Biogeosciences

Speciation and distribution of P associated with Fe and Al oxides in aggregate-sized fraction of an arable soil

X. Jiang[1], R. Bol[1], S. Willbold[2], H. Vereecken[1], and E. Klumpp[1]

[1]Institute of Bio- and Geosciences, Agrosphere Institute (IBG-3), Jülich, Germany
[2]Central Institute for Engineering, Electronics and Analytics, Analytics (ZEA-3), Forschungszentrum Jülich GmbH, Wilhelm Johnen Straße, 52425 Jülich, Germany

Correspondence to: X. Jiang (x.jiang@fz-juelich.de)

Abstract. To maximize crop productivity fertilizer P is generally applied to arable soils, a significant proportion of which becomes stabilized by mineral components and in part subsequently becomes unavailable to plants. However, little is known about the relative contributions of the different organic and inorganic P bound to Fe/Al oxides in the smaller soil particles. Alkaline (NaOH–Na$_2$EDTA) extraction with solution ^{31}P-nuclear magnetic resonance (^{31}P-NMR) spectroscopy is considered a reliable method for extracting and quantifying organic P and (some) inorganic P. However, any so-called residual P after the alkaline extraction has remained unidentified. Therefore, in the present study, the amorphous (a) and crystalline (c) Fe/Al oxide minerals and related P in soil aggregate-sized fractions (>20, 2–20, 0.45–2 and $<0.45\,\mu$m) were specifically extracted by oxalate (a-Fe/Al oxides) and dithionite–citrate–bicarbonate (DCB, both a- and c-Fe/Al oxides). These soil aggregate-sized fractions with and without the oxalate and DCB pre-treatments were then sequentially extracted by alkaline extraction prior to solution ^{31}P-NMR spectroscopy. This was done to quantify the P associated with a- and c-Fe/Al oxides in both alkaline extraction and the residual P of different soil aggregate-sized fractions.

The results showed that overall P contents increased with decreasing size of the soil aggregate-sized fractions. However, the relative distribution and speciation of varying P forms were found to be independent of soil aggregate-size. The majority of alkaline-extractable P was in the a-Fe/Al oxide fraction (42–47 % of total P), most of which was orthophosphate (36–41 % of total P). Furthermore, still significant amounts of particularly monoester P were bound to these oxides. Intriguingly, however, Fe/Al oxides were not the main bonding sites for pyrophosphate. Residual P contained similar amounts of total P associated with both a- (11–15 % of total P) and c-Fe oxides (7–13 % of total P) in various aggregate-sized fractions, suggesting that it was likely occluded within the a- and c-Fe oxides in soil. This implies that, with the dissolution of Fe oxides, this P may be released and thus available for plants and microbial communities.

1 Introduction

Phosphorus is, after nitrogen, the most limiting soil nutrient for agricultural crops and plays an important role in the overall functioning of the agro-ecosystems (Bowman and Moir, 1993; Wei et al., 2014). To increase or maintain crop productivity, P in the form of synthetic and animal-based fertilizer is applied to arable soils. However, the long-term (over)application of P in excess of plant crop requirements has increased P in surface and subsurface soils, generally over time, transforming it into various unavailable forms (Arai et al., 2005; He et al., 2009; Sims et al., 2000).

Soil organic and inorganic P are, in the majority of cases, stabilized by association with mineral components. Negatively charged phosphorus compounds attach themselves to mineral components such as aluminosilicate minerals and hydrous Fe or Al oxides (Solomon and Lehmann, 2000; Turner et al., 2005). The P reactivity in Fe/Al oxyhydroxides turns large proportions of soil P into unavailable forms (Arai and Livi, 2013; Solomon and Lehmann, 2000; Solomon et al., 2002). Different Fe/Al oxides, however, have varying P

adsorption capacities and some studies showed amorphous Fe/Al oxides carried the majority of P in soils, despite higher abundance of crystalline Fe oxides (Arai and Livi, 2013; Arai et al., 2005; Rick and Arai, 2011). Few studies have distinguished organic and inorganic P associated with different Fe/Al oxides (i.e., amorphous and crystalline Fe/Al oxides) (Mahieu et al., 2000), despite the fact that P speciation will ultimately determine the different P bioavailability, mobility and mineralization in soil (Dick and Tabatabai, 1978; Liu et al., 2014). The study by Mahieu et al. (2000) found that amorphous Fe oxides had strong correlations with some organic P forms in the humic acid and calcium humate extracts of lowland rice soils. Long-term soil management and development (e.g., cultivation, fertilized management, and forest growth and development) affect soil chemistry, such as the transformation of Fe oxides (Li et al., 2008). Inevitably, the ecosystem-driven transformation of Fe oxides alters the related P retention and bioavailability in soil. Therefore, the study of various P/Fe oxide relationships is helpful for understanding soil P dynamics in long timescales. However, little is known about speciation and distribution of P associated with varying Fe/Al oxides. Additionally, finer-sized soil fractions were found to be enriched in highly active and easily mineralized organic P than larger particles (Rubæk et al., 1999). Similarly, organic P forms in general increased with decreasing particle size in forest and cropland soils (Cade-Menun, 2005). It seems that smaller soil particles are more reactive and have higher P-retaining capacity due to increased surface area than larger soil particles. In this context, it is important that different soil aggregate-sized fractions be also considered when studying P associated with Fe/Al oxides in soil.

Alkaline extraction and solution ^{31}P-NMR spectroscopy are widely thought as reliable methods for quantifying organic phosphorus (Turner, 2008). Inorganic phosphate (Pi) in alkaline soil extracts is assumed to originate from complexes with both Fe and Al (Turner, 2008). However, the distribution of organic P (Po) related to Fe/Al oxides in the alkaline extracts is still unclear. Our study aims to provide a novel method to understand the distribution of Pi and Po on Fe/Al oxides in the alkaline extract of soil. Furthermore, the residual P after alkaline extraction still accounts for significant proportion of P for some soils, most apparent in high-pH soil or for unamended soils with low P concentration (Cade-Menun and Liu, 2014; Cheesman et al., 2012; McDowell et al., 2007; Turner et al., 2007; Turner et al., 2003). The residual P is by definition unidentified and is simply presumed to be recalcitrant in the environment (Cheesman et al., 2010). Richter et al. (2006) indicated that recalcitrant P as slowly cycling P did still contribute to P bioavailability on decadal timescales. Therefore, an improved understanding of the residual P distribution, its bonding and "true" recalcitrance in soil is important for developing strategies to exploit this P as an "in part additional" source for plant uptake or microbial usage. This is probably feasible in line with the

observation by He et al. (2008), which suggested that most of this residual P could be orthophosphate.

Our current study aimed (i) to provide a comprehensive insight into the distribution of P bound to amorphous and crystalline Fe and Al (hydr)oxides in different soil aggregate-sized fractions, (ii) to identify the speciation and distribution of Pi and Po associated with amorphous and crystalline Fe/Al (hydr)oxides in NaOH–Na$_2$EDTA soil extracts, and (iii) to provide detailed information on residual P distribution after alkaline extraction. This was done in order to provide further information on the partition and quantification of these (unavailable) P forms, especially for the P/Fe oxide fraction of the arable soil, which may help to improve current soil P sustainable development management strategies. In this study, we extracted amorphous and crystalline Fe/Al oxides from a bulk soil and different soil aggregate-sized fractions of an arable field. Additionally, the isolated amorphous Fe oxide-free and all Fe oxide-free aggregate-sized fractions were then treated by alkaline extraction. Simultaneously, the original bulk soil and various aggregate-sized fractions were also treated with alkaline extraction and studied by solution ^{31}P-NMR spectroscopy.

2 Materials and methods

2.1 Site description and soil fractionation

Composite topsoil sample (0–15 cm, pH: 7.64) was collected from a cultivated field in the German TERENO (Terrestrial Environmental Observatories) experimental platform site Selhausen (50°52′08″ N, 6°26′59″ E; arable soil, Luvisol) in March 2013. The field was cultivated with winter wheat in October 2011–2012 and winter barley in September 2013. No P fertilization was applied in the years 2011–2013. More details about soil physicochemical characteristics and N fertilization of the test field are provided by Table S1 in the Supplement and Kupisch et al. (2015). The soil sample was fractionated using the soil particle-size fractionation method (Séquaris and Lewandowski, 2003), which explicitly avoids the destruction of small aggregates in soil (Berns et al., 2008). In brief, 100 g of soil sample was suspended in 200 mL of ultrapure water (Milli-Q) in a 1 L Duran bottle (Schott, Mainz, Germany) and horizontally shaken at 150 rpm for 6 h. After that, 600 mL of ultrapure water was added and mixed allowed to settle. Soil phases containing varying soil-aggregated sizes were collected by the pipette method based on Stoke's law. The soil fraction > 20 μm (sand-sized aggregates, with mass ratio of 82.3 % of total soil) was obtained by removing supernatant after settling for 6 min. The supernatant was subsequently settled for 12 h and then the new supernatant was removed to obtain a soil fraction from 2 to 20 μm (silt-sized aggregates, with mass ratio of 12.9 % of total soil). The newly obtained supernatant was subsequently separated into particle size of 0.45–2 μm

(with mass ratio of 4.0 % of total soil) by spinning the samples at $2525 \times g$ for 4 min (Biofuge, Heraeus), according to Stoke's law calculations with an assumed particle density of $2.65\,\mathrm{g\,cm^{-3}}$. Lastly, a $< 0.45\,\mathrm{\mu m}$ fraction (with mass ratio of 0.57 % of total soil) was obtained by spinning the supernatant at $2525 \times g$ for 68 min (Biofuge, Heraeus). The final supernatant only contained the electrolyte phase as well as a small quantity of nanoparticles; this has been investigated in our other concurrent work (Jiang et al., 2015). The soil aggregate-sized fractions were then freeze-dried for the elements analysis (i.e., Fe, Al, P and Ca) by inductively coupled plasma mass spectrometry (ICP-MS).

2.2 Oxalate and dithionite–citrate–bicarbonate (DCB) treatments

Acid ammonium oxalate was used to dissolve amorphous, poorly crystalline and organo-Fe and Al (hydr)oxides (Kleber et al., 2005; Masiello et al., 2004; Neubauer et al., 2013). The bulk soil and different aggregate-sized fractions were treated with acid ammonium oxalate according to the extraction method of Kiem and Kögel-Knabner (2002) and Schwertmann (1964). Briefly, 200 mg of soil sample was dispersed in 40 mL of 0.2 M acidic oxalate solution (0.113 M ammonium oxalate and 0.087 M oxalic acid) and shaken for 2 h in the dark, followed by centrifugation. The supernatants were subsequently analyzed for Fe ($\mathrm{Fe_{ox}}$), Al ($\mathrm{Al_{ox}}$), P ($\mathrm{P_{ox}}$) and Ca ($\mathrm{Ca_{ox}}$) by ICP-MS.

The DCB mainly extracts organically bound, amorphous and crystalline Fe oxides and only parts of dissolved oxides for Al and Si. For DCB extraction the protocol of Kiem and Kögel-Knabner (2002) was used. Briefly, 200 mg of sample was extracted using 30 mL of 0.3 M sodium citrate solution, 10 mL of 1 M sodium hydrogen carbonate solution and 1 g of sodium dithionite. After shaking for 16 h at room temperature, the soil suspension was centrifuged. The residue was then dispersed in 32 mL of magnesium sulfate (0.05 M) to exchange the adsorbed Fe with magnesium and thereafter centrifuged a second time. The two supernatant phases were combined and ICP-MS was used to measure Fe ($\mathrm{Fe_{DCB}}$), Al ($\mathrm{Al_{DCB}}$), P ($\mathrm{P_{DCB}}$) and Ca ($\mathrm{Ca_{DCB}}$).

2.3 Solution ^{31}P-NMR spectroscopy

To highlight the chemical composition of inorganic and organic P species in the bulk soil and different aggregate-sized fractions (> 20, 2–20, 0.45–2 and $< 0.45\,\mathrm{\mu m}$), these aggregate-sized fractions without and with oxalate and DCB pre-treatments were shaken for 16 h with a mixture of 0.25 M NaOH and 50 mM $\mathrm{Na_2EDTA}$ (soil and solution mass ratio is 1 : 20–25, pH $\geq$ 13) (Cade-Menun and Preston, 1996) and centrifuged at $2525 \times g$ for 68 min (Biofuge, Heraeus). The P ($\mathrm{P\text{-}NaOH}$), Fe ($\mathrm{Fe\text{-}NaOH}$), Al ($\mathrm{Al\text{-}NaOH}$) and Ca ($\mathrm{Ca\text{-}NaOH}$) were analyzed by ICP-MS for the supernatants. These supernatants were then frozen and subsequently lyophilized.
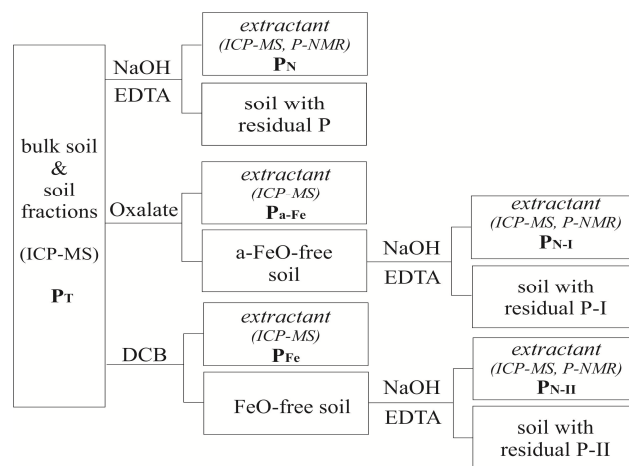

Figure 1. A schematic diagram of the soil sample treatments.

$\mathrm{Na_2S}$ dissolved in $\mathrm{D_2O}$ was added to the lyophilized materials to maintain reducing conditions for the removal of paramagnetic ions (i.e., Fe and Mn) during precipitation (Vestergren et al., 2012). The solution was centrifuged at $13\,200 \times g$ for 20 min (Centrifuge 5415R, Eppendorf). Solution ^{31}P-NMR spectra were obtained using a Bruker Avance 600 MHz spectrometer equipped with a prodigy probe, operating at 242.95 MHz for ^{31}P (Izarova et al., 2014). Extracts were measured with a $\mathrm{D_2O}$-field lock at room temperature. Chemical shifts were referenced to 85 % orthophosphoric acid (0 ppm). The NMR parameters generally used were 32 000 data points, 0.5 s repetition delay (we tested the bulk soil with 0.5 and 2 s repetition delay and no differences for the solution ^{31}P-NMR spectra were observed), 30° pulse width, 24 000 scans and 0.7 s acquisition time.

2.4 Calculations

The schematic diagram of whole soil sample preparation is shown in Fig. 1. The P contents in the various extracted fractions were calculated as follows:

$$(\mathrm{P_{a\text{-}Fe}})_N = \mathrm{P_N} - \mathrm{P_{N\text{-}I}}, \tag{1}$$
$$(\mathrm{P_{c\text{-}Fe}})_N = \mathrm{P_{N\text{-}I}} - \mathrm{P_{N\text{-}II}}, \tag{2}$$
$$(\mathrm{P_{other}})_N = \mathrm{P_{N\text{-}II}}, \tag{3}$$

where $(\mathrm{P_{a\text{-}Fe}})_N$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P associated with amorphous Fe/Al oxides, $(\mathrm{P_{c\text{-}Fe}})_N$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P associated with crystalline Fe oxides, $(\mathrm{P_{other}})_N$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P associated with other soil compounds, $\mathrm{P_N}$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P in soil samples, $\mathrm{P_{N\text{-}I}}$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P in "amorphous FeO-free" soil samples, and $\mathrm{P_{N\text{-}II}}$ is NaOH–$\mathrm{Na_2EDTA}$-extractable P in "FeO-free" soil samples.

Relative distributions of Pi and Po in NaOH–$\mathrm{Na_2EDTA}$ extracts of soil samples, a-Fe/Al oxide-free and Fe/Al oxide-
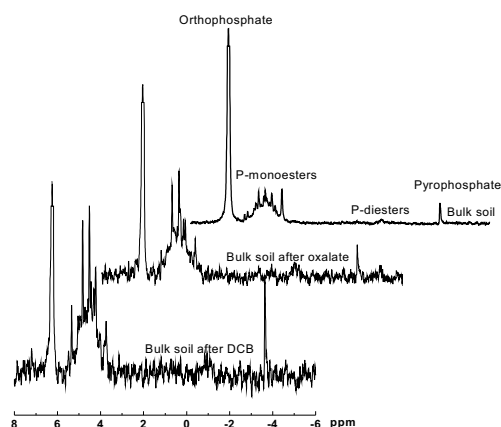
	Orthophosphate (%)	P-monoesters (%)	Pyrophosphate* (%)
Bulk soil	79.4	19.1	1.4
Bulk soil after oxalate	60.8	35.0	4.2
Bulk soil after DCB	51.5	43.0	5.5

*All other P forms are not included.

Figure 2. Solution phosphorus-31 nuclear magnetic resonance spectra of NaOH–Na$_2$EDTA extracts of bulk soil without and with oxalate and dithionite (DCB) pre-treatments (all subfigures have been reduced by the same factors). The associated table only shows the relative mass distribution (%) of orthophosphate, P-monoesters and pyrophosphate in NaOH–Na$_2$EDTA extracts of bulk soil without and with oxalate and DCB pre-treatments.

free soil samples were characterized by solution ^{31}P-NMR spectroscopy (Figs. 2 and S1 in the Supplement). Here only orthophosphate, phosphate monoesters and pyrophosphate were scaled to 100 %. Therefore, the distribution of Pi and Po associated with a- and c-Fe/Al oxides in NaOH–Na$_2$EDTA extracts (Table 1) was calculated with the combination of NaOH–Na$_2$EDTA extraction (Table S2) and corresponding solution ^{31}P-NMR spectra (Figs. 2 and S1).

The residual P after alkaline extraction was separated into P bound to a-Fe oxides, c-Fe oxides and other soil compounds as follows:

$$(P_{\text{a-Fe}})_{\text{resi}} = P_{\text{a-Fe}} - (P_{\text{a-Fe}})_N, \quad (4)$$

$$(P_{\text{c-Fe}})_{\text{resi}} = \text{``}P_{\text{c-Fe}}\text{''} - (P_{\text{c-Fe}})_N =$$
$$(P_{\text{Fe}} - P_{\text{a-Fe}}) - (P_{\text{c-Fe}})_N, \quad (5)$$

$$(P_{\text{other}})_{\text{resi}} = P_T - P_{\text{Fe}} - P_{\text{N-II}}, \quad (6)$$

where $(P_{\text{a-Fe}})_{\text{resi}}$ is residual P associated with amorphous Fe oxides, $(P_{\text{c-Fe}})_{\text{resi}}$ is residual P associated with crystalline Fe oxides, $(P_{\text{other}})_{\text{resi}}$ is residual P associated with other soil compounds, $P_{\text{a-Fe}}$ is P associated with amorphous Fe/Al oxides (i.e., oxalate-extractable P), P_{Fe} is P associated with amorphous and crystalline Fe/Al oxides (i.e., DCB-extractable P), $P_{\text{c-Fe}}$ is P associated with crystalline Fe/Al oxides, and P_T is total P.

3 Results and discussion

3.1 Total and oxalate- and DCB-extractable P, Fe, Al and Ca in soil aggregate-sized fractions

Table 2 represents ICP-MS results of elemental contents (i.e., P, Fe, Al and Ca) in the bulk soil and different aggregate-sized fractions, as well as their oxalate and DCB extracts. Total P was 0.73 g kg^{-1} in bulk soil with a significant increase from large particles to small particles (range between 0.54 and 2.47 g kg^{-1}). Total Fe and Al in different soil aggregate-sized fractions showed the same gradient with total P. Total P had a strong positive relationship with total Fe and Al ($R^2 > 0.99$; $P < 0.006$) in these aggregate-sized fractions, which indicated that P was, to a large extent, associated with Fe and Al in all aggregate-sized fractions. The high correlation also indicated the reason why smaller particles contained more P. There was more Fe and Al in the smaller size fractions, and the minerals containing these elements (i.e., Fe and Al) acted as important P carriers.

Oxalate-extractable P, Fe and Al (P_{ox}, Fe_{ox} and Al_{ox}) also had an increasing trend with smaller particle sizes. Oxalate-extractable P corresponded to 53–62 % of the total P in varying soil aggregate-sized fractions, although the amounts of amorphous Fe and Al oxides fractions were low with respect to total Fe (15–17 %) and total Al (2–4 %; Table 2). DCB-extractable P (P_{DCB}) was 70–75 % of the total P in these aggregate-sized fractions, which implied that Fe/Al oxides were the major carriers of P in the soil (Table 2). The differences between DCB-extractable Fe and Al oxides and oxalate-extractable Fe and Al oxides represent the amounts of extracted crystalline Fe (c-Fe) and Al (c-Al) oxides. There was a large amount of c-Fe (6.31–28.4 g kg^{-1}, 31–37 % of total Fe). In contrast, c-Al content was low (only 0–0.34 g kg^{-1}, 0–0.6 % of total Al) in the various aggregate-sized fractions (Table 2). Similarly, a high amount of c-Fe and a low amount of c-Al were also found in sandy soils (Borggaard et al., 1990). This is probably because organic matter in soil inhibits Al oxides crystallization (Borggaard et al., 1990). There is currently ongoing discussion in the literature (Acebal et al., 2000; Borggaard et al., 1990; Ryan and Gschwend, 1991) with respect to the extent to which c-Al is extracted by DCB and what reasons for such an incomplete extraction of this Al are. Only 12–20 % of total P (c-P, the difference between P_{DCB} and P_{ox}, Table 2) was released with crystalline Fe and Al oxides. This shows that amorphous Fe/Al oxides are more important for P bonding compared to crystalline Fe/Al oxides. Several researchers have already reported that P was dominantly associated with amorphous Fe and Al oxides fractions in various soil types in the USA (Arai et al., 2005; Rick and Arai, 2011). It was presumed in those studies that specific anion adsorption (e.g., P) suppressed the transformation from amorphous to crystalline Fe oxides (Arai et al., 2005; Biber et al., 1994), which could

Table 1. NaOH–Na$_2$EDTA-extractable P and residual P distribution (%, with respect to total P of each soil aggregate-sized fraction) associated with amorphous and crystalline oxides, and other soil compounds as shown in Eqs. (1–6).

| | NaOH–Na$_2$EDTA-extractable P | | | | | | Residual P | | |
| | $(P_{a-Fe})_N$ | | $(P_{c-Fe})_N$ | | $(P_{other})_N$ | | $(P_{a-Fe})_{resi}$ | $(P_{c-Fe})_{resi}$ | $(P_{other})_{resi}$ |
	Ortho.	Mono.	Ortho.	Mono.	Ortho.	Mono.			
Bulk soil	39	6	5	2	5	4	12	9	18
Sand-sized > 20 μm	36	6	6	1	4	4	11	13	18
Silt-sized 2–20 μm	39	7	3	1	6	5	13	7	18
Clay 0.45–2 μm	37	8	4	1	6	5	13	9	16
Clay < 0.45 μm	41	6	6	1	6	5	15	8	12

Ortho. stands for orthophosphate and Mono. for P monoesters. $(P_{a-Fe})_N$: NaOH–Na$_2$EDTA-extractable P associated with amorphous Fe/Al oxides. $(P_{c-Fe})_N$: NaOH–Na$_2$EDTA-extractable P associated with crystalline Fe oxides. $(P_{other})_N$: NaOH–Na$_2$EDTA-extractable P associated with other soil compounds. $(P_{a-Fe})_{resi}$: residual P associated with amorphous Fe oxides. $(P_{c-Fe})_{resi}$: residual P associated with crystalline Fe oxides. $(P_{other})_{resi}$: residual P associated with other soil compounds.

explain the low amount of P associated with crystalline Fe oxides.

Oxalate extracted P also had a strong positive linear correlation with oxalate extracted Fe ($R^2 = 0.997$) and Al ($R^2 = 0.976$). Similarly high correlation between oxalate-extractable P and Fe oxides has already been shown in acidic and neutral soils (Forsmann and Kjaergaard, 2014). Nevertheless, c-Fe and c-Al contents were not strongly correlated with c-P. Although there was a smaller amount of Ca in different aggregate-sized fractions compared to Fe and Al (Table 2), DCB also dissolved between 48 and 100 % of total Ca in varying aggregate-sized fractions (Table S3). Therefore, it could be assumed that a small amount of the measured c-P (Table 2) was related to Ca minerals (Ca–P precipitates) in the soil.

Although there were higher amounts of total Fe, Al and P in smaller particles compared with larger particles, there were no clearly discernible proportional differences in oxalate and DCB-extractable Fe, Al and P fractions with respect to total Fe, Al and P between various aggregate-sized fractions. Therefore, there was a clear indication that the relative proportional distributions of amorphous, crystalline Fe/Al oxides and related P in this soil were independent of the aggregate size of soil particles, a result not found previously. Kiem and Kögel-Knabner (2002) suggested that there was a similar Fe$_{ox}$ / Fe$_{DCB}$ ratio across three size separates of arable soil fractions < 6 μm. Fe/Al (hydr)oxides and organic matter bind clay particles together into soil aggregates (Tisdall and Oades, 1982). Therefore, these Fe/Al oxides as inorganic binding agents and associated P were distributed on soil aggregates with all varying sizes proportionally.

3.2 Speciation and distribution of P forms in soil aggregate-sized fractions

We found that 58–65 % of total P was extracted by NaOH–Na$_2$EDTA in different soil size fractions (Table S2). A similar extraction efficiency (average of 63 % of total P)

was found in a recent study of dried wetland soil samples (Cheesman et al., 2012). Inorganic and organic P contents in NaOH–Na$_2$EDTA extracts were characterized by solution ^{31}P-NMR spectroscopy. Inorganic (orthophosphate and pyrophosphate) and organic (phosphate monoesters, phosphate diesters and phosphonates) P forms were present in our soil aggregate-sized fractions.

The orthophosphate and phosphate monoesters were major detected inorganic and organic P forms in all soil aggregate-sized fractions (Fig. 3). NaOH–Na$_2$EDTA-extractable orthophosphate (^{31}P-NMR chemical shift of 5–7 ppm; Cade-Menun, 2005) ranged from 0.25 to 1.27 g kg^{-1}, accounting for the majority of P (47–51 % of total P) in all the aggregate-sized fractions (Fig. 3). Phosphate monoesters (3–6 ppm; Bol et al., 2006; Cade-Menun, 2005; Fuentes et al., 2012) were always the dominant organic P, with contents of 53–332 mg kg^{-1} (10–14 % of total P; Fig. 3). Phosphate monoesters are generally the dominant group of organic phosphorus compounds in most soils: they occur mainly as inositol phosphates, a family of phosphoric esters of hexahydroxy cyclohexane (inositol; Turner et al., 2005). The content of pyrophosphate (−4 to −5 ppm; Cade-Menun, 2005) was only up to 15 mg kg^{-1} (less than 1 % of total P). Phosphonates (12 ppm) and phosphate diesters (2.5 to −1 ppm; Cade-Menun, 2005) only contributed 0.6–1.0 % of total P (Fig. 3). We found that there were only few, if any, P diesters in fine particles (Fig. 3). Many microbial products such as teichoic acid P or DNA-P exhibit these structures (Makarov et al., 2002).

All the identified P forms were present in higher concentrations in < 2 μn soil fraction when compared to larger-sized particles. Small-sized soil fractions, such as soil colloids isolated in this study, are well established as being efficient carriers of nutrients (especially phosphorus; Haygarth et al., 2006). Therefore, soil managements, which control soil colloids loss from productive land (e.g., tillage and wind/water erosion), are crucial to restrain any unwanted strong declines in soil phosphorus levels and thus help to retain the poten-

Table 2. The amounts of P, Fe, Al and Ca in bulk soil and soil aggregate-sized fractions, and the amounts of these elements extracted by oxalate and dithionite–citrate–bicarbonate (DCB) ($g\,kg^{-1}$). Fractions with respect to total P, Fe, and Al values of each aggregate-sized fraction shown in Table 2 are given in parentheses. Data are the mean values of three replicates with standard deviations.

Aggregate-sized fractions	P_T^c	Fe_T^c	Al_T^c	Ca_T^c	P_{ox}^d	Fe_{ox}^d	Al_{ox}^d	P_{DCB}^e	Fe_{DCB}^e	Al_{DCB}^e	c-P^f	c-Fe^f	c-Al^f
Bulk soil[a, b]	0.73 ± 0.03	24.0 ± 0.7	44.6 ± 2.1	4.03 ± 0.12	0.41 ± 0.01 (56)	3.75 ± 0.10 (16)	0.88 ± 0.03 (2)	0.53 ± 0.02 (72)	11.6 ± 0.5 (48)	1.03 ± 0.08 (2)	0.12 (16)	7.80 (33)	0.15 (0.3)
Sand-sized > 20 µm[a, b]	0.54 ± 0.05	19.5 ± 2.9	37.4 ± 2.3	3.63 ± 0.32	0.29 ± 0.01 (53)	2.92 ± 0.24 (15)	0.59 ± 0.04 (2)	0.40 ± 0.04 (73)	9.24 ± 0.53 (47)	0.81 ± 0.07 (2)	0.11 (20)	6.31 (32)	0.22 (0.6)
Silt-sized 2–20 µm[a, b]	1.40 ± 1.00	44.7 ± 3.9	73.8 ± 0.9	5.63 ± 0.40	0.82 ± 0.04 (58)	7.00 ± 0.23 (16)	1.83 ± 0.07 (2)	0.98 ± 0.04 (70)	20.7 ± 0.5 (46)	1.93 ± 0.04 (3)	0.17 (12)	13.7 (31)	0.10 (0.1)
Clay 0.45–2 µm[a, b]	2.37 ± 0.06	69.3 ± 3.5	108 ± 2	7.10 ± 0.30	1.38 ± 0.01 (58)	11.6 ± 0.1 (17)	3.28 ± 0.05 (3)	1.72 ± 0.06 (73)	36.8 ± 0.7 (53)	3.62 ± 0.31 (3)	0.33 (14)	25.2 (36)	0.34 (0.3)
Clay < 0.45 µm[a, b]	2.47 ± 0.06	76.4 ± 3.3	114 ± 2	8.23 ± 0.35	1.54 ± 0.07 (62)	12.4 ± 0.5 (16)	4.36 ± 0.28 (4)	1.85 ± 0.09 (75)	40.8 ± 1.1 (53)	4.11 ± 0.35 (4)	0.31 (13)	28.4 (37)	ND

[a] Amounts increase with decreasing particle size. [b] Relative proportions of isolated fractions are independent of decreasing particle size. [c] Total P, Fe, Al and Ca. [d] Oxalate-extractable P, Fe and Al. [e] DCB-extractable P, Fe and Al. [f] c-(P, Fe, Al) means the difference between (P, Fe, Al)$_{DCB}$ and (P, Fe, Al)$_{ox}$.

tial bioavailability of phosphorus over longer time periods. However, the distributions of different P forms in our study seemed to be independent of soil aggregate size (Fig. 3). In contrast, some studies have found that soil size fractions drive the differential P distributions in forest and arable soils (Liu et al., 2014; Solomon et al., 2002). Our novel finding about the similar P distribution in various aggregate-sized fractions of this soil was probably due to the comparable Fe and Al oxide distribution in aggregate-sized fractions when considering that Fe and Al oxides were domain P carriers in the soil.

### 3.3 NaOH–Na₂ EDTA-extractable P associated with Fe and Al oxides in soil aggregate-sized fractions

The bulk soil and aggregate-sized fractions after oxalate and DCB pre-treatments were also extracted by NaOH–Na₂EDTA for ^{31}P-NMR analysis. We found that the bulk soil (Fig. 2) and other soil aggregate-sized fractions (Fig. S1) after oxalate pre-treatment revealed a higher phosphate monoester / orthophosphate ratio in NaOH–Na₂EDTA extracts compared to that without oxalate treatment. The bulk soil (Fig. 2) and other soil aggregate-sized fractions (Fig. S1) after DCB pre-treatment had the highest phosphate monoester / orthophosphate ratio among the three types of samples. This finding implies that relatively high amounts of orthophosphate were removed by oxalate and particularly DCB – i.e., it was mainly orthophosphate that was bound to a- and c-Fe oxides in aggregate-sized fractions rather than organic P. Furthermore, most pyrophosphate still remained in Fe/Al oxide-free aggregate-sized fractions (Figs. 2 and S1). Pyrophosphate is thought to be contained within live fungal tissue (Koukol et al., 2008) or sorbed to the mineral soil matrix (Gunary, 1966). However, the present study suggests that Fe/Al oxides (part of mineral matrix) were not the main sites for pyrophosphate adsorption.

Because orthophosphate and phosphate monoesters were the dominant P forms, only these are discussed below (Table 1). The amount of P bound to Fe/Al oxides in NaOH–

Na₂EDTA extracts accounted for 49–54 % of total P in various aggregate-sized fractions, including orthophosphate (41–47 % of total P) and phosphate monoesters (7–9 % of total P; Table 1). The amorphous oxides carried more orthophosphate and phosphate monoesters (36–41 and 6–8 % of total P, respectively) than did the crystalline oxides (3–6 and 1–2 % of total P, respectively) in the NaOH–Na₂EDTA extracts (Table 1). The P adsorption experiment from Borggaard (1983) showed that a-Fe oxides absorbed more phosphate than c-Fe oxides in soils. Generally, phosphate monoesters are commonly assumed to be stabilized in soils by association with amorphous metal oxides, which have greater sorption affinity compared to crystalline metal oxides (Celi and Barberis, 2007; Turner and Engelbrecht, 2011).

It is worth noting that only small amounts of Fe (0–1 % of total Fe) from "untreated" soil aggregate-sized fractions were dissolved by NaOH–Na₂EDTA (Table S3). Although the presence of Na₂EDTA caused some dissolved Fe ions to precipitate in humic–iron compounds, the precipitation was negligible at hydroxide ion concentrations $\geq$ 100 mM ($\geq$ pH 13; Turner, 2008). The NaOH–Na₂EDTA extracted P was not occluded in the Fe-containing minerals (e.g., Fe oxides) but probably associated with the surface of Fe-containing minerals and bound to other minerals. Therefore, a- and c-Fe oxide-associated P present in NaOH–Na₂EDTA extracts was probably attached to the surface of Fe oxides. Alkaline extraction could remove P held to Fe and Al components of soil surface by chemisorption (Hedley et al., 1982; McLaughlin et al., 1977; Ryden et al., 1977). It is worth noting that there was unavoidable P release from P–goethite complexes after oxalate treatment by ligand exchange; the amount of released P was negligible at low initial P level (Johnson and Loeppert, 2006), as was the case in our soil samples.

High contents of dissolved Al were still found in NaOH–Na₂EDTA extracts; these were similar to those in oxalate and DCB extracts of soil aggregate-sized fractions (Tables 2 and S3). Similarly, high Al and low Fe contents were found in NaOH–Na₂EDTA extracts from a tropical forest soil (Turner, 2008). Considering that little Si was dissolved in NaOH–
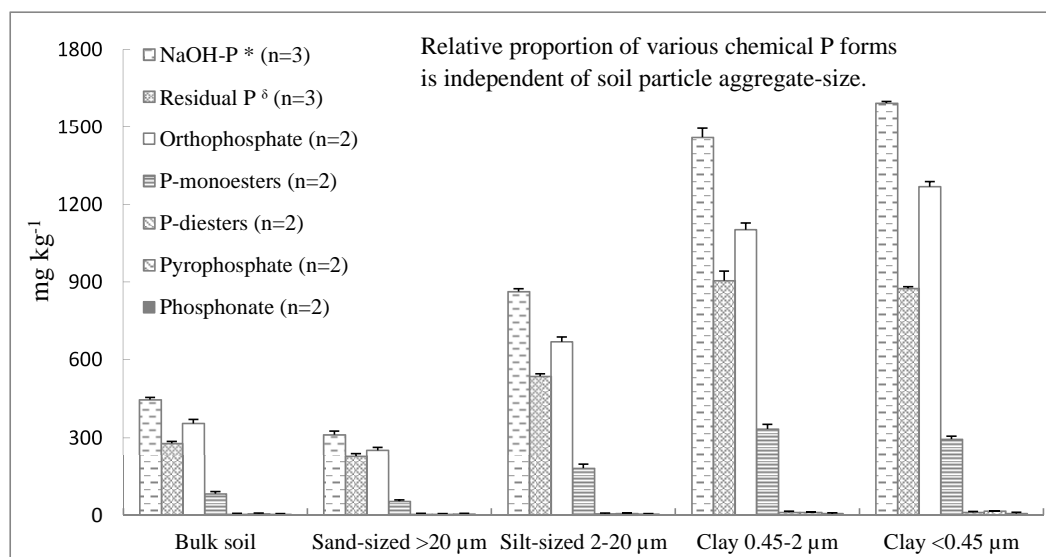
* NaOH-Na$_2$EDTA extractable P. $^\delta$ NaOH-Na$_2$EDTA non-extractable P.

Figure 3. NaOH–Na$_2$EDTA-extractable P, residual P content, and phosphorus forms/contents (mg kg^{-1}) from the NaOH–Na$_2$EDTA extracts in different aggregate-sized fractions as identified by solution phosphorus-31 nuclear magnetic resonance spectroscopy. The varying chemical P contents were determined by multiplying the proportion of spectral area by the total concentration of the NaOH–Na$_2$EDTA-extractable P.

Na$_2$EDTA in all aggregate-sized fractions (data not shown), it was indicative that NaOH–Na$_2$EDTA extracted Al mainly stemmed from amorphous Al oxides (rare c-Al oxides in the soil, Table 2) rather than aluminosilicate minerals in the soil. Therefore, the Al–P in NaOH–Na$_2$EDTA extracts probably contained P on the surface of Al oxides as well as occluded in Al oxides.

Between 8 and 11 % of total P (including 4–6 % orthophosphate and 4–5 % phosphate monoesters) was still present in NaOH–Na$_2$EDTA extracts which were not associated with Fe/Al oxides of different aggregate-sized fractions (Table 1). The NaOH–Na$_2$EDTA extraction included P contained within microbial cells (Turner and Blackwell, 2013). Furthermore, inositol phosphate is stabilized mainly through strong adsorption on the surface of amorphous metal oxides and clay minerals (Celi and Barberis, 2007), so we assumed that a part of these P compounds was adsorbed on the surfaces of clay minerals. Additionally, some P was probably associated with Ca minerals in this NaOH–Na$_2$EDTA extracts considering that 43–98 % of total Ca was dissolved in NaOH–Na$_2$EDTA extracts of different aggregate-sized fractions (Table S3).

3.4 Residual P in soil aggregate-sized fractions

Using our specific separation method, the residual P was separated into P bound to a-Fe oxides, c-Fe oxides and other soil compounds (Eqs. 4–6 and Table 1). The P in residual fractions accounted to 35–42 % of total P in aggregate-sized fractions. We found that 11–15 % of total P in different

aggregate-sized fractions was bound to a-Fe oxides and 7–13 % of total P was associated with c-Fe oxides (Table 1). The 20–24 % of total P associated with Fe oxides (Table 1) was equivalent to 53–66 % of the P present in the residual fraction. Therefore, the majority of P in residual fraction was associated with Fe oxides (Table 1). The remaining 12–18 % of total P (i.e., 34–47 % of the P present in residual fractions) was bound to other minerals or organic matter which was not dissolved or released in either DCB or NaOH–Na$_2$EDTA of different aggregate-sized fractions (Table 1).

Our novel results suggest that the a- and c-Fe oxide-associated P in the residual P fraction was most likely occluded inside of a- and c-Fe oxides. This is in contrast to the a- and c-Fe oxide-associated P present in NaOH–Na$_2$EDTA extracts which were absorbed on the surface of Fe oxides. The P associated with Fe oxides in residual fractions was probably held at the internal surfaces of Fe oxides by chemisorption at protonated surface sites or by the replacement of surface hydroxyls in soil aggregates (Hedley et al., 1982; Ryden et al., 1977) or diffused into the bulk of Fe oxides or into pores and defects (McLaughlin et al., 1977). This means that, with the changes in soil conditions (e.g., soil anoxic condition, acidic condition, high concentrations of organic acid or siderophores; Forsmann and Kjaergaard, 2014; Kraemer, 2004) when Fe oxides become dissolved, P associated with the Fe oxides may become available to plants or the microbial population. The a-Fe/Al oxides adsorbed more orthophosphate and monoesters than c-Fe/Al oxides (Table 1: NaOH–Na$_2$EDTA-extractable P). However, there were simi-

lar amounts of occluded P inside of both a- and c- Fe oxides (Table 1: Residual P).

The Ca–P complexes present in residual fractions of soil aggregate-sized fractions should contribute to a proportion of the remaining residual P, ca. 12–18 % of total P. Cheesman et al. (2010) suggested that there were inorganic Ca phosphates in the residual P from detritus and surface soils. In the present study, 12 % of total P was not associated with Fe oxides in residual P of $< 0.45\,\mu$m soil fractions (Table 1), despite the fact that almost all of the Ca was already extracted by NaOH–Na_2EDTA and DCB (Table S3). Therefore, it seemed that the majority of the 12–18 % of total P was bound to other materials. In our other concurrent work (Jiang et al., 2015), we found that some P in the soil nanoparticles after DCB treatment was still bound to Fe-bearing phyllosilicate minerals (i.e., Fe structurally embedded into the crystalline structure of phyllosilicate minerals via isomorphic substitution; Regelink et al., 2014). It is possible that these Fe-bearing phyllosilicate minerals may also be responsible for the bonding of the remaining P in the NaOH–Na_2EDTA non-extracts. It was worth noting that soil aggregate-sizes do not have a significant effect on the relative distribution of P forms bond to a- and c-Fe/Al oxides for NaOH–Na_2EDTA extracts and residual soil P (Table 1).

4 Conclusions

We draw the following conclusions for this arable German soil. (1) With decreasing aggregate-sized fractions, soil P content increased; however, the distribution and speciation of varying P forms were independent of aggregate size. (2) The majority of NaOH–Na_2EDTA-extractable P (Pi and Po) was probably attached to the surface of amorphous Fe oxides and Al oxides, or alternatively inside of the Al oxides. (3) The majority of P in the residual fraction was occluded within Fe oxides, which implies that this P may be released and become available for plants and microbial communities following the dissolution of Fe oxides in soil.

References

Acebal, S. G., Mijovilovich, A., Rueda, E. H., Aguirre, M. E., and Saragovi, C.: Iron-oxide mineralogy of a mollisol from argentina: a study by selective-dissolution techniques, X-ray diffraction, and mössbauer spectroscopy, Clay. Clay Miner., 48, 322–330, 2000.

Arai, Y. and Livi, K. J.: Underassessed phosphorus fixation mechanisms in soil sand fraction, Geoderma, 192, 422–429, 2013.

Arai, Y., Livi, K. J. T., and Sparks, D. L.: Phosphate reactivity in long-term poultry litter-amended southern delaware sandy soils, Soil Sci. Soc. Am. J., 69, 616–629, 2005.

Berns, A. E., Philipp, H., Narres, H. D., Burauel, P., Vereecken, H., and Tappe, W.: Effect of gamma-sterilization and autoclaving on soil organic matter structure as studied by solid state NMR, UV and fluorescence spectroscopy, Eur. J. Soil Sci., 59, 540–550, 2008.

Biber, M. V., dos Santos Afonso, M., and Stumm, W.: The coordination chemistry of weathering: IV. Inhibition of the dissolution of oxide minerals, Geochim. Cosmochim. Ac., 58, 1999–2010, 1994.

Bol, R., Amelung, W., and Haumaier, L.: Phosphorus-31–nuclear magnetic–resonance spectroscopy to trace organic dung phosphorus in a temperate grassland soil, J. Plant Nutr. Soil Sci., 169, 69–75, 2006.

Borggaard, O. K.: The influence of iron oxides on phosphate adsorption by soil, J. Soil Sci., 34, 333–341, 1983.

Borggaard, O. K., Jørgensen, S. S., Møberg, J. P., and Raben-Lange, B.: Influence of organic matter on phosphate adsorption by aluminium and iron oxides in sandy soils, J. Soil Sci., 41, 443–449, 1990.

Bowman, R. A. and Moir, J. O.: Basic EDTA as an extractant for soil organic phosphorus, Soil Sci. Soc. Am. J., 57, 1516–1518, 1993.

Cade-Menun, B. J.: Characterizing phosphorus in environmental and agricultural samples by ^{31}P nuclear magnetic resonance spectroscopy, Talanta, 66, 359–371, 2005.

Cade-Menun, B. and Liu, C. W.: Solution phosphorus-31 nuclear magnetic resonance spectroscopy of soils from 2005 to 2013: a review of sample preparation and experimental parameters, Soil Sci. Soc. Am. J., 78, 19–37, 2014.

Cade-Menun, B. J. and Preston, C. M.: A comparison of soil extraction procedures for ^{31}P NMR spectroscopy, Soil Sci., 161, 770–785, 1996.

Celi, L. and Barberis, E.: Abiotic reactions of inositol phosphates in soil, in: Inositol Phosphates, Linking Agriculture and the Environment, edited by: Turner, B. L., Richardson, A. E., and Mullaney, E. J., CAB International, Wallingford, UK, 207–220, 2007.

Cheesman, A. W., Turner, B. L., Inglett, P. W., and Reddy, K. R.: Phosphorus transformations during decomposition of wetland macrophytes, Environ. Sci. Technol., 44, 9265–9271, 2010.

Cheesman, A. W., Turner, B. L., and Ramesh Reddy, K.: Soil phosphorus forms along a strong nutrient gradient in a tropical ombrotrophic wetland, Soil Sci. Soc. Am. J., 76, 1496–1506, 2012.

Dick, W. A. and Tabatabai, M. A.: Hydrolysis of organic and inorganic phosphorus compounds added to soils, Geoderma, 21, 175–182, 1978.

Forsmann, D. M. and Kjaergaard, C.: Phosphorus release from anaerobic peat soils during convective discharge — Effect of soil Fe:P molar ratio and preferential flow, Geoderma, 223–225, 21–32, 2014.

Fuentes, B., Dixon, E., de la Luz Mora, M., Turner, B. L., and Bol, R.: Dissolved phosphorus composition of grassland leachates

following application of dairy-slurry size fractions, J. Plant Nutr. Soil Sci., 175, 78–85, 2012.

Gunary, D.: Pyrophosphate in soil; some physico-chemical aspects, Nature, 210, 1297–1298, 1966.

Haygarth, P. M., Bilotta, G. S., Bol, R., Brazier, R. E., Butler, P. J., Freer, J., Gimbert, L. J., Granger, S. J., Krueger, T., Macleod, C. J. A., Naden, P., Old, G., Quinton, J. N., Smith B., and Worsfold, P.: Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: an overview of key issues, Hydrol. Process., 20, 4407–4413, 2006.

He, Z., Honeycutt, C. W., Cade-Menun, B. J., Senwo, Z. N., and Tazisong, I. A.: Phosphorus in poultry litter and soil: enzymatic and nuclear magnetic resonance characterization, Soil Sci. Soc. Am. J., 72, 1425–1433, 2008.

He, Z., Honeycutt, C. W., Tazisong, I. A., Senwo, Z. N., and Zhang, D.: Nitrogen and phosphorus accumulation in pasture soil from repeated poultry litter application, Commun. Soil Sci. Plan., 40, 587–598, 2009.

Hedley, M. J., Stewart, J. W. B., and Chauhan, B. S.: Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations, Soil Sci. Soc. Am. J., 46, 970–976, 1982.

Izarova, N. V., Maksimovskaya, R. I., Willbold, S., and Kögerler, P.: Tetrapalladium-containing polyoxotungstate $[Pd_4^{II}(\acute{a}\text{-}P_2W_{15}O_{56})_2]^{16-}$: a comparative study, Inorg. Chem., 53, 11778–11784, 2014.

Jiang, X., Bol, R., Nischwitz, V., Siebers, N., Willbold, S., Vereecken, H., Amelung, W., and Klumpp, E.: Phosphorus containing water dispersible nanoparticles in arable soil, J. Environ. Qual., 44, 1772–1781, 2015.

Johnson, S. E. and Loeppert, R. H.: Role of organic acids in phosphate mobilization from iron oxide. Soil Sci. Soc. Am. J., 70, 222–234, 2006.

Kiem, R. and Kögel-Knabner, I.: Refractory organic carbon in particle-size fractions of arable soils II: organic carbon in relation to mineral surface area and iron oxides in fractions $<6\,\mu$, Org. Geochem., 33, 1699–1713, 2002.

Kleber, M., Mikutta, R., Torn, M. S., and Jahn, R.: Poorly crystalline mineral phases protect organic matter in acid subsoil horizons, Eur. J. Soil Sci., 56, 717–725, 2005.

Koukol, O., Novák, F., and Hrabal, R.: Composition of the organic phosphorus fraction in basidiocarps of saprotrophic and mycorrhizal fungi, Soil Biol. Biochem., 40, 2464–2467, 2008.

Kraemer, S.: Iron oxide dissolution and solubility in the presence of siderophores, Aquat. Sci., 66, 3–18, 2004.

Kupisch, M., Stadler, A., Langensiepen, M., and Ewert, F.: Analysis of spatio-temporal patterns of CO_2 and H_2O fluxes in relation to crop growth under field conditions, Field Crop. Res., 176, 108–118, 2015.

Li, J., Richter, D., Mendoza, A., and Heine, P.: Four-decade responses of soil trace elements to an aggrading old-field forest: B, Mn, Zn, Cu, and Fe, Ecology, 89, 2911–2923, 2008.

Liu, J., Yang, J., Liang, X., Zhao, Y., Cade-Menun, B. J., and Hu, Y.: Molecular speciation of phosphorus present in readily dispersible colloids from agricultural soils, Soil Sci. Soc. Am. J., 78, 47–53, 2014.

Mahieu, N., Olk, D. C., and Randall, E. W.: Analysis of phosphorus in two humic acid fractions of intensively cropped lowland rice soils by ^{31}P-NMR, Eur. J. Soil Sci., 51, 391–402, 2000.

Makarov, M. I., Haumaier, L., and Zech, W.: Nature of soil organic phosphorus: an assessment of peak assignments in the diester region of 31P NMR spectra, Soil Biol. Biochem., 34, 1467–1477, 2002.

Masiello, C. A., Chadwick, O. A., Southon, J., Torn, M. S., and Harden, J. W.: Weathering controls on mechanisms of carbon storage in grassland soils, Global Biogeochem. Cy., 18, GB4023, doi:10.1029/2004GB002219, 2004.

McDowell, R. W., Cade-Menun, B., and Stewart, I.: Organic phosphorus speciation and pedogenesis: analysis by solution 31P nuclear magnetic resonance spectroscopy, Eur. J. Soil Sci., 58, 1348–1357, 2007.

McLaughlin, J. R., Ryden, J. C., and Syers, J. K.: Development and evaluation of a kinetic model to describe phosphate sorption by hydrous ferric oxide gel, Geoderma, 18, 295–307, 1977.

Neubauer, E., Schenkeveld, W. D. C., Plathe, K. L., Rentenberger, C., von der Kammer, F., Kraemer, S. M., and Hofmann, T.: The influence of pH on iron speciation in podzol extracts: Iron complexes with natural organic matter, and iron mineral nanoparticles, Sci. Total Environ., 461–462, 108-116, 2013.

Regelink, I. C., Voegelin, A., Weng, L., Koopmans, G. F., and Comans, R. N. J.: Characterization of colloidal Fe from soils using field-flow fractionation and Fe K-Edge X-ray absorption spectroscopy, Environ. Sci. Technol., 48, 4307–4316, 2014.

Richter, D., Allen, H. L., Li, J., Markewitz, D., and Raikes, J.: Bioavailability of slowly cycling soil phosphorus: major restructuring of soil P fractions over four decades in an aggrading forest, Oecologia, 150, 259–271, 2006.

Rick, A. R. and Arai, Y.: Role of natural nanoparticles in phosphorus transport processes in ultisols Soil Sci. Soc. Am. J., 75, 335–347, 2011.

Rubæk, G. H., Guggenberger, G., Zech, W., and Christensen, B. T.: Organic phosphorus in soil size separates characterized by phosphorus-31 nuclear magnetic resonance and resin extraction, Soil Sci. Soc. Am. J., 63, 1123–1132, 1999.

Ryan, J. N. and Gschwend, P. M.: Extraction of iron oxides from sediments using reductive dissolution by titanium (III), Clay Clay Miner., 39, 509–518, 1991.

Ryden, J. C., McLaughlin, J. R., and Syers, J. K.: Mechanisms of phosphate sorption by soils and hydrous ferric oxide gel, J. Soil Sci., 28, 72–92, 1977.

Schwertmann, U.: Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung, Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde, 105, 194–202, 1964.

Séquaris, J. M. and Lewandowski, H.: Physicochemical characterization of potential colloids from agricultural topsoils, Colloids Surf. A, 217, 93–99, 2003.

Sims, J. T., Edwards, A. C., Schoumans, O. F., and Simard, R. R.: Integrating soil phosphorus testing into environmentally based agricultural management practices, J. Environ. Qual., 29, 60–71, 2000.

Solomon, D. and Lehmann, J.: Loss of phosphorus from soil in semi-arid northern Tanzania as a result of cropping: evidence from sequential extraction and 31P-NMR spectroscopy, Eur. J. Soil Sci., 51, 699–708, 2000.

Solomon, D., Lehmann, J., Mamo, T., Fritzsche, F., and Zech, W.: Phosphorus forms and dynamics as influenced by land use changes in the sub-humid Ethiopian highlands, Geoderma, 105, 21–48, 2002.

Tisdall, J. M. and Oades, J. M.: Organic matter and water-stable aggregates in soils, J. Soil Sci., 33, 141–163, 1982.

Turner, B. and Engelbrecht, B. J.: Soil organic phosphorus in lowland tropical rain forests, Biogeochemistry, 103, 297–315, 2011.

Turner, B., Condron, L., Richardson, S., Peltzer, D., and Allison, V.: Soil organic phosphorus transformations during pedogenesis, Ecosystems, 10, 1166–1181, 2007.

Turner, B. L.: Soil organic phosphorus in tropical forests: an assessment of the NaOH–EDTA extraction procedure for quantitative analysis by solution 31P NMR spectroscopy, Eur. J. Soil Sci., 59, 453–466, 2008.

Turner, B. L. and Blackwell, M. S. A.: Isolating the influence of pH on the amounts and forms of soil organic phosphorus, Eur. J. Soil Sci., 64, 249–259, 2013.

Turner, B. L., Cade-Menun, B. J., and Westermann, D. T.: Organic Phosphorus Composition and Potential Bioavailability in Semi-Arid Arable Soils of the Western United States, Soil Sci. Soc. Am. J., 67, 1168–1179, 2003.

Turner, B. L., Cade-Menun, B. J., Condron, L. M., and Newman, S.: Extraction of soil organic phosphorus, Talanta, 66, 294–306, 2005.

Vestergren, J., Vincent, A. G., Jansson, M., Persson, P., Ilstedt, U., Gröbner, G., Giesler, R., and Schleucher, J.: High-resolution characterization of organic phosphorus in soil extracts using 2D ^{1}H–^{31}P NMR correlation spectroscopy, Environ. Sci. Technol., 46, 3950–3956, 2012.

Wei, K., Chen, Z., Zhu, A., Zhang, J., and Chen, L.: Application of 31P NMR spectroscopy in determining phosphatase activities and P composition in soil aggregates influenced by tillage and residue management practices, Soil Till. Res., 138, 35–43, 2014.