be released to the future water column (Loeb et al., 2008; Renneson et al., 2015).

The P quantification plus the consideration of P binding factors resulting in a prediction of P release will help to answer the question if the restoration project of lake Søborg will be a success and meet the desired goals or if it will come to a major nutrient release resulting in an algae bloom, eutrophication and accompanied problems for humans and nature. Based on the underlying objectives from the Danish ministry of Environment and Food for the restoration project lake Søborg, this study has following aims and objectives:

I)   Quantify total and potentially available soil P and clarify if agricultural activity changed the soil P content of lake Søborg significantly since drainage of the lake

II) Give a prediction if implementing the restoration project and flooding the area will lead to a major P release

For this study soil samples of up to 100 cm depth were sampled from two transects and two pits across the future lake area. Quantification of P concentrations were carried out through chemical sequential extractions. Additionally soil properties like pH, bulk density, organic carbon and calcium carbonate content and iron and aluminum oxide concentrations were determined to characterize the sediments of lake Søborg.

2. Material and methods

2.1. Site description

The whole project site has an area of approximately 500 ha and is located in the north of the Danish island of Zealand, 4 km southeast of the town of Gilleleje (56°5'0 N, 12°18'0 E) (fig. 1). As all of Denmark it is located in the temperate climate zone. Like most of northern Europe, the area is geological influenced by the Weichselian glaciation (Houmark-Nielsen, 1989).

2.2. Site history

Being a fjord in the Pleistocene times with connection to the Kattegat sea area, Søborg became a lake with approximately 6 m above sea level throughout time due to the geological process of post-glacial rebound (Riis, 2014). It used to be the fourth largest lake on the island of Zealand until it was started to drain the lake in the 1790th to reclaim the land for agricultural purposes by using a system of channels. In the 1870th the lake was completely drained and nearly two centuries of agricultural activity started in the area (Miljø- og Fødevareministeriet, 2018). Nowadays this location is not an agricultural success anymore and is only partly tilled. It attracted notice of the Danish state and it was decided in 2016 to restore the area and reestablish the lake Søborg. Of the 500 ha project area 337 ha are supposed to be the lake in the future with a depth of mostly approximately 1 m. The rest of the area is dedicated to meadows and other green spaces (Miljø- og Fødevareministeriet, 2018).

Figure 1: Location of the project site (in red) on the Danish island of Zealand (Miljø- og Fødevareministeriet).

2.3. Experimental design and soil sampling

To localize the future lake site and set soil sampling spots, a project map from 2017, provided by the Danish Ministry of Environment and Food showing the boundaries of the future lake, was used (Miljø- og Fødevareministeriet, 2017). This map was georeferenced using ArcGis version 10.3. For covering most parts of the future lake area, 10 sampling points along two orthogonal transects were set on the georeferenced map (fig. 2). To investigate if there are differences in P concentrations or soil characteristics between the future inner lake and shore, the edges of each transect were set on locations that will be not covered by water according to the proposal from 2017 (fig. 2). The design was digitalized to gain the GPS coordinates of the sampling spots (appendix 2). Transect 1. had a total length of 2.3 km and each sampling spot was in 253 m distance, while transect 2. had a length of 1.6 km and the sampling spots were in 178 m distance of each other. Samples were taken in July 2018 to analyze the soil of the lake Søborg project site.
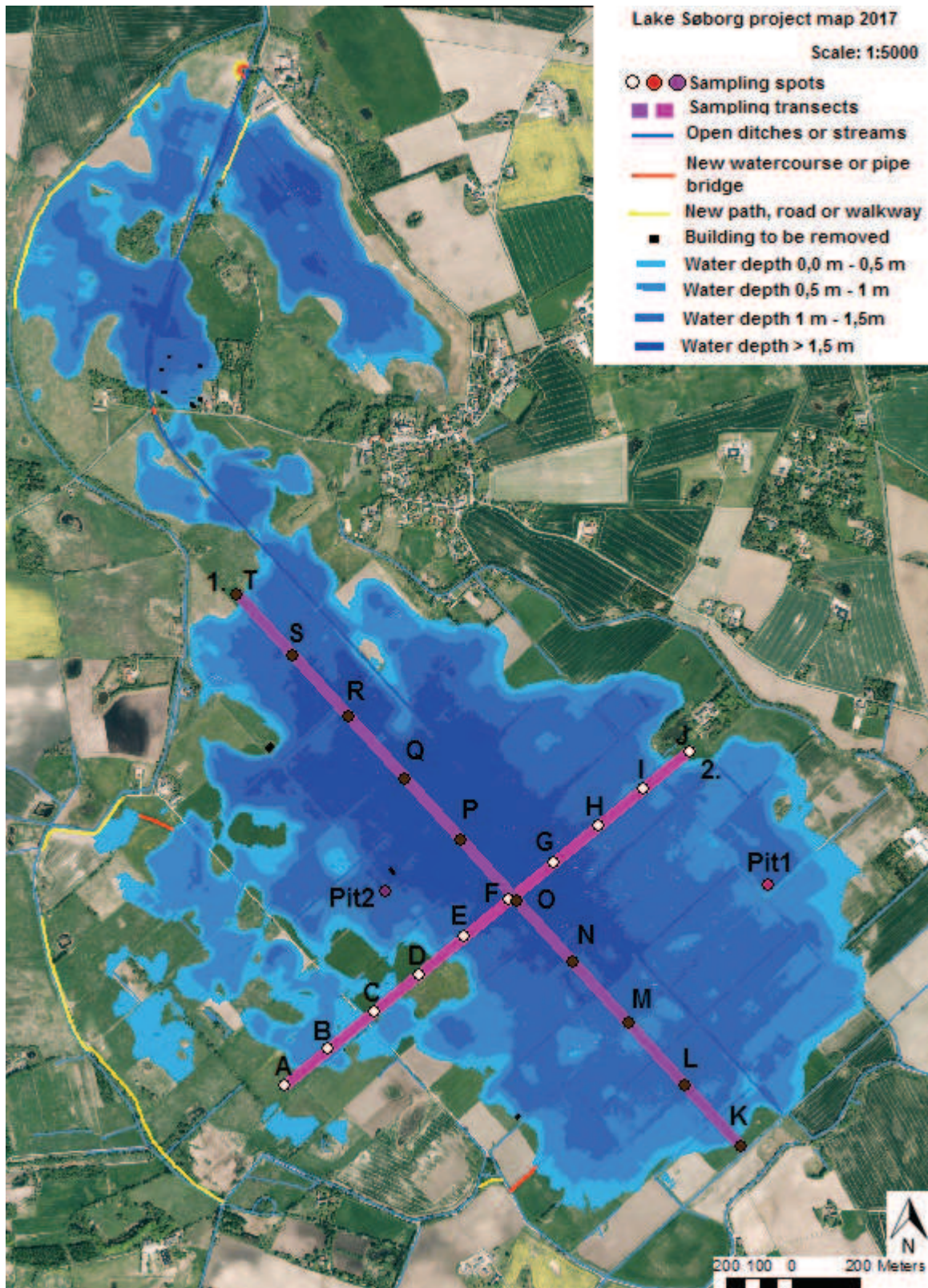
Figure 2: Shape of the projected lake Søborg and the experimental design of this study. Edited after Miljø- og Fødevareministeriet (2017).

To sample the soil samples, a one meter long steel soil auger was used. The one meter soil cores were then divided into parts of 20 cm length, dividing the core into five

different samples from different depths. In the following sample names are referred to as the name of the sampling spot (fig. 2) and carry the location in depth in cm (e.g. A 20-40 cm) (fig. 3).

Figure 3: Soil auger with taken soil core. Schematic design of horizontal subdivision of depths.

Besides the 20 sampling spots on the transects, two one meter deep pits with approximately one meter width and one meter length were dug (fig. 2, appendix 4 + 5). Samples of each horizon of the profiles were taken for analyses of P. With a steel ring of known volume, samples were taken for determination of bulk density (BD). Pit

samples were also used to get an overview of calcium carbonate ($CaCO_3$) and carbon (C) content of the soil.

2.4. Soil analyses

Prior analyses, the soil samples were oven dried at 105° C for 48 hours and sieved to 2 mm. Part of it was ground using a ball mill.

2.4.1. pH determination

The pH values of the soil samples were analyzed according to the Austrian standard method described in ÖNORM L 1083 (1999). 2.5 g of dry and 2 mm sieved soil was weighed into vials and mixed with 6.25 ml of 0.01 M calcium chloride ($CaCl_2$). The suspension was shaken well by hand and left for two hours for equilibration and sedimentation of the suspended soil particles. The pH was measured in the liquid phase using a pH-meter.

2.4.2. Bulk density

Pit samples for BD determination were oven dried at 55° C until constant weight. To get the BD the dry weight was divided through the known volume of the steel ring.

2.4.3. $CaCO_3$- and C content

$CaCO_3$- and inorganic C content of the pit samples were determined by the Institute of Soil Research (IBF) of BOKU. For $CaCO_3$ content the Scheibler method described in ÖNORM L 1084 (1999) was used. Total C contents were determined according to ÖNORM L 1080 (1999) and inorganic C calculated.

Total C concentrations of the pit samples were also determined at KU on ground samples by dry combustion, based on the Dumas method (Matejovic, 1993). Inorganic C values were then subtracted from total C to get the organic C (C_{org}) content of the pit samples.

2.4.4. Soil P extraction methods

I. Acidified ammonium oxalate extraction in darkness

The method description by Sparks (1996) was followed. To reach homogeneity of the samples the soil was finely ground using a ball mill. 0.5 g of each soil sample was weighed into vials for analysis. As a pre-step before the extraction could take place, $CaCO_3$ had to be removed from the samples. To do so, 30 ml of pH 5.5 1.0 M ammonium acetate was added to each sample and left to react for 1 h with intermittent stirring in vented containers. Acetic acid was added on top hourly until a constant pH value of 5.5 was reached. The samples were cleaned afterwards from acid, washing them with distilled water and air-drying for two weeks.

The vials containing the samples were wrapped in aluminum foil to prevent precipitation of iron in a light induced reaction and 30 ml of ammonium oxalate extraction solution was added. The samples were then transferred to an overhead shaker and shaken for two hours. They were afterwards centrifuged and the decant filtered through paper filter. Measurement for P_{ox}, Fe_{ox} and Al_{ox} took place using inductively coupled plasma optical emission spectrometry (ICP-OES). To ensure accuracy of the conducted data, a quality check in form of solution with known concentration of P, Fe and Al was used and measured like the actual samples. The extraction method dissolves amorphous inorganic forms of Fe- and Al-oxides (Sparks, 1996).

II. Soil digestion with aqua regia

A soil digestion with *aqua regia* was carried out following the Austrian standard method described in ÖNORM L1085 (1999). 0.5 g of fine ground and homogenized soil was weighed into glass tubes. After adding first 4.5 ml of 37 % hydrochloride acid and then 1.5 ml of 65 % nitric acid a drop of octanol was added to inhibit foaming. The mixture was left over night with coolers on top. The samples were placed into a digestion heater and the digestion temperature was stepwise increased to 150 C°. After reaching the final temperature, the digestion was run for three more hours. When the digestion was over, the inside of the coolers was rinsed inside the tubes and the volume of each sample was made up to approximately 50 ml using distilled water. The samples were shaken using a vortex shaker and filtered through paper filter into appropriate vials. Weights of glass tubes, samples and final weight were written down. The solution was

colored using the molybdenum blue method (Murphy and Riley, 1962) and P_{AR} measured at a photometer. To ensure accuracy of the data the reference soil ISE 885 from Wageningen (WEPAL, 2014) was treated and measured like the actual samples.

For simplicity the two methods are in the following also referred to as ammonium oxalate (ox)- and *aqua regia* (AR) extraction.

2.5. Data analyses and statistical methods

Statistical analyses were carried out using SPSS version 25. To determine mean concentrations of P and the soil parameters the frequency function was used. To see if the mean P concentrations of the different depths (transects) and horizons (pits) differ significantly from each other analyses of variance (ANOVA) were used. To check for correlations between P and Fe_{ox} or Al_{ox} linear functions were fitted with Excel version 16.22 and Pearson correlation coefficients were calculated.

The P stocks were determined using the formula: Bulk density x thickness of layer x P concentration. Since the bulk density was just determined for the pits, the mean of those values per depth was calculated and used as input for P stock calculation of the sites along the two transects. To see if there were significant differences in P stocks of the edges plus islands and the rest of the sampling spots ANOVA were applied. ANOVA were applied as well to see if there were significant differences in P stocks of spots where the future lake will be deeper than 1 m compared to the spots which will be more shallow (>1 m). A Pearson correlation test was performed to check for correlation between the two P extraction methods and the data was fitted with a linear function in Excel.

3. Results

3.1. Pits

The soil pH for the different horizons of the pits ranged between 6.9 and 7.3. C_{org} contents showed a higher variability in Pit1 with a range of 0.7 % in the deepest horizon to 8.1% in the upper horizon. In Pit2 there was no gradual trend in C_{org} and less variability with a range between 10.2 % and 14.6 %. $CaCO_3$ contents were high in both Pits and all horizons with a lowest value of 9.1 % (Pit1_A2) and a highest value of 45.4 % (Pit2_Cg2). The bulk density was low for both pits and almost all horizons. Sample Pit1_C2 had a comparatively high bulk density of 1.43 g cm^{-3} and was also the horizon with the lowest C_{org} content (tab. 1).

Table 1: pH, organic carbon, calcium carbonate content, soil bulk density, P extracted by *aqua regia* (AR) and ammonium oxalate (ox), iron and aluminum extracted by ox for the five horizons of Pit1 and Pit2. The presented values are means of duplicate measurements, except for pH, P_{ox}, P_{AR}, Fe_{ox}, Al_{ox} and bulk density of certain samples (*) which were single measurements.

Horizon	pH	C_{org} %	$CaCO_3$ %	Bulk density g cm^{-3}	P_{AR}	P_{ox}	Fe_{ox}	Al_{ox}
					——	g kg^{-1}	——	
Pit1								
Ap	7.1	8.1	12.2	0.85	0.91	0.70	8.70	0.43
A2	7.2	7.0	9.1	0.72	0.84	0.50	7.97	0.41
Bw	7.3	5.5	27.3	0.76	0.65	0.26	11.08	0.21
C1	7.2	4.2	29.8	0.66	0.56	0.27	10.23	0.34
C2	7.1	0.7	18.0	1.43*	0.60	0.38	4.38	0.53
Pit2								
Ap	7.2	10.2	13.2	0.80	0.74	0.33	9.28	0.41
Bwg	7.1	14.6	29.3	0.69	0.64	0.30	15.14	0.33
Cg1	7.0	12.0	31.2	0.64*	0.72	0.32	7.54	0.31
Cg2	6.9	13.3	45.4	0.42*	0.69	0.30	3.68	0.23
Cg3	6.9	14.0	39.2	0.31*	0.71	0.30	4.10	0.22

While P_{AR} and P_{ox} concentrations in Pit1 showed a trend of higher values in the upper layers, horizons of Pit2 showed almost no difference in P concentrations. Fe_{ox} concentrations showed high variability in both Pits and ranged between 3.7 g kg^{-1} (Pit2_Cg2) and 15.1 g kg^{-1} (Pit2_Bwg). Al_{ox} concentration for Pit1 showed no gradual trend in depth and was the highest in the deepest horizon. Pit2 had the highest Al_{ox} concentration in the upper horizon and the lowest in the deepest horizon (tab. 1).

3.2. Transects

Mean soil pH value for every depth was 7.3, except for the top soil (0-20 cm) which had a mean of 7.1 (tab. 2).

Table 2: Mean soil pH, P extracted by *aqua regia* (AR) and ammonium oxalate (ox), iron and aluminum extracted by ox for 20 sites along two transects (fig. 2). Standard deviations of means are shown in brackets.

Soil depth cm	pH	P_{AR} g kg^{-1}	P_{ox} g kg^{-1}	Fe_{ox} g kg^{-1}	Al_{ox} g kg^{-1}
0-20	7.1 (0.1)	0.8 (0.3)	0.4 (0.3)	7.8 (3.1)	0.4 (0.1)
20-40	7.3 (0.1)	0.7 (0.3)	0.4 (0.3)	9.7 (5.1)	0.4 (0.1)
40-60	7.3 (0.2)	0.7 (0.3)	0.4 (0.3)	8.4 (4.6)	0.4 (0.1)
60-80	7.3 (0.3)	0.6 (0.3)	0.3 (0.2)	6.9 (4.2)	0.3 (0.2)
80-100	7.3 (0.2)	0.7 (0.3)	0.4 (0.3)	8.2 (4.2)	0.3 (0.1)

Fe_{ox} showed a high variability between but also within the five different depths. Mean Al_{ox} values of the different depths showed only little variability.

There were no significant differences of mean P_{AR} (p = 0.68) or P_{ox} (p = 0.75) concentrations between the different depths.

Mean P_{ox} or P_{AR} concentrations of the upper layer (0-20 cm) did not show significant differences to the underlying layer 20-40 cm or 40-60 cm (tab. 3).

Table 3: ANOVA between mean P_{ox} and P_{AR} concentrations of the top soil (0-20 cm) and underlying layers.

	p value
P_{ox}	
0-20cm ≠ 20-40 cm	0.83
0-20 cm ≠ 40-60 cm	0.45
P_{AR}	
0-20cm ≠ 20-40 cm	0.71
0-20 cm ≠ 40-60 cm	0.52

There was a high variance of P_{AR} and P_{ox} concentrations within the different depths (tab. 2, appendix 1).

3.3. P stocks of transects

The end spots (A, J, K, T) of both transects had the lowest P stocks while stocks at spots that will be the future inner part of the lake were higher (fig. 4, fig. 5).
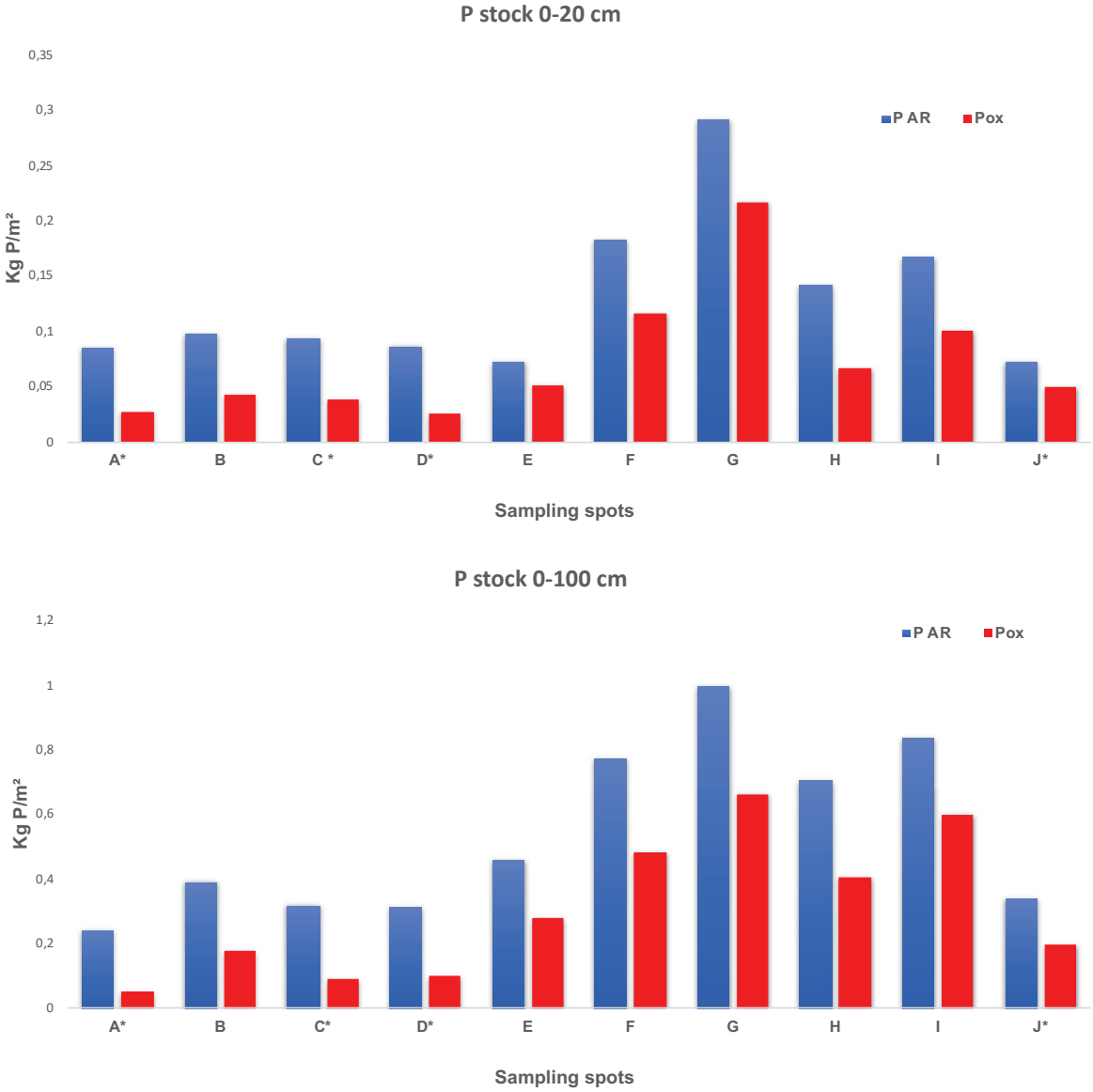
Figure 4: P stocks (Kg m⁻²) for the top soil (0-20 cm) and the whole profile (0-100 cm) calculated from P_{AR} and P_{ox} for sites along transect 1. (fig. 2). Spots A* and J* symbolize future edges of the lake, C* and D* elevated islands. Means of bulk densities of Pit samples taken for stock calculation.

Sampling spot G showed the highest P stock for the upper layer and the whole profile while spot A, which symbolizes an edge, showed the lowest stock for transect 1 (fig. 4).

P stock 0-20 cm
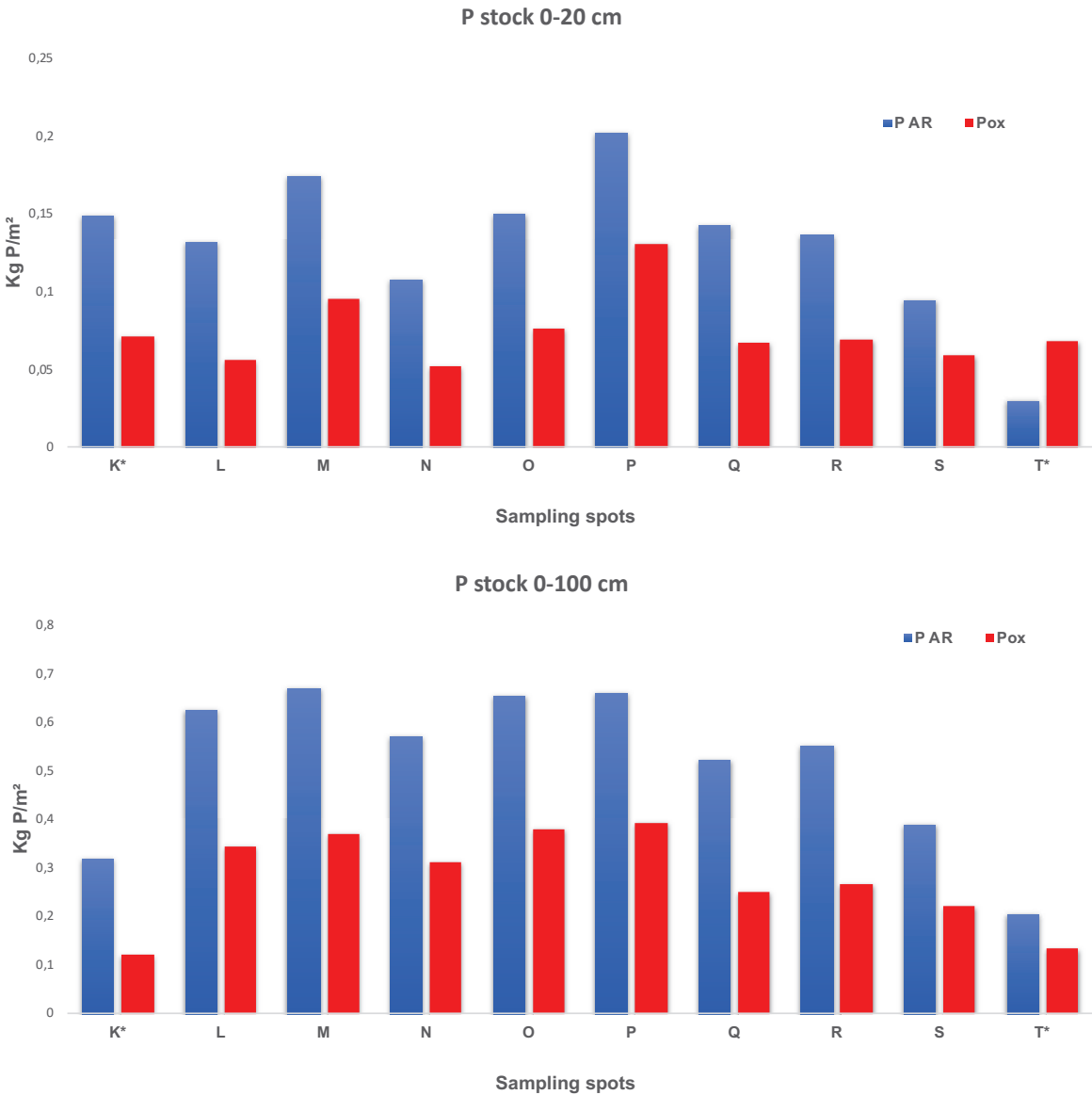
P stock 0-100 cm

Figure 5: P stocks (Kg m^{-2}) for the top soil (0-20 cm) and the whole profile (0-100 cm) calculated from P$_{AR}$ and P$_{ox}$ for sites along transect 2. (fig. 2). Spots K* and T* symbolize future edges of the lake. Mean of bulk densities of Pit samples taken for stock calculation.

For transect 2. sampling spot P showed the highest stock for the upper layer (both extractions). However spot M showed the highest stock for the whole profile, slightly higher than for Spot P (P$_{AR}$). For P$_{ox}$ it was the opposite. Spots T (P$_{AR}$) and N (P$_{ox}$)

showed the lowest stocks for the upper layer while T (P_{AR}) and K (P_{ox}) showed the lowest stocks for the whole profile (fig. 5).

Applied ANOVA revealed that for the upper layer (0-20 cm) there was no significant difference between mean P_{ox} stocks of the edges plus islands and the rest of the sampling spots (p = 0.06) but a significant difference when considering the P_{AR} stocks (p = 0.02).

For the whole profile (0-100 cm) there was a significant difference between mean P_{ox} stocks of the edges plus islands and the rest of the sampling spots (p < 0.001), taken the P_{AR} stocks there was a significant difference as well (p < 0.001). Mean P_{ox} stocks of spots where the future lake will be deeper than 1 m (fig. 2, appendix 3) were significantly higher than stocks of spots where the lake will be shallow (>1 m) (p = 0.01). The same accounts when considering P_{AR} stocks (p = 0.004).

3.4. Soil pH of transects and pits

Soil pH of all samples ranged between 6.9 (sample Pit2_Cg2) and 7.9 (sample A 80-100 cm) (appendix 1). Mean soil pH was 7.3 (St. Dev. 0.2).

3.5. Ammonium oxalate extraction transects and pits

An overall high variability of P_{ox} concentrations within all samples could be observed with 0.03 g kg^{-1} (sample A 60-80 cm) as the lowest and 1.3 g kg^{-1} (sample G 0-20 cm) as the highest value (appendix 1). The mean P_{ox} concentration was 0.4 g kg^{-1} (St. Dev. 0.2).

For the Fe quality check the recovery was in a range between 100 %-106 %. For P a recovery range between 79 % as worst and 99 % as the best result could be reached. For Al the recovery range was between 85 %-100 %. Considering the lower recovery values it should be considered that the ammonium oxalate extractable P and Al concentrations might be slightly underestimated.

P_{ox} concentrations in all samples showed a stronger correlation with Fe_{ox} (r = 0.64) and a moderate correlation with Al_{ox} (r = 0.48) values (fig. 6).

Figure 6: Linear correlation between P_{ox}, Fe_{ox} and Al_{ox} concentrations of all samples. Value of Pearson correlation test given.

3.6. *Aqua regia* extraction transects and pits

An overall high variability of P_{AR} concentrations within all samples could be observed with 0.2 g kg^{-1} (sample A 60-80 cm) as the lowest and 1.8 g kg^{-1} (sample G 0-20 cm) as the highest value (appendix 1). Mean P_{AR} concentration was 0.7 g kg^{-1} (St. Dev.

0.3). The recovery for the quality check turned out to be in between 83 % and 87 %. Since a recovery of at least 95 % was not reached, the P_{AR} concentrations of the actual samples might be slightly underestimated.

P_{AR} concentrations of all samples showed a stronger correlation with Fe_{ox} (r = 0.62) and a moderate correlation with Al_{ox} values (r = 0.37) (fig. 7).

Figure 7: Linear correlation between P_{AR}, Fe_{ox} and Al_{ox} concentrations of all samples. Value of Pearson correlation test given.

3.7. Comparison of extraction methods

A linear correlation and Pearson correlation test between P_{AR} and P_{ox} concentrations of all samples revealed a strong correlation between these two P pools (r = 0.95) (fig. 8).

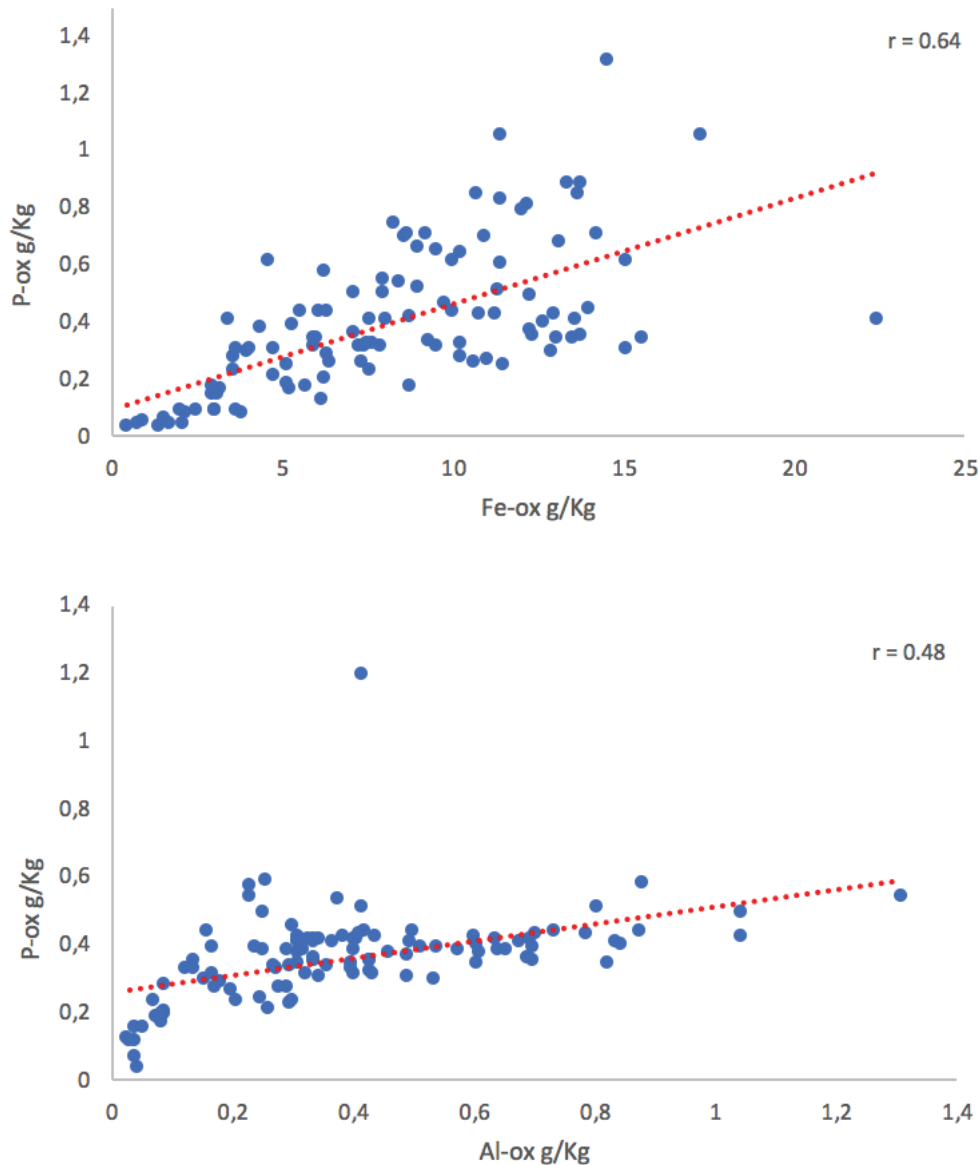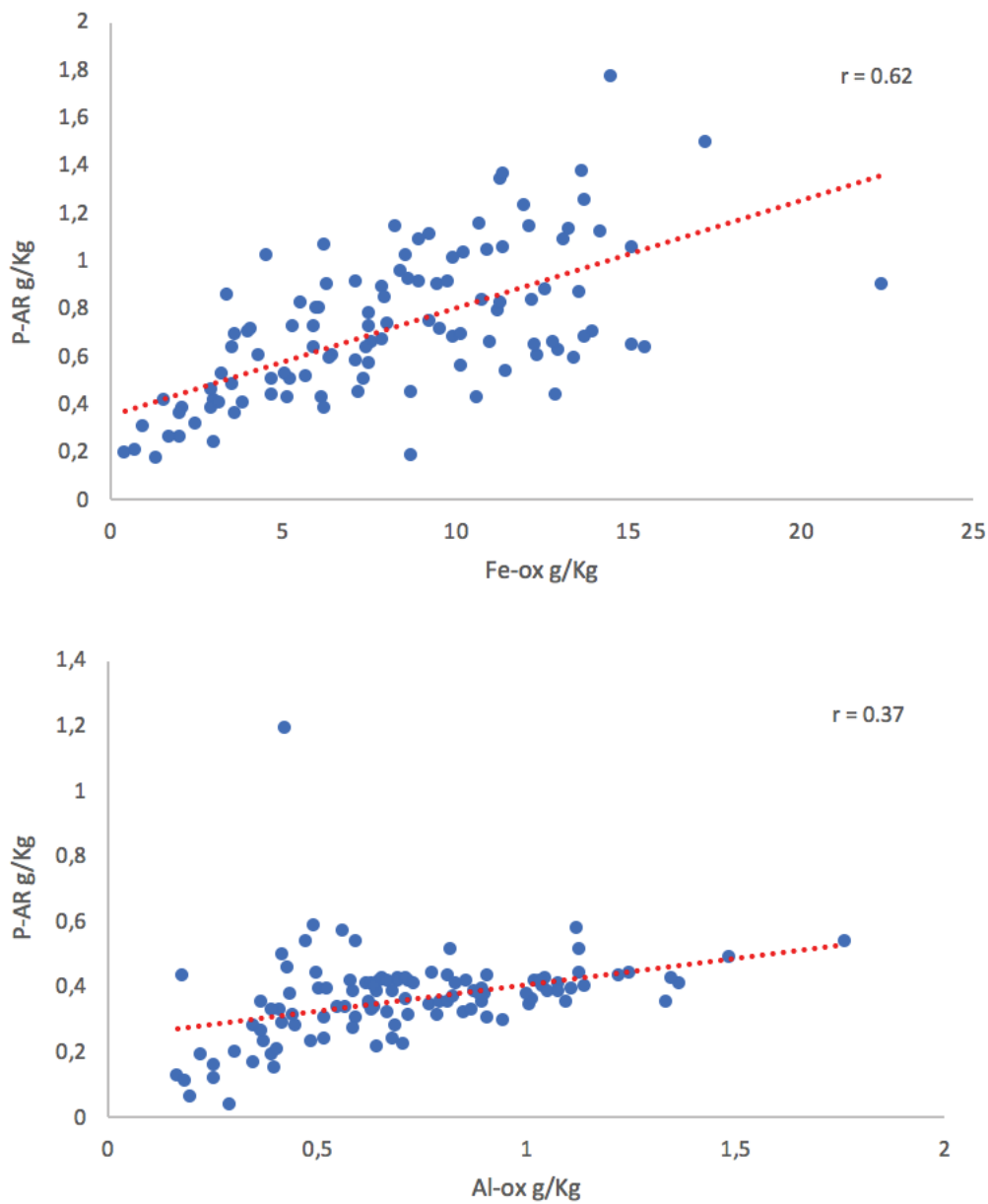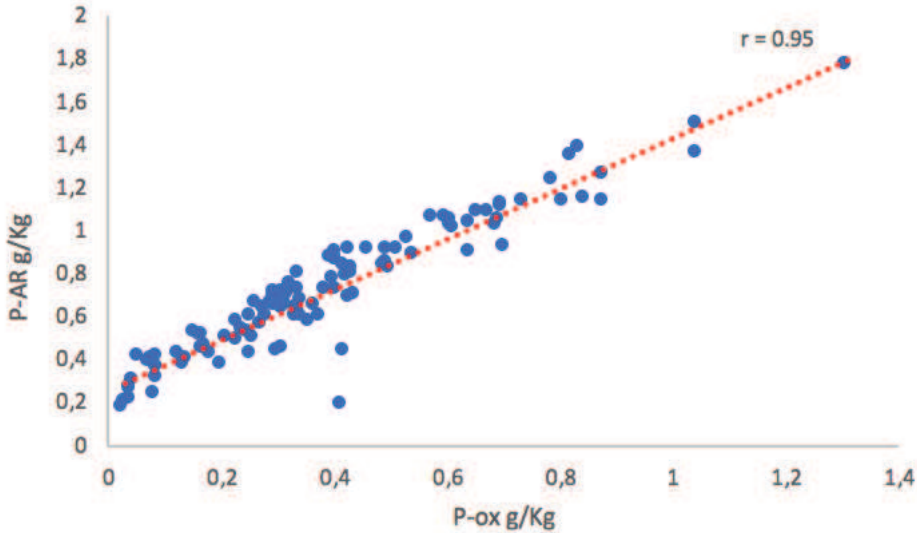**Figure 8: Linear correlation between P_{AR} and P_{ox} concentrations of all samples. Value of Pearson correlation test given.**

4. Discussion

Comparison of the different extraction methods

A*qua regia* was, except for sample T 0-20 cm (appendix 1), able to extract more P compared to ammonium oxalate and P concentrations of both methods were highly correlated with each other (r = 0.95) (fig. 8). To dissolve all P-bonds in the soil and extract all the available P, very strong acid solutions like a mixture of *aqua regia* and hydrofluoric acid are being used (Gaudino et al., 2007). *Aqua regia* can be considered as slightly weaker, it breaks most but not all of the P bonds. It can be referred to as a method which extracts the semi or pseudo total P (Schnug and De Kok, 2016). Nawara et al. (2017) state that the ammonium oxalate extraction can extract between 50 and 90 percent of the total soil P, depending on the content of amorphous Fe- and Al-oxides. Considering that the *aqua regia* extraction extracted in average 0.7 g kg^{-1} P and the ammonium oxalate extraction 0.4 g kg^{-1} P, which makes approximately 57 % of what was extracted by *aqua regia*, the results are in line with that.

P content of the study area

The P content of the project site is moderate to high but does not follow a usual P gradient typical for a common agricultural soil (tab. 2). Usually the content and availability of phosphates in agricultural soils is the highest in the top layer and declines with increasing depth (Giehl and Wirén, 2014). This big surplus of P in the top part of agricultural soils is typically due to application of mineral fertilizer and manure (Withers et al., 2006; Jayarathne et al., 2016). For lake Søborg the top layer did not show significant differences in P concentration compared to subsoil layers and in general there were no significant differences between mean P_{AR} or P_{ox} concentrations of the different depths (tab. 2). The *aqua regia* extraction for example revealed that the top soil (0-20 cm) along the transects contains in average 0.8 g kg^{-1} P_{AR}, while in a depth of 80-100 cm a content of 0.7 g kg^{-1} P_{AR} could still be found (tab. 2). Hence, the results suggest that P concentrations in the soil of lake Søborg were not significantly influenced by the decades of agricultural activity in the area, the high concentrations rather originated from the sediments of the original lake. The P stocks give as well information about origin of the soil P and can provide indication about possible behavior after flooding. Except for the P_{ox} stocks of the top layer, mean P stocks of the future edges and islands of the lake were significantly lower than stocks of the rest of

the spots (fig. 4 + 5). Mean P stocks of spots where the lake will be deeper than 1 m were significantly higher than stocks of the rest of the spots (calculated for 0-100 cm thickness layer). Those geomorphologically lower areas used to be the lake bottom back then before the lake got drained.

To explain the circumstance of such high P concentrations and to understand why there was a major P retention when Søborg used to be a lake, the history and geology of the area needs to be considered. Massive ice sheets which caused isostatic depression and thereby a sinking of major parts of the earth's crust disappeared with the end of the Weichselian glaciation. The result was a rebound and lifting of land masses (Lambeck, 2001). Major parts of Scandinavia and northern Germany are geological influenced by this phenomenon (Lambeck et al., 1998). The project area used to be part of the Kattegat sea and this sea ground most likely got lifted up (Devoy, 1987; Riis, 2014). Indication that we are dealing with marine sediments in the case of lake Søborg is given by the low bulk density and the high organic C contents of the pit samples (tab. 1). Low bulk densities can be the outcome of high organic C contents in soils (Curtis and Post, 1964), which seems to be the case for the project area. The pit samples showed very low bulk densities but in turn high organic C content. The only exception was the sample Pit1_C2, where the bulk density was much higher compared to the other samples but in turn the organic C content was low (tab. 1). The high organic C contents that were determined in depths up to 100 cm can be of marine origin and could have derived from marine plants (Meyers and Ishiwatari, 1995). Additionally, the bulk density can be linked to the $CaCO_3$ content of a soil, Chaudhari et al. (2013) for example showed a negative correlation between $CaCO_3$ content and soil bulk density. Similar seems to account for lake Søborg, the pit samples with very low bulk densities like Pit2_Cg2 or Pit2_Cg3 showed also the highest $CaCO_3$ contents (tab. 1).

To understand how former sea ground can influence the P content in soils of today, it needs to be closer looked at the geochemistry of that matter. The ground of the Baltic sea consists in large parts of carbonate bearing limestone (Winterhalter et al., 1981). Through the described geological processes of post-glacial rebound this limestone got lifted up. Besides observations during the lab work like heavy reactions of the soil after adding acid, the pH values of the samples and the high $CaCO_3$ contents of the pit samples of up to 45.4 % clearly show that the project area is highly calcareous and

limestone influenced (Rogovska et al., 2007). In calcareous sediments, phosphates can be strongly adsorbed to the bearing $CaCO_3$ and the compound can occur as precipitated phosphate salts (Golterman, 1997; Koch et al., 2001; Dong et al. 2011). Williams and Mayer (1972) subdivide the adsorption of P to inorganic compounds in three major cases, one of them is the P associated with carbonates. Freeman and Rowell (1981) and Amer et al. (1985) emphasize the big influence of precipitation reactions and adsorption through $CaCO_3$ on P sorption in calcareous soils. Kaiserli et al. (2002) highlight calcium bound P as stable fraction and its contribution to permanent P burial in soils. Zhou and Li (2001) and Wandruszka (2006) point out that at relatively high soil P concentrations calcium carbonates play a significant role in the P retention of calcareous soils by precipitation and adsorption. This P fraction is likely contributing to the high P contents of lake Søborg.

To gain the crucial information about the P distribution in depth which makes it possible to draw conclusions on history and the origin of the available P pools justifies the relatively high sampling depth of up to 100 cm in this study, while in many other studies just the approximately top 10 cm were reported as important for the lake nutrient dynamics (Boström et al., 1982; Wang et al., 2003). Other studies investigated a sediment P release to water bodies from depths down to 25 cm (Søndergaard et al., 1999). It needs to be also considered that in the investigated area there will likely be a major influx and input from ground water into the lake which could potentially mobilize P from layers lower than 25 cm.

Soil pH

The soil pH ranged between 6.9-7.9 and the mean was around 7.3. Thus, the soil of the project site can be classified as neutral to slightly alkaline (Jayarathne et al., 2016). Soil pH can be seen as proxy or indicator of how the P is interacting in the soil solid phase and which minerals might be the most influential. While at low pH values and respectively in acidic soils Fe and Al play a bigger role in P retention, in rather alkaline soils like in this study the solubility of P is dominated by the contents of Ca (FIFA, 2006; Vohla et al., 2011). This supports the conclusion that $CaCO_3$ plays a bigger role of P retention in lake Søborg.

Considering the calcareous character of the soil, $CaCO_3$ content is most likely also controlling the pH level (Huang et al., 2012; Carating et al., 2014). To explain why there was less $CaCO_3$ in the A horizon of the pit samples (tab. 1), geochemical processes

should be considered. Jensen et al. (2005) emphasize that soils in eastern Denmark are highly influenced through the Saale and Weichselian glaciation, which created limestone influenced soils of high $CaCO_3$ content. They elaborate that $CaCO_3$ can be found in lower horizons and can make up to 30-40 % of the till. However, the topsoil would have lost $CaCO_3$ partly through exposure to acidic rain or more generally acidification processes which can be for example decomposition linked. Lake Søborg's soil is from marine origin, nevertheless these findings describe the picture of $CaCO_3$ distribution in depth and might give the answer for reduced $CaCO_3$ content in the A horizon.

Ponnamperuma (1972) and Fageria et al. (2011) emphasize a pH drop of submerged alkaline soils due to microbial decomposition, which would lead to CO_2 production and respectively to formation of carbonic acid and acidification. However it should be kept in mind that microbial decomposition of organic matter is usually much lower in submerged soils since it will just take place through anaerobic bacteria anymore (Kozlowski and Pallardy, 1997). A decrease of soil pH in alkaline calcareous soils could promote solubility of calcium carbonates and thereby result in loss of Ca ions which influences P sorption (Yan et al., 2018). For lake Søborg a major change of pH does not need to be expected. $CaCO_3$ contents are still quite high to buffer acidification and exposure to acidification processes like through acidic rain will stop after flooding.

Fe$_{ox}$ and associated P

The high P concentrations and the associated high amounts of Al and Fe measured in ammonium oxalate indicated that a substantial fraction of P was bound to amorphous Fe- and Al-oxides and that these Fe- and Al-oxides play a role in controlling the P sorption in the soil of the investigated site (Arai et al., 2005; Rick and Arai, 2011; Arai and Livi, 2013). P_{AR} and P_{ox} showed both strong correlations with Fe_{ox} (r = 0.62 for P_{AR}; r = 0.64 for P_{ox}) and moderate correlations with Al_{ox} (r = 0.37 for P_{AR}; r = 0.48 for P_{ox}) (fig. 6 + 7). In the mean P_{ox} concentrations of all samples had a moderate value of 0.4 g Kg^{-1}. One of the most common and traditional described scenarios for P release from lake sediments is the reduction of sediment iron (III) to iron (II) (Einsele, 1936; Mortimer, 1942; Surridge et al., 2012) which has been also shown in context with continuous flooding (Richardson and Marhsall, 1986; Phillips, 2001). Iron (III) has a high capability to bind phosphate. When the redox potential in the soil-water interface drops below a certain value, iron (III) gets reduced to iron (II) (Loeb et al., 2008). P can

be partly released since it shows a weaker affinity to iron (II) (Ponnamperuma, 1972; Loeb et al., 2008; Kröger et al., 2012). Anaerobic conditions cause this drop of redox potential which gets created when an area gets flooded (Amarawansha et al., 2015). Thus, restoration and reestablishing of lakes may likely induce the process described above. Looking at the mentioned 57 % of P that the ammonium oxalate extraction was able to extract in relation to the semi-total P_{AR} and at the strong correlations with Fe_{ox} (fig. 6 +7), the P content that is associated with Fe and could be potentially mobilized through changes in redox potential after flooding is moderate to high. However, Freese et al. (1992) have a contradicting remark by stating that in calcareous soils P_{ox} can also include forms of P such as Ca-P. Studies reported a major P release also in calcareous and alkaline soils after flooding induced anaerobic conditions (e.g. Amarawansha et al., 2015; Jayarathne et al., 2016). While some studies showed a bigger P release and mobilization after the reduction of iron (III), this process is not expected to occur in a relevant manner in the future lake Søborg. Lake Søborg, which will have a depth of 1.0-1.5 m in most of its area according to the proposal from 2017, could be classified as a shallow lake. Shallow lakes can be defined as lakes where sun light can penetrate to the lake bottom (Meerhoff and Jeppesen, 2009). Usually they are well mixed in aspect of oxygen and will therefore most likely be well oxidized throughout the whole water column (Søndergaard et al., 2003). An associated aerobic layer at the sediment surface will maintain iron (III) which in turn retains P (Scheffer, 2004; Aldous et al., 2005). However, P sorbents other than Fe like Ca or Al are considered as being not affected by the redox conditions (Hupfer and Lewandowski, 2008).

Al_{ox} and associated P

Various authors have shown the ability of Al to permanently bind P in soils (e.g. Rydin et al., 2000; Lewandowski et al., 2003; Huser et al., 2011). Aluminum containing agents have been widely used in lake restoration to control internal P loadings (Cooke et al., 2005). In their review paper about the oxygen control of P release from lake sediments Hupfer and Lewandowski (2008) conclude that the presence of Al-oxides can completely prevent P release and can even immobilize P released from Fe. Renneson et al. (2015) have found Al_{ox} in connection with P_{ox} concentrations as most useful parameter to predict P retention or release for their studied neutral to alkaline soils in Belgium. Their soils were also obtained from agricultural areas and P fixation linked to

calcium ions or carbonates played an important role as well. However, the study focused on short term experiments under lab conditions and not long term field monitoring and therefore results can be just partly projected on long term real case flooding. In the case of lake Søborg, Al_{ox} showed weaker correlations with P_{AR} and P_{ox} compared to Fe_{ox} (fig. 6 +7). As can be seen in table 2, Al_{ox} contents did not show any significant differences throughout the depths. While the top soil (0-20 cm) had in average a concentration of 0.4 g Kg^{-1} Al_{ox}, in the deepest layer 0.3 g Kg^{-1} Al_{ox} were found. This indicates that Al contents have not been changing throughout the decades of agricultural use of the area and concentrations likely hardly changed after drainage. Due to this fact and the described stable and redox insensitive characteristics of Al bound P, Al_{ox} will most likely play a subordinated role for potential P release after flooding the project area.

Calcareous soil character and potential P release

Amarawansha et al. (2016) pointed out that most studies of P release in context with flooding have been carried out for acidic soils, however limited literature and studies are available for alkaline soils. Kolahchi and Jalali (2013) performed leaching experiments with two different calcareous soils. They concluded that P movement in their calcareous soils from Iran is markedly influenced by precipitation and sorption of $CaCO_3$ minerals which significantly reduced P leaching. Plach et al. (2018) investigated potential P loss and runoff from glacial landforms of the lower Great Lakes region (USA and Canada). The study was dealing with soils from agricultural fields which were either of highly calcareous hummocky till or slightly calcareous lacustrine origin. Their P fractionation based approach suggests that the highly calcareous hummocky till although having a very high total P content has a low risk for P loss and leaching due to its stable P pools. Total P concentrations of their study were comparable to P_{AR} contents of lake Søborg or even exceeded them with a concentration of 0.9 g Kg^{-1} P in the top 5 cm. Christophoridis and Fytianos (2006) studied the sediment P release rates of two lakes in Greece and concluded that the compared to other cases relatively low release rates are due to the calcareous character of the lakes sediments which would represent stable P pools. The authors were also using a P fractionation based approach to determine P pools and also carried out soil column experiments under oxic conditions to determine P release.

Summing up, P associated with calcareous sediment properties has been described as a stable fraction, rather unsusceptible to drastic mobilization. Nonetheless, there is a lack in literature of field monitoring of long term real case flooding of calcareous soils and associated P release. Results of short term release experiments under lab conditions can be just partly used for the case of lake Søborg or similar cases.

5. Conclusion and outlook

The results of this study revealed that the P content of the project ground lake Søborg was moderate to high but not influenced by the nearly two centuries of agricultural activity in the area. The P distribution in depth emphasizes that P concentrations were determined by the geological history of the region. There is a moderate fraction of P associated to Fe_{ox} which would inhibit the risk of P release due to redox potential changes in context with flooding. Due to the circumstance that the future lake Søborg will be a shallow lake this risk is however quite low.

Since there was likely no significant change in P concentrations in the approximately last two hundred years since drainage, P fluxes will behave probably in a similar manner like when Søborg was still a lake. Thus, no drastic P release is expected. There is still a gap in literature of flooding of calcareous soils, more research needs to be done in that field. Further studies could include flooding experiments with soil samples of lake Søborg, determine concentrations of other P sorbents like calcium, manganese or magnesium or investigate the geological age of the soil.

6. References

Aldous, A., McCormick, P., Ferguson, C., Graham, S. & Craft, C. Hydrologic Regime Controls Soil Phosphorus Fluxes in Restoration and Undisturbed Wetlands. *Restor. Ecol.* **13**, 341–347 (2005).

Amarawansha, G., Kumaragamage, D., Flaten, D., Zvomuya, F. & Tenuta, M. Predicting Phosphorus Release from Anaerobic, Alkaline, Flooded Soils. *J. Environ. Qual.* **45**, 1452 (2016).

Amarawansha, E. A. G. S., Kumaragamage, D., Flaten, D., Zvomuya, F. & Tenuta, M. Phosphorus Mobilization from Manure-Amended and Unamended Alkaline Soils to Overlying Water during Simulated Flooding. *J. Environ. Qual.* **44**, 1252 (2015).

Amer, F., Mahmoud, A. A. & Sabet, V. Zeta Potential and Surface Area of Calcium Carbonate as Related to Phosphate Sorption. *Soil Sci. Soc. Am. J.* **49**, 1137 (1985).

Arai, Y., Livi, K. J. T. & Sparks, D. L. Phosphate Reactivity in Long-Term Poultry Litter-Amended Southern Delaware Sandy Soils. *Soil Sci. Soc. Am. J.* **69**, 616 (2005).

Arai, Y. & Livi, K. J. Underassessed phosphorus fixation mechanisms in soil sand fraction. *Geoderma* **192**, 422–429 (2013).

Benayas, J. M. R., Newton, A. C., Diaz, A. & Bullock, J. M. Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. *Science* **325**, 1121–1124 (2009).

Biggs, J., von Fumetti, S. & Kelly-Quinn, M. The importance of small waterbodies for biodiversity and ecosystem services: implications for policy makers. *Hydrobiologia* **793**, 3–39 (2017).

Bormans, M., Maršálek, B. & Jančula, D. Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: a review. *Aquat. Ecol.* **50**, 407–422 (2016).

Boström, B., Andersen, J. M., Fleischer, S. & Jansson, M. Exchange of phosphorus across the sediment-water interface. *Hydrobiologia* **170**, 229–244 (1988).

Boström, B., Ahlgren, I. & Bell, R. Internal nutrient loading in a eutrophic lake, reflected in seasonal variations of some sediment parameters. *SIL Proc. 1922-2010* **22**, 3335–3339 (1985).

Boström, B., Jansson, M. & Forsberg, C. Phosphorus release from lake sediments. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* **18**: 5–59 (1982).

Buckley, M. C. & Crone, E. E. Negative Off-Site Impacts of Ecological Restoration: Understanding and Addressing the Conflict. *Conserv. Biol.* **22**, 1118–1124 (2008).

Bukowska, A., Kaliński, T., Koper, M., Kostrzewska-Szlakowska, I., Kwiatowski, J., Mazur-Marzec, H. & Jasser, I. Predicting blooms of toxic cyanobacteria in eutrophic lakes with diverse cyanobacterial communities. *Sci. Rep.* **7**, 8342 (2017).

Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., Galloway, J. N., Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M. A., McRae, L., Minasyan, A., Morcillo, M. H., Oldfield, T. E. E., Pauly, D., Quader, S., Revenga, C., Sauer, J. R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N., Symes, A., Tierney, M., Tyrrell, T. D., Vié, J.-C. & Watson, R. Global Biodiversity: Indicators of Recent Declines. *Science* **328**, 1164–1168 (2010).

Carating, R. B., Galanta, R. G. & Bacatio, C. D. *The soils of the Philippines*. (Springer, 2014).

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M. & Maity, S. Soil Bulk Density as related to Soil Texture, Organic Matter Content and available total Nutrients of Coimbatore Soil. *International Journal of Scientific & Research Publications.* **3**, 1– 8 (2013).

Christophoridis, C. & Fytianos, K. Conditions Affecting the Release of Phosphorus from Surface Lake Sediments. *J. Environ. Qual.* **35**, 1181 (2006).

Cooke, G. D., Welch, E. B., Peterson, S. & Nichols, S. A. Restoration and management of lakes and reservoirs. Taylor & Francis, CRC, (2005).

Cui, Y., Xiao, R., Xie, Y. & Zhang, M. Phosphorus fraction and phosphate sorption-release characteristics of the wetland sediments in the Yellow River Delta. *Phys. Chem. Earth Parts ABC* **103**, 19–27 (2018).

Curtis, R. O. & Post, B. W. Estimating Bulk Density from Organic-Matter Content in Some Vermont Forest Soils1. *Soil Sci. Soc. Am. J.* **28**, 285 (1964).

Devoy, R.J.N. Sea-level changes during the Holocene: the North Atlantic and Arctic oceans. In Devoy, R.J.N. (ed.), Sea Surface Studies, 294–347. London: Croom Helm (1987).

Dong, L. M., Yang, Z. F. & Liu, X. H. Factors affecting the internal loading of

phosphorus from calcareous sediments of Baiyangdian Lake in North China. *Environ. Earth Sci.* **64**, 1617–1624 (2011).

Einsele, W. Über die Beziehungen des Eisenkreislaufs zum Phosphatkreislauf im eutrophen See. *Arch Hydrobiol.* **29**: 664–686 (1936).

Erwin, K. L. Wetlands and global climate change: the role of wetland restoration in a changing world. *Wetl. Ecol. Manag.* **17**, 71–84 (2009).

Fageria, N. K., Carvalho, G. D., Santos, A. B., Ferreira, E. P. B. & Knupp, A. M. Chemistry of Lowland Rice Soils and Nutrient Availability. *Commun. Soil Sci. Plant Anal.* **42**, 1913–1933 (2011).

FIFA. Australian soil fertility manual, 3rd edition. Fertilizer Industry Federation of Australia (FIFA), CSIRO Publishing, Collingwood, Victoria (2006).

Fink, J. R., Inda, A. V., Tiecher, T. & Barrón, V. Iron oxides and organic matter on soil phosphorus availability. *Ciênc. E Agrotecnologia* **40**, 369–379 (2016).

Fischer, P., Pöthig, R. & Venohr, M. The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. *Sci. Total Environ.* **599–600**, 1130–1139 (2017).

Filippelli, G. M. The Global Phosphorus Cycle. *Rev. Mineral. Geochem.* **48**, 391–425 (2002).

Fleming, C. M. & Cook, A. The recreational value of Lake McKenzie, Fraser Island: An application of the travel cost method. *Tour. Manag.* **29**, 1197–1205 (2008).

Freeman, J. S. & Rowell, D. L. THE ADSORPTION AND PRECIPITATION OF PHOSPHATE ONTO CALCITE. *J. Soil Sci.* **32**, 75–84 (1981).

Freese, D., Zee, S. E. A. T. M. & Riemsdijk, W. H. Comparison of different models for phosphate sorption as a function of the iron and aluminium oxides of soils. *J. Soil Sci.* **43**, 729–738 (1992).

Gaudino, S., Galas, C., Belli, M., Barbizzi, S., Zorzi, P., Jacimovic, R., Jeran, Z., Pati, A. & Sansone, U. The role of different soil sample digestion methods on trace elements analysis: a comparison of ICP-MS and INAA measurement results. *Accreditation Qual. Assur.* **12**, 84–93 (2007).

Giehl, R. F. H. & von Wiren, N. Root Nutrient Foraging. *PLANT Physiol.* **166**, 509–517 (2014).

Golterman, H.L. The distribution of phosphate over iron-bound and calcium-bound

phosphate in stratified sediments. *Hydrobiologia* 364: **75** (1997).

Hahn, C., Prasuhn, V., Stamm, C. & Schulin, R. Phosphorus losses in runoff from manured grassland of different soil P status at two rainfall intensities. *Agric. Ecosyst. Environ.* **153**, 65–74 (2012).

Hansen, K. Det tabte land: den store fortælling om magten over det danske landskab. Gad (2008).

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P., Perry, M. P, Selig, E. R., Spalding, M., Steneck, R. & Watson, R. A Global Map of Human Impact on Marine Ecosystems. *Science* **319**, 948–952 (2008).

Houmark-Nielsen, M. The last interglacial-glacial cycle in Denmark. *Quat. Int.* **3–4**, 31–39 (1989).

Huang, P. M., Li, Y. & Summer, M. E. Handbook of soil sciences: Properties and processes. (CRC Press, 2012).

Hupfer, M. & Lewandowski, J. Oxygen Controls the Phosphorus Release from Lake Sediments - a Long-Lasting Paradigm in Limnology. *Int. Rev. Hydrobiol.* **93**, 415–432 (2008).

Huser, B., Brezonik, P. & Newman, R. Effects of alum treatment on water quality and sediment in the Minneapolis Chain of Lakes, Minnesota, USA. *Lake Reserv. Manag.* **27**, 220–228 (2011).

Jalali, M. & Hemati Matin, N. Sorption of phosphorus in calcareous paddy soils of Iran: effects of soil/solution ratio and pH. *Environ. Earth Sci.* **73**, 2047–2059 (2015).

Jayarathne, P. D. K. D., Kumaragamage, D., Indraratne, S., Flaten, D. & Goltz, D. Phosphorus Release to Floodwater from Calcareous Surface Soils and Their Corresponding Subsurface Soils under Anaerobic Conditions. *J. Environ. Qual.* **45**, 1375 (2016).

Jensen, N. H., Balström, T., & Breuning-Madsen, H. The relations between soil water retention characteristics, particle-size distributions, bulk densities and calcium carbonate contents for Danish soils. *Nordic Hydrology*. **36**. 235–244 (2005).

Jordan-Meille, L., Rubæk, G.H., Ehlert, P. A. I., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G.& Barraclough, P. An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. *P fertilizer methods in Europe*. *Soil Use Manag.* **28**, 419–435 (2012).

Kaiserli, A., Voutsa, D. & Samara, C. Phosphorus fractionation in lake sediments – Lakes Volvi and Koronia, N. Greece. *Chemosphere* **46**, 1147–1155 (2002).

Kinsman-Costello, L. E., O'Brien, J. & Hamilton, S. K. Re-flooding a Historically Drained Wetland Leads to Rapid Sediment Phosphorus Release. *Ecosystems* **17**, 641–656 (2014).

Koch, M. S., Benz, R. E. & Rudnick, D. T. Solid-phase Phosphorus Pools in Highly Organic Carbonate Sediments of Northeastern Florida Bay. *Estuar. Coast. Shelf Sci.* **52**, 279–291 (2001).

Kolahchi, Z. & Jalali, M. Phosphorus Movement and Retention by Two Calcareous Soils. *Soil Sediment Contam. Int. J.* **22**, 21–38 (2013).

Kozlowski, T. T. & Pallardy, S. G. Environmental Regulation of Vegetative Growth. In: Growth Control in Woody Plants. 195–322 (Elsevier, 1997).

Kröger, R., Lizotte, R. E., Douglas Shields, F. & Usborne, E. Inundation Influences on Bioavailability of Phosphorus in Managed Wetland Sediments in Agricultural Landscapes. *J. Environ. Qual.* **41**, 604 (2012).

Lambeck, K. Glacial Crustal Rebound, Sea Levels and Shorelines. in *Encyclopedia of Ocean Sciences* 1157–1167 (Elsevier, 2001).

Lambeck, K., Smither, C. & Johnston, P. Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophys. J. Int.* **134**, 102–144 (1998).

Lewandowski, J., Schauser, I. & Hupfer, M. Long term effects of phosphorus precipitations with alum in hypereutrophic Lake Süsser See (Germany). *Water Res.* **37**, 3194–3204 (2003).

Lijklema, L. Considerations in modeling the sediment—water exchange of phosphorus. In: *Proceedings of the Third International Workshop on Phosphorus in Sediments* (eds. Boers, P. C. M., Cappenberg, Th. E. & van Raaphorst, W.) 219–231 (Springer Netherlands, 1993).

Lijklema, Lambertus. Interaction of orthophosphate with iron(III) and aluminum hydroxides. *Environ. Sci. Technol.* **14**, 537–541 (1980).

Loeb, R., Lamers, L. P. M. & Roelofs, J. G. M. Prediction of phosphorus mobilisation in inundated floodplain soils. *Environ. Pollut.* **156**, 325–331 (2008).

MacDonald, G. K., Bennett, E. M., Potter, P. A. & Ramankutty, N. Agronomic phosphorus imbalances across the world's croplands. *Proc. Natl. Acad. Sci.* **108**, 3086–3091 (2011).

McDonald, T., Jonson, J. & Dixon, K. W. National standards for the practice of

ecological restoration in Australia: National restoration standards, Australia. *Restor. Ecol.* **24**, S4–S32 (2016).

Matejovic, I. Determination of carbon, hydrogen and nitrogen in soils by automated elemental analysis (dry combustion method). *Communications in Soil Science and Plant Analysis*, **24** (17&18), 2213-2222 (1993).

Meerhoff, M. & Jeppesen, E. Shallow Lakes and Ponds. In: *Encyclopedia of Inland Waters* 645–655 (Elsevier, 2009).

Meyers, P. A. & Ishiwatari, R. Organic Matter Accumulation Records in Lake Sediments. in *Physics and Chemistry of Lakes* (eds. Lerman, A., Imboden, D. M. & Gat, J. R.) 279–328 (Springer Berlin Heidelberg, 1995).

Miljø- og Fødevareministeriet. Projektforslag og vanddybder. [online] https://naturstyrelsen.dk/media/217554/2017_05_10_kortbilag-1-projektkort-a3-3.pdf (2017) (Last accessed 04/14/2019)

Miljø- og Fødevareministeriet. Projektforslag og vanddybder. [online] https://naturstyrelsen.dk/naturbeskyttelse/naturprojekter/soeborg-soe/ (Last accessed 05/05/2019)

Miljø- og Fødevareministeriet. Idéoplæg. [online] https://mst.dk/media/146155/ideoplaeg-endelig-version.pdf (2018) (Last accessed 04/14/2019)

Moody, P. W., Speirs, S. D., Scott, B. J. & Mason, S. D. Soil Phosphorus Tests I: What Soil Phosphorus Pools and Processes Do They Measure? *Crop and Pasture Science* **64** (5), 68-461 (2013).

Moreno-Mateos, D., Power, M. E., Comín, F. A. & Yockteng, R. Structural and Functional Loss in Restored Wetland Ecosystems. *PLoS Biol.* **10**, e1001247 (2012).

Mortimer, C. H. The Exchange of Dissolved Substances between Mud and Water in Lakes. *J. Ecol.* **30**, 147 (1942).

Murphy, J. & Riley, J. P. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* **27**, 31–36 (1962).

Nawara S., van Dael T., Merckx R., Amery F., Elsen A., Odeurs W., Vandendriessche H., McGrath S., Roisin C., Jouany C., Pellerin S., Denoroy P., Eichler-Löbermann B., Börjesson G., Goos P., Akkermans W., Smolders E. A comparison of soil tests for available phosphorus in long-term field experiments in Europe: Comparing soil P tests in European long-term fields. *Eur. J. Soil Sci.* **68**, 873–885 (2017).

Nilsson, C., Aradottir, A. L., Hagen, D., Halldórsson, G., Høegh, K., Mitchell, R. J., Raulund-Rasmussen, K., Svavarsdóttir, K., Tolvanen, A. & Wilson, S. D. Evaluating the process of ecological restoration. *Ecol. Soc.* **21**, (2016).

ÖNORM L 1083: Chemische Bodenuntersuchungen - Bestimmung der Acidität (pH Wert) Ausgabe: 1999-04-01.

ÖNORM L 1084: Chemische Bodenuntersuchungen - Bestimmung von Carbonat Ausgabe: 1999-04-01.

ÖNORM L 1080: Chemische Bodenuntersuchungen - Bestimmung des organischen Kohlenstoffs durch trockene Verbrennung Ausgabe: 1999-04-01.

ÖNORM L 1085: Chemische Bodenuntersuchungen - Säureextrakt zur Bestimmung von Nähr- und Schadelementen Ausgabe: 1999-04-01.

Phillips, I. R. Nitrogen and Phosphorus transport in soil using simulated waterlogged conditions. Commun. *Soil Sci. Plant Anal.* **32**, 821–842 (2001).

Plach, J. M., Macrae, M. L., Williams, M. R., Lee, B. D. & King, K. W. Dominant glacial landforms of the lower Great Lakes region exhibit different soil phosphorus chemistry and potential risk for phosphorus loss. *J. Gt. Lakes Res.* **44**, 1057–1067 (2018).

Ponnamperuma, F. N. The Chemistry of Submerged Soils. in *Advances in Agronomy* **24**, 29–96 (Elsevier, 1972).

Psenner, R., Boström, B., Dinka, M., Petterson, K., Pucsko, R. & Sager, M. Fractionation of Phosphorus in suspended matter and sediment. *Archiv für Hydrobiologie Beihefte, Ergebnisse der Limnologie,* **30**, 98-110 (1988).

Rast, W. & Thornton, J. A. Trends in eutrophication research and control. Hydrol. Process., 10: 295-313 (1996).

Renneson, M., Vandenberghe, C., Dufey, J., Marcoen, J. M., Bock, L. & Colinet, G. Degree of phosphorus saturation in agricultural loamy soils with a near-neutral pH. *Eur. J. Soil Sci.* **66**, 33–41 (2015).

Richardson, C. J. & Marshall, P. E. Processes Controlling Movement, Storage, and Export of Phosphorus in a Fen Peatland. *Ecol. Monogr.* **56**, 279–302 (1986).

Rick, A. R. & Arai, Y. Role of Natural Nanoparticles in Phosphorus Transport Processes in Ultisols. *Soil Sci. Soc. Am. J.* **75**, 335 (2011).

Riis, N. Søborg Sø – et landskab af muligheder Debatoplæg med fremtidsscenarier

[online] https://naturstyrelsen.dk/media/246522/2014_01_soeborg-soe-et-landskab-af-muligheder_naturraadgivningen_niels-riis.pdf (2014) (Last accessed 04/16/2019)

Roy, E. D., Nguyen, N. T. & White, J. R. Changes in estuarine sediment phosphorus fractions during a large-scale Mississippi River diversion. *Sci. Total Environ.* **609**, 1248–1257 (2017).

Rogovska, N. P., Blackmer, A. M. & Mallarino, A. P. Relationships between Soybean Yield, Soil pH, and Soil Carbonate Concentration. *Soil Sci. Soc. Am. J.* **71**, 1251 (2007).

Ruttenberg, K. C. Phosphorus Cycle. in *Encyclopedia of Ocean Sciences* 401–412 (Elsevier, 2001).

Rydin, E., Huser, B. & Welch, E. B. Amount of phosphorus inactivated by alum treatments in Washington lakes. *Limnol. Oceanogr.* **45**, 226–230 (2000).

Sand-Jensen, K. Søer-en beskyttet naturtype. Gad (2001).

Scheffer, M. Chapter 2: The abiotic environment. In: The ecology of Shallow Lakes. 20-75 (Springer, 2004).

Schnug, E. & De Kok, L. J. Phosphorus in Agriculture: 100 % Zero. (Springer New York, 2016).

Schönach, P., Nygrénb, N. A., Tammeorga, O., Heikkinena, M., Holmroosa, H., Massaa, I., Niemistöa, J., Tapiob, P. & Horppila, J. The past, present, and future of a lake: Interdisciplinary analysis of long-term lake restoration. *Environ. Sci. Policy* **81**, 95–103 (2018).

Seo, D. & Canale, R. P. Analysis of Sediment Characteristics and Total Phosphorus Models for Shagawa Lake. *J. Environ. Eng.* **125**, 346–350 (1999).

Smith, V. H., Tilman, G. D. & Nekola, J. C. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environ. Pollut.* **100**, 179–196 (1999).

Smith, V. H. Cultural Eutrophication of Inland, Estuarine, and Coastal Waters. In: *Successes, Limitations, and Frontiers in Ecosystem Science* (eds. Pace, M. L. & Groffman, P. M.) 7–49 (Springer New York,1998).

Søndergaard, M. Nutrient dynamics in lakes – with emphasis on phosphorus, sediment and lake restorations. Doctor's dissertation (DSc). National Environmental Research Institute, University of Aarhus, Denmark. 276 pp (2007).

Søndergaard, M., Jensen, J. P. & Jeppesen, E. Role of sediment and internal loading

of phosphorus in shallow lakes. *Hydrobiologia* **506–509**, 135–145 (2003).

Søndergaard, M., Jensen, J.P. & Jeppesen, E. Internal phosphorus loading in shallow Danish lakes. *Hydrobiologia* **408**: 145 (1999).

Sparks, D. L. Methods of soil analysis. Part 3: Chemical methods. (Soil Science Society of America : American Society of Agronomy, 1996).

Steinman, A. D. & Ogdahl, M. E. Does converting agricultural fields to wetlands retain or release P? *J. North Am. Benthol. Soc.* **30**, 820–830 (2011).

Surridge, B. W. J., Heathwaite, A. L. & Baird, A. J. Phosphorus mobilisation and transport within a long-restored floodplain wetland. *Ecol. Eng.* **44**, 348–359 (2012).

Tandy, S., S. Mundus, J. Yngvesson, T. C. de Bang, E. Lombi, J. K. Schjoerring, & S. Husted The Use of DGT for Prediction of Plant Available Copper, Zinc and Phosphorus in Agricultural Soils. *Plant and Soil* **346** (1–2), 80-167 (2011).

Tóth, G., Guicharnaud, R.-A., Tóth, B. & Hermann, T. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *Eur. J. Agron.* **55**, 42–52 (2014).

Vohla, C., Kõiv, M., Bavor, H. J., Chazarenc, F. & Mander, Ü. Filter materials for phosphorus removal from wastewater in treatment wetlands—A review. *Ecol. Eng.* **37**, 70–89 (2011).

Wandruszka, R. Phosphorus retention in calcareous soils and the effect of organic matter on its mobility. *Geochem. Trans.*, **7** (6) (2006).

Wang, S.-L., Johnston, C. T., Bish, D. L., White, J. L. & Hem, S. L. Water-vapor adsorption and surface area measurement of poorly crystalline boehmite. *J. Colloid Interface Sci.* **260**, 26–35 (2003).

Wang, Z., Huang, S. & Li, D. Decomposition of cyanobacterial bloom contributes to the formation and distribution of iron-bound phosphorus (Fe-P): Insight for cycling mechanism of internal phosphorus loading. *Sci. Total Environ.* **652**, 696–708 (2019).

WEPAL, 2014, ISE 885 Braunerde Pseudoclay [online] http://www.wepal.nl/website/download_files/consensus/ISE/ISE885.pdf (Last accessed 05/13/2019)

Winterhalter, B., Flodén, T., Ignatius, H., Axberg, S. & Niemistö, L. Chapter 1: Geology of the Baltic Sea. in *Elsevier Oceanography Series* **30,** 1–121 (Elsevier, 1981).

Withers, P. J. A., Edwards, A. C. & Foy, R. H. Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil. *Soil Use Manag.* **17**, 139–149 (2006).

Williams, J. D. H. & T. Mayer,. Effects of sediment diagenesis and regeneration of phosphorus with special reference to lakes Eire and Ontario, In H. E. Allen & J. R. Kramer (eds), Nutrients in natural waters. J. Wiley & Sons, NY: 281–315 (1972).

Yan, Z., Chen, S., Dari, B., Sihi, D. & Chen, Q. Phosphorus transformation response to soil properties changes induced by manure application in a calcareous soil. *Geoderma* **322**, 163–171 (2018).

Yin, H. & Kong, M. Reduction of sediment internal P-loading from eutrophic lakes using thermally modified calcium-rich attapulgite-based thin-layer cap. *J. Environ. Manage.* **151**, 178–185 (2015).

Zedler, J. B. & Kercher, S. WETLAND RESOURCES: Status, Trends, Ecosystem Services, and Restorability. *Annu. Rev. Environ. Resour.* **30**, 39–74 (2005).

Zhou, M. & Li, Y. Phosphorus-Sorption Characteristics of Calcareous Soils and Limestone from the Southern Everglades and Adjacent Farmlands. *Soil Sci. Soc. Am. J.* **65**, 1404 (2001).

7. Appendix

Appendix 1: pH, P_{AR}, P_{ox}, Fe_{ox} and Al_{ox} concentrations for all samples.

Sample	pH	P_{AR}	P_{ox}	Fe_{ox}	Al_{ox}
			mg Kg^{-1}		
A_0-20 cm	7.22	510.45	167.00	5716.10	385.05
A_20-40 cm	7.59	257.52	42.05	2093.98	150.36
A_40-60 cm	7.73	404.73	54.61	1594.01	149.74
A_60-80 cm	7.81	167.92	27.65	1411.27	119.64
A_80-100 cm	7.88	257.66	40.60	1731.33	110.72
B_0-20 cm	7.30	593.33	253.17	6452.69	381.68
B_20-40 cm	7.48	526.59	239.64	11491.85	388.27
B_40-60 cm	7.31	627.14	334.78	15561.75	348.20
B_60-80 cm	7.19	493.03	210.18	4744.91	228.86
B_80-100 cm	7.05	445.16	169.60	8775.30	311.12
C_0-20 cm	7.34	563.58	229.58	7574.85	566.91
C_20-40 cm	7.42	414.88	125.01	6194.43	323.86
C_40-60 cm	7.53	394.19	77.06	3869.58	182.98
C_60-80 cm	7.64	411.87	89.28	3078.00	198.96
C_80-100 cm	7.68	380.38	71.93	2165.01	225.59
D_0-20 cm	7.08	519.46	156.19	3247.70	295.55
D_20-40 cm	7.17	500.92	161.52	5268.00	433.08
D_40-60 cm	7.51	351.33	88.26	3649.30	277.03
D_60-80 cm	7.74	371.68	136.95	2948.30	347.96
D_80-100 cm	7.59	393.83	139.20	3174.00	323.66
E_0-20 cm	7.20	438.84	309.86	7244.49	370.94
E_20-40 cm	7.39	696.30	438.23	13991.95	419.97
E_40-60 cm	7.23	621.70	338.32	13065.87	400.16
E_60-80 cm	7.16	772.59	399.08	7587.17	340.98
E_80-100 cm	7.29	675.40	429.86	10007.62	318.64
F_0-20 cm	6.91	1098.38	698.84	9269.34	351.10
F_20-40 cm	7.32	1248.65	877.53	13804.78	437.85

F_40-60 cm	7.16	1050.50	600.72	11468.13	416.74
F_60-80 cm	6.97	633.36	275.19	3615.51	323.26
F_80-100 cm	7.19	1134.22	734.79	8280.72	433.22
G_0-20 cm	7.15	1763.51	1309.64	14566.27	535.34
G_20-40 cm	7.18	1488.74	1044.86	17294.82	487.05
G_40-60 cm	7.04	1371.29	837.61	13693.84	405.92
G_60-80 cm	7.13	1115.37	697.46	14278.33	387.08
G_80-100 cm	7.32	1043.84	608.02	15137.72	395.59
H_0-20 cm	6.89	854.19	403.37	3468.67	311.54
H_20-40 cm	7.11	793.41	433.88	6083.30	307.85
H_40-60 cm	7.27	1336.15	821.88	11391.60	343.53
H_60-80 cm	7.17	897.83	641.53	9537.22	378.55
H_80-100 cm	7.12	949.15	533.84	8447.08	293.24
I_0-20 cm	7.07	1012.18	608.71	4615.11	338.98
I_20-40 cm	7.38	1145.92	844.43	10730.54	395.29
I_40-60 cm	7.45	1126.32	879.68	13374.50	573.00
I_60-80 cm	7.27	1018.35	690.12	8641.20	358.20
I_80-100 cm	7.24	1354.39	1044.26	11435.86	418.80
J_0-20 cm	7.07	433.16	299.28	4759.36	451.63
J_20-40 cm	7.38	450.17	170.80	2965.34	271.03
J_40-60 cm	7.45	478.07	228.89	3608.45	535.83
J_60-80 cm	7.27	428.27	417.72	12973.95	1188.67
J_80-100 cm	7.24	494.00	257.18	7382.50	581.16
K_0-20 cm	7.13	898.13	428.02	6329.34	344.98
K_20-40 cm	7.32	523.45	246.47	5148.50	234.42
K_40-60 cm	7.58	295.19	46.04	967.16	35.07
K_60-80 cm	7.44	201.68	38.96	799.24	60.16
K_80-100 cm	7.39	188.11	31.69	454.10	107.83
L_0-20 cm	6.98	797.80	338.04	6052.80	349.70
L_20-40 cm	7.35	722.75	406.76	8058.85	408.89
L_40-60 cm	7.15	659.44	310.62	7918.09	421.35
L_60-80 cm	7.04	1024.76	639.56	10262.53	410.15
L_80-100 cm	7.24	1082.27	676.51	13156.63	404.40
M_0-20 cm	7.01	1053.21	575.04	6256.80	377.39

M_20-40 cm	7.30	1081.88	656.41	9016.73	376.73
M_40-60 cm	7.29	878.39	540.24	7966.80	383.40
M_60-80 cm	7.20	909.37	493.13	7144.58	301.57
M_80-100 cm	7.01	700.95	308.96	9586.85	408.59
N_0-20 cm	7.12	651.11	315.69	7664.67	410.06
N_20-40 cm	7.27	1130.25	805.75	12203.59	508.71
N_40-60 cm	7.16	779.21	422.27	11291.24	432.70
N_60-80 cm	7.18	691.38	293.98	4024.10	270.96
N_80-100 cm	7.29	688.37	317.80	10255.31	379.12
O_0-20 cm	7.16	904.55	459.52	9802.40	370.54
O_20-40 cm	7.34	815.36	500.89	11385.51	430.90
O_40-60 cm	7.40	1036.72	693.44	10990.74	413.70
O_60-80 cm	7.06	814.28	431.45	5541.95	346.59
O_80-100 cm	7.29	901.61	512.09	9003.58	389.64
P_0-20 cm	7.16	1223.50	787.59	12072.29	425.54
P_20-40 cm	7.34	827.58	489.78	12286.28	364.77
P_40-60 cm	7.03	633.23	309.38	5945.89	406.04
P_60-80 cm	7.00	718.72	387.40	5363.78	418.42
P_80-100 cm	7.10	1007.71	612.43	9983.67	371.47
Q_0-20 cm	7.19	862.09	403.22	13641.85	409.50
Q_20-40 cm	7.03	649.91	292.13	12882.70	380.76
Q_40-60 cm	7.09	714.92	336.53	5944.91	353.12
Q_60-80 cm	7.07	629.51	311.11	7469.22	342.62
Q_80-100 cm	7.09	673.60	343.90	13777.34	413.75
R_0-20 cm	7.22	825.66	418.33	10817.93	508.34
R_20-40 cm	7.37	893.20	404.88	22428.00	375.60
R_40-60 cm	7.23	871.24	397.20	12684.00	326.40
R_60-80 cm	7.14	598.54	343.34	12398.39	300.85
R_80-100 cm	7.20	588.34	279.56	6376.35	269.46
S_0-20 cm	7.18	573.04	359.76	7161.52	330.90
S_20-40 cm	7.37	422.47	180.24	5182.70	282.47
S_40-60 cm	7.33	420.26	253.96	10661.63	489.02
S_60-80 cm	7.29	587.97	334.95	13526.84	411.60
S_80-100 cm	7.37	640.62	366.44	12322.07	399.26

T_0-20 cm	7.27	182.42	412.81	8741.32	427.25
T_20-40 cm	7.36	374.09	201.32	6276.65	258.32
T_40-60 cm	7.70	309.67	88.03	2484.69	191.84
T_60-80 cm	7.70	352.43	86.02	2037.35	165.66
T_80-100 cm	7.78	228.84	84.02	3090.84	189.86
PIT1_Ap	7.12	914.49	702.17	8704.82	425.06
PIT1_A2	7.23	837.83	495.30	7974.50	405.42
PIT1_Bw	7.33	648.97	261.33	11077.11	207.47
PIT1_C1	7.21	555.99	270.42	10225.25	335.23
PIT1_C2	7.08	598.22	377.56	4375.55	532.79
Pit2_Ap	7.16	737.10	325.65	9280.32	407.48
PIT2_Bwg	7.09	642.61	295.68	15144.00	330.48
Pit2_Cg1	7.00	722.32	322.32	7542.00	305.52
Pit2_Cg2	6.87	686.15	301.32	3679.20	232.44
PIT2_Cg3	6.94	710.65	297.96	4102.61	221.60

Appendix 2: GPS coordinates of the sampling spots in decimal degrees (WGS 84)

Sampling spot	N	E
A	56.068448	12.310145
B	56.069336	12.312678
C	56.070384	12.314797
D	56.071338	12.317069
E	56.072260	12.319444
F	56.073154	12.321764
G	56.074195	12.324150
H	56.075120	12.326367
I	56.076105	12.328641
J	56.077116	12.331025
K	56.066110	12.332638
L	56.067850	12.330118
M	56.069718	12.327343
N	56.071372	12.324708
O	56.073233	12.322145
P	56.074976	12.319518
Q	56.076690	12.316888
R	56.078460	12.314370
S	56.080236	12.311638
T	56.082008	12.309066
Pit1	56.073310	12.334560
Pit2	56.073610	12.315850

Appendix 3: P stocks (Kg m^{-2}) for the top soil (0-20 cm) and the whole profile (0-100 cm) calculated from P$_{AR}$ and P$_{ox}$ for sites along the transects. Sampling spots where the future lake will be deeper than 1 m are being marked *.

Spot and layer thickness	P$_{ox}$ stock	P$_{AR}$ stock
	Kg m^{-2}	
A 0-20 cm	0.02760	0.08435
B 0-20 cm	0.04184	0.09805
C 0-20 cm	0.03794	0.09313
D 0-20 cm	0.02581	0.08584
E 0-20 cm*	0.05120	0.07252
F 0-20 cm*	0.11548	0.18151
G 0-20 cm*	0.21642	0.29142
H 0-20 cm*	0.06666	0.14115
I 0-20 cm	0.10059	0.16726
J 0-20 cm	0.04946	0.07158
K 0-20 cm	0.07073	0.14841
L 0-20 cm*	0.05586	0.13184
M 0-20 cm*	0.09502	0.17404
N 0-20 cm*	0.05217	0.10760
O 0-20 cm*	0.07594	0.14948
P 0-20 cm*	0.13015	0.20218
Q 0-20 cm*	0.06663	0.14246
R 0-20 cm*	0.06913	0.13644
S 0-20 cm*	0.05945	0.09470
T 0-20 cm	0.06822	0.03015
A 0-100 cm	0.05123	0.24038
B 0-100 cm	0.17479	0.39101
C 0-100 cm	0.08853	0.31766
D 0-100 cm	0.10000	0.31446
E 0-100 cm*	0.27843	0.45903
F 0-100 cm*	0.48098	0.77066
G 0-100 cm*	0.66232	0.99578
H 0-100 cm*	0.40540	0.70268

I 0-100 cm	0.59941	0.83268
J 0-100 cm	0.19565	0.33440
K 0-100 cm	0.12160	0.31806
L 0-100 cm*	0.34383	0.62559
M 0-100 cm*	0.37036	0.67004
N 0-100 cm*	0.31194	0.57068
O 0-100 cm*	0.37955	0.65481
P 0-100 cm*	0.39112	0.66085
Q 0-100 cm*	0.24853	0.51967
R 0-100 cm*	0.26767	0.55156
S 0-100 cm*	0.22055	0.38838
T 0-100 cm	0.13284	0.20424

Appendix 4: Soil profile of Pit1

Appendix 5: Soil profile of Pit2

Appendix 6: Bulk density of pit samples. R1 and R2 stand for the measured replicates. Single measurements marked (*).

Sample	Bulk density
	g cm^{-3}
Pit1Ap_R1	0.81
Pit1Ap_R2	0.89
Pit1A2_R1	0.62
Pit1A2_R2	0.82
Pit1Bw_R1	0.75
Pit1Bw_R2	0.76
Pit1C1_R1	0.65
Pit1C1_R2	0.67
Pit1C2*	1.43
Pit2Ap_R1	0.80
Pit2Ap_R2	0.81
Pit2Bwg_R1	0.71
Pit2Bwg_R2	0.67
Pit2Cg1*	0.64
Pit2Cg2*	0.42
Pit2Cg3*	0.31

Appendix 7: CaCO$_3$ and inorganic C values determined by the Institute of Soil Research (IBF) of BOKU. R1 and R2 stand for the measured replicates.

Sample	CaCO$_3$	C$_{inorganic}$
	%	
Pit1Ap_R1	12.16	1.47
Pit1Ap_R2	11.97	1.42
Pit1A2_R1	9.09	1.09
Pit1A2_R2	9.07	1.09
Pit1Bw_R1	27.26	3.27
Pit1Bw_R2	27.84	3.34
Pit1C1_R1	29.78	3.57

Pit1C1_R2	29.84	3.58
Pit1C2_R1	17.97	2.13
Pit1C2_R2	18.41	2.23
Pit2Ap_R1	13.19	1.58
Pit2Ap_R2	13.16	1.58
Pit2Bwg_R1	29.26	3.51
Pit2Bwg_R2	28.70	3.44
Pit2Cg1_R1	31.24	3.75
Pit2Cg1_R2	31.58	3.79
Pit1Cg2_R1	45.38	5.45
Pit1Cg2_R2	44.47	5.34
Pit1Cg3_R1	39.16	4.70
Pit1Cg3_R2	39.68	4.76

Appendix 8: Total C values. R1 and R2 stand for the measured replicates.

Sample	C_{Total}
	%
Pit1Ap_R1	10.33
Pit1Ap_R2	8.91
Pit1A2_R1	8.15
Pit1A2_R2	8.01
Pit1Bw_R1	8.70
Pit1Bw_R2	8.89
Pit1C1_R1	7.82
Pit1C1_R2	7.80
Pit1C2_R1	2.88
Pit1C2_R2	2.83
Pit2Ap_R1	11.70
Pit2Ap_R2	11.81
Pit2Bwg_R1	18.15
Pit2Bwg_R2	18.03
Pit2Cg1_R1	15.67

Pit2Cg1_R2	15.74
Pit1Cg2_R1	18.69
Pit1Cg2_R2	18.77
Pit1Cg3_R1	18.78
Pit1Cg3_R2	18.65