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Phosphorus budget and phosphorus availability in soils under organic and conventional farming

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Abstract

The aim of this work was to assess to which extent organic farming practices would affect the accumulation of total and available phosphorus (P) in a cropped soil in comparison to conventional practices. In order to achieve this, soil samples were taken from a long-term field trial comparing a non-fertilised control (NON), two conventionally cultivated treatments (MIN, CON), and two organically cultivated treatments (ORG, DYN). Soil samples were taken from each treatment at two depths (0-20 and 30-50 cm) before starting the field trial (1977) and at the end of every three crop rotations (1984, 1991 and 1998). They were then analysed for total P (P_t), total inorganic P (P_i), total organic P (P_o) and isotopically exchangeable P_i. After 21 years, the average P input-output budget reached -20.9 kg P ha^{-1} a^{-1} for NON, -7.8 for DYN, -5.7 for ORG, -5.0 for MIN and +3.8 for CON. Total P, P_i as well as the amount of P_i isotopically exchangeable within 1 minute (E_1) were positively correlated to the P budget. Comparison between P budget and P_t in the top- and subsoils of the fertilised treatments suggested a net transfer of P from the 0–20 to the 30–50 cm layers between 13 and 26 kg P ha^{-1} a^{-1}during the first rotation and between 3 and 12 kg P ha^{-1} a^{-1}during the second rotation. During the third rotation a net upward movement of P from the subsurface to the topsoil ranging between 3.7 and 10.5 kg P ha^{-1} a^{-1}was estimated. In the topsoil, E_1decreased from an initial value of 12 mg P kg^{-1} to 11 in CON, 8 in MIN, 6 in ORG, 5 in DYN and 2 in NON after 21 years. In the subsoil, E_1 increased from an initial value of 2 mg P kg^{-1} to 4 in MIN, ORG, DYN and NON and to 6 in CON. These results show that, with the exception of NON, all treatments had still an adequate level of available P after 21 years of trial and that, in this low to moderately P sorbing soil, an equilibrated input-output budget allows to maintain P availability at a constant level. In the organic systems, yields have so far partly been attained at the expense of soil reserves or residual P from earlier fertiliser applications.

Abbreviations: CON – soil fertilised with mineral fertilisers and animal manure and conventionally cultivated; c_P – water extractable P_i; DYN – soil fertilised exclusively with composted animal manure and cultivated according to guidelines of bio-dynamic farming; E_1 – quantity of P_i isotopically exchanged in the first minute; LU – livestock units; MIN – conventionally cultivated soil amended exclusively with mineral fertilisers; NON – non-fertilised control; ORG – soil fertilised almost exclusively with animal manure and cultivated according to guidelines of Swiss bio-organic farming; P_i – total inorganic soil phosphorus; P_o – total organic soil phosphorus; P_t – total soil phosphorus; r_1/R – proportion of the introduced radioactivity remaining in the water extract after the first minute of the isotopic exchange experiment

Introduction

Conventional farming systems practices in Western and Northern Europe have resulted in the application of phosphorus (P) fertilisers in excess to plant needs and in an accumulation of soil available P in the surface horizon of agricultural soils (Barberis et al., 1995; De Smet et al., 1996). These practises led to increased diffuse losses of P from agricultural soils to surface water and to water eutrophication (Sharpley et al., 1994; Jordan et al., 2000).

Integrated and organic farming systems may help to reduce P losses to water (Walther et al., 1994; Ulen, 1999). The Swiss guidelines of fertilisation for integrated production demand a balanced P budget at the farm level, implying that the amount of P imported on the farm in feed and fertiliser does not exceed P export in harvested products (KIP, 1999). In organic farming systems, the use of synthetic fertilisers is forbidden and fertilisation is mainly or exclusively based on animal manure (FiBL, 1999). Applications of manure produced on farm from 1.2–2.0 livestock units (LU) ha^{-1} a^{-1} are common (Hartnagel, 1997). In organic farming systems, rock phosphate can also be applied (FiBL, 1999), but in practice, its use is very limited. It is assumed, although not proven, that the implementation of integrated or organic farming systems can lower or stop available P accumulation in agricultural topsoils and thereby reduce diffuse P losses to waters.

The aim of the present study was to assess to which extent organic farming practices would affect the accumulation of available and total P in the surface and a subsurface horizon of a cropped soil in comparison to conventional practices. In order to achieve this, P inputs in fertilisers, P exports in harvested products and the P balance at the plot level were calculated for three 7-year long rotations in a long term field experiment comparing the effects of organic and conventional farming on crop performance and soil fertility (Besson and Niggli, 1991). Then, soil samples taken from two depths (0–20 and 30–50 cm) before starting the field trial and at the end of every rotation were analysed for total (P_t), total inorganic (P_i) and total organic (P_o). Finally, inorganic P availability was assessed in the same samples using the isotopic exchange kinetics approach (Fardeau, 1993).

Materials and methods

Description of the field trial

The soils used for this study derive from a long-term field experiment established in 1978 in Therwil (near Basel, Switzerland) on an Haplic Luvisol developed on loess in a temperate climate (Besson and Niggli, 1991; Siegrist et al., 1998). The trial is located on gently inclined land (about 3%, Besson et al., 1978) in a small valley protected from wind erosion. In addition, each plot (100 m^2) is surrounded by a grass strip which strongly reduces surface erosion. This trial compares two types of organic crop production systems (bio-dynamic, DYN and bio-organic, ORG) with two conventional crop production systems (CON, MIN) and a non fertilised control (NON). The treatments mainly differ in fertilisation and plant protection practices (Table 1). All treatments are cultivated at four field replicates with the same 7-year crop rotation in a split-split-plot-design (Besson and Niggli, 1991; Siegrist et al., 1998). The first crop rotation (1978–1984) included spring barley, two years of grass-clover mixture, potatoes, winter wheat, white cabbage and winter wheat. The second rotation (1985–1991) was identical, but spring barley was replaced by winter barley, and white cabbage by red beet. In the third rotation (1992–1998), winter barley was replaced by a third year of grass-clover. Crop residues of potatoes, cabbage and red beet were always left on the plots and incorporated into the surface horizon while the straw of the cereals was harvested. Since 1992, the depth of ploughing is identical in all treatments (18–20 cm). During the first two rotations, the ploughing depth was 15–20 cm in organically and 20–25 cm in conventionally cultivated plots (Besson and Niggli, 1991). Samples from the ploughed layer (0–20 cm, in the following referred to topsoil) and from a subsoil layer (30–50 cm; ‘subsoil’) were investigated. Samples had been taken at establishment of the trial (November 1977) or at the end of the rotation after harvesting the winter wheat (first decade of August in 1984, 1991 and 1998) from each field replicate. Samples were taken over the inner 3 m × 16 m area of the 5 m × 20 m plots to avoid border effects. Within each plot, 15–20 cores were sampled using a 3 cm diameter auger. The cores were cut into layers (0–20 cm, 30–50 cm), and the corresponding segments of a field replicate were mixed. After the samples were transported to the field station, they were air-dried at 40 °C and sieved (2 mm). The 20–30 cm depth was never sampled. Se-

Table 1. Average rate of N, P and K fertilisation (kg ha^{-1} a^{-1}) for the three rotations, type of fertilisers added and plant protection strategy applied in the investigated farming systems

	DYN			ORG CON			MIN			NON			NON		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
1978–84	112	29	122	113	29	124	135	51	281	0	0	0	0	0	0
1985–91	90	28	99	94	25	124	135	44	232	102	46	225	0	0	0
1992–98	91	17	220	81	25	138	173	34	281	145	36	282	0	0	0
Type of manure/ fertiliser	Aerobically composted FYM and slurry amended bio-dynamic preparations (1.2/1.4 LU ha^{-1} a^{-1})[a]			Slightly aerobically rotted FYM and slurry (1.2/1.4 LU ha^{-1} a^{-1})[a]			Anaerobically rotted FYM and slurry (1.2/1.4 LU ha^{-1} a^{-1})[a] plus mineral fertilisers			Exclusively mineral fertilisers since 1985; 1978–1984: non-ferilised			non-fertilised since 1978		
Plant protection	Mineral and herbaceous preparations according to bio-dynamic farming; no synthetic pesticides			according to the Swiss guidelines of organic farming; no synthetic pesticides			according to the guide-lines of Swiss integrated production since 1991; synthetic pesticides used respecting thresholds			according to the guide-lines of Swiss integrated production since 1991; synthetic pesticides used respecting thresholds			according to bio-dynamic farming		

FYM = farmyard manure; LU = Livestock units.
[a] Increase from 1.2 to 1.4 LU ha^{-1} a^{-1} occurred at the beginning of the third crop rotation (1992–98).

lected chemical soil characteristics after 21 years of different farming are given in Table 2.

P budget

Average annual P budgets were calculated at the plot level as the difference between P input by fertilisation (amount of fertiliser multiplied by the P content of fertiliser; P_f) and the P export from field by harvested products (P_h) (Spiess and Besson, 1995) for the respective treatment during the respective period:

$$\text{Annual P budget}[\text{kg P ha}^{-1}\text{a}^{-1}] = [(\text{P}_\text{f} - \text{P}_\text{h})/years] \quad (1)$$

Average annual P budgets were determined for each 7-year rotation period and for all 21 years.

Total, total inorganic and total organic P

The P_t, P_i and P_o contents were determined with the ignition method of Saunders and Williams (1955). One set of soil samples (1 g) finely ground using a mortar were ignited for 5 hours at 550 °C. Afterwards, P was extracted by 50 ml of an 1 N H_2SO_4 solution by shaking the samples for 16 h. After filtration of the extracts (Whatman 40), P_t was determined according to Tiessen and Moir (1993). Inorganic P content was determined with the same procedure applied on non-ignited samples. Organic P content was calculated as difference between P_t and P_i. For soils from this experimental site, P_t obtained by ignition agrees well with the amount of P_t determined using perchloric acid digestion or KNO_3/$NaNO_3$ fusion (Oberson, unpublished results). The P content in kg P ha^{-1} was calculated using the bulk density of the respective soil layers. Since treatments were shown to not affect the bulk density (Alföldi et al., 1993), the average value of 1.25 kg l^{-1} (Stauffer, personal communication) was used for the topsoil and 1.47 kg l^{-1} for the subsoil layer.

P movement

Phosphorus losses from the topsoil other than by harvested products occurred over the 21 years experimentation period if measured P_t changes in the topsoil between 1977 and 1998 (ΔP_t = P_t(1998) minus P_t(1977)) are not accounted for by the total P budget of the respective treatments, i.e. if Equation (2) becomes negative:

$$\text{Unaccounted P [kg P ha}^{-1}] = [(\Delta \text{P}_\text{t}) - (\text{annual P budget} * 21\text{years})] \quad (2)$$

Positive values for unaccounted P indicate P enrichment in the topsoil that is not caused by fertiliser P input. Unaccounted P was also calculated for each rotation.

P availability

The isotope exchange kinetics technique (Fardeau, 1993) was used to assess soil P_i availability. This approach, which is based on the kinetics of disappearance of radioactive phosphate ions from the solution of a soil–solution system at steady state (i.e., at a constant $^{31}PO_4$ concentration in the solution), gives information on the intensity, quantity and capacity factors controlling soil P availability (Fardeau, 1993; Frossard et al., 1994). After shaking a 1:10 soil:water suspension (5 g soil in 49 ml deionised water) during 16 h, 1 ml of carrier-free $^{33}PO_4$ ion tracers (0.02 MBq) was added and the isotopic exchange between the soil solution and the soil solid phase followed. In this experiment, 1, 10, 20 and 60 minutes after the addition of the tracer, about 2 ml of suspension were removed with a polyethylene syringe and the solution immediately separated from soil particles using a membrane filter (0.2 μm pore size). The $^{33}PO_4$ in the filtered aliquots was determined with a scintillation counter. The P_i concentration in the soil solution (c_P, mg P l^{-1}) was determined colorimetrically (Tiessen and Moir, 1993) at the end of the batch experiment after centrifugation (6000 rpm; 10 min) on filtered (0.2 μm pore size) aliquots.

The quantity E_1 (mg P kg^{-1}) represents the pool of P ions that is exchanged during the first minute of the batch experiment. It is immediately available to crops without chemical transformation and is calculated using the following equation (Fardeau, 1993):

$$E_1 = 10c_P/(r_1/R), \tag{3}$$

where E_1 presents the quantity factor, c_P the intensity factor and r_1/R the capacity factor. The ratio r_1/R describes the ratio between the radioactivity remaining in the solution after one minute of exchange (r_1) and the initially added radioactivity (R) and is well correlated with the P adsorption capacity of soils (Fardeau, 1993; Frossard et al., 1993). Soils with a $r_1/R < 0.2$ show a high, soils with a $r_1/R > 0.4$ a low P sorbing capacity (Fardeau, 1993).

Statistics

Each parameter was analysed on the 4 field replicates per treatment and tested using SAS (1989). Significance of differences between treatments or between rotation periods was tested using Duncan's multiple range test after two-way ANOVA. Significance of changes in P contents and P availability parameters between 1977 and 1998 as well as differences between ΔP_t in topsoil and the P budget after 21 years were tested using *post hoc* tests after two-way ANOVA. The profiles of the P availability parameters and total P_t, P_i and P_o contents were analysed using repeated measures ANOVA. Dependency of the P contents and P availability parameters from the P budget, and of P availability from P budgets, soil Ca, P_i and P_t contents after 21 years was tested using simple and multiple linear regression analysis, respectively.

Results and discussion

P budget

Average annual P budgets of both organic farming systems were negative for each single rotation period and for the 21 years of field experimentation (Table 3). This indicates that P removal by harvested products exceeded the P input in fertilisers and that soil reserves or residual P from earlier fertiliser applications provided P for uptake.

For the conventionally cultivated (CON) soil, receiving mineral fertilisers and farmyard manure, the P budget decreased from an average of +15.2 kg P ha^{-1} a^{-1} for the first rotation to −8.6 kg P ha^{-1} a^{-1} for the third rotation. This was partly caused by a reduction of the fertilisation level from 1.2 to 1.0 fold standard fertilisation in 1991 and by an additional reduction in fertilisation in 1994 (Table 1) when the Swiss guidelines for fertilisation were revised (Walther et al., 1994). Only the CON soil showed a positive budget over all three rotations. The MIN soil, receiving mineral fertiliser since 1985 only, showed a negative P budget over the 21 years. This was caused by the absence of fertilisation during the first rotation period. After being positive for the second period, a balanced budget was obtained for the third period, showing that the fertilisation correctly met the P export by harvested products. The budget of the non-fertilised soil (NON) went from an average of −26.2 kg P ha^{-1} a^{-1} for the first rotation to −15.8 kg P ha^{-1} a^{-1} for the third rotation due to the decreasing P export caused by decreasing crop yields.

Recovery of P_t in the surface and subsurface horizons

Total P contents in topsoil are positively correlated with the budget (Figure 1). In all fertilised systems, the P_t decrease over 21 years was greater than expected from the P budget (Table 4). The unaccounted difference suggests mean annual P losses from the topsoil of 5–11 kg P ha^{-1} a^{-1} in the fertilised soils while P loss from topsoil in NON soil was not significant (Table 4). Phosphorus losses out of the topsoil increased significantly with the P budget (Figure 2). While P_t decreased

Table 2. Selected characteristics of the soils after 21 years of different farming

Soils	DYN	ORG	CON	MIN	NON
pH (H_2O)	6.8 (0.2)	6.6 (0.1)	6.1 (0.1)	6.2 (0.2)	6.4 (0.2)
Organic C (g kg^{-1})	14.7 (0.3)	13.1 (1.3)	12.6 (0.3)	13.2 (1.4)	12.6 (1.4)
Ca (g kg^{-1})	2.7 (0.4)	2.0 (0.2)	1.7 (0.1)	1.6 (0.2)	1.9 (0.3)

Mean and standard error of the mean (in brackets) of 4 field replicates; total organic carbon was analysed by chromic acid digestion (Walkley and Black, 1934); Ca content using 0.05 *M* HCl and 0.0125 *M* H_2SO_4 at a 1:10 soil:solution ratio (Cooperative Extension Service, 1970).

Table 3. Average annual P input, P export and P budget of the investigated soils for each crop rotation and as average of all three rotations (kg P ha^{-1} a^{-1})

	First rotation 1977–1984			Second rotation 1985–1991			Third rotation 1992–1998			Three rotations 1977–1998		
Soils	input	export	budget	input	export	budget	input	export	budget	input	export	budget
DYN	28.5	30.5	−2.0 b	27.5	32.6	−5.1 c	16.6	33.0	−16.4 c	24.2	32.0	−7.8 c
ORG	29.3	31.2	−1.8 b	25.2	33.7	−8.5 d	25.0	31.6	−6.6 b	26.5	32.2	−5.7 bc
CON	51.1	35.9	15.2 a	43.9	39.2	4.8 b	34.0	42.6	−8.6 b	43.0	39.2	3.8 a
MIN	0	27.5	−27.5 c	46.1	34.1	12.0 a	36.3	35.7	0.5 a	27.5	32.5	−5.0 b
NON	0	26.2	−26.2 c	0	20.7	−20.7 e	0	15.8	−15.8 c	0	20.9	−20.9 d
sem		0.74	0.74		0.82	0.82		0.79	0.79		0.65	0.65

The P budgets are calculated as differences between P input by fertilisation and P export by harvested products; different letters in the same column show significant differences in P budgets between farming systems (Duncan's multiple range test). *sem* denotes the standard error of the mean.

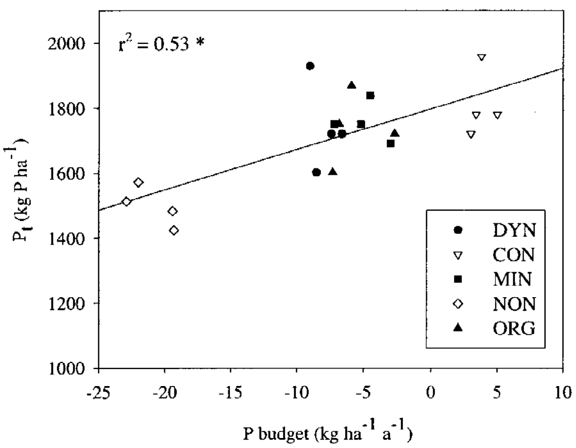

Figure 1. Relationship between mean annual P budget and P_t content of the topsoils after 21 years of different farming. * denotes a significant slope (linear regression); each point presents a field replicate.

in the topsoil with time, an increase was found in the subsoil (Table 4). This increase accounts for the losses observed in the topsoil. This result suggests a downward movement of P. However, the information remains limited due to the missing data on the 20–30 cm layer. Phosphorus downward movement may have been caused by percolating water or by deposition by plant roots (Campbell et al., 1993). The highest downward P movement occurred during the first crop rotation (13–27 kg P ha^{-1} a^{-1}; Figure 3) and decreased in the following rotation. In the third rotation period, the observed P_t decrease in the topsoil was lower than expected from the budget. This suggests that a net upward P movement took place (between 3.5 and 10.5 kg P ha^{-1} a^{-1}; Figure 3). Richards et al. (1995) and Beck and Sanchez (1996) had shown the concomitant occurrence of P downward and upward movement depending on fertilisation regimes in 10 and 13-year old long-term field trials, respectively. Stumpe et al. (1994) and Wechsung and Pagel (1993) observed an upward transport and proposed that crops obtained much of their P requirement from the subsoil when the P budget had been negative in 40- and 84-year-old long-term field trials, respectively. Significant P accumulation of plant residues at the surface and impoverishment of the deeper layers were observed in no-tillage systems (Scheiner and Lavado, 1998).

Table 4. Comparison of the total P budget with the changes in total P contents in the soils during 21 years of different farming (kg P ha^{-1})

Soils	Topsoil (0–20 cm)					Subsoil (30–50 cm)		
	P_t 1977	P_t 1998	ΔP_t 1998–1977	P budget	Unaccounted difference	P_t 1977	P_t 1998	ΔP_t 1998–1977
DYN	2025	1743	−282*	−166	−116*	1370	1519	148*
ORG	1958	1736	−223*	−120	−103 (P = 0.07)	1370	1501	131*
CON	1958	1810	−148*	80	−228*	1388	1571	183*
MIN	2018	1758	−260*	−105	−155*	1379	1519	140*
NON	2010	1498	−512*	−439	−73	1388	1388	0
sem	42.3	46.1	44.4	13.6	52.4	37.7	56.5	40.5

*denotes a significant change in P_t of the same soil layer after 21 years, or significant differences between ΔP in the topsoil and the P budget (for testing the existence of unaccounted differences) using one sample t-test with the overall *sem*. *sem* denotes the standard error of the mean and was calculated by a two-way ANOVA.

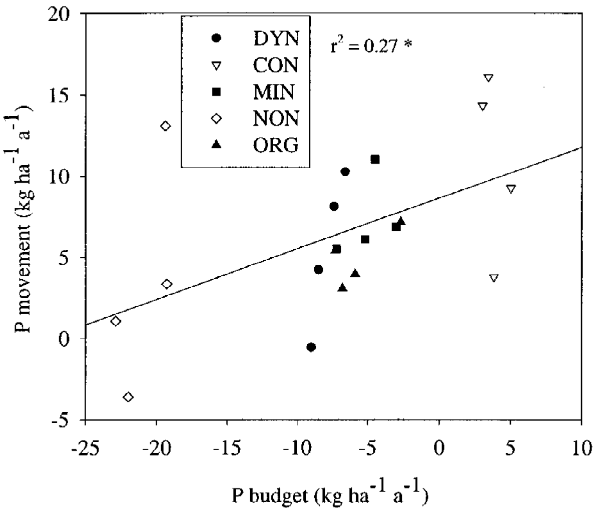

Figure 2. Relationship between P budget and P downward movement from topsoil after 21 years of different farming. * denotes a significant slope (linear regression); each point presents a field replicate.

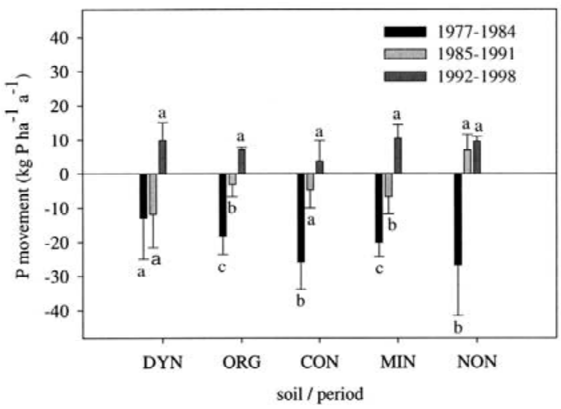

Figure 3. Net downward P movement out of the topsoil (0–20 cm; negative values) and net upward movement into the topsoil (positive values) for each rotation period. Data followed by the same lowercase letters for the same soil are not significantly different (Duncan's multiple range test).

Changes in P_i and P_o content in the surface and subsurface horizons

The P_i and P_o contents in the top- and subsoils of the different treatments between 1977 and 1998 are presented in the Figure 4. The P_i content of the topsoil is significantly correlated to the P budget (Figure 5) whereas P_o in the topsoil and P_i and P_o in the subsoil are not related to it. A sharp decrease in the P_o content of topsoil was observed in all treatments during the first rotation. The reason for this decrease however remained unclear.

Both P_i and P_o might have contributed to the downward movement of P. Increases in the subsoil were 58 and 63 kg P ha^{-1} for P_i and P_o, respectively, and accounted for the respective decreases in the topsoil. However, since soil P is continuously recycled between inorganic and organic forms, it is not possible from these results to conclude how both forms contributed to the P movement to the subsurface horizon.

Changes in inorganic P availability in the surface and subsurface horizons

Data presented in the Figures 6, 7 and 8 show that the ratio r_1/R, the concentration of P_i in the solution (c_P) and the amount of P_i isotopically exchanged within

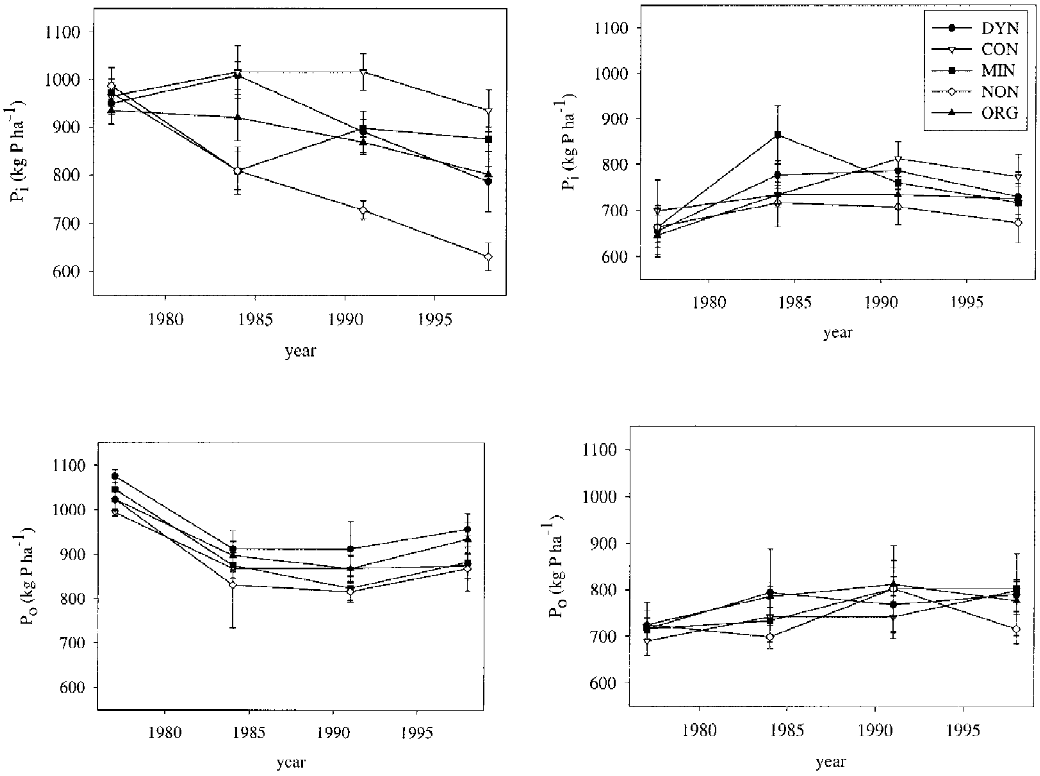

Figure 4. Changes in P_i and P_o contents of the topsoil (left) and subsoil (right) during 21 years of different farming.

1 min (E_1) in the topsoil regularly decreased during the 21 years of the trial in all treatments except CON. In the treatment CON, c_P and E_1 increased during the first rotation, and then decreased to values slightly lower than those observed at the beginning of the trial. The r_1/R value only slightly decreased during the 21 years of the field trial. These results indicate a decrease in P_i availability in all treatments except in CON where P availability remained overall constant. In contrast, c_P, E_1 and r_1/R increased with time in the subsurface horizon, which indicates an increase in P availability (Figures 6, 7 and 8). The largest increases were observed for CON while the changes in NON were minor.

The c_P, E_1 and r_1/R values of the topsoil were linearly positively correlated to the P budget (Figure 9), to P_t (r^2= 0.30 for c_P, 0.40 for $E_1$and 0.19 for r_1/R) and to P_i (r^2= 0.55, 0.61 and 0.42). The differences in P budget, P_t and P_i only partly explain the variation of c_P, E_1 and r_1/R (multiple regression r^2= 0.78, 0.78 and 0.70 for c_P, E_1 and r_1/R, respectively). At similar budgets, the MIN topsoils show higher c_P, E_1 and r_1/R values than topsoils of ORG and DYN (Figure 9). The largest differences between these three treatments

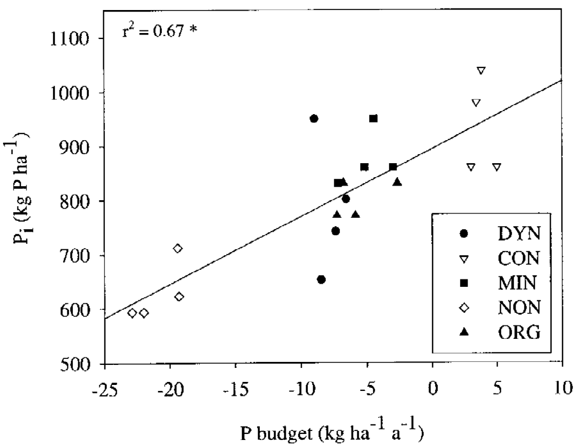

Figure 5. Relationship between mean annual P budget and P_i content of the topsoils after 21 years of different farming. * denotes a significant slope (linear regression); each point presents a field replicate.

were observed for r_1/R (Figure 9). This suggests that these different types of cropping systems have modified some soil properties affecting r_1/R, i.e. the P sorption capacity. The increase in P sorption capacity in DYN could be due to the higher input of Ca with

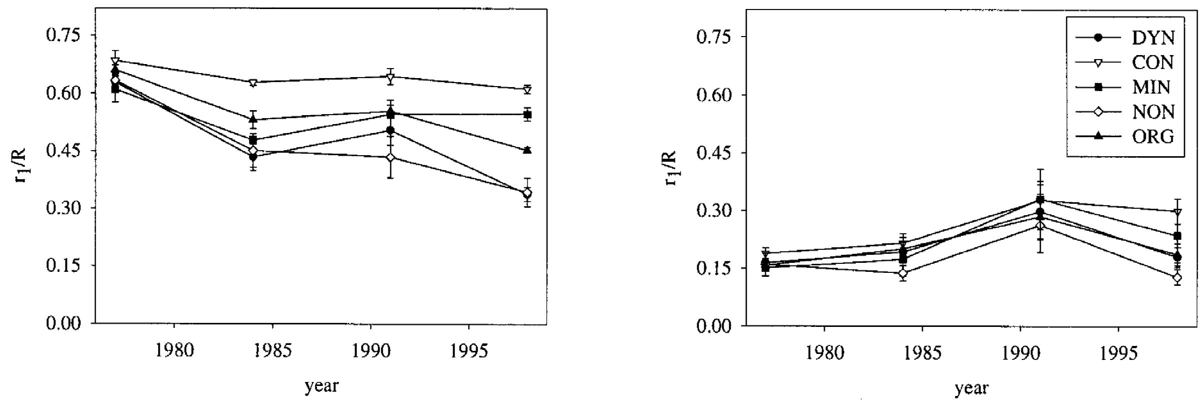

Figure 6. r_1/R ratio in the top- (0–20 cm; left) and in the subsoil (30–50 cm; right) sampled before the beginning of the trial and at the end of each rotation period. r_1/R denotes the proportion of the introduced radioactivity remaining in the water extract after the first minute of the isotopic exchange.

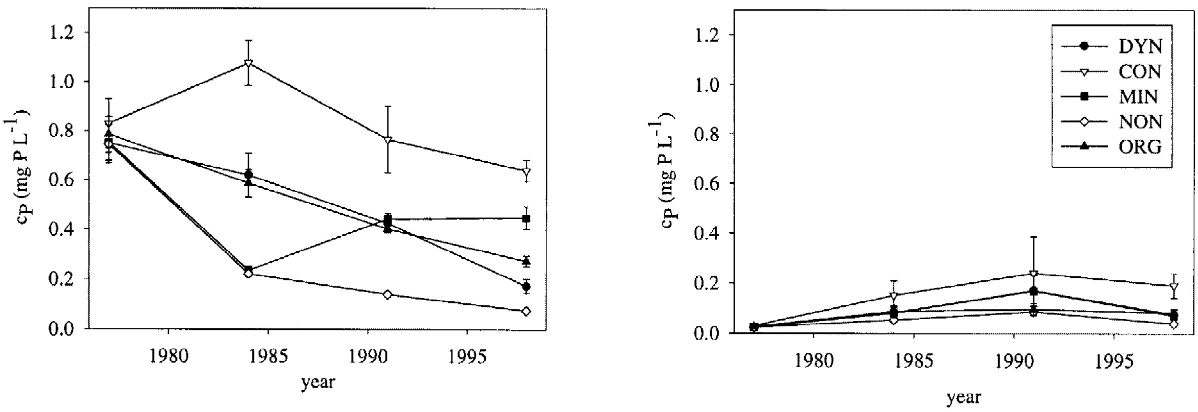

Figure 7. P_i concentration in the water extract (c_P) in the top- (0–20 cm; left) and in the subsoil (30–50 cm; right) sampled before the beginning of the trial and at the end of each rotation period.

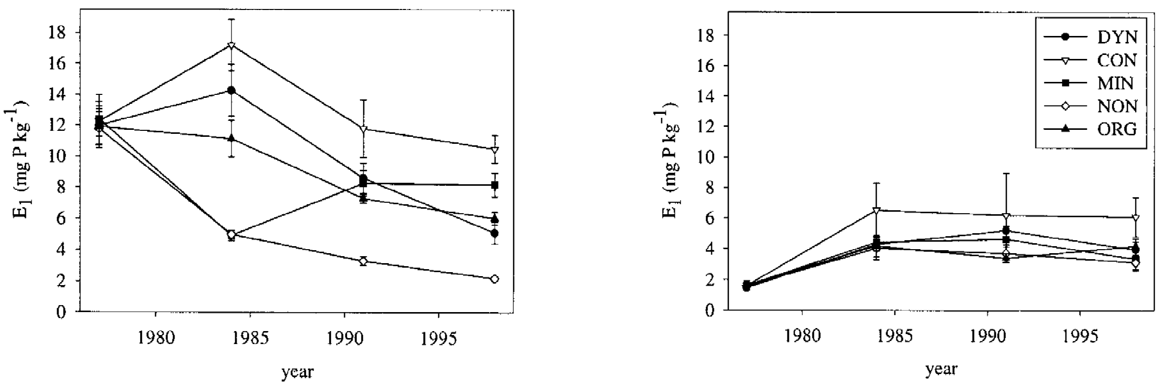

Figure 8. Quantity of P_i isotopically exchanged within 1 minute (E_1) in the top- (0–20 cm; left) and in the subsoil (30–50 cm; right) sampled before the beginning of the trial and at the end of each rotation period.

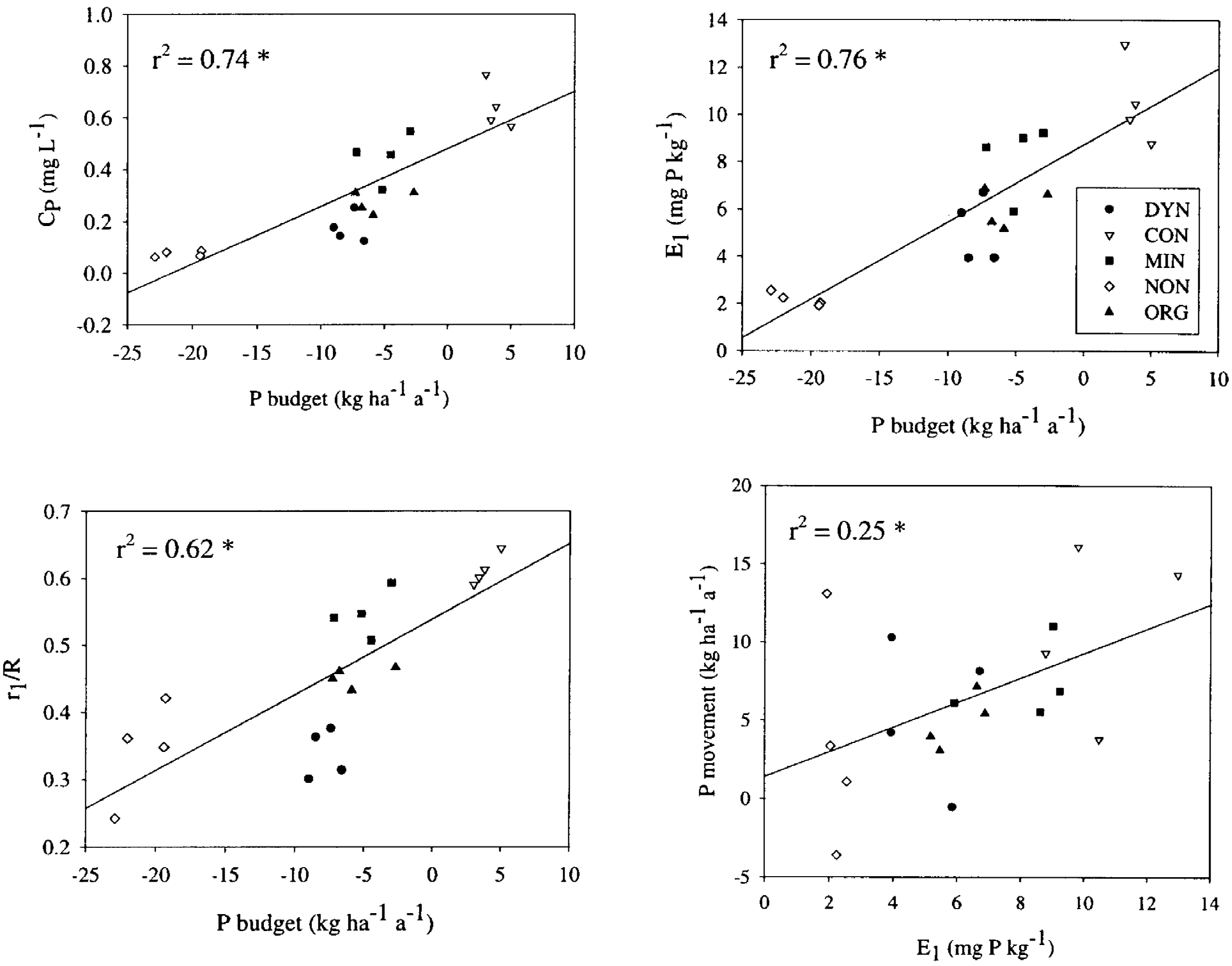

Figure 9. Relationship between the P budget and the isotopic exchange parameters, and relationship between E_1 and the P movement out of the topsoil after 21 years of different farming. * denotes a significant slope (linear regression); each point presents a field replicate.

the composted manure, which resulted in an increase in soil pH and exchangeable Ca (Table 2) as already proposed by Oberson et al. (1993). Multiple regression analysis including the Ca content alone or with soil pH as independent variables together with P budget, P_t and P_i contents increases r^2 for r_1/R to 0.82 and 0.87, respectively. Finally, E_1 in topsoil was positively related to the quantity of P lost from the surface horizon (Figure 9). Positive linear correlations were also observed between c_P, E_1 and r_1/R in the subsurface horizon and the P budget (r^2 = 0.36; 0.20 and 0.37) and P_i (r^2= 0.30, 0.17 and 0.32).

The ratio of E_1 of the topsoil to E_1 of the subsoil decreased significantly in all treatments from 8 in 1977 to between 0.7 (in NON) and 2.5 (in MIN) in 1998. In NON, P_i availability was higher in the subsoil than in the topsoil in 1998, suggesting that plant P uptake from deeper layers may have got increasing importance. Net P upward movement estimated for the third crop rotation period (Figure 3) showed that this was also probable for the organically cultivated and the MIN soils, despite that P availability was still at an adequate level in their topsoils. Kuhlmann and Baumgärtel (1991) also showed that P uptake from subsoil increased with decreasing P supply in the topsoil.

P availability slightly decreased during 21 years in the CON topsoil despite of a positive P budget. In contrast, c_p and E_1 did not decrease in the MIN topsoil anymore during the third rotation when the budget was balanced, showing that, in this low P sorbing soil, P availability can be stabilised with an equilibrated input-output budget, although at a lower level than in CON. The MIN soil, which had not been fertilised in the first rotation, achieved highest winter wheat yields in 1984, suggesting that P availability (E_1 of 4.9 mg P kg^{-1}; Figure 8) was not limiting for crop yield (5.4 t ha^{-1}). This confirms the results of Morel et al. (1992) who deduced for winter wheat production on French agricultural soils an E_1 value of 3.5 mg P kg^{-1} to guarantee achievement of 95% potential yield.

According to Morel et al. (1992), the E_1 values observed in the upper horizon of ORG and DYN are not yet limiting for wheat production while these treatments also have a significant reserve of available P in the subsurface horizon. In these treatments, the mineralisation of organic P might also significantly contribute to plant nutrition. Oehl et al. (1998) found in ORG and DYN higher quantities of P, C and N in the microbial biomass than in MIN and NON. Similarly, Oberson et al. (1996) observed a higher rate of ATP turnover and a higher phosphatase activity in the DYN and ORG soils compared to CON, MIN and NON. Finally, weathering of the soil parent material is also considered as a P source for crops in organic farming (Kahnt, 1999). However, although it is now known that organic farming system can promote a higher soil biological activity (Fliessbach and Mäder, 1997), there is no precise estimation of P release to agricultural crops through weathering. Letkeman et al. (1996) estimated an annual P weathering of 0.1 kg P ha^{-1} a^{-1} in soils developed on glacial till of similar age as the Luvisol of this study. Newman (1995) found weathering rates between 0.05 and 1.0 kg P ha^{-1} a^{-1}, but assumed up to 5 kg P ha^{-1} a^{-1} to occur. Therefore, it remains unanswered if biological processes and weathering can maintain soil P availability to an optimum level for plant production.

Conclusion

With exception of the CON treatment, P budgets were negative for all treatments, indicating that P removal by harvested products exceeded P input by fertiliser. Consequently, yields had partly been attained on expense of the P reserves of the site present at the beginning of the trial. Comparison between the P budget and the changes in P_t contents between 1977 and 1998 revealed a P loss from topsoil by processes other than removal by harvested product. The increase of P_t in the subsoil layer almost completely accounted for P lost from the topsoil (5–11 P kg ha^{-1} a^{-1}), suggesting a downward movement of P. In the third rotation period, the observed P_t decrease in the topsoil was lower than expected suggesting that a net upward P movement had taken place. This upward movement of P might be related to plant uptake that returned P back to the topsoil. The importance of this process probably increased with time because of the decrease of total and available P in the topsoil.

The P_i availability in the topsoil decreased markedly in all treatments during the field trial except in CON which showed a slightly positive P budget. The P availability in the subsoil increased significantly in all treatments during the 21 years. Results obtained in the MIN topsoils demonstrate that, in this moderately to low P sorbing soil, an equilibrated input output budget allows to stabilise soil P. For the organically cultivated soils, continued monitoring is needed to determine if an ongoing decrease of availability in the top- and subsoil can be balanced by an increased organic P mineralisation and P weathering to maintain adequate yields.

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References

Alföldi T, Stauffer W, Mäder P, Niggli U & Besson JM (1993) DOK-Versuch: vergleichende Langzeit-Untersuchungen in den drei Anbausystemen biologisch-dynamisch, organisch-biologisch und konventionell: III. Boden: Physikalische Untersuchungen, 1. und 2. Fruchtfolgeperiode. Schweiz Landwirtsch Forsch 32: 465–477

Barberis E, Ajmone Marsan F, Scalenghe R, Lammers A, Schwertmann U, Edwards AC, Maguire R, Wilson MJ, Delgado A & Torrent J (1995) European soils overfertilised with phosphorus: Part 1. Basic properties. Fert Res 45: 199–207

Beck MA & Sanchez PA (1996) Soil phosphorus movement and budget after 13 years of fertilized cultivation in an Amazon basin. Plant Soil 184: 23–31

Besson JM & Niggli U (1991) DOK-Versuch: vergleichende Langzeit-Untersuchungen in den drei Anbausystemen biologisch-Dynamisch, Organisch-biologisch und Konventionell. I. Konzeption des DOK-Versuchs: 1. und 2. Fruchtfolge. Schweiz Landwirtsch Forsch 31: 79–109

Besson JM, Vogtmann H, Lehmann V & Augstburger F (1978) DOK: Versuchsplan und erste Ergebnisse eines Projektes zum

Vergleich von drei Anbaumethoden. Schweiz Landwirtsch Forsch 17: 191–209

Cooperative Extension Service (1970) Lab procedures. Soil testing and plant analysis laboratory, Athens, Ga.

Campbell CA, Lafond GP, Biederbeck VO & Winkleman GE (1993) Influence of legumes and fertilization on deep distribution of available phosphorus (Olsen-P) in a thin Black Chenozemic soil. Can J Soil Sci 73: 555–565

De Smet J, Hofman G, Vanderdeelen J, Van Meirvenne M and Baert L (1996) Phosphate enrichment in the sandy loam soils of West-Flanders, Belgium. Fert Res 43: 209–215

Fardeau JC (1993) Le phosphore assimilable des sols: sa représentation par un modèle fonctionnel à plusieurs compartiments. Agronomie 13: 317–331

FiBL (1999) Richtlinien und Verordnungen zum Biolandbau – Umfassende Sammlung der Verordnungen des Bundes und der Labelrichtlinien zum Biolandbau. In: Research Institute of Organic Agriculture (ed). Frick, Switzerland

Fliessbach A & Mäder P (1997) Carbon source utilisation by microbial communities in soils under organic and conventional farming practice. In: Insam H and Rangger A (eds) Substrate use for characterisation of microbial communities in terrestrial ecosystems, pp 102–120. Proceedings of the conference: SUBMECO, Innsbruck, Oct. 16–18, 1996. Berlin: Springer

Frossard E, Fardeau JC, Brossard M & Morel JL (1994) Soil isotopically exchangeable phosphorus: comparison between E and L values. Soil Sci Soc Am J 58: 846–851

Frossard E, Feller C, Tiessen H, Stewart JWB, Fardeau JC & Morel JL (1993) Can an isotopic method allow for the determination of the phosphate fixing capacity? Comm Soil Sci Plant Anal 24: 367–377

Hartnagel S (1997) Statistik der biologischen Landwirtschaftsbetriebe der Schweiz. In: Forschungsinstitut für biologischen Landbau (ed), Frick, Switzerland

Jordan C, McGuckin SO & Smith RV (2000) Increased predicted losses of phosphorus to surface waters from soils with high Olsen-P concentrations. Soil Use Manage 16: 27–35

Kahnt G (1999) Betrachtung von grundsätzlichen Aspekten des ökologischen Landbaus – Vergleiche mit anderen Landbaumethoden: Pflanzenernährung. In: Keller ER, Hanus H & Heyland KU (eds) Grundlagen des landwirtschaftlichen Pflanzenbaus, pp 648–656. Ulmer, Stuttgart, Germany

KIP (1999) Richtlinien für den ökologischen Leistungsnachweis. In: Koordinationsgruppe Richtlinien Deutschschweiz (ed), Landwirtschaftliche Beratungszentrale, Lindau, Switzerland

Kuhlmann H and Baumgärtel G (1991) Potential importance of the subsoil for the P and Mg nutrition of wheat. Plant & Soil 137: 259–266

Letkeman LP, Tiessen H & Campbell CA (1996) Phosphorus transformations and redistributions during pedogenesis of western Canadian soil (1996) Geoderma 71: 201–218

Morel C, Plenchette C & Fardeau JC (1992) La fertilisation phosphatée raisonnée de la culture du blé. Agronomie 12: 565–579

Newman EI (1995) Phosphorus inputs to terrestrial ecosystems. J Ecology 83: 713–726

Oberson A, Besson JM, Maire N & Sticher H (1996) Microbiological processes in soil organic phosphorus transformations in conventional and biological farming systems. Biol Fert Soils 21: 138–148

Oberson A, Fardeau JC, Besson JM & Sticher H (1993) Soil phosphorus dynamics in cropping systems according to conventional and biological agricultural soils. Biol Fert Soils 16: 111–117

Oehl F, Oberson A, Frossard E, Fliessbach A & Probst M (1998) Phosphorus in soil microbial biomass – Influence of conventional and biological farming. 16th World Congress of Soil Science, Montpellier, Symp. 13B

Richards JE, Bates TE & Sheppard SC (1995) Changes in forms and distribution of soil phosphorus due to long-term corn production. Can J Soil Sci 75: 311–318

SAS Institute (1989) SAS/STAT user's guide. Version 6, 4th edn Cary, NC: SAS Inst

Saunders WMH & Williams EG (1955) Observations on the determination of total organic phosphorus in soils. J Soil Sci 6: 247–267

Scheiner JD & Lavado RS (1998) The role of fertilisation on phosphorus stratification in no-till soils. Comm. Soil Sci Plant Anal 29: 2705–2711

Sharpley AN, Chapra SC, Wedepohl R, Sims JT, Daniel TC & Reddy KR (1994) Managing agricultural phosphorus for protection of surface waters: Issues and Options. J Environ Qual 23: 437–451

Siegrist S, Schaub D, Pfiffner L & Mäder P (1998) Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. Agriculture Ecosyst Environ 69: 253–264

Spiess E & Besson JM (1995) Erträge, Ertragsbildung und Nährstoffbilanz. In: FAC-Oktobertagung 1995: Biologischer Landbau: Beitrag des DOK-Versuches, pp 27–35

Stumpe H, Garz J & Scharf H (1994) Effect of differential P fertiliser application over a period of 40 years in a long-term field experiment on a Phaeosem near Halle, Germany. Z Pflanzenernähr Bodenk 157: 105–110

Tiessen H & Moir JO (1993) Characterization of available P by sequential extraction.. In: Carter MR (ed) Soil sampling and methods of analysis, pp 75–86. Boca Raton: Can Soc Soil Sci: Lewis Publishers

Ulen B (1999) Leaching and balances of phosphorus and other nutrients in lysimeters after application of organic manures or fertilizers. Soil Use Manage 15: 56–61

Walkley A & Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic and titration method. Soil Sci 37: 29–38

Walther U, Menzi H, Ryser JP, Flisch R, Jeangros B, Kessler W, Maillard A, Siegenthaler A & Vuilloud P (1994) Grundlagen für die Düngung im Acker- und Futterbau. Agrarforschung 1: 3–40

Wechsung G and Pagel H (1993) Accumulation and mobilisation of phosphate in Haplic Chernosem of the static long-term experiment at Lauchstädt – consideration of the P balance after 84 years. Z Pflanzenernähr Bodenk 156: 301–306