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Effect of compost and soil properties on the availability of compost phosphate for white clover (*Trifolium repens* L.)

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Abstract

Wide variation in results exists in the literature on the effectiveness of composts to sustain the phosphorus (P) nutrition of crops. The aim of this work was to assess the importance of some soil and composts properties on the utilization of compost-P by white clover (*Trifolium repens* L.). This study was carried out with samples collected from four composts made from solid kitchen and garden wastes, and with two soil samples taken from the A horizon of a P-rich sandy acidic Dystrochrept and of a P-limited clayey calcareous Eutrochrept. Changes in the amount of inorganic P (Pi) isotopically exchangeable within 1 min (E_{1min}) were measured during 32 weeks in incubated soil-composts or soil-KH_2PO_4mixtures where P sources had been added at the rate of 50 mg P kg^{-1} soil. Uptake of compost-P or KH_2PO_4-P by white clover was measured on the same amended soils during 16 weeks. In both soils, the application of composts resulted after 32 weeks of incubation in E_{1min} values ranging between those observed in the control without P and those observed in the KH_2PO_4treatment, i.e., in values ranging between 4.2 and 5.9 mg P kg^{-1} in the sandy acidic soil and between from 1.6 to 4.3 mg P kg^{-1} in the clayey calcareous soil. The total coefficient of utilization of compost-P (CU-P) by white clover reached values in both soils for the four composts ranging between 6.5% and 11.6% of the added P while in the presence of KH_2PO_4 the CU-P reached values ranging between 14.5% in the clayey calcareous soil and 18.5% in the sandy acidic soil. Results obtained in the sandy acidic soil suggest, that white clover initially used a fraction of the rapidly exchangeable compost P, while at a latter stage plant roots enhanced the mineralisation of compost organic P and took up a fraction of the mineralized P. These relations were not observed in the clayey calcareous soil probably because of its high sorbing capacity for P. In the sandy acidic soil, composts application increased the uptake of soil P by the plant from 31.4 mg P kg^{-1} soil in the control without P to values ranging between 37.9 to 42.7 mg P kg^{-1} soil in the presence of composts. This indirect effect was related to a general improvement of plant growth conditions in this soil induced by compost addition (from 9.9 g DM kg^{-1} soil in the control without P to values ranging between 14.0 to 16.1 g DM kg^{-1} soil in the presence of composts) and/or to the release of Al- or Fe bound soil P to the solution due to soil pH increase following compost application. Finally the total coefficient of utilization of P (CU-P) derived from KH_2PO_4 and composts was related to the total amount of N exported by white clover in the P-limited clayey calcareous soil but not in the P-rich sandy acidic soil. This suggests that in a soil where N_2 biological fixation is limited by low P availability, the CU-P of a compost by white clover is not only related to the forms of P present in the compost but also to its effect on N nutrition. However, it is not clear whether this improved N nutrition was due to compost mineralisation, or to an indirect compost effect on the N_2 biological fixation.

Introduction

Wide variation in results exists in the literature on the effectiveness of composts to sustain the phosphorus (P) nutrition of crops (Cabrera et al., 1991; Murillo et al., 1997). The amount of P taken up by a plant from compost in a soil/compost mixture can vary from 10 to 264% of the amount of P taken up from a water soluble mineral fertilizer used as a reference (Bezzola et al., 1994; Frei et al., 1997; Pommel , 1982; Sikora et al., 1982). This variability is related to the wide range of compost/soil/plant systems studied and to the different methodologies used. Furthermore the results of a lot of these studies are difficult to interpret because of the lack of information on the forms of P in the added compost. Using complementary approaches, isotope exchange kinetics, sequential extraction and solid state ^{31}P NMR, Frossard et al. (2002) showed that composted organic solid wastes contained between 2 and 16% of their total P as rapidly exchangeable inorganic P, between 40 and 77% of their total P as slowly exchangeable or not exchangeable inorganic P, probably in the form of condensed calcium phosphates, and some organic P. The first objective of this paper is to assess the effect of compost application on soil P availability in incubated soil/compost mixtures using the isotopic exchange kinetic method as proposed by Fardeau (1996). A second objective of this paper is to assess the effectiveness of compost as a source of P for white clover using an indirect isotopic method as proposed by Fardeau et al. (1996). By labeling soil available P with a radioactive tracer (^{33}P), this method allows to calculate the amount of P derived from the fertilizer which has been taken up by a plant grown in a soil/fertilizer mixture. Finally, the effectiveness of compost to increase soil P availability and to sustain white clover P nutrition is related to compost and soil properties.

Material and methods

Composts

The samples used in this study were collected in Switzerland from four composts made from solid kitchen and garden wastes. These are the samples 1, 2, 8 and 14 of the compost collection studied in Frossard et al. (2002). Some of their characteristics are summarized in the Table 1. In this paper these composts are named after their origin, Eglisau (compost 1), Zurich (compost 2), Fehraltorf (compost 8) and Leibstadt (compost 14).

Soils

The surface horizon (0–20 cm) of a clayey calcareous and of a sandy acidic soil were collected for this study. The clayey calcareous soil was sampled in Sissach (canton of Baselland, Switzerland) and was classified as an Eutrochrept (US Taxonomy), and the sandy acidic soil was sampled in Cadenazzo (canton of Ticino, Switzerland) and was classified as a Dystrochrept (US Taxonomy). Soil samples were air-dried and sieved at 2 mm before analysis. Selected physico-chemical properties of both soils are given in the Table 2.

Incubation experiment

Five hundred grams of air-dried soil were incubated in plastic pots in the presence of P added at the rate of 50 mg P kg^{-1} soil in the form of compost or as KH_2PO_4. Both P sources will be considered in the rest of the text as fertilizers for the sake of simplicity. Five treatments were considered for each soil: control (no P added), KH_2PO_4 (P added as KH_2PO_4), Eglisau (P added as compost from Eglisau), Zurich (P added as compost from Zurich), Fehraltorf (P added as compost from Fehraltorf) and Leibstadt (P added as compost from Leibstadt). Soil/compost mixtures were watered at 80% of the soil water holding capacity covered with an aluminum foil and incubated at 25°C for 32 weeks. The humidity of the soil/compost mixtures was daily controlled by weighing the pots during the incubation. Samples were taken after 0, 1, 2, 4, 8, 16 and 32 weeks, air-dried and analyzed for the pH and the amount of P isotopically exchangeable within 1 min (Fardeau , 1996). Each treatment was replicated 3 times.

Inorganic P isotopically exchangeable within one minute (E_{1min})

The method of isotopic exchange kinetic and the measurement of the amount of inorganic P isotopically exchangeable within one minute (E_{1min}) have been described in the literature (Fardeau, 1996). Compost/water with a solid/solution ratio of 1:99 (g:ml) or soil/water suspensions with a solid/solution ratio of 10:99 are first shaken during 17 h. At t = 0 minute, 1 ml of solution containing about 0.1 MBq carrier free

Table 1. Selected chemical properties of the studied composts

Compost[a]	Origin	pH	Total N[b]	Pt[c]	Po[d]	r_{1min}/R_0[e]	E_{1min}[e]
			g kg^{-1}			(g P kg^{-1})	
1	Eglisau	8.8	16.6	3.24	0.49	0.96	0.53
2	Zurich	8.6	13.1	3.40	0.41	0.97	0.21
8	Fehraltorf	8.8	13.8	3.75	1.23	0.95	0.38
14	Leibstadt	8.0	8.3	4.78	1.07	0.80	0.12

[a]Identity number given to each compost by Frossard et al. (2002). [b]Total nitrogen was analyzed with a Carlo Erba C/N analyzer. [c]Total P content of composts was measured after digestion in hot concentrated (11.6 M) $HClO_4$. [d]Organic P content was determined according to Saunders & Williams (1955) [e]These parameters were measured using the isotopic exchange kinetics method (Fardeau, 1996). See the text for the description of the method used.

Table 2. Selected physico-chemical properties of the studied soils

		Clayey calcareous soil	Sandy acidic soil
pH		7.5	5.7
Clay	g kg^{-1}	475	75
Sand	g kg^{-1}	148	453
Total organic C	g kg^{-1}	29	12
Total N	g kg^{-1}	2.6	1.2
Total $CaCO_3$	g kg^{-1}	30	0.0
Fe_{CBD} [a]	g kg^{-1}	38.7	12.2
r_{1min}/R_0[b]		0.09	0.69
E_{1min}[b]	g kg^{-1}	4.35	7.98

[a]Total iron oxide (citrate, bicarbonate, dithionite extraction).
[b]These parameters were measured using the isotopic exchange kinetics method (Fardeau, 1996). See the text for the description of the method used.

$^{33}PO_4^{3-}$ diluted in water is introduced into the suspension, which is then stirred. After 1 min a sample is taken from the suspension, filtered through a 0.2 μm membrane and the radioactivity r_{1min} remaining in the solution is analyzed by scintillation counting, in parallel the Pi concentration in the solution (Cp, mg P l^{-1}) was measured by a colorimetric method (John, 1970). The proportion of radioactivity remaining in the solution after 1 min of isotopic exchange (r_{1min}/R_0) gives an information on the P sorbing capacity of the soil or of the compost. According to the classification given by Fardeau (1996), the composts and the sandy acidic soil have a low P fixing capacity ($r_{1min}/R_0>0.4$) while the clayey calcareous soil has a high P fixing capacity ($r_{1min}/R_0<0.2$). The quantity of P isotopically exchangeable in 1 min (E_{1min}) was calculated as follow

$$E_{1min} = \frac{A \times Cp \times [R_0]}{[r_{1min}]} \quad (1)$$

In (1) the factor A equals 100 for the composts and 10 for the soils, it arises from the solid/solution ratio so that $A \times C$p is equivalent to the water-soluble phosphate content of the compost or of the soil expressed in mg P kg^{-1}. According to Tran et al. (1988) the sandy acidic soil is P-rich ($E_{1min}>$ 5 mg P kg^{-1} soil) while the clayey clacareous soil is P-limited (E_{1min} <5 mg P kg^{-1} soil).

Pot experiment

Principles. The P taken up by a crop from a fertilized soil is the sum of the P derived from the soil (P_{dfs}) and the P derived from the fertilizer (P_{dff}). The two sources can be distinguished by labeling the soil available P with carrier free $^{33}PO_4$ions before P fertilization assuming that in the absence of P fertilization the plant takes up only soil isotopically exchangeable P (Fardeau et al., 1996). In the fertilized treatment, P_{dfs} is calculated from the radioactivity taken up by the plant ($r_{fertilized}$) and from the specific activity of P in the plant grown on the unfertilized soil ($r_{control}/P_{control}$):

$$r_{fertilized}/P_{dfs} = r_{control}/P_{control} \quad (2)$$

hence

$$P_{dfs} = P_{control} \times (r_{fertilized}/r_{control}) \quad (3)$$

The difference between the total P taken up from the fertilized soil ($P_{fertilized}$) and P_{dfs} yields the P derived from the fertilizer (P_{dff}):

$$P_{dff} = P_{fertilized} - P_{dfs} \quad (4)$$

hence

$$P_{dff} = P_{fertilized} - [P_{control} \times (r_{fertilized}/r_{control})] \quad (5)$$

The agronomic effectiveness of the fertilizer is assessed by calculating its coefficient of utilization (CU-P), i.e., the percentage of fertilizer P that has been taken up by the crop (Morel and Fardeau, 1990):

$$CU - P = 100 \times P_{dff}/\text{added P}. \quad (6)$$

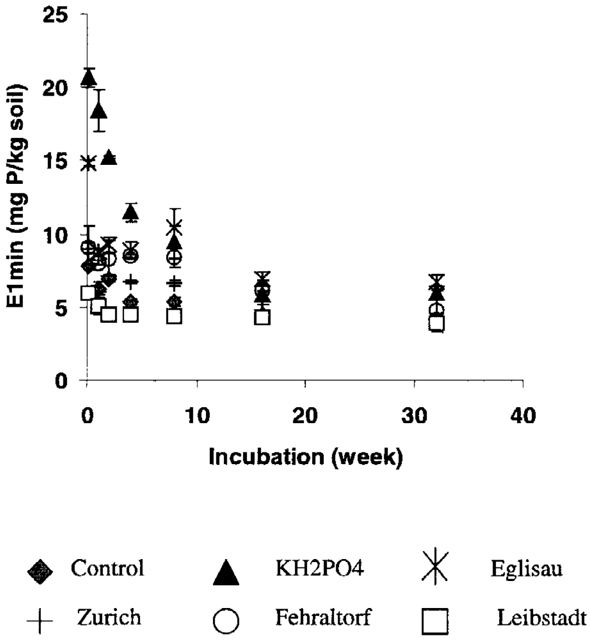

Figure 1. Changes in the quantity of P isotopically exchangeable within 1 min (E_{1min}) in the sandy acidic soil after the addition of P as KH_2PO_4 or as compost.

Experiment.

The pot experiment was conducted in a completely randomized design by growing white clover (*Trifolium repens* L. cv. Milkanova) on the two soils considering the same treatments as in the incubation experiment. One kilogram of soil per pot was applied. Prior to P fertilization, soils were labeled with carrier free $H_3{}^{33}PO_4$ ions at the rate of 4.97 MBq kg^{-1} soil for the sandy acidic soil, and the rate of 8.70 MBq kg^{-1} soil for the clayey calcareous soil. Then the composts and KH_2PO_4were added to the soils at the rate of 50 mg P kg^{-1} soil. Basal fertilization prior to sowing was 60 mg K kg^{-1} soil (as K_2SO_4), 2 mg Cu kg^{-1} soil (as $CuSO_4{\cdot}5H_2O$), 2 mg Mn kg^{-1} soil (as $MnSO_4{\cdot}2H_2O$), 1 mg Zn kg^{-1} soil (as $ZnSO_4{\cdot}7H_2O$), 1mg B kg^{-1} soil (as H_3BO_3), 0.1mg Mo kg^{-1}soil (as MoO_3). Soils were then sown with five to eight grains of white clover per pot and were watered at 80% of the water holding capacity. Pots were then placed in a growth chamber (25°C, 75% atmospheric humidity and 16 h day^{-1} photoperiod). Soil humidity was kept at 80% of the water holding capacity by daily controlling pot weight. One week after germination, clover was inoculated with *Rhizobium leguminasorum* bv. *trifolii* (strain RBL 5020, Leiden, The Netherlands). The aerial parts of white clover were harvested after 6, 10, 13 and 16 weeks of plant growth. At each harvest, the dry matter was weighed, and the total P and ^{33}P content in the dry matter were determined. Each treatment was replicated four times.

Phosphorus analysis

Water soluble orthophosphate was colorimetrically measured in an aliquot of the solution (John, 1970). The P content of plant material was measured after calcination (4 h at 550°C) and subsequent solubilization of the ashes in 1 ml of concentrated HCl. The ^{33}P was measured by liquid scintillation counting.

Statistical analysis

Analysis of variance were conducted to detect the effect of treatments and means were compared with the Duncan's test (SAS Institute, 1985). Relations between composts chemical characteristics, soil parameters and plant performance indexes were obtained by using the general linear regression model and by correlation analysis (SAS Institute, 1985). Statistical significance in this paper indicates a 0.05 probability level.

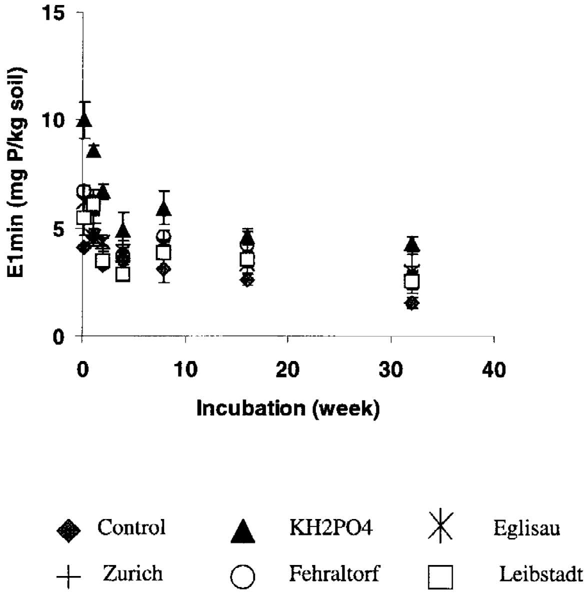

Figure 2. Changes in the quantity of P isotopically exchangeable within 1 min ($E_{1\text{min}}$) in the clayey calcareous soil after the addition of P as KH_2PO_4 or as compost.

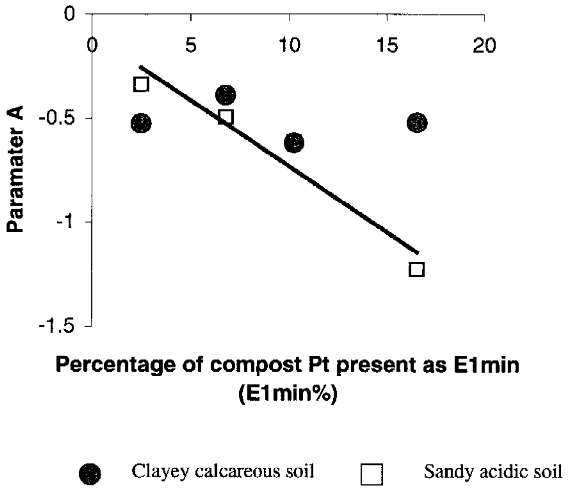

Figure 3. Relation between the rate of soil P isotopically exchangeable in 1 min ($E_{1\text{min}}$) decrease with incubation time (parameter *A* of eq. (7)) in two soils incubated with four composts and the proportion of $E_{1\text{min}}$ to total P present in each compost ($E_{1\text{min}}\%$). The regression equation obtained for the sandy acidic soil is: $A = -0.06 \times E_{1\text{min}}\% - 0.10$; $r^2 = 0.93$.

Results and discussion

Changes in $E_{1\text{min}}$ and in pH in incubated soil/compost and soil/KH_2PO_4 mixtures.

Changes in $E_{1\text{min}}$

Compared to the control, the addition of KH_2PO_4in the sandy acidic soil increased $E_{1\text{min}}$ from 7.7 to 20.7 mg P kg^{-1} at the beginning of the incubation and from 4.2 to 5.9 mg P kg^{-1} after 32 weeks of incubation (Figure 1). The application of composts resulted in variable increases in $E_{1\text{min}}$. The composts Eglisau, Fehraltorf and Zurich gave $E_{1\text{min}}$ values ranging between those observed in the control and those in the treatment KH_2PO_4. The application of the compost Leibstadt did not affect, or even slightly decreased $E_{1\text{min}}$ in this soil.

Compared to the non fertilized control, the addition of KH_2PO_4 in the clayey calcareous soil increased $E_{1\text{min}}$ from 4.1 to 10.0 mg P kg^{-1} at the beginning of the incubation and from 1.6 to 4.3 mg P kg^{-1} after 32 weeks of incubation (Figure 2). The application of composts resulted in $E_{1\text{min}}$ values ranging between those observed in the control and those observed in the KH_2PO_4 treatment.

$E_{1\text{min}}$ values decreased with incubation time in all treatments and in both soils. These changes were modeled by the following equation for the entire duration of incubation.

$$E_{1\text{min}} = A \times Ln(t) + B \tag{7}$$

In this equation 't' is the duration of the incubation in weeks and 'A' and 'B' two constants expressed in mg P kg^{-1} soil. The parameter 'B' estimates the $E_{1\text{min}}$ value of the soil after 1 week of incubation time following P input, while 'A' estimates the rate of $E_{1\text{min}}$ decrease with increasing incubation time. The parameters *A* and *B* are given for each treatment in the Table 3. Both the parameters *A* and *B* were linearly correlated to the percentage of compost-P isotopically exchangeable within 1 min to the total P when the composts were incubated in the sandy acidic soil with a low P fixing capacity, while no relation was observed in the clayey calcareous soil (Figures 3 and 4). These results suggest that the increase in available P immediately following compost addition and the subsequent rate of $E_{1\text{min}}$ decrease with increasing incubation time were, in the sandy acidic soil, directly related to the proportion of rapidly available Pi added with these organic materials.

Changes in pH in the two soils following compost and KH_2PO_4 applications

The addition of KH_2PO_4in the sandy acidic soil did not affect its pH compared to the control while the addition of compost strongly increased soil pH. The highest increases were observed with the compost

Table 3. Correlation between incubation time (t) and the amount of P isotopically exchangeable within 1 min (E_{1min}) in two soils after the addition of P as KH_2PO_4 or composts according to the following statistical model: $E_{1min}[t] = A \times Ln(t) + B$

	A (mg P kg^{-1} soil)	B (mg P kg^{-1} soil)	r^2	Standard error
Sandy acidic soil				
Control	−0.63	6.52	0.89	0.48
KH_2PO_4	−2.93	15.81	0.92	1.78
Eglisau	−1.23	10.86	0.76	1.48
Zurich	−0.49	7.26	0.55	0.93
Fehraltorf	−0.62	8.32	0.60	1.07
Leibstadt	−0.33	5.04	0.94	0.17
Clayey calcareous soil				
Control	−0.42	3.75	0.69	0.60
KH_2PO_4	−1.06	7.65	0.90	0.76
Eglisau	−0.51	4.85	0.93	0.29
Zurich	−0.40	4.48	0.81	0.42
Fehraltorf	−0.61	5.25	0.67	0.91
Leibstadt	−0.53	4.61	0.59	0.92

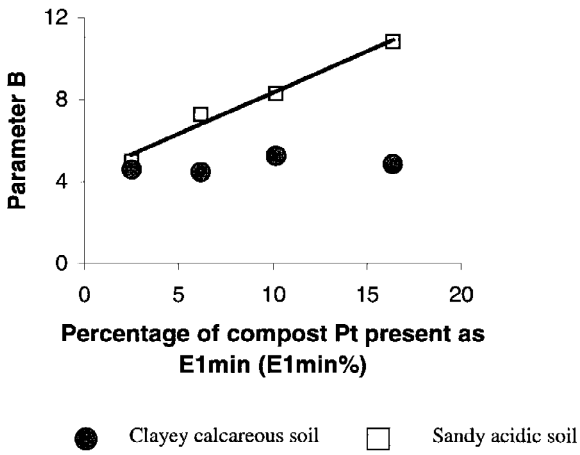

Figure 4. Relation between soil P isotopically exchangeable in 1 min (E_{1min}) in the soil/compost mixtures after 1 week of incubation (parameter B of eq. (7)) in two soils incubated with four composts and the proportion of E_{1min} to total P present in each compost ($E_{1min}\%$). The regression equation obtained for the sandy acidic soil is: $B = 0.40 \times E_{1min}\% + 4.31$; $r^2 = 0.98$.

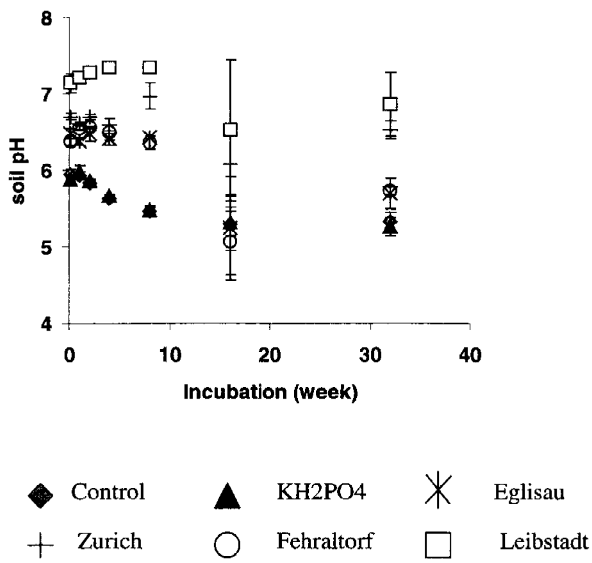

Figure 5. Changes in soil pH in the sandy acidic soil after the addition of P as KH_2PO_4 or as compost.

Leibstadt (Figure 5). In the clayey calcareous soil pH was unaffected by KH_2PO_4 or compost additions and remained between 7.6 and 8.2 during the entire duration of the incubation (Figure 6).

Effects of compost and KH_2PO_4 applications on dry-matter production by the aerial parts of white clover, total P and N exportations, P_{dff}, CU-P and P_{dfs}.

Dry-matter production.

In the sandy acidic soil the addition of P as KH_2PO_4 had no effect on dry-matter (DM) production of white

Table 4. Dry matter production of aerial parts (expressed in g DM kg^{-1} soil) of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils

Cut	1	2	3	4	Total[a]
Sandy acidic soil					
Control	3.09 Ba[b]	2.49 Dab	2.53 BCab	1.85 Cb	9.96 B
KH_2PO_4	3.45 Ba	3.35 CDab	2.38 Cbc	2.00 Cc	11.17 B
Eglisau	4.80 Aa	3.74 BCb	2.95 BCbc	2.82 ABc	14.30 A
Zurich	4.32 ABa	4.14 Bca	3.40 ABa	2.15 Cb	14.00 A
Fehraltorf	3.39 Bb	4.47 ABa	3.20 ABCb	3.20Ab	14.26 A
Leibstadt	4.17 ABa	5.33 Aa	3.98 Aab	2.67 Bb	16.15 A
Clayey calcareous soil					
Control	1.77 Bb	3.84 Ba	1.75 Bb	1.10 Bb	8.46 B
KH_2PO_4	5.03 Aa	4.40 ABa	2.13 Bb	1.77 Ab	13.33 A
Eglisau	4.47 Aa	4.35 ABa	2.10 Bb	1.76 Ab	12.66 A
Zurich	3.85 Aa	3.98 ABa	2.39 ABb	1.69 Ab	11.92 A
Fehraltorf	4.09 Aa	4.37 ABa	2.03 Bb	1.65 Ab	12.13 A
Leibstadt	4.31 Aa	5.10 Aa	2.91 Ab	1.83 Ac	14.15 A

[a]Total: dry matter produced during the entire pot experiment.
[b]Different upper case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

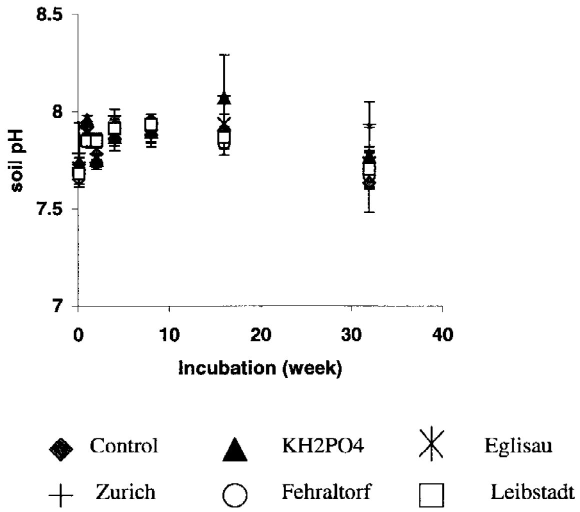

Figure 6. Changes in soil pH in the clayey calcareous soil after the addition of P as KH_2PO_4 or as compost.

clover compared to the control (Table 4) demonstrating that P was not a limiting nutrient for plant growth in this soil. The addition of composts however significantly increased the dry-matter production. In the clayey calcareous soil the addition of P as KH_2PO_4 increased significantly dry-matter production compared to the control (Table 4) showing that P was a limiting nutrient for plant growth in this soil. In this soil the addition of compost increased significantly dry-matter production as much as KH_2PO_4.

Total P exportation.

The addition of P as KH_2PO_4 in the sandy acidic soil slightly increased total P exportation by white clover compared to the control (Table 5). This was due to a slight increase in P concentration in the plant aerial which increased in average from 3.2 mg P kg^{-1} DM in the control to 3.4 mg P kg^{-1} DM in the presence of KH_2PO_4. Compost application significantly increased the total amount of P exported by white clover compared to the control and KH_2PO_4 treatments. These increases in P exportation subsequent to compost addition were not related to an increase in P concentration in the aerial parts of the plant, but to a strong increase in dry-matter production (Table 4). The P concentration in the aerial parts of white clover grown on the sandy acidic soil ranged from 2.7 to 3.6 mg P kg^{-1} DM. These values were within the range of 3.0 to 5.0 mg P kg^{-1} DM considered by Bergmann (1988) as being the optimum range for white clover, confirming that P was not limiting plant growth in this soil.

In the clayey calcareous soil the addition of P as KH_2PO_4 strongly increased P exportation by white

Table 5. Amount of P exported by the aerial parts (expressed in mg P kg^{-1} soil) of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils

Cut	1	2	3	4	Total[a]
Sandy acidic soil					
Control	9.17 Ba[b]	7.26 Cab	8.33 Cab	6.61 Db	31.37 C
KH_2PO_4	13.05 ABa	10.15BCab	8.69 Cab	7.08 CDb	38.56 B
Eglisau	15.87 Aa	10.67 Bb	9.62 BCb	9.74 Bb	45.89 A
Zurich	12.35 ABa	11.79 ABa	10.59 BCa	6.57 Db	41.30 B
Fehraltorf	11.84 AB	12.54 AB	11.63 AB	12.05 A	48.07 A
Leibstadt	10.74 Bbc	14.73 Aa	13.33 Aab	8.86 BCc	47.51 A
Clayey calcareous soil					
Control	2.58 Bb	4.46 Ca	2.76 Cb	1.94 Cb	11.72 C
KH_2PO_4	8.24 Aa	8.00 Aa	4.73 Ab	4.12 Ab	25.08 A
Eglisau	6.49 Aa	6.39 ABa	3.29 BCb	3.08 Bb	19.24 B
Zurich	8.78 Aa	5.99 BCab	4.25 ABb	2.99 Bb	22.01 AB
Fehraltorf	7.36 Aa	5.83 BCa	3.65 ABCb	3.02 Bb	19.85 B
Leibstadt	7.25 Aa	7.06 ABa	4.92 Ab	3.13 Bc	22.35 AB

[a]Total: P exported during the entire pot experiment.
[b]Different higher case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

clover compared to the control (Table 5). This was due both to a strong increase in dry-matter production (Table 4) and to an increase in P concentration in the plant aerial parts which went in average from 1.5 mg P kg^{-1} DM in the control to 2.0 mg P kg^{-1} DM in the presence of KH_2PO_4 confirming that P was limiting plant growth in the non-fertilized soil (Bergmann, 1988). Compost application also significantly increased the total amount of P exported by white clover compared to the control. The increases in P exportation subsequent to compost application were always smaller or at most equal to those caused by the addition of KH_2PO_4. The increases in P exportation subsequent to compost addition were related both to an increase in P concentration in the aerial parts of the plant, and to an increase in dry-matter production (Table 4).

Total N exportation.

In the sandy acidic soil the addition of P as KH_2PO_4 slightly increased N exportation by white clover compared to the control (Table 6). This was due to an increase in N content in the plant aerial parts which went in average from 26.8 mg N kg^{-1} DM in the control to 28.2 mg N kg^{-1} DM in the presence of KH_2PO_4. The range of N concentration observed in the plant aerial parts of the control treatment was a little below the range of 28.0 to 40.0 mg N kg^{-1} DM given by Bergmann (1988) as the optimum range of N concentration for white clover. Compost application significantly increased the total amount of N exported by white clover compared to the control and KH_2PO_4 treatments. The increases in N exportation subsequent to compost addition were related both to an increase in N concentration in the aerial parts of the plant and to a strong increase in dry-matter production. The increase in N concentration observed after the 1^{st} cut in the presence of KH_2PO_4 suggests this source of water soluble P slightly increased the biological N_2 fixation. The larger N content and exportation observed after compost addition can be related either to the release of N through mineralisation from the compost (Hadas et al., 1996), or to an indirect positive effect of compost on the ability of the white clover–Rhizobium association to fix N_2. This improvement in biological N_2 fixation might be related to (i) the increase in soil pH observed after compost addition, since acidic pH have been shown to inhibit rhizobial survival in soils (Hartwig, 1998), (ii) the increased demand of N by the plant due to better growth conditions (Hartwig, 1998) and/or (iii) to changes in the microbial flora of the rhizosphere following compost addition (Janzen et al., 1995).

Table 6. Amount of N exported by the aerial parts (expressed in mg N kg^{-1} soil) of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils.

Cut	1	2	3	4	Total[a]
Sandy acidic soil					
Control	88.7 Ca[b]	63.5 Eb	67.4 Cab	46.4 Cb	266.1 D
KH_2PO_4	124.9 ABCa	88.28 DEab	65.9 Cb	47.7 Cb	326.9 CD
Eglisau	164.5 Aa	111.6 CDb	93.9 BCb	68.9 Bc	439.0 B
Zurich	130.5 ABCa	111.4 Ca	81.6 BCb	49.8 Cc	379.3 BC
Fehraltorf	107.8 BCb	143.6 Ba	103.4 ABb	89.7 Ab	444.5 B
Leibstadt	143.8 ABa	174.1 Aa	131.1 Aab	97.1 Ab	546.2 A
Clayey calcareous soil					
Control	47.9 Cb	95.2 Ca	55.4 Cb	32.8 Bb	231.4 C
KH_2PO_4	158.4 Aa	141.7 ABa	76.8 ABCb	62.8 Ab	439.7 A
Eglisau	132.4 ABa	132.9 ABa	55.4 Cb	57.2 Ab	377.9 B
Zurich	119.0 Ba	110.3 BCab	82.5 ABbc	54.9 Ac	366.8 B
Fehraltorf	119.9 Ba	128.9 ABCa	67.8 BCb	55.9 Ab	372.6 B
Leibstadt	113.0 Bb	148.5 Aa	96.3 Ab	56.6 Ac	414.5 B

[a]Total: N exported during the entire pot experiment.
[b]Different higher case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

In the clayey calcareous soil the addition of P as KH_2PO_4 strongly increased N exportation by white clover compared to the control (Table 6). This was due both to an increase in N concentration in the plant aerial parts which increased from 28.6 mg N kg^{-1} DM in the control to 33.9 mg N kg^{-1} DM in the presence of KH_2PO_4 and to an increase in dry-matter production (Table 4). Compost applications also significantly increased N exportation compared to the control during the entire period of plant growth. The effect of compost additions on N exportation remained however lower or equal to the results observed after the addition of KH_2PO_4. The increase in N exportation subsequent to compost addition was related both to an increase in N concentration in the aerial parts of the plant and to a strong increase in dry-matter production. The influence of water-soluble P addition on the N concentration and exportation by the aerial parts of white clover strongly suggests that the biological fixation of $N_2$was impaired in this soil by a low P availability. The positive influence of a fertilization with water soluble P on N_2 biological fixation in low-P soils has also been shown in other studies (Almeida et al., 1999; Hartwig, 1998). As in the sandy acidic soil the larger N content and exportation observed after compost addition might also be related to the release of N through mineralisation from the compost (Hadas et al., 1996), to a higher plant demand for N, and/or to changes in the microbial flora following compost addition (Janzen et al., 1995).

Phosphate taken up by the plant and derived from the fertilizer (P_{dff})

The P_{dff} is a measurement of the amount of P in the plant which is derived from the fertilizer. In both soils the highest P_{dff} values were observed in the KH_2PO_4 treatment (Table 7). In the sandy acidic soil, the P_{dff} of the KH_2PO_4 decreased during the plant growth experiment from 3.70 mg P kg^{-1} soil at the first cut to 1.56 mg P kg^{-1}soil at the fourth cut, whereas the P_{dff} observed in the compost treatments remained constant or slightly increased with time.

Coefficient of utilization of P (CU-P) derived from compost and KH_2PO_4

The CU-P is a measure of the proportion of the added P fertilizer which has been taken up by the plant. The CU-P values ranged in the presence of KH_2PO_4 between 14.5% and 18.5% of the added P fertilizer (Table 8), which is in agreement with values observed for water-soluble P sources (Fardeau et al., 1996). In the sandy acidic soil the CU-P of the

Table 7. Proportion of P derived from the fertilizer (P_{dff} expressed in mg P kg^{-1} soil) in the aerial parts of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils.

Sandy acidic soil	1	2	3	4	Total[a]
KH_2PO_4	3.70 Aa[b]	2.23 Ab	1.84 Ab	1.56 ABb	9.32 A
Eglisau	1.25 B	1.16 B	0.78 B	1.26 AB	4.45 B
Zurich	0.61 BCab	1.09 Bab	1.24 ABa	0.49 CDb	3.43 B
Fehraltorf	0.97 BC	1.02 B	1.71 A	1.85 A	5.55 B
Leibstadt	0.57 BC	1.35 B	1.50 AB	1.01 BC	4.76 B
Clayey calcareous soil					
KH_2PO_4	1.92 Aab	2.66 Aa	1.48 Ab	1.18 Ab	7.25 A
Eglisau	1.34 ABab	1.73 Ba	0.71 Bb	0.63 Bb	4.41 BC
Zurich	0.20 Bc	1.24 Ba	1.02 ABab	0.69 Bb	3.25 C
Fehraltorf	2.08 Aa	1.41 Bab	0.97 ABb	0.80 ABb	5.27 B
Leibstadt	1.68 AB	1.72 B	1.45 A	0.98 AB	5.82 AB

[a]Total: total P_{dff} exported during the entire pot experiment.
[b]Different higher case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

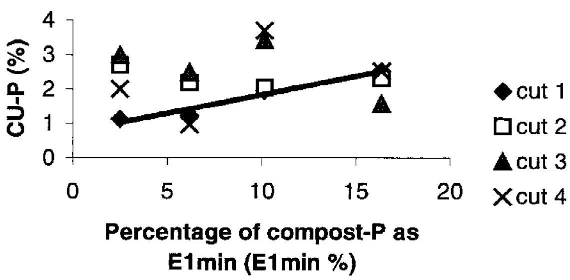

Figure 7. Relation between the coefficient of utilization of compost-P by white clover in the sandy acidic soil measured after each cut (CU-P%) and the fraction of compost P isotopically exchangeable within 1 min (E_{1min}%). The regression equation obtained for the first cut is: CU-Pcut1 = 0.11 × E_{1min}% + 0.77; r^2 = 0.95.

KH_2PO_4 decreased during the plant growth experiment while the CU-P of composts remained constant. In the clayey calcareous soil, the CU-P of the two last cuts of KH_2PO_4 and of the composts Fehraltorf and Eglisau were lower than those observed in two first cuts whereas the CU-P of the two other composts first increased from the first cut to the second and then decreased afterwards. The total CU-P of each compost measured for the entire pot experiment attained similar values in both soils.

Regression analysis showed that the CU-P of composts obtained at the first cut of white clover in the acidic soil was significantly positively related to the proportion of compost P isotopically exchangeable within one minute (Figure 7). This relationship was no longer valid for the results obtained during the rest of the pot experiment. The proportion of compost P in an organic form was significantly positively related to the total CU-P of compost calculated for the entire pot experiment in the sandy acidic soil (Figure 8). None of these relationships were statistically significant in the clayey calcareous soil although the same trend could be seen between total CU-P and the fraction of organic P in compost (Figure 8). These results suggest that in the sandy acidic soil, white clover used first the fraction of rapidly exchangeable P added with the composts, while afterwards a fraction of the organic P added with the compost was mineralized was taken up by the plant. The rapid uptake by plant of quickly exchangeable P is in agreement with previously published results (Fardeau, 1996; Frossard et al., 1996a). Mineralisation of organic P added with the composts in the sandy acidic soil did not seem to occur to a large extend in the incubation experiment with the acid soil, since the fraction of P isotopically exchangeable decreased with time and was only related to the fraction of inorganic P exchangeable within one minute in the composts (Figures 1, 3 and 4 and Table 3). This suggests that the presence of white clover strongly increased Po mineralisation. This increased rate of mineralisation in the presence of plant is in agreement with the presence of a high phosphatase activity observed on the roots of white clover and other leguminous plants (Almeida et al., 1999; Rao et al., 1997; Tarafdar

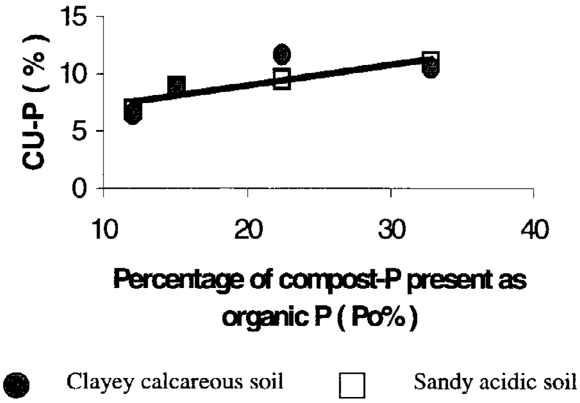

Figure 8. Relation between the total coefficient of utilization of compost-P by white clover in the acidic sandy soil and in the clayey calcareous soil (CU-P%) and the fraction of compost-P present in organic forms (Porg%). The regression equation obtained for the sandy acidic soil is: CU-Ptot = 0.18 × Porg% + 5.44; $r^2 = 0.87$.

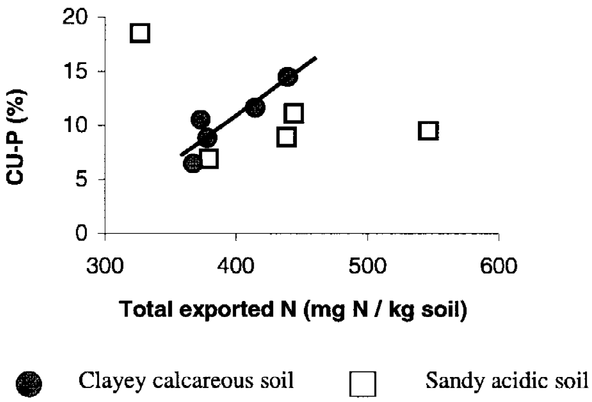

Figure 9. Relation between the total coefficient of utilization of P derived from the KH_2PO_4 and from the composts (CU-P%) and the total N exported by white clover in a sandy acidic soil and in a clayey calcareous soil. The regression equation obtained for the clayey calcareous soil is: CU-P = 0.09 × Nexp - 23.48; $r^2 = 0.81$.

and Claassen, 1988). The fact that these relations were not observed in the clayey calcareous soil, does not mean that such processes were not taking place. These were probably masked by the high sorbing capacity of this soil which led to a rapid sorption of the P released from composts (Frossard et al., 1996b).

Given the neutral or high pH values observed in all the incubated soil/composts mixtures of both soil (Figures 5 and 6) the calcium phosphates species observed in these composts by Frossard et al. (this issue) were probably not solubilized to a great extend by the plant (Fardeau et al., 1988). Finally, the total CU-P was also related to the total amount of N exported by white clover in the clayey calcareous soil but not in the sandy acidic soil (Figure 9). This result suggests that in a soil where N_2 biological fixation is limited by low P availability, the CU-P of a compost by a leguminous plant is not only related to the forms of P present in the compost but also to its effect on N nutrition. However, as mentioned above, it is not clear whether this increased N exportation was related to the release of N from the composts or to an effect of the compost on the N_2 biological fixation.

Phosphate taken up by the plant and derived from the soil (P_{dfs})

In the sandy acidic soil the addition of KH_2PO_4 did not increase the P_{dfs} significantly compared to the control (Table 9). The addition of composts on the contrary significantly increased P_{dfs} (Table 9). This increase can be related to a combination of the following processes: (i) composts addition increased the soil pH which resulted in an increased release to the solution of soil inorganic P bound to Fe and Al (oxy)hydroxides, (ii) composts addition improved plant growth and increased its needs for P which were compensated for by a higher P uptake from soil reserves.

In the clayey calcareous soil the highest P_{dfs} values were observed with KH_2PO_4. The addition of composts resulted in P_{dfs} values higher than those observed in the control, but lower or equal to those observed in the KH_2PO_4 treatment. There was no indirect effect of compost addition on the uptake of P derived from the soil.

Conclusions

The results presented in this paper allow to make the following conclusions. The addition of water-soluble phosphate (KH_2PO_4) increased soil available P, measured as the amount of P isotopically exchangeable within one minute ($E_{1\mathrm{min}}$), in incubated soil/fertilizer mixtures to a similar or higher degree than the same quantity of P added as composts. This result was confirmed in the 16-week long pot experiment which showed that the fraction of P taken up by the white clover derived from the fertilizer (P_{dff}, CUP) was higher in the case of KH_2PO_4 than in the presence of composts. This lower efficiency of compost P compared to KH_2PO_4 to increase soil P availability or to sustain the P nutrition of white clover was related to the presence of many complex insoluble P species in the studied composts (Frossard et al., 2002).

Table 8. Coefficient of utilization of P derived from the fertilizer (CU-P expressed in percentage added P) in the aerial parts of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils

Sandy acidic soil	1	2	3	4	Total[a]
KH_2PO_4	6.74 Aa[b]	4.46 Aab	3.68 Ab	3.11 ABb	18.52 A
Eglisau	2.51 B	2.32 B	1.57 B	2.51 ABC	8.90 B
Zurich	1.23 Bab	2.18 Bab	2.49 ABa	0.98 Cb	6.87 B
Fehraltorf	1.95 B	2.04 B	3.42 A	3.69 A	11.10 B
Leibstadt	1.14 B	2.70 AB	3.00 AB	2.01 BC	9.53 B
Clayey calcareous soil					
KH_2PO_4	3.84 Aab	5.33 Aa	2.97 Ab	2.36 Ab	14.49 A
Eglisau	2.69 ABab	3.45 Ba	1.42 Bb	1.27 Bb	8.83 BC
Zurich	0.40 Bc	2.49 Ba	2.04 ABab	1.39 Bb	6.50 C
Fehraltorf	4.17 Aa	2.83 Bab	1.95 ABb	1.61 ABb	10.54 B
Leibstadt	1.92 ABb	3.44 Ba	2.89 Aa	1.95 ABb	11.65 AB

[a]Total: total CU-P calculated for the entire pot experiment.
[b]Different higher case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

Table 9. Proportion of P derived from the soil (P_{dfs} expressed in mg P kg^{-1} soil) in the aerial parts of white clover as affected by the addition of P as composts or as KH_2PO_4 during a pot experiment conducted in two soils.

Sandy acidic soil	1	2	3	4	total[a]
Control	9.17 C[b]	7.26 C	8.33 C	6.61 CD	31.37 C
KH_2PO_4	9.35 Ca	7.92 Cab	6.86 BCab	5.51 Db	29.30 C
Eglisau	14.61 Aa	9.51 CBb	8.83 Bb	8.48 Bb	41.44 AB
Zurich	11.74 ABa	10.71 ABa	9.34 Ba	6.08 Db	37.87 B
Fehraltorf	10.87 C	11.52 AB	9.92 AB	10.21 A	42.52 A
Leibstadt	10.16 Cab	11.99 Aa	11.83 Aa	7.86 BCb	42.75 A
Clayey calcareous soil					
Control	2.58 B	4.46	2.76	1.94 B	11.72 B
KH_2PO_4	6.32 Aa	5.33 a	3.24 b	2.94 Ab	17.83 A
Eglisau	5.14 Aa	4.67 a	2.58 b	2.45 ABb	14.83 AB
Zurich	6.46 Aa	4.75 b	3.23 c	2.30 ABc	16.73 A
Fehraltorf	5.28 Aa	4.42 ab	2.68 bc	2.22 ABc	14.58 AB
Leibstadt	5.57 Aa	5.32 a	3.48 b	2.15 ABc	16.53 A

[a]Total: total amount of P_{dfs} exported during the entire pot experiment.
[b]Different higher case letters for the same soil and the same cut indicate a statistically significant difference between treatment at the 5% probability level by the test of Duncan. Different lower case letters within the same soil and treatment indicate a statistically significant difference between cuts at the 5% probability level by the test of Duncan.

Results obtained in the low P fixing sandy acidic soil suggest, that white clover took up at the beginning of the pot experiment a fraction of the rapidly exchangeable compost-P, while at a latter stage plant roots enhanced the mineralisation of compost organic P and took up a fraction of the mineralized P. The fact that these relations were not observed in the clayey calcareous soil does not mean that such processes were not taking place. These were probably masked by the high sorbing capacity of this soil which led to a rapid sorption of the P released from composts. Given the neutral or high pH values observed in the incubated soil/composts mixtures the calcium phosphates species observed in these composts (Frossard et al., 2002) were probably not solubilized to a large extent. Composts inputs in the sandy acidic soil strongly increased the uptake of soil P by the plant. This indirect effect might be related to a general improvement of plant growth conditions in this soil induced by compost addition and/or to a release of soil Al or Fe bound P to the solution due to soil pH increase following compost application. Finally the total CU-P of KH_2PO_4 and composts was shown to be positively related to the total amount of N exported by white clover in the P-limited clayey calcareous soil. This result suggests that in a soil where N_2 biological fixation is limited by low P availability, the CU-P of a compost by white clover is not only related to the forms of P present in the compost but also to its effect on N nutrition. However, it is not clear whether this improved N nutrition was related to compost mineralisation, or to an indirect compost effect on the N_2 biological fixation.

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