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Effect of organic and mineral fertilizers on soil P and C levels, crop yield and P leaching in a long term trial on a silt loam soil

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ABSTRACT

The main objective of the present study was to compare fertilizer types in their ability to increase the soil organic matter content without increasing potential P leaching losses. Differences in soil organic carbon content, crop yield, P-$CaCl_2$, P-AL, P export by the crop and P leaching from soil supplied with three compost types, cattle slurry, farmyard manure or mineral fertilizers were compared in a 8 years field experiment with arable, vegetable and fodder crops. P leaching losses were assessed separately in a soil column leaching experiment. As expected, farmyard manure and compost are the better options to increase the soil organic carbon level. Cattle slurry and mineral fertilizers tended to produce lower crop yields. P-$CaCl_2$ was increased when farmyard manure was used as organic fertilizer, leading to an increased P leaching but not to an increased crop P export. Therefore it seems that the higher dissolved P concentrations in the soil solution for farmyard manure, measured as P-$CaCl_2$ in the soil, are a source of potential P losses. All three compost types could gradually increase soil organic carbon levels without increasing P leaching losses.

1. Introduction

Since the 1950s, agriculture in northwestern Europe can be characterized by the development of farms with large livestock densities (Chardon and Schoumans, 2007). Disposal of excessive amounts of manure together with the use of mineral fertilizers can lead to an imbalance between P input and P output and the accumulation of P in soil over time, resulting in an increased risk for P transfer from soil to ground and surface water (Haygarth et al., 1998; De Bolle et al., 2013). Loss of P to the environment can be ascribed to erosion and surface run-off, but important amounts of P can also be lost through the soil profile through leaching (Chardon and Schoumans, 2007). In order to prevent nutrient losses, restrictions on N and P supply with organic and mineral fertilizers have been enforced in Belgium from the 1990s on. Currently, P fertilization levels are restricted to P equilibrium fertilization level, balancing P inputs to farmland (organic and inorganic fertilizers) with P export (harvested crops). In the future, P fertilization levels might even decrease to allow P mining. As a consequence the supply of organic matter to soils is expected to further decrease. Sleutel et al. (2003) already observed declining soil organic carbon stocks in intensively managed Belgian cropland soils due to adoption of short crop rotations or monocultures, deep tillage (dilution effect) and higher harvest indices (Sleutel et al., 2006; Gardi and Sconosciuto, 2007).

P equilibrium fertilization or P mining might ultimately decrease the level of plant available P to an extent below crop requirements (Verloop et al., 2010) and a restricted application of organic fertilizers may jeopardize the physical, biological and

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Abbreviations: Ca-AL, ammonium lactate extractable calcium; DM, dry matter; Fe-AL, ammonium lactate extractable iron; HWC, hot water extractable carbon; HWP, hot water extractable phosphorus; IC, ion chromatography; ICP–OES, inductively coupled plasma–optical emission spectroscopy; OP, orthophosphate; P-AL, ammonium lactate extractable phosphorus; P-$CaCl_2$, 0.01 M $CaCl_2$ extractable phosphorus; P_{tot}, soil total phosphorus; SOC, soil organic carbon; TDC, total dissolved carbon; TDP, total dissolved phosphorus; TP, total phosphorus.

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chemical soil fertility (Diacono and Montemurro, 2009). Indeed, sufficiently high soil organic carbon levels have to be maintained as they may affect crop yield indirectly by modifying soil physical and chemical properties, offering an improved root environment (Darwish et al., 1995; Stratton et al., 1995; D'Hose et al., 2014). Krey et al. (2013) observed a similar or even stronger impact of organic fertilizers applied every third year on plant traits and P availability, compared to the annual application of inorganic P fertilizers. In the long term field trial we sampled in our study, Leroy (2008) and Moeskops et al. (2012) showed that not only the quantity, but also the quality of the exogenous organic matter applied has a significant influence on the soil physical properties and soil microbial community, respectively.

Organic fertilizer amendment may affect the P leaching in the short or the long term. Tarkalson and Leytem (2009) found that more P leached shortly after (1–2 weeks) application of dairy cattle slurry, compared to an application of dairy farmyard manure or monoammonium phosphate. Brock et al. (2007) showed a 1.5–10.5 fold increase in dissolved reactive P leaching, just after surface application of dairy manure. A history of P surplus fertilization can amplify this effect and further increase the P leaching risk (Djojic and Mattsson, 2013). Longer term effects of organic fertilizer amendments were investigated by McDowell and Sharpley (2004). After 5 year amendments with equal P supply, they found a clearly higher P leaching from a treatment with dairy farmyard manure compost, compared to a treatment with dairy farmyard manure. They found no differences between a farmyard manure and superphosphate treatment (McDowell and Sharpley, 2004).

To predict the risk of P leaching losses, van der Zee's model (van der Zee and Van Riemsdijk, 1988) of P saturation is widely used. According to this model, the soil P saturation degree is determined by the soil P sorption capacity and the total amount of P adsorbed in the soil. As P accumulates in the soil, the soil P sorption capacity decreases and P leaching risks increase. van der Zee's model of P saturation is however only valid in acid sandy soils (van der Zee et al., 1990), where the P sorption capacity is dominated by non-crystalline Al and Fe compounds (Freese et al., 1992). Above, P saturation levels are the result of historical P fertilization management and can only be changed on the long term by changing the total P input (and output). With van der Zee's model, it is unlikely to detect any difference in P leaching, based on changes in fertilizer types used at the same total P input rate. In contrast, laboratory leaching experiments have successfully been used in several studies to reveal differences in P leaching between farmlands under a different fertilizer management (Lookman, 1995; Brock et al., 2007), between treatments with different organic/inorganic fertilizer types in a long-term field trial (McDowell and Sharpley, 2004; Tarkalson and Leytem, 2009) and between soil columns with a single addition of several types of exogenous organic matter or organic fertilizers (Yang et al., 2008; Ashjaei et al., 2010). Another advantage of laboratory leaching experiments is that their application is not limited to sandy soil, like van der Zee's model. However, van der Zee's model takes into account the whole soil profile from surface to groundwater table, while working with topsoil samples in soil column experiments will only allow to assess relative differences in P that potentially will leach from the topsoil. Soil layers deeper in the soil profile, with their generally higher P sorption capacity, can adsorb P that is transported through the soil profile with leaching water. Preferential flow, on the other hand, allows P in leachate to by-pass areas of higher P sorption capacity in the subsoil (Brock et al., 2007), resulting in less sorption of P by the soil than would result from matrix flow.

To maintain soil quality, addition of exogenous organic matter is necessary. Due to intensive livestock farming, animal manure is easily available in northwestern Europe. However, using more animal manure would lead to higher P input, while more than 65% farmland has already a P surplus status compared to Belgian recommended P fertility standards (120–180 mg P-AL kg^{-1} DS) (Maes et al., 2012), which are among the highest for Europe (Jordan-Meille et al., 2012). Agriculture will need organic fertilizers that provide the soil with enough organic material to maintain the soil organic carbon levels (SOC) without increasing the P leaching. Compost seems to be an interesting product in soils with low organic carbon levels. Twice as much of the applied C through compost addition is retained in the soil, compared to farmyard manure (Powlson et al., 2012). Although composts (Ehlert et al., 2004; Vandecasteele et al., 2014) contain mainly P in inorganic forms, much of the inorganic P in composts is bound on organic material, and is therefore less soluble (Ehlert et al., 2004). This suggest that composts may provoke less P leaching compared to animal manure. In contrast, McDowell and Sharpley (2004) reported increased P leaching when soils were fertilized with composted farmyard manure, instead of untreated farmyard manure. This highlights the need to study effects of organic fertilizers on P leaching.

The objective of this study was to compare different fertilizer types in their ability to increase the soil organic matter content while not increasing P leaching losses. This objective was achieved by (i) analysis of soil and plant samples of a long term field trial on silt loam established in 2005 and (ii) by conducting a soil column leaching experiment under laboratory conditions with soil samples of this long term field trial.

We hypothesized (i) that owing to differences in C stability and organic matter quality, different types of exogenous organic matter are contributing differently to the build-up of soil organic carbon; and (ii) that P leaching losses are dependent both on the total P input and on fertilizer type.

2. Material and methods

2.1. Field trial

In 2005, a long term field experiment was started in Melle (50°59′N, 03°49′E, 11 m above sea level), Belgium. Prior to the experiment this field was 8 years cropped with mineral fertilized forage maize. The initial SOC level of the field experiment was with 1.01% (Leroy, 2008) suboptimal, compared to the recommended levels of 1.2–1.6% by the Belgian Soil Service (Maes et al., 2012). The soil contains 11.7% clay (0–2 μm), 52.0% silt (2–50 μm) and 36.3% sand (>50 μm), and its texture is classified as silt loam (USDA). The experiment is a randomized complete block design with 4 replicates comparing 8 fertilizer treatments: MIN (only mineral fertilizers), FYM (dairy farmyard manure), CSL (cattle slurry), VFG (vegetable, fruit and garden waste compost), CMC1 (farm compost with high C/N), CMC2 (farm compost with low C/N), NF+ (no fertilizer) and NF− (unfertilized fallow) (Leroy, 2008). NF+ and NF− can be considered as control treatments. Farm composts CMC1 and CMC2 were made out of wood and bark chips, straw, mowed grass and crop residues (Steel et al., 2012). The crop rotation consisted of arable, feed and vegetable crops (Table 1). After each crop harvest, above ground crop residues were removed by hand. In the CSL treatment, the cattle slurry dose was calculated yearly based on a N balance method to fulfill crop demands, considering residual mineral N in the soil profile, the estimated N mineralization of the cattle slurry and the estimated soil N mineralization (based on incubation experiments every 4 years). All other organic fertilizer treatments (FYM, VFG, CMC1 and CMC2) were equalized for C input with the CSL treatment. There was a high variability in yearly C input between 2005 and 2012 (Table 1). In the MIN treatment, no organic fertilizers were added. To fulfill N

Table 1
Crop rotation of the field trial and yearly, average and total (2005–2012) C and P input.

Year	Crop rotation	C input (kg ha^{-1})	P input (kg ha^{-1})							
		FYM/VFG/CMC1/CMC2/ CSL	FYM	VFG	CMC1	CMC2	CSL	MIN	NF +	NF−
2005	*Beta vulgaris* L. (fodder beet)	8000	169	167	104	205	87	87	0	0
2006	*Triticum aestivum* L. (winter wheat) + *Phacelia tanacetifolia* Benth. (*Phacelia* as catch crop)	1500	36	28	33	21	27	0	0	0
2007	*Brassica oleracea* L. var. Rubra (red cabbage)	2000	44	44	44	44	46	44	0	0
2008	*Lolium perenne* L. (perennial ryegrass)	1101	44	44	44	44	46	44	0	0
2009	*Zea mays* L. (forage maize)	3259	99	33	33	33	69	33	0	0
2010	*Beta vulgaris*L. (fodder beet)	3101	59	44	44	44	64	44	0	0
2011	*Brassica oleracea* L. var. Rubra (red cabbage)	2600	57	44	44	44	57	44	0	0
2012	*Solanum tuberosum* L. (potato)	2350	44	44	44	44	48	44	0	0
	Average input (kg ha^{-1} year^{-1})	2989	69	56	49	60	56	42	0	0
	Total input (kg ha^{-1})	23911	551	446	388	477	444	338	0	0
	Total P input with organic fertilizers (kg ha^{-1})	–	459	375	235	366	419	0	0	0

crop demands in the CMC1, CMC2, VFG, FYM and MIN treatments, extra mineral N was applied. These extra N doses were calculated for each treatment, based on residual mineral N in the soil profile, the soil N mineralization in every treatment (based on incubation experiments every 4 years) and the estimated N mineralization of the organic fertilizer. The crop growth was hence not restricted by N availability. If P and K supply through organic fertilizers was below 44 kg P ha^{-1} year^{-1} and/or 250 kg K ha^{-1} year^{-1}, respectively, additional mineral P and K fertilizers were added except in 2006 and 2009. The mean composition of all organic fertilizers used is presented in Table 2. In all cases, the organic and mineral fertilizers were incorporated to a depth of 30 cm using a spading rotary tiller just before planting or sowing. During the experimental period, the NF− plots were kept fallow by harrowing.

2.2. Soil analysis

Immediately after harvest, soil samples (0–30 cm) were taken with an auger (regular grid, 20 soil cores plot^{-1}) in 2011 and 2012 on every plot for analysis of 0.01 M $CaCl_2$ extractable P (P-$CaCl_2$), ammonium lactate extractable P (P-AL), Fe (Fe-AL) and Ca (Ca-AL), hot water extractable C (HWC) and P (HWP), total P (P_{tot}), pH-KCl and soil organic C (SOC).

P-$CaCl_2$, as an estimate of easily soluble P, was measured with ICP–OES (Varian Vista-pro axial), after shaking (165 rpm) 10.00 g of fresh soil with 100 ml of a 0.01 M $CaCl_2$ -solution for 2 h in dark polypropylene containers, and filtration on a Whatman N° 42 filter (NEN 5704, 1996). P-AL, as an agronomic parameter to estimate the plant available P, was measured with ICP–OES, after shaking 5.00 g air-dry soil sieved at 2 mm with 100 ml ammonium lactate–acetic acid buffer (pH 3.75) (Egner et al., 1960; NEN 5793, 2008) for 4 h at 200 rpm in dark polyethylene containers, filtration on a Macherey Nagel 640w filter and a 1 h digestion of 10.0 ml subsample of the filtrate with 3.0 ml HCl (37%) and 1.0 ml HNO_3 (65%) in a microwave oven (Milestone ETHOS One). Also Fe-AL and Ca-AL were measured in this ammonium lactate extract. For the hot water extraction of C and P, the method of Ghani et al. (2003) was used, but subject to modifications. A subsample of 5.00 g oven-dry soil (70 °C), sieved at 250 μm was extracted with 25 ml demineralized water for 16 h in a hot water bath (70 °C). The soil suspension was filtered on a Whatman N° 42 filter, after a centrifugation at 3274 g during 15 min. HWC and HWP are the amount of C and P respectively in this filtrate, measured with ICP–OES. These parameters estimate the labile C and P fraction of the soil. To measure the total P content of the soil, the method of Ivanov et al. (2012) for a microwave digestion method was used as follows: 0.5000 g of oven-dry soil (70 °C, <250 μm) was destructed for 30 min at 200 °C in 12 ml aqua regia in a microwave oven. After filtration on a Whatman 640 d filter, the P concentration of the filtrate was measured with ICP–OES. To measure pH-KCl, a subsample of 20 ml oven dry soil (70 °C), was added to an open polyethylene cup of 200 ml and 100 ml of a 1 M KCl solution was added. The suspension was thoroughly mixed, and shaken 1 h on a rotary shaker (150 rpm). After an additional 2 h the pH-KCl was measured with a pH electrode (Consort C832), immediately after stirring the soil suspension (ISO 10390, 2005). SOC level was measured in a TOC-analyzer (Skalar Primacs SLC Analyzer), directly on an oven dry (70 °C) subsample of 1.000 g at 1050 °C (ISO 10694, 1995).

The difference in SOC level between treatments FYM, VFG, CMC1, CMC2, CSL on one hand and treatment MIN on the other (ΔSOC) was calculated per block and divided by the plot specific P-$CaCl_2$. Hence, the MIN treatment served as reference treatment for SOC level. To combine the evolution in SOC level and P in the soil solution per organic fertilizer type in one parameter, the ΔSOC/P-$CaCl_2$ ratio was calculated.

Table 2
Mean (±SD) composition of all organic fertilizers used in the field trial from 2005 to 2012 (FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry).

Treatment	Mean composition (g kg^{-1} fresh matter)				
	C	N	P	K	C/P
FYM	89.0 ± 15.7	4.9 ± 1.5	1.5 ± 0.5	10.9 ± 5.0	67 ± 36
VFG	149.4 ± 23.4	11.5 ± 3.0	2.40 ± 01.1	8.2 ± 1.9	75 ± 33
CMC1	100.5 ± 42.5	3.9 ± 1.2	0.80 ± 00.4	3.9 ± 2.4	156 ± 100
CMC2	81.4 ± 21.1	5.9 ± 2.4	1.10 ± 00.6	4.1 ± 2.3	107 ± 73
CSL	31.2 ± 6.3	3.8 ± 0.6	0.60 ± 00.1	4.1 ± 1.1	53 ± 8

2.3. Leaching experiment

A leaching experiment in controlled unsaturated conditions with fresh soil samples was conducted in the laboratory to estimate the P leaching losses out of the top layer. Soil samples (0–30 cm) were taken in December 2011 in 3 of the 4 replicates of the field trial with an auger (regular grid, 20 soil cores plot^{-1}) to get one mixed sample per plot (3 replicates × 8 treatments = 24 samples). Visible crop residues were removed.

The laboratory leaching equipment (Fig. 1) consisted of a vacuum pump (Becker), a peristaltic pump (Watson Marlow 503S/RL), 15 leaching columns (ROBU, diameter 125 mm and height 80 mm), 15 filtrate bottles and a digital pressure gauge (KNF

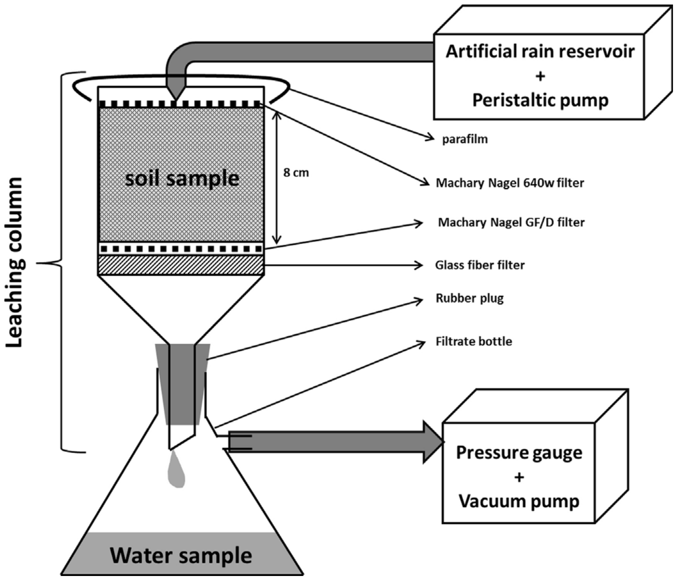

Fig. 1. Design of the laboratory leaching experiment. Example of one leaching column.

Neuberger). At the bottom of the leaching columns there was a Macherey-Nagel GF/D filter (2.7 μm) and glass fiber filter (10–16 μm). The leaching columns were placed on the filtrate bottles and connected with tubes to the pressure gauge and the vacuum pump. This set-up was based upon the study of Lookman (1995). The leaching columns were filled with soil subsamples of 1.680 kg moist soil (equivalent of 1.374 kg dry soil, bulk density of 1.4 kg dm^{-3}). A Macherey Nagel 640w paper filter was placed on top of the soil in the leaching columns, to ensure a better distribution of the synthetic rainwater and prevent a preferential water flow. The top of the leaching columns were covered with parafilm. The peristaltic pump permanently provided an aqueous mixture of 'artificial rain' (pH 5.45), which consisted of 0.02 mM SO_4^{2-}, 0.04 mM Cl^-, 0.02 mM Ca^{2+}, 0.003 mM K^+, 0.02 mM Na^+. This composition was based upon the composition of 'artificial rai' used by Lookman (1995) and the composition of rain nearby Chimay (Belgium), measured by André et al. (2007). The water flow rate was 2.85 ml h^{-1}. This water flow was only interrupted whenever a water sample was taken. The digital pressure gauge controlled the vacuum pump in order to keep the pressure in the whole system at 10 kPa below atmospheric pressure (=pressure of a sandy soil at field capacity) enabling soil samples in the leaching columns to be held permanently in unsaturated conditions. The entire system was installed in the dark, at a constant temperature of 18.0 ± 0.5 °C. Twice a week, a water sample was collected from the filtrate bottles.

Since the leaching experiment can only be conducted with 15 soil samples at a time, the leaching experiment was conducted in 2 batches. For the first batch (CSL, FYM, MIN, NF−; and VFG), the leaching experiment was conducted immediately after soil sampling. Samples of NF+, CMC1 and CMC2, not participating in the first batch were stored in closed plastic bags at 0–4 °C until a second batch was started in May 2012. Subsamples of NF− and FYM, stored similarly as NF+, CMC1 and CMC2, were included in this second batch to check for reproducibility (see Section 3). Both leaching experiment batches lasted for 36 days and in both cases 165 (±20) l m^{-2} was added to the soil surface.

2.4. Water analysis

The volume of percolated water at each sampling moment was recorded. Water samples were analysed within 8 h for total P concentration (TP), filtered ($<0.45\,\mu$m) and measured for total dissolved P (TDP), total dissolved C (TDC), and Fe-concentration. The filtration step at 0.45 μm was necessary to make the distinction between TP and TDP in the water samples, following Worsfold et al. (2005). If storage before orthophosphate (OP) measurement was necessary, the filtered water samples were stored in the dark at 0–4 °C.

Fe concentrations were measured, because a sudden increase in Fe concentration of the water samples may indicate anaerobic conditions in the soil columns due to silting or saturation by the water flow. Anaerobic soil conditions lead to reduction of Fe and may therefore also lead to an enhanced P desorption from the mineral soil, causing higher P leaching losses than in the in aerobic field conditions. Instead of the digestion and spectrophotometric method (Worsfold et al., 2005), the ICP–OES (Varian Vista-pro axial) was used to measure TP in the water samples immediately after collection, and to measure TDP, TDC and total Fe concentration in filtered (MN Chromafil GF/P-45/25 membrane filter, $<0.45\,\mu$m) subsamples. Ion chromatography (Dionex ICS-3000) was used to measure OP in the water samples.

2.5. Validation of the leaching experiment

It is thought that an increased P leaching, also causes a P enrichment of the subsoil (Brock et al., 2007). We used this knowledge in order to validate the findings of the leaching experiment. We measured the HWP and P-AL levels of the shallow subsoil (30–40 cm) of all treatments in the field trial. The subsoil was sampled in 2012 with an auger (regular grid, 20 soil cores $plot^{-1}$) after potato harvest.

2.6. Crop yield and plant analysis

To determine crop yields, a crop specific area in the middle of each plot was harvested: 10 m^2 for fodder beet (roots + leaves), 6 m^2 for maize, 5.6 m^2 for perennial ryegrass, 7.5 m^2 for red cabbage (cabbage + residual leaves) and 9.5 m^2 for potatoes. There were no crop yield determinations for winter wheat and *Phacelia* (both in 2006) due to severe lodging of the crops. Dry matter content (DM%) was measured by drying a plant sample of minimum 1000 g for 48 h in an oven at 70 °C. To calculate the relative crop yield, first a yearly arbitrary expected yield was calculated by averaging all replicates of treatments of FYM, VFG, CMC1, CMC2, CSL and MIN. All further calculations were determined relative to that average expected yield. After calculating all relative yields, we averaged the relative yields per treatment, including all replicates, for all years (2005, 2007–2012). The resulting averages are then compared (Table 3). After drying, the plant samples were chopped to pass a sieve of 1 mm in a plant mill (Fritsch pulverisette 19). To determine the total P concentration of the plant samples in 2011 and 2012, a subsample of 0.1000 g (+0.05 g $CaCO_3$) was incinerated in a muffle oven for 4 h at 480 °C. 10.0 ml H_2O and 1 ml HCl was added to the ash, and the mixture was evaporated. Afterwards 10.0 ml HNO_3 (1 M) was added, and the mixture was boiled for 5 min. After filtration (MN 640 m), the filtrate was mixed with ammonium molybdate and ammonium metavanadate reagent (Cavell, 2006) and diluted with H_2O. The P in the solution was measured in a spectrophotometer (Varian Cary 50 UV–VIS).

Table 3
Year and treatment effect for soil properties measured in the 0–30 cm soil layer. The soil properties are calculated per mass unit of dry soil. Data are arithmetic means (±SD) of all treatments sampled in 2011 and 2012. Data with the same letter(s) (factor treatment: lower case letters, factor year: upper case letters) in a column are not significantly different (Scheffé's test, $p < 0.05$) from each other (SOC: soil organic carbon; ΔSOC: SOC levels of FYM, VFG, CMC1, CMC2, CSL minus SOC-levels of MIN per block; FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry; MIN: only mineral fertilizers; NF+: no fertilizer; NF−: fallow).

Treatment	P-$CaCl_2$ (mg kg^{-1} DS)	HWP (mg P kg^{-1})	P-AL (mg P kg^{-1})	P_{tot} (mg P kg^{-1})	Fe-AL (mg Fe kg^{-1})	Ca-AL (mg Ca kg^{-1})	HWC (mg C kg^{-1})	pH-KCl	SOC (%)	ΔSOC/P-$CaCl_2$
FYM	4.1 ± 1.0^{b}	22.7 ± 2.7^{b}	284 ± 28^{b}	644 ± 52^{a}	762 ± 82^{a}	1477 ± 91^{ab}	932 ± 133^{bc}	5.82 ± 0.19^{c}	1.23 ± 0.08^{de}	0.06 ± 0.02^{ab}
VFG	3.0 ± 1.0^{ab}	16.7 ± 2.2^{a}	268 ± 17^{ab}	612 ± 30^{a}	733 ± 85^{a}	1689 ± 80^{c}	964 ± 151^{c}	6.09 ± 0.08^{d}	1.31 ± 0.03^{e}	0.12 ± 0.04^{c}
CMC1	2.2 ± 0.6^{a}	15.5 ± 1.9^{a}	221 ± 18^{a}	571 ± 38^{a}	788 ± 71^{a}	1475 ± 74^{ab}	839 ± 118^{abc}	5.67 ± 0.10^{bc}	1.19 ± 0.07^{cde}	0.10 ± 0.04^{bc}
CMC2	2.5 ± 0.3^{a}	16.6 ± 1.2^{a}	242 ± 22^{ab}	602 ± 40^{a}	764 ± 41^{a}	1528 ± 113^{b}	854 ± 94^{abc}	$5.83 \pm$ – 00.12^{c}	1.25 ± 0.07^{de}	0.11 ± 0.04^{bc}
CSL	2.9 ± 1.1^{ab}	17.4 ± 3.7^{a}	230 ± 23^{a}	571 ± 58^{a}	769 ± 94^{a}	1352 ± 61^{a}	898 ± 149^{abc}	5.64 ± 0.12^{abc}	1.11 ± 0.10^{bcd}	0.05 ± 0.03^{a}
MIN	2.7 ± 1.0^{a}	16.7 ± 2.8^{a}	235 ± 23^{a}	565 ± 63^{a}	767 ± 119^{a}	1342 ± 74^{a}	756 ± 116^{ab}	5.42 ± 0.09^{a}	1.00 ± 0.09^{ab}	–
NF+	2.2 ± 0.4^{a}	16.0 ± 1.3^{a}	238 ± 28^{ab}	586 ± 41^{a}	860 ± 97^{a}	1337 ± 87^{a}	794 ± 65^{abc}	5.46 ± 0.12^{ab}	1.06 ± 0.03^{abc}	–
NF−	2.9 ± 0.7^{ab}	16.7 ± 1.8^{a}	228 ± 24^{a}	578 ± 45^{a}	783 ± 89^{a}	1372 ± 71^{a}	737 ± 62^{a}	5.58 ± 0.08^{ab}	0.96 ± 0.05^{a}	–
Year										
2011	2.6 ± 0.9^{A}	16.5 ± 2.7^{A}	239 ± 30^{A}	565 ± 36^{A}	751 ± 94^{A}	1405 ± 124^{A}	915 ± 115^{B}	5.72 ± 0.23^{B}	1.15 ± 0.12^{A}	–
2012	3.1 ± 1.0^{B}	18.1 ± 3.3^{B}	247 ± 30^{A}	618 ± 51^{B}	806 ± 77^{B}	1488 ± 142^{B}	778 ± 115^{A}	5.66 ± 0.23^{A}	1.13 ± 0.15^{A}	–

3. Statistical analysis

The data were analysed using STATISTICA 11.0 software. The soil parameters of 2011 and 2012 were analysed in a two-way ANOVA and Scheffé's test ($p < 0.05$) with factors 'soil parameter' and 'year'. There was no interaction effect between the two factors. Yearly DM crop yields, yearly relative DM crop yield and yearly P export were analysed in a one-way ANOVA and Scheffé's test ($p < 0.05$). Statistics on the relative DM crop yield were performed on all relative DM crop yields from 2008 to 2012 together for FYM, VFG, CMC1, CMC2, CSL and MIN.

Data of water samples were statistically compared by calculating the cumulative TP, TDP, TDC and OP leached per unit of leached water (mg l^{-1}) at the end of the percolation experiment and using a one-way ANOVA analysis ($p < 0.05$). We analysed the reproducibility of the leaching experiment in a separate two-way ANOVA with 'batch' and 'treatment' (NF− and FYM) as factors. There were no interaction effects between the 'batch' and 'treatment' factor for TP ($p = 0.83$), TDP ($p = 0.71$) and OP ($p = 0.83$). The 'batch' factor was not significant for TP ($p = 0.10$), TDP ($p = 0.10$) and OP ($p = 0.35$). As the interaction term and the batch factor were not significant, statistical analysis was conducted on the pooled dataset of the two batches of the leaching experiment.

Data of the subsoil samples to validate the leaching experiment, were compared using a contrast analysis with the FYM treatment as contrast C_1 and all other treatments as contrast C_2 ($p < 0.05$).

4. Results

4.1. P and C content in the soil

SOC levels were significantly increased ($p < 0.001$) after 8 years of application of farmyard manure, CMC1, CMC2 and VFG compost addition, compared to mineral fertilizers (Table 3). Despite an equal C input for all organic fertilizer treatments, SOC increase was not significant for the cattle slurry treatment compared to MIN treatment (Table 3).

P-$CaCl_2$ was the highest for the FYM treatment and this increase was significant ($p < 0.001$) compared to CMC1, CMC2, MIN and NF+ (Table 3). The HWP level in the FYM treatment was significantly increased (Table 3), confirming the results of P-$CaCl_2$. Differences in soil pH between the organic fertilizer treatments were small, except for the treatment with VFG compost, which had a significantly ($p < 0.001$) higher pH-KCl compared to all other treatments. There was no correlation ($R^2 = 0.02$, $p = 0.26$) between P-$CaCl_2$ and pH-KCl.

The FYM treatment had a significantly ($p < 0.001$) higher P-AL level than the CMC1, CSL, MIN and NF− treatments. No significant differences were observed for P_{tot} between the treatments. The difference in P_{tot} between 2011 and 2012 was significant but small.

Fe-AL levels were not significantly ($p = 0.22$) different. After 8 years Ca-AL was increased for CMC1 compost and the farmyard manure treatments compared to all other treatments and significantly ($p < 0.001$) increased for the CMC2 and VFG compost treatments, compared to the mineral fertilized treatment, the cattle slurry treatment and the control treatments. These differences were expected since the organic fertilizers used typically have different Ca contents and there was no correction for Ca input in the field trial. Although the soil is not alkaline, we observed a weak, but significant positive correlation between Ca-AL and P-AL ($R^2 = 0.24$, $p < 0.01$) and no correlation between P-AL and Fe-AL ($R^2 = 0.09$, $p = 0.22$).

The parameter ΔSOC/P-$CaCl_2$ estimates the gain in SOC level in relation to the mineral fertilized treatment (MIN) per unit of P availability in the soil (P-$CaCl_2$) after 8 years addition of exogenous organic matter. All three compost treatments (CMC1, CMC2 and VFG) led to a significantly ($p < 0.001$) higher ΔSOC/P-$CaCl_2$ ratio, compared to CSL (Table 3). VFG had a significantly higher ΔSOC/P-$CaCl_2$ ratio than FYM. The C/P and ΔSOC/P-$CaCl_2$ ratios for the two types of animal manure (FYM and CSL) are in the same range, the same holds for the two types of farm compost (CMC1 and CMC2). Although VFG compost led to the highest ΔSOC/P-$CaCl_2$ ratio, the C/P ratio of VFG compost is between those of animal manure and the other composts (Table 2).

4.2. Crop yield and P export

Significant differences in DM crop yields among the fertilized treatments were only detected in 2005, 2008 and 2009 (Table 4). However calculations of the relative DM crop yield averaged over 8 years (2005–2012) indicated only a significant ($p < 0.001$) difference in DM crop yield between CSL and CMC2 (Table 4). The DM crop yield of the control treatment NF+ fluctuated from 31% (maize, 2009) to 75% (potatoes, 2012) of the mean DM crop yield. We assume that the lower crop yields for CSL in 2005 were not a result of the fertilizer as such. In 2005 the soil of the CSL plots was very moist due to the combination of a wet spring season and the slurry application, resulting in soil compaction during tillage practices. The emergence of fodder beet on the CSL plots was hampered and during the whole growing season the development of these plants lagged behind, resulting in a significant lower crop yield.

Table 4

Dry matter crop yield in kg ha^{-1} (±SD) and relative crop yield calculated over the entire measurement period. Data are arithmetic means (±SD). Data with the same letter(s) in a column are not significantly different (Scheffé's test, $p < 0.05$) from each other. Treatments NF+ and NF− are not included in the statistical tests and in the calculation of the mean DM crop yield (DM: dry matter, FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry; MIN: only mineral fertilizers; NF+: no fertilizer; NF−: fallow).

Year/crop	2005 Fodder beet	2007 Red cabbage	2008 Perennial ryegrass	2009 Maize	2010 Fodder beet	2011 Red cabbage	2012 Potatoes	2005–2012 Relative crop yield
FYM	21 825 ± 3 336^{ab}	14 169 ± 748^{a}	6 063 ± 447^{ab}	22 265 ± 776^{b}	27 319 ± 3 758^{a}	13 609 ± 771^{a}	12 740 ± 2 111^{a}	102 ± 11^{ab}
VFG	22 809 ± 506^{ab}	14 271 ± 414^{a}	5 212 ± 561^{ab}	20 036 ± 1 087^{ab}	27 822 ± 1 501^{a}	14 610 ± 1 013^{a}	12 614 ± 576^{a}	100 ± 6^{ab}
CMC1	24 138 ± 2 224^{b}	13 380 ± 1 012^{a}	5 572 ± 463^{ab}	20 977 ± 1 291^{b}	26 395 ± 5 335^{a}	14 252 ± 678^{a}	12 924 ± 1 526^{a}	101 ± 10^{ab}
CMC2	25 175 ± 1 121^{b}	14 161 ± 563^{a}	6 693 ± 204^{b}	21 694 ± 761^{b}	28 364 ± 4 993^{a}	14 641 ± 662^{a}	11 299 ± 530^{a}	106 ± 11^{b}
CSL	18 594 ± 2 811^{a}	14 451 ± 1 602^{a}	5 143 ± 667^{ab}	17 766 ± 1 273^{a}	27 171 ± 4 612^{a}	13 153 ± 725^{a}	12 555 ± 1 774^{a}	94 ± 13^{a}
MIN	24 716 ± 1 978^{b}	13 810 ± 1 257^{a}	4 607 ± 978^{a}	20 305 ± 886^{ab}	25 368 ± 2 262^{a}	13 741 ± 917^{a}	11 549 ± 938^{a}	96 ± 11^{ab}
mean DM-crop yield	22 876 ± 3 000	14 040 ± 970	5 548 ± 872	20 507 ± 1 736	27 073 ± 3 678	14 001 ± 904	12 280 ± 1 375	100
NF+	16 200 ± 2 279	8 701 ± 877	2 710 ± 1 797	6 354 ± 556	12 369 ± 826	8 982 ± 1 330	9 243 ± 960	57 ± 19
NF−	–	–	–	–	–	–	–	–

We measured an average P export of 53 (±5) kg P ha^{-1} by red cabbage in 2011 and 29 (±4) kg P ha^{-1} by potatoes in 2012, for all fertilized treatments. There were no significant differences in P export among the organic and mineral fertilized treatments. The P export of the control treatment NF+ was with 30 (±5) kg P ha^{-1} in 2011 and 21 (±2) kg P ha^{-1} in 2012 significantly lower compared to all fertilized treatments in 2011 and compared to the FYM and VFG compost treatments in 2012.

4.3. P leaching

The TP, TDP and OP concentrations in the percolation water were significantly ($p < 0.001$) increased for the FYM treatment, but there were no significant differences in P leaching losses between the other fertilized and control treatments (Table 5). The TP, TDP and OP concentrations increased between the 1st and 2nd water sampling event for all treatments (data not shown). Afterwards, the P concentration level remained constant over time at a treatment-specific level. The total P input (2005–2012) was indeed the highest in the FYM treatment (Table 1), but differences in total P input among all other treatments seem to have no effect on TP (Fig. 2a).

The variability in proportion of TP, that leached as TDP or OP in the leaching experiment was high (Fig. 3). Most of TP leached in form of TDP (TDP/TP ratio = 77–92%). The OP/TP ratio of the FYM treatment (OP/TP = 63%) was significantly higher than the treatments CMC1 (OP/TP = 39%) and NF− (OP/TP = 44%). The OP/TDP ratio varied from 41 to 68% for CMC1 and FYM respectively (data not shown).

Fe concentrations in the leachate always remained between 1 and 6 mg l^{-1},depending on treatment and time of measurement, and no sudden increases in Fe concentration were detected (data not shown). Therefore, we conclude that silting and/or anaerobic conditions did not occur. TDC concentrations in the water samples were approximately 74 mg l^{-1} for all treatments and constant over time. The TDC leaching was lower in the control treatments NF− and NF+, compared to all other treatments. The TDC leaching was remarkably the highest in the MIN treatment and comparable to the TDC leaching in the VFG treatment. These differences were however not significant ($p = 0.06$) (Table 5).

Table 5

TP, TDP, OP and TDC concentrations in the leaching water of the percolation experiments. Data are arithmetic means (±SD) of the cumulative leached P and C per unit of cumulative leached percolation water. Data with the same letter(s) in a column are not significantly different (Scheffé's test, $p < 0.05$) from each other (FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry; MIN: only mineral fertilizers; NF+: no fertilizer; NF−: fallow).

Treatment	TP (mg l^{-1})	TDP (mg l^{-1})	OP (mg l^{-1})	TDC (mg l^{-1})
FYM	1.87 ± 0.39^{b}	1.69 ± 0.4^{b}	1.18 ± 0.29^{b}	74.0 ± 13.5^{a}
VFG	0.99 ± 0.11^{a}	0.91 ± 0.16^{a}	0.59 ± 0.11^{a}	92.5 ± 5.7^{a}
CMC1	0.93 ± 0.03^{a}	0.75 ± 0.07^{a}	0.36 ± 0.07^{a}	67.3 ± 10.8^{a}
CMC2	0.96 ± 0.27^{a}	0.85 ± 0.23^{a}	0.49 ± 0.19^{a}	72.3 ± 8.3^{a}
CSL	0.97 ± 0.21^{a}	0.81 ± 0.26^{a}	0.52 ± 0.21^{a}	80.9 ± 20.7^{a}
MIN	1.12 ± 0.30^{a}	0.87 ± 0.27^{a}	0.56 ± 0.17^{a}	95.1 ± 35.4^{a}
NF+	0.89 ± 0.15^{a}	0.75 ± 0.12^{a}	0.40 ± 0.10^{a}	52.2 ± 16.9^{a}
NF−	1.08 ± 0.32^{a}	0.84 ± 0.27^{a}	0.50 ± 0.20^{a}	64.5 ± 13.4^{a}

4.4. Validation of the leaching experiment

To validate the findings in the leaching experiment, the HWP and P-AL levels of the subsoil (30–40 cm) were both analyzed in a contrast analysis with contrasts C_1 (FYM) and C_2 (VFG, CMC1, CMC2, CSL, MIN, NF+, NF−). Both the HWP (17 mg kg^{-1} DS) and the P-AL level (219 mg kg^{-1} DS) of C_1 were significantly (HWP: $p = 0.01$; P-AL: $p = 0.006$) increased, compared to the HWP (11 mg kg^{-1} DS) and the P-AL level (155 mg kg^{-1} DS) of C_2. The higher HWP and P-AL levels for C_1 confirm the higher P leaching from the topsoil of the FYM treatment.

5. Discussion

5.1. P availability in the soil

In the present study several soil extraction methods were used to estimate the P availability in the soil: P-$CaCl_2$, HWP, P-AL and P_{tot}. P-$CaCl_2$ results from an extraction with a weak $CaCl_2$ solution to imitate the salt condition of soil water (Eriksson et al., 2013) and estimates the soil solution P concentration (Hesketh and Brookes, 2000) or the easily soluble P fraction (Djojic and Mattsson, 2013). The hot water extraction method, which is used to estimate the easily available organic C (HWC) (Ghani et al., 2003) and N pool (Keeney and Bremner, 1966), can also be used to determine the easily available organic P pool (HWP), since the high temperatures lead to decomposition of organic compounds (Füleky and Czinkota, 1993). More P was extracted with HWP, and HWP turned out to have a lower variability than P-$CaCl_2$. The ammonium lactate acid in the P-AL measurement leads to a dissolution of Al and Fe from their oxides followed by a P release, and inhibits any secondary P resorption in the extracts (Eriksson et al., 2013). P-AL can be considered as an agronomic soil P test, to estimate the desorbable P of the soil in the longer term. P_{tot} is an estimation of all soluble, microbial, organic, adsorbed and precipitated/secondary mineral P forms in the soil.

P-$CaCl_2$ was higher when farmyard manure was used, but differences were not always significant, while HWP showed a significant distinction between FYM and all other organic fertilizers, mineral fertilizer and control treatments. This means

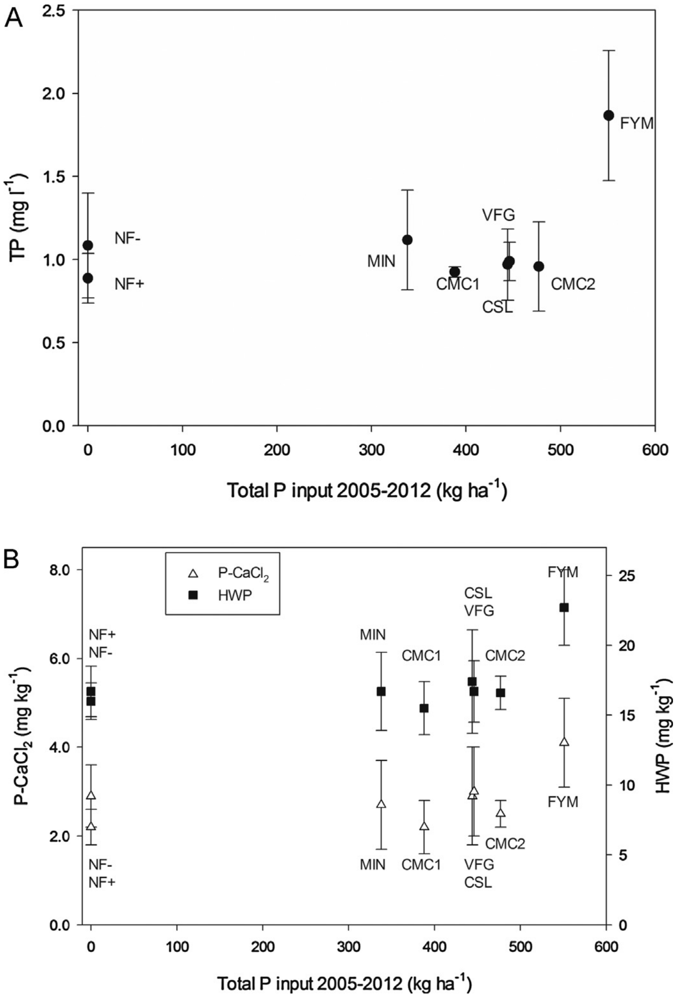

Fig. 2. The TP leaching concentration (mg l^{-1}) in the leaching experiment (a) and the P availability measured as P-CaCl$_2$ (mg kg^{-1}) and HWP (mg kg^{-1}) (b) in relation to the total P input (kg P ha^{-1}) in the 2005–2012 period. Data are arrhythmic means of the TP, P-CaCl$_2$ and HWP per treatment, error bars represent ± SD (FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry; MIN N: only mineral fertilizers).

that both the amount of P in the soil solution and the easily available organic P are enhanced by fertilizing with farmyard manure. This is unlikely a pH effect or an effect of increased microbial activity. Although the P concentration in the soil solution is dependent on the soil pH (Jones, 1979), we did not find any correlation between soil pH and P-CaCl$_2$ in our study. Moeskops et al. (2012) studied the microbial soil quality of the field trial presented in this study in the winter of 2009–2010 and reported that all organic fertilizers have a positive effect on microbial soil quality compared to mineral fertilizers. Differences in microbial biomass and microbial enzyme activity between farmyard manure and all other organic fertilizer treatments were however small (Moeskops et al., 2012).

We suggest three possible explanations for the differences in P-CaCl$_2$ and HWP between the organic fertilizer treatments remain: (i) organic acids released by the organic fertilizer, (ii) a combination of increased total P input and increased P-AL levels and (iii) the importance of Ca-P bindings.

Jiao et al. (2007) revealed that in soils with farmyard manure addition there is not only an increased P release to the soil solution, but also a decreased P retention, compared to soils with triple

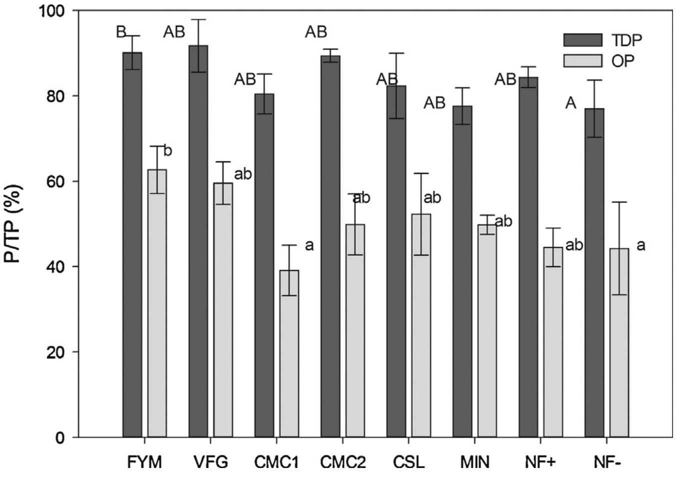

Fig. 3. The mean composition (±SD) of the percolated total P (TP), calculated as TDP/TP and OP/TP over the whole leaching experiment. Groups with the same letter (s) are not significantly different (Scheffé's test, $p < 0.05$) from each other (TDP: total dissolved P; OP: orthophosphate; FYM: farmyard manure; VFG: vegetable, fruit and garden waste compost; CMC1: farm compost with low C/N; CMC2: farm compost with high C/N; CSL: cattle slurry; MIN: only mineral fertilizers; NF+: no fertilizer; NF−: fallow).

superphosphate addition. The authors proposed that the increased P desorption is caused by release of organic acids from manure decomposition, (i) which can chelate Fe and Al oxides and bring them into soil solution and thus reducing the number of P binding sites and (ii) which can compete with orthophosphate for the binding sites. This is in line with Ehlert et al. (2004) who states that the multiple use of exogenous organic matter will lead in the long term to decreasing soil P sorption maxima. Since we observed an increased P-CaCl$_2$ and HWP level for farmyard manure, but not for the composts and cattle slurry, we assume that the amount and type of organic acids released is depending on the exogenous organic matter type.

Djojic and Mattsson (2013) observed that in soils with high initial P-AL levels, increasing the P rate caused a stronger increase in P-CaCl$_2$ levels, compared to soils with lower initial P-AL levels. Since the farmyard manure treatment in our field trial, had both an increased P-AL level and a higher total P input (2005–2010) compared to all other treatments, the increased P-CaCl$_2$ could indeed be the result of a combination effect. Differences in total P input among all other treatments which had lower P-AL levels, had no effect on P-CaCl$_2$ and HWP (Fig. 2b).

Application of organic fertilizers resulted in differences in Ca input and Ca status of the soil (as measured in the AL extracts, Table 3). Steel et al. (2012) observed for several composts increased Ca concentrations in the AL extract in an incubation trial with a single compost dose. High soil concentrations of plant-available Ca, Na, Mg and K after incubation with compost corresponded to high concentrations of these elements in the composts, which were affected by concentrations in the feedstock materials (Steel et al., 2012). The difference in Ca input by organic fertilizers may affect the P availability in the soil. We observed however only a weak correlation between P and Ca in the AL extract. Results of Vandecasteele et al. (2014) indicated that apatite P was the dominant P form in several organic fertilizers based on chicken manure and that P binding and availability in the products after manure processing is related to Ca. Possibly Ca-P bindings formed during composting, prevent P to become available in the soil solution when compost is applied, in contrast to farmyard manure.

Despite higher P availability in the farmyard manure treatments, we did not find an effect of fertilizer type on P export. This is similar to the findings of Krey et al. (2013). Probably because of the high initial P-AL levels, the soil provided already enough P for optimal crop growth. Therefore more P in the soil solution was available for leaching.

The relative crop yields were slightly increased for compost and farmyard manure, compared to mineral fertilizers and cattle slurry. Although this might be caused by improved soil quality (Diacono and Montemurro, 2009; Krey et al., 2013 ; D'Hose et al., 2014), causal effects are difficult to prove and differences in crop yield could also be the result of a change in N mineralization capacity.

5.2. P leaching

Based on the laboratory leaching experiment, we observed that the higher P availability (measured as P-$CaCl_2$ and HWP) in the treatment with farmyard manure lead to an increased P leaching loss. The reliability of the leaching experiment was checked and confirmed by measuring the P enrichment at 10 cm below tillage depth in 2012. Although, the desorbable P (measured as P-AL) varied across the treatments (Table 3), with FYM having the highest P-AL value, but VFG also having a high P-AL value, the TP concentrations in the leachate (Table 5) is comparable in all treatments, except for the farmyard manure treatment. The TP concentrations in the leaching water of the farmyard manure treatment is almost twice as high as for of all other treatments, including the VFG compost treatment. This could be due to a change point in the relationship between the desorbable P fraction of the soil and the P leaching. Heckrath et al. (1995) observed such a change-point between Olsen-P measurements and the total P concentration of drainage water. Below this change-point the P concentrations in the drainage water were low. Above the change-point, the P concentrations in the drainage water were linearly related to the Olsen-P level. A similar change-point was observed by Hesketh and Brookes (2000) and Maguire and Sims (2002), although in their case P-$CaCl_2$ was used as a proxy for P leaching. It is possible, that in our study, this change point is only crossed for the farmyard manure treatment. Therefore we cannot distinguish whether the higher P leaching is due to specific FYM properties or to the fact that the change point has been exceeded.

A major part of TP leached as TDP ($<0.45\ \mu m$). As expected the TDP and TP leaching are close to each other and provide the same information. Similar to McDowell and Sharpley (2004), we found all OP/TP ratios close to 50%. Not only the TP, TDP and OP leaching were the highest for the treatments with farmyard manure, this was also true for the OP/TP ratio. In other words, farmyard manure amended soils leach a greater proportion of P in the form of OP. This indicates that organic acids released from the farmyard manure are more able to facilitate P loss by blocking P sorption sites or are released in greater amounts, compared to the compost and cattle slurry. The differences in OP/TP remain however small. This is not surprising since P addition mainly affects orthophosphate amounts in the soil and does not lead to a build-up of soil organic P, regardless of form and amount of fertilizer (Ahlgren et al., 2013). Svanbäck et al. (2013) observed in several Swedish soils with animal manure or mineral fertilizers, that the percentage of dissolved reactive P (which is according to McDowell and Sharpley (2004) largely OP) in TP in leachate is increased with increased P-AL levels and is more dependent from the soil P status than from the applied type of fertilizer.

Since the OP/TDP-ratios were 41–68%, an important fraction of TDP leached in other soluble forms than OP, probably dissolved organic P forms. The OP/TDP ratios in our study are however in the same range as the OP/TDP ratios (OP measured as dissolved reactive P) in the leaching experiments of the study of McDowell and Sharpley (2004) (45–60%) with application of manure, manure compost and superphosphate and the study of Fuentes et al. (2012) (60–70%) with application of dairy slurry and separation products of dairy slurry.

5.3. Soil C versus P availability

Like Powlson et al. (2012), we observed higher SOC levels after 8 years of compost additions compared to cattle slurry addition at the same C input rate. Although the application of farmyard manure leads to a similar SOC level as the three compost types, farmyard manure resulted in a lower ΔSOC/P-$CaCl_2$ ratio, compared to compost. This means that compost additions are a better option than farmyard manure to enhance the SOC levels of arable land without increasing P availability and related P leaching.

6. Conclusions

We conclude that fertilizer type had a clear effect on the SOC level. Although C input of all treatments with organic fertilizers was equal, SOC levels measured after 8 years were as follows: VFG > CMC2 > FYM > CMC1 > CSL due to differences in the characteristics of the exogenous organic matter. The relative crop yield was little influenced by fertilizer type.

We found an increase in P availability (P-$CaCl_2$ and HWP), when farmyard manure was used as an organic fertilizer. This increased P availability was not compensated by an increased P export. Since soil P levels in the field trial are high, it is unlikely that the crops would suffer from P deficiency. It was shown in a laboratory leaching experiment with soil columns that this increased P availability in farmyard manure amended soils can be a source of P losses through leaching. This leaching experiment proved to be a reliable method to investigate differences in P leaching, as the results were confirmed by the P enrichment at 10 cm below tillage depth in the treatments of the field trial. We conclude that in soils with a high P status the use of composts allows to increase SOC levels without increasing P leaching, but farmyard manure does not.

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