Phosphorus status of diverse soils in Finland as influenced by long-term P fertilisation
2. Changes of soil test values in relation to P balance with references to incorporation depth of residual and freshly applied P

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Fertilising with phosphorus (P) ensures continuous supply of an essential growth factor as necessary for productive and sustainable agriculture. The amounts of P required to attain and maintain an adequate P status in the soil were investigated in field experiments at 22 sites in Finland on soils containing large amounts of residual fertiliser P. The effects of five rates (0, 15, 30, 45 and 60 kg ha^{-1}) of annual P application were measured in the soil by chemical methods after 9 to 15 experimental years, and the changes in soil test P values (STP) were compared with P balances. Stratification of P in ley soil by broadcast application of fertilisers was assessed at four sites. The mean changes of STP in the whole topsoil caused by P fertilisation expressed as per cent of the balance difference were 3.5% (0.0159 mg dm^{-3})/(kg ha^{-1}) in the acid ammonium acetate test (P_{Ac}), 4.7% (0.0214 mg dm^{-3})/(kg ha^{-1}) in water extraction (P_w) and 9.7% (0.058 mg kg^{-1})/(kg ha^{-1}) in sodium bicarbonate extraction (modified Olsen P). Initially high P_{Ac} values tended to slowly decrease at zero P balance, while low values

did not change without some particular reason, such as soil acidification or mixing of the topsoil with some of the less fertile subsurface soil. A thin layer of the uppermost soil was quickly enriched by broadcast application of P fertiliser.

Key words: Acetate extractable P, Olsen P, sampling depth, total P, water extractable P

Introduction

The amounts and chemical fractions of phosphorus (P) in Finnish soils were discussed in a recent review (Saarela 2002) and reported for 24 experimental sites (Saarela et al. 2003). Native P reserves are fairly abundant in Finnish soils but occur mostly in stable inorganic and organic compounds which are poorly available to plants. The long-term balance surplus which markedly improved the P status in a major part of the cultivated soils in Finland has primarily increased the secondary inorganic fractions assumed to be bound to Al and Fe (Al,Fe-P). In some virgin mineral soils the mean size of this P pool was about 250 kg ha^{-1}, in cultivated minerals soils studied in the early 1960s it was 550 kg ha^{-1} and in the 18 mineral soils of this study sampled in 1977–1981 it was approximately 850 kg ha^{-1}. The relative changes in the inorganic P fractions have been still larger in organic soils than in mineral soils. Repeated broadcast applications of fertilisers on untilled soil according to the common practice in ley enrich the surface efficiently with extractable and potentially transportable P (Saarela 1992a), while mixing the rich topsoil with the poorer subsurface soil by deep tillage decreases the STP values (Saarela et al. 2000, Peltovuori 2002).

The STP values determined by the acid ammonium acetate method (P_{Ac}), which is used in agricultural practice and mainly indicate the intensity factor of soil P status, have increased relatively about as sharply as the less soluble P reserves. The high rates of P fertilisation generally applied since the late 1940s have more than doubled the P_{Ac} values in Finnish soils. The average application of fertiliser P to field crops was about 30 kg ha^{-1} in the 1970s and 1980s, but it

dropped to 12 kg ha^{-1} during the 1990s. During the last decades the input in manure has been almost 10 kg ha^{-1} and the offtake in crops somewhat larger. The balance surplus is small but probably positive though all outputs including the reforestation of fertilised fields are taken into account (Saarela 2002). In spite of the improved supply of P from the soil, significant yield responses to P fertilisation were common in almost all field crops (Saarela et al. 1995). Nowadays almost 50% of the arable land of Finland is cropped with cereals, about 30% with intensive grass ley and 1.4 to 3% with rapeseed, sugar beet and potato.

For optimising long-term P fertilisation of crops grown on soils containing large amounts of accumulated P, field experiments were established at 24 sites on diverse soils in Finland. A more detailed introduction to the research project together with physical and chemical characteristics and the initial P status of the experimental soils were presented earlier (Saarela et al. 2003). According to the P_{Ac} values, the average initial P status of these soils was slightly better than that obtained in routine soil testing for the whole country at the same time. The mean initial P_{Ac} value for the 24 soils was 13.1 mg dm^{-3}, which is exactly the same as that obtained for 705 Finnish soils in a recent monitoring study (Mäkelä-Kurtto and Sippola 2002). The amounts of P extracted with water (P_w, v/v 1/60, mean 11.5 mg dm^{-3}) were usually similar to P_{Ac}, but in some acid sandy soils where the bioavailability of P was exceptionally poor (Saarela et al. 1995, Saarela 1998), P_w was lower than P_{Ac}. A modified Olsen procedure, which is a more quantitative P test in acid soils, produced about fourfold the other STP values (mean P_{Olm} 61 mg kg^{-3}).

The changes in soil P status caused by different rates of P fertilisation during the 9 to 15

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Table 1. Topsoil characteristics of soil groups (Saarela et al. 2003).

Soil group	Sites number	Organic C, %	Clay, % (< 2 µm)	Bulk density, kg dm^{-3}	pH$_w$
Clay and loam soils with lower STP, CLP1	1, 3, 4	3.6	53	0.92	6.0
Clay and loam soils with higher STP, CLP2	5, 6, 8	4.0	31	1.00	6.0
Silt and sand soils with lower STP, SSP1	9–11, 14	3.4	12	1.02	5.6
Silt and sand soils with higher STP, SSP2	15–18	2.5	19	1.00	6.3
Organic soils, low to medium STP, OSPM	19–22, 24	22.3	n.d.	0.53	4.8
All soils		8.3[2]	27[1]	0.87[2]	5.7[2]

n.d. = not determined
STP = soil test P value
[1] mineral soils (n = 14)
[2] all soils (n = 19)

year's experimental period at 22 of the 24 sites are reported in this paper. Several chemical soil testing methods were used in the 19 soils briefly characterised in Table 1 and the acetate test was employed in other three soils. Two experiments were excluded because of short experimental period (23) or incomplete plant P data (13). Stratification of surface-applied P was assessed with additional ley plots at four of the sites.

Material and methods

Treatments and cropping

Single and triple (1988–) superphosphate (8.7 or 20% P) were used as P fertilisers, and one of them was applied each year (except at site 18, Saarela et al. 2003) at rates 0, 15, 30, 45 and 60 kg P ha^{-1}. Most experiments were cropped with spring cereals in every year or in an irregular rotation with a few rapeseeds and winter cereals. Grass ley was the main crop at one site (21) and included in the rotation at five sites (4, 8, 14, 16 and 18). Potato was grown at one site (18). To cereals, rapeseeds and potato the P fertiliser was drilled before sowing to a depth of 8 cm with the row distances of 12.5 or 15 cm, and to ley the P source was broadcast at the beginning of

the growing season. From the thirteenth experimental year onward (Exp. 8 from the tenth, not in Exp. 4) the P rates 30 and 60 kg ha^{-1} were withdrawn in order to investigate the residual effects of previously applied P. At site 18, 5/3-fold P rates (0–100 kg ha^{-1}) were applied 8 times to potato during the 12 year's period resulting in 10/9-fold mean annual rates. The tillage effect of fertiliser drilling was usually equalised by treating the P0 controls with the drill without any fertiliser distribution.

At two sites (8 and 22, Saarela et al. 2003) each P rate was studied without and with liming, which doubled the treatments to ten. All treatments were established with four replicates using a randomised block layout, modified to avoid extreme adjacent P rates. Thus, each simple P fertilisation experiment comprised 20 plots and the experiments with liming 40 plots. The differences of the treatments (probability of F and Tukeys' honestly significant differences, HSD) were tested by the analysis of variance using individual experiments as replications. In the regression calculus including all sites the limed parts were treated as separate experiments (n = 24). Three acid soils (4, 11, 24) were limed over the whole studied area in the early or middle years of the experimental period. These treatments were consider as common soil fertility control operations and were not separated in calculating the results.

Sufficient rates of nitrogen (N) and potassium (K) fertilisers were applied (Saarela et al. 1995). A Finnish ammonium nitrate fertiliser formulated with a mixture of ground dolomite, "Oulunsalpietari", was used as the N source. This compound was physiologically less acid than the common NPK fertilisers, which contain more NH_4-N and no lime. The chemical form of nitrogen was a major reason for the maintenance of pH at the initial level in most of the soils (Saarela et al. 1995). The size of the plots differed slightly depending on the field machinery used. Total plot width was 4 to 5 m and length was 12 to 24 m. A 1.5–2.5 m wide and 10–16 m long area in the centre of each plot was harvested and sampled for plant and soil analyses. Plant residues were chopped and ploughed under.

Vertical movement of surface-applied P in ley was studied with additional short-term experiments at four sites (1, 11, 21 and 22, Saarela et al. 2003) by determining the P_{Ac} values separately for several thin layers. Of the six treatments made in four replications (Saarela 1992a) two were used in this study: control and 50 kg P in superphosphate broadcast annually at the beginning of the growing season for four years. The two annual harvests caused a total balance deficit of 49–77 kg ha^{-1} in the control and a balance surplus of 98–131 kg ha^{-1} in the fertilised treatment.

Soil and plant analyses

Soil samples were obtained from two layers of each plot before the first fertiliser application in the spring of the establishing year and subsequently the autumn of the experimental years 3, 6, 9, 12, 15 and 18, of which the year 9, 12 or 15 was used as the final year. The two sampled layers represented the ploughed topsoil to a depth of 20 or 25 cm and the subsurface soil within the next 20 cm. Each sample comprised about 0.5 l soil, which was a composite of five or more subsamples obtained with an auger. The initial samples and final (or the next before them) samples of the P rates 0, 15 and 45 kg kg ha^{-1} were prepared and analysed for total P, P_{Ac}, P_w and P_{Olm} employing the methods described earlier (Saarela et al. 2003).

Most of the longest-run experiments (1, 4, 5, 8, 9, 10, 15, 18 and 22, Saarela et al. 2003) were also sampled to 40 or 60 cm in 3 or 4 layers and analysed by the acetate method (Saarela et al. 1995). The effects of P fertilisation on the P status of the subsoil are not presented in details but discussed shortly with some other long-term experiments conducted in Histosols in Finland and published in Finnish. For illustrating the importance of soil types and intitial P status, the experiments were divided into five soil groups formed according to: organic carbon percentage, texture/region and initial STP value; clay and loam soils with lower and higher STP (CLP1 and CLP2, CLPM when combined), silt and sand soils similarly as SSP1, SSP2 and SSPM, and all organic soils, OSPM (Saarela et al. 2003). The STP values of the five groups (and of a sandy peat deviating from the other four Histosols) are presented in Table 2.

According to recalculation of the data published by Vuorinen and Mäkitie (1955), the P_{Ac} values of mineral soils are closely correlated with the P values determined by the better-known Morgan's sodium acetate method from which the Finnish method was modified (Saarela 2002), ($P_{Morgan} = 0.694 * P_{Ac} - 0.27$, n = 40, w = 1.5 – 12, R^2 = 0.89). A very simple correction factor (0.7) can be used in comparing these methods in mineral soils. Bulk density of soil was obtained with ground dry soil samples and the true BD values in the field were approximated according to Erviö (1970). Final P values of the three treatments were adequate because the relationship of STP and P balance was practically linear in each individual experiment. The modification of the Olsen method (by Sillanpää 1982, accidentally in this study) means a prolonged sodium bicarbonate extraction, 60 min vs. the normal 30 min, which was found to increase the P_{Ol} values by about 20%. P_{Ac} values were determined in every soil sample and their changes were examined by regression equations.

Harvested crops were analysed for P and macrocations by dry combustion and colorime-

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Table 2. Differences in P balance of soil groups between the P fertilisation rates 0 and 45 kg ha^{-1} and corresponding differences in soil test P values (STP), in absolute differences (mean) and in per cent of the differences in P balance ($\bar{x}$ = mean, s = standard deviation).

Soil group	Number of soils	$\Delta P_{balance}$ kg ha^{-1}	ΔP_{total} kg ha^{-1}	% $\bar{x}$	% s	ΔP_{Olm} mg kg^{-1}	% $\bar{x}$	% s	ΔP_{Ac} mg dm^{-3}	% $\bar{x}$	% s	ΔP_{w} mg dm^{-3}	% $\bar{x}$	% s
CLP1	3	609	207	34	12	27	4.3	2.8	4.1	0.65	0.38	3.9	0.62	0.24
CLP2	3	560	240	43	31	28	4.9	0.4	14.6	2.64	2.44	12.5	2.21	1.49
SSP1	4	529	315	62	27	18	3.3	1.0	3.6	0.66	0.18	3.3	0.60	0.50
SSP2	4	570	248	43	15	26	4.6	1.1	14.9	2.59	0.59	17.2	2.99	0.65
OSPM	4	552	273	50	29	39	6.8	3.0	7.0	1.23	0.39	12.1	2.11	1.09
Soil 21	1	333	120	36		77	23.1		8.3	2.49		30.3	9.10	
All soils	19	550	253	47	23	30	5.8	4.7	8.8	1.59	1.26	11.1	2.12	2.08

CLP1 = Clay and loam soils with lower STP, CLP2 = Clay and loam soils with higher STP, SSP1 = Silt and sand soils with lower STP, SSP2 = Silt and sand soils with higher STP, OSPM = Organic soils, low to medium STP

try or AAS (Kähäri and Nissinen 1978) or by wet combustion and ICP-AES, and for N by Kjeldahl digestion or NIR. The P balance of each treatment was calculated as the difference of the amounts of P applied in fertilisers and removed in harvested crops and compared with the corresponding changes in soil test values during the experimental period. The relationships between the changes in P_{Ac} and the P balances were studied by model calculations.

Results and discussion

The mean length of the 19 experiments presented in Figs 1–4 was 12.7 seasons and fairly similar for each soil group (Tables 2 and 3). The corresponding balance difference between 0 and 45 kg P ha^{-1} was 550 kg P ha^{-1}. The balances based on tens of plant analyses for each treatment and site can be considered highly accurate. The amounts of total P and the STP values summed in Table 2 and presented in Figs 1–4 which were obtained from smaller numbers of samples are less reliable. However, the trends for each soil group can be considered meaningful

and the means for all soils fairly accurate. Because all samples were analysed at the same time, significant analytical errors between the different sampling times were practically impossible, at least in total P which is certainly stable in stored dry soil samples.

Changes in total P with applied P

Although significant analytical errors were improbable, the observed concentration of total P in the final mineral soil samples (Fig. 1) was substantially lower than was estimated on the basis of the initial values and the balances. A probable explanation for the apparent error is the unplanned mixing of the less rich subsoil with the topsoil by ploughing, as seen in one rich soil (8) and what possibly occurred to a significant extent at most of the sites. The apparent increase in the concentration of total P in organic soils (OSPM in Fig. 1) may be explained by a gradual decomposition of organic matter and the consequent reduction in soil mass. The strong demand for P by plants growing on the less fertile control plots has increased the amounts of P removed from the deeper soil layers. The deep exploitation of P and a corresponding decrease in the

uptake from the topsoil was presumably largest in organic soils, in which the soil test values varied little with depth (Saarela at al. 2003). The final STP values of the subsoil differed with the rate of P application much more in Histosols than in mineral soils (Saarela et al. 1995).

The boundaries of the plots of long-term experiments are diffusible even in the horisontal direction because of solute and soil movements. The exchange of topsoil between adjacent plots caused by annual tillage could have affected the spatial distribution of P in the soil markedly during the last experimental years (Jaakkola et al. 1997, Sibbesen et al. 2000). Recent soil tests for a clay soil in Mietoinen suggest that soil mixing may occur more rapidly than estimated previously. Theoretically, this error would be largest with the lowest and highest fertiliser rates, 0 and 60 kg P ha^{-1}, because the intermediate treatments were balanced with the negative and positive errors at opposite edges of the plots.

Transfer of fertilised soil from adjacent plots to the controls obviously decreased the measured differences of the total P values between the control treatment and the smallest rate of fertiliser application, which were smaller than estimated in all but one soil group (Fig. 1). The total pool of soil P was also influenced by leaching and erosion. Its transfer outside the plots, up to two kg ha^{-1} y^{-1} (Turtola 1999), was too small to be detected in total P determinations, but larger amounts of soluble and solid P removed from the topsoil were perhaps retained by the subsoil. Because of the disappearance of the smallest rate of applied P, the observed mean difference in the amount of total topsoil P between the rates 0 and 45 kg ha^{-1} was as low as 47% (Table 2). The analytical recovery of applied P was higher between the medium rates of P, 15 and 45 kg ha^{-1}, on average 65%. This is comparable to other studies (Yli-Halla 1989, Jaakkola et al. 1997) and can be considered as a reasonably high recovery
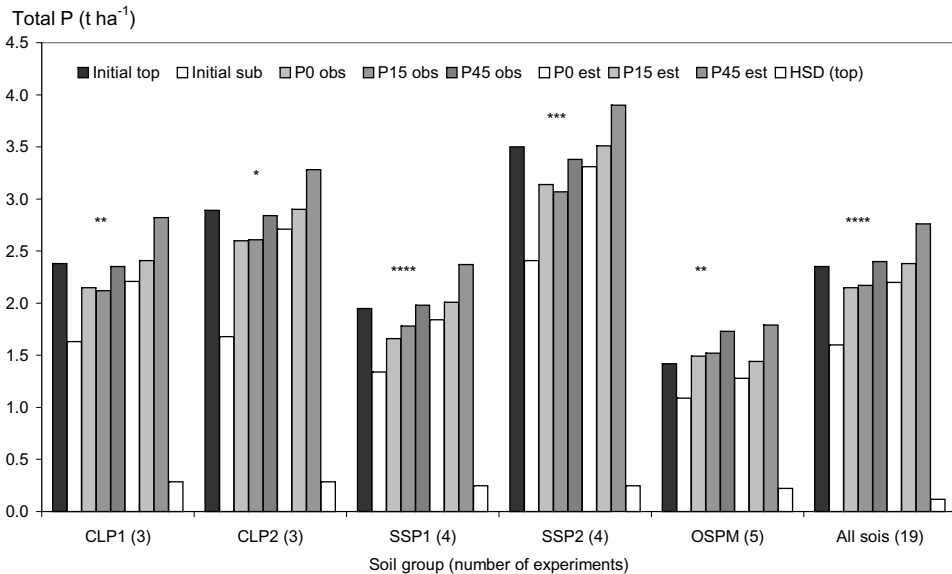

Fig. 1. Total amount of P in the experimental soils by two layers at establishment (left) with observed (middle) and estimated (right) final values in the topsoil for three rates of annual P fertilisation. HSD = honestly significant difference for the four observed topsoil values at P 0.05 (based on the total error, df = 54). Asterisks indicate significant differences between the four observed topsoil values tested separately for each soil group at P 0.05 (*), 0.01 (**), 0.001 (***) and 0.0001 (****). Letters CL, SS, and OS by the soil groups denotes clay/loam soils, silty/sandy soils and organic soils, respectively.

under field conditions. The higher percentages of applied P previously recovered by Barkoff (1959) in the chemical fractionation of soil P may be explained at least in part by the infrequent tillage operations, as typical for the old ley-dominated crop rotation. The large pools of total P were clearly insensitive to moderate differences in P fertilisation.

Changes in STP values with P application

The relative differences in the final STP values determined by the modified Olsen method (P_{Olm}) presented in Table 2 and illustrated in Fig. 2 were much larger than those found in total P. Even the smallest application rate was distinguished from the control. The mean difference in P_{Olm} between the rates 0 and 45 kg P ha^{-1} (47 and 77) was 30 mg kg^{-1}, which according to the mean bulk density of 0.87 kg dm^{-3} (Table 1) and the

soil depth of 22 cm (1.91 Mg soil ha^{-1}) corresponds to 57.3 kg P ha^{-1}. However, separate calculation of each soil gives of mean pool of 53.4 kg ha^{-1}, which is 9.7% of the corresponding difference in P balance, 550 kg ha^{-1} (Table 2). Dividing the mean increase in P_{Olm} by the corresponding difference in P balance (30/550) gives 0.054 (mg kg^{-1})/(kg ha^{-1}), but the mean of the ratios calculated separately for each soil (Table 2) is 0.058 (mg kg^{-1})/(kg ha^{-1}). The differences of the Olsen P values between the treatments (Fig. 2) were almost equal in all soil groups and varied little even within the groups, except for the weakly buffered sandy peat soil (21), which was included in the Histosol group in the Figs (1–4) but presented alone in the Tables (1–2).

The changes in P_{Olm} are in agreement which previous results obtained for a fine-textured acid soil with short-term biological desorption studies by Yli-Halla et al. (2002). The final P_{Olm} values at 45 kg P ha^{-1} (Fig. 2) were relatively high
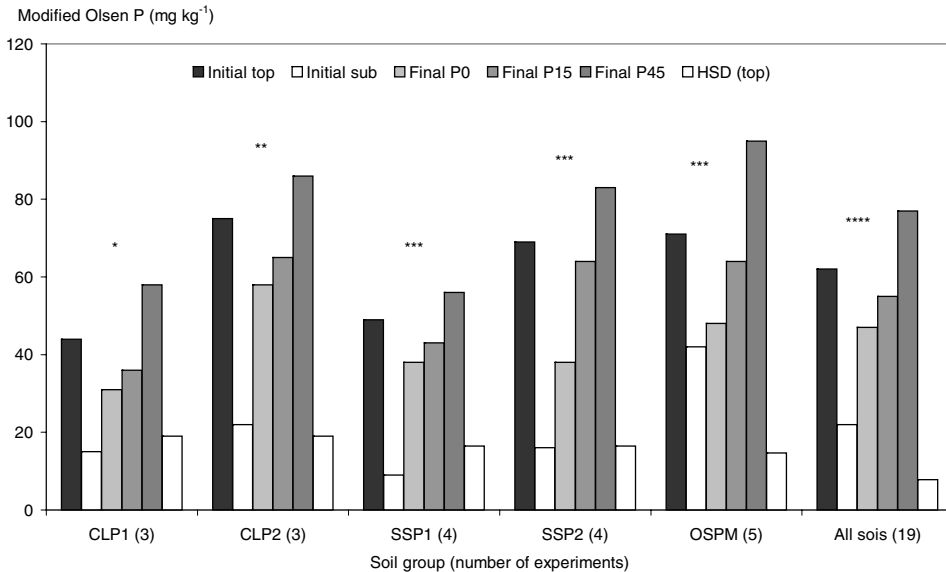

Fig. 2. Extractable P in the experimental soils as determined by the modified Olsen method for two layers at establishment and for three rates of annual P fertilisation after 9–15 experimental years in the topsoil. HSD = honestly significant difference for the four topsoil values at P 0.05 (based on the total error, df = 54). Asterisks indicate significant differences between the four topsoil values tested separately for each soil group at P 0.05 (*), 0.01 (**), 0.001 (***) and 0.0001 (****). Letters CL, SS, and OS in the soil groups denotes clay/loam soils, silty/sandy soils and organic soils, respectively.

in all soil groups when compared with a global assessment (Sillanpää 1982). However, the bio-availability of P in Finnish soils is poorer (Sippola and Saarela 1986) and the leaching of soluble P to runoff water obviously slower (Turtola and Yli-Halla 1999) than this method indicates.

With the acetate and water extraction methods the recoveries of applied P were 3.5% for P_{Ac} (or 0.0159 mg dm^{-3})/(kg ha^{-1} in P balance) and 4.7% for P_w (0.0214 mg dm^{-3})/(kg ha^{-1}) in all soils, and with both methods, 3.6% (0.0163 mg dm^{-3})/(kg ha^{-1}) in mineral soils (Table 2, recovery = 2.2 * Δ STP). In the weakly buffered peat soil (21) the relative extraction efficiency

was much higher in water extraction. P surpluses up to 500 kg ha^{-1} during the experimental period (Table 3) were insufficient to raise the intensity factor of soil P status to a high level in the poorest soils, which efficiently fixed applied phosphate. For optimum yields, such problem soils require more applied P than is removed in the harvested crops (Saarela et al. 1995, Saarela 1998).

The critical STP value determined by the Morgan method in the soils of Vermont and New York of the United States, 4 mg kg^{-1}, range 3–7 mg kg^{-1} (Jokela et al. 1998) corresponds to 5.7 mg dm^{-3} (range 4.3–10 mg dm^{-3}) P_{Ac}, and were

Table 3. Initial and final sampling years, P balance and soil P_{Ac} without P fertilisation and the effect of annual application of 45 kg P ha^{-1} (difference between fertilised and control) with the ratio of the change in P_{Ac} and P the balance. Letter L on experiment number means liming with 10 t ha^{-1} of ground limestone in 1980. Soil characteristics presented earlier (Saarela et al. 2003).

Experiment number	Sampling year Initial/final	P balance, kg ha^{-1} Without P	45 kg P ha^{-1}	Soil P_{Ac}, mg dm^{-3} Without P	45 kg P ha^{-1}	ΔP_{Ac}, % of Δ balance
1	77/91	−160	+651	2.4	+ 4.4	0.68
2	78/89	−132	+528	2.4	+6.7	1.27
3	77/88	−121	+532	6.1	+1.4	0.26
4	77/91	−234	+645	3.9	+6.6	1.92
5	77/91	−179	+659	6.8	+12.3	1.87
6	78/89	−122	+498	7.1	+3.4	0.68
7	77/88	−114	+529	9.9	+3.8	0.72
8	80/91	−217	+524	31.5	+28.2	5.38
8L	80/91	−216	+518	46.0	+18.9	3.65
9	79/93	−97	+611	2.3	+5.4	0.88
10	77/88	−119	+511	3.3	+2.7	0.53
11	77/91	−83	+625	5.0	+4.6	0.74
12	77/88	−78	+512	7.8	+2.6	0.51
14	78/86	−124	+368	7.4	+1.8	0.49
15	77/91	−172	+644	9.1	+17.0	2.64
16	78/89	−214	+506	5.7	+8.8	1.74
17	77/88	−111	+533	18.5	+15.8	2.96
18	81/92	−202	+596	32.6	+17.9	3.00
19	77/88	−106	+515	3.5	+5.0	0.97
20	78/89	−95	+520	4.2	+5.6	1.08
21	78/87	−164	+333	2.7	+8.3	2.49
22	80/91	−153	+526	4.5	+5.5	1.05
22L	80/91	−159	+526	4.2	+6.1	1.16
24	77/91	−168	+647	11.3	+11.7	1.81
Mean		−148	+544	9.9	+8.5	1.57

A G R I C U L T U R A L   A N D   F O O D   S C I E N C E

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reached at all sites with the highest P fertilisation rates. In Finland the American guidelines may be sufficient in the best clay and clay loam soils (Salonen and Tainio 1957, Jaakkola et al. 1977, Yli-Halla 1989, Saarela et al. 2000), but not in the biologically less fertile loam, silt loam and sandy soils (Sippola and Saarela 1986, Jaakkola et al. 1997).

The greater sensitivity of the water extraction and acetate tests than the modified Olsen method for the intensity factor of soil P status was apparent in the recovery of applied P in the mineral soils grouped by P_{Ac} (Table 2, Figs. 3 and 4). The relative differences in the P_{Ac} and P_w values between the P fertilisation rates were similar in both poor and rich soils, but the absolute differences increased with the concentration of extractable P. These tests recovered only 1.3–1.5% $(0.0060–0.0066$ mg dm$^{-3})$/(kg ha^{-1}) of the calculated balance differences of P in poor mineral soils (5 mg dm^{-3}), but much more in rich soils. The relationships of the P_{Ac} values and the balance of soil P were quantified by a regression equation based on 23 soils (Table 3, soil 21 excluded) and some values of the model are presented in Table 4. Although the correlation between the initial values and the changes was not particularly close ($R^2 = 0.63$), the small effects of application and removal of P on low P_{Ac} values were demonstrated fairly convincingly.

The small changes in the concentration of extractable P in relation to the amount of applied P have been obtained earlier for several Finnish soils. In the long-term fertilisation experiments conducted by Salonen and Tainio (1957), applied P changed the typically low P_{Ac} values of mineral soils by about $(0.01$ mg dm$^{-3})$/(kg ha^{-1}), and caused larger differences with originally higher values as well as in organic soils. In the sandy soil at site 10 of this study assessed by Luos-
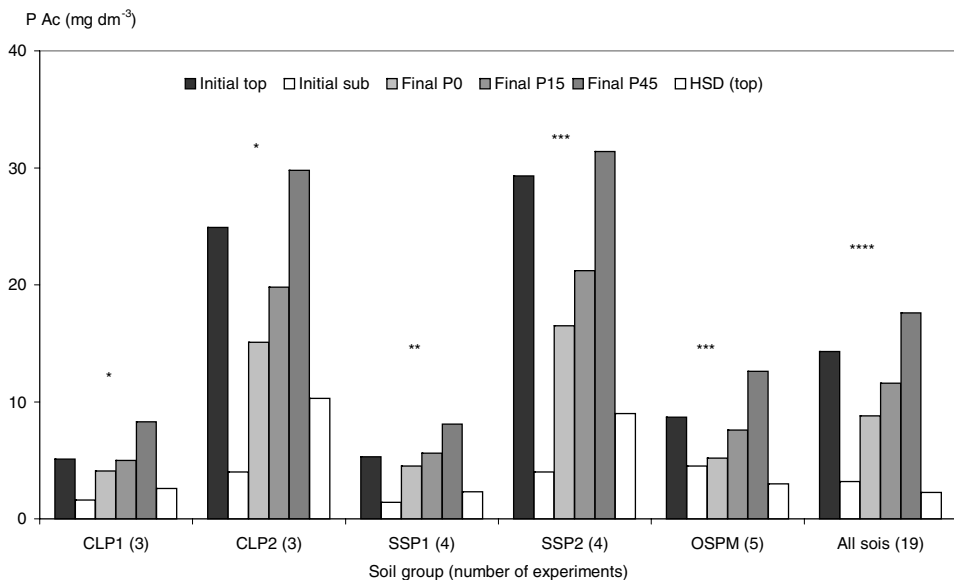

Fig. 3. Extractable P in the experimental soils as determined by the acid ammonium acetate (P_{Ac}) method for two layers at establishment with three rates of annual P fertilisation after 9–15 experimental years in the topsoil. HSD = honestly significant difference for the four topsoil values at P 0.05 (based on the total error, df = 54). Asterisks indicate significant differences between the logarithms of the four topsoil values tested separately for each soil group at P 0.05 (*), 0.01 (**), 0.001 (***) and 0.0001 (****). Letters CL, SS, and OS in the soil groups denotes clay/loam soils, silty/sandy soils and organic soils, respectively.
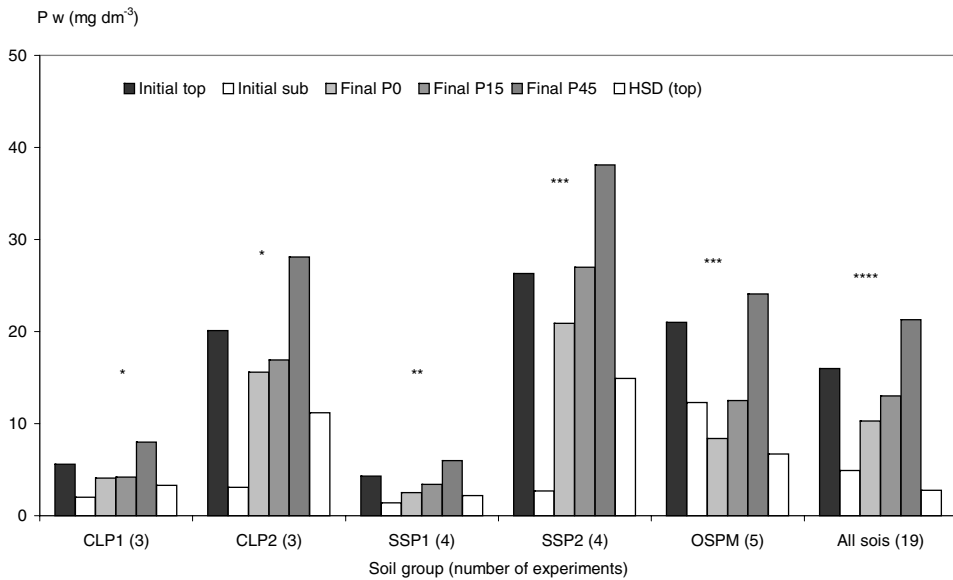
Fig. 4. Extractable P in the experimental soils as determined by the water (P_w) extraction method for two layers at establishment and for three rates of annual P fertilisation after 9–15 experimental years in the topsoil. HSD = honestly significant difference for the four topsoil values at P 0.05 (based on the total error, df = 54). Asterisks indicate significant differences between the logarithms of the four topsoil values tested separately for each soil group at P 0.05 (*), 0.01 (**), 0.001 (***) and 0.0001 (****). Letters CL, SS, and OS in the soil groups denotes clay/loam soils, silty/sandy soils and organic soils, respectively.

tarinen (1967), P_{Ac} values increased from 3.8 to 5.8 mg dm^{-3} with 440 kg P ha^{-1} applied in 20 years (0.0045 mg dm^{-3})/(kg ha^{-1}). Jaakkola et al. (1977 and unpublished data) measured P_{Ac} values by which this ratio was about 0.0075 for 3 mineral soils and 0.015 for a peat soil. The changes in P_{Ac} appear to have been slightly larger in the oldest experiments, in which the incorporation depth of applied P was smaller than in later field studies.

The chemically dissimilar tests, P_{Ac} and P_w, produced similar recovery percentages even for

Table 4. Final P_{Ac} values at zero balance as function of the initial values and the P balance surplus required to maintain initial P_{Ac} unchanged.

Initial P_{Ac} mg dm^{-3}	Final P_{Ac} mg dm^{-3}	Decrease mg dm^{-3}	(ΔP_{Ac} mg dm^{-3}) per (Δ balance kg ha^{-1})[1]	Surplus for maintaining initial P_{Ac} kg ha^{-1} (12.5 y)$^{-1}$	kg ha^{-1} y^{-1}
2	1.88	0.12	0.0039	30	2
5	4.48	0.52	0.0075	70	6
12	10.32	1.68	0.0149	110	9
25	20.36	4.64	0.0243	190	15

[1] $(\Delta P_{Ac})/(\Delta$ balance$) = 0.0013 + 0.001325 *$ initial $P_{Ac} - 0.0000161*$ (initial $P_{Ac})^2$. This empirical equation was calculated using the data presented in Table 3. The weakly buffered sandy peat of Experiment 21 was excluded (n = 23, R^2 = 0.63).

most of the individual mineral soils. Similar results were previously reported by Yli-Halla (1989) for two clay loam soils in Southern Finland, except for that the ratio P_w/P_{Ac} was markedly higher in the less acid of the two soils (pH_w 6.0 vs. 5.4). In the short-term biological desorption study with rye grass performed with one of these soils (Yli-Halla et al. 2002) the changes in P_w relative to the changes in inorganic P were much larger than in the long-term experiments (1/response index = 3.8–10%), but the decrease of the buffer power with increasing concentration of extractable P in the soil (P_w 4.0–15.2 mg dm^{-3}) was in agreement with the result of the present study.

Very close correlation between P_w and diffusible P (Saarela 1992b) and other biological and chemical studies suggest that the water extraction method is an accurate indicator of the intensity factor of the P status of Finnish mineral soils. The low final P_w values in spite of the large amounts of residual P in the soil (Fig. 4) are reliable indicators of a poor supply of P to plants as well as to the run-off water (Turtola 1999, Hooda et al. 2000). It means that P remains a growth limiting factor not only in agricultural soils but also in watercourses.

The five rates of P application were distinguishable as separate lines for P_{Ac} at all sites (Saarela et al. 1995). Two examples are presented in Fig. 5. Freshly applied P was more efficient in raising the STP values than were older P residues, particularly in the heavy clay soil. The regular lines for P_{Ac} suggest that this soil test is an accurate indicator of the changes in the concentration of readily soluble P in soils, at least when the sampling and laboratory work is done as carefully as in research projects. The slow changes of the low and intermediate STP values at zero balance showed that soil P status is very stable if it is not influenced by some particular factor. On the other hand, changing the factors that control the balances between the different forms of soil P can affect the content of extractable P even without any net change in the total pool. Significant increases in STP can be expected after heavy liming (Lakanen and Vuo-

rinen 1963, Jaakkola et al. 1977, Saarela and Sippola 1990, Saarela et al. 2000), and substantial decreases are probable after deep ploughing (Saarela et al. 2000, Peltovuori 2002).

Acid soils rich in active Al and Fe compounds resist effectively any changes of the concentration of P in soil solution and also the size of the most labile fractions measured by mild soil tests (Maguire et al. 2001), so these soils are strongly buffered for easily soluble phosphate. However, the efficient capacity to sorb applied P do not seem to affect the P status of soils improved with long-term application of P in amounts exceeding the offtake. Large amounts of recently applied P being not equilibrated as completely as older additions are slowly converted into less labile forms, as happened in the heavy clay with the discontinued P applications (Fig. 5).

Effect of long-term P fertilisation on Histosol profiles

One of the six Histosols, a sandy Carex peat (21), exerted a weak capacity to sorb P, and the differences in P_{Ac} between the treatments increased rather sharply even in the subsurface soil, ranging from 1.6 to 4.7 mg dm^{-3} in the final samples (Saarela et al. 1995). This is a strong effect in relation to the 10 year's duration of the experiment and to the corresponding values in the topsoil, initial 8.0 mg dm^{-3} and final from 2.6 to 14.4 mg dm^{-3} with 0 and 60 kg P ha^{-1}. Even more rapid effects of P fertilisation on the concentration of extractable P in the subsurface layer were measured in a cut-away peatland at Valkeasuo, Tohmajärvi (Virkajärvi and Huhta 1993), where P_{Ac} varied from 0.3 to 4.7 or 9.5 mg dm^{-3}, depending on fertilisation, in the sandy subsurface soil, and from 0.7 to 19.4 or 27.6 mg dm^{-3} in the topsoil.

The plough layer of the other five Histosols of this study exerted a moderate or fairly strong (22) capacity to retain P, but especially in the soil 22 amended with heavy clay, the mobility of P was much greater in the subsoil, and a significant effect of P fertilisation was measured

Soil test P (P_{Ac}, mg dm^{-3})
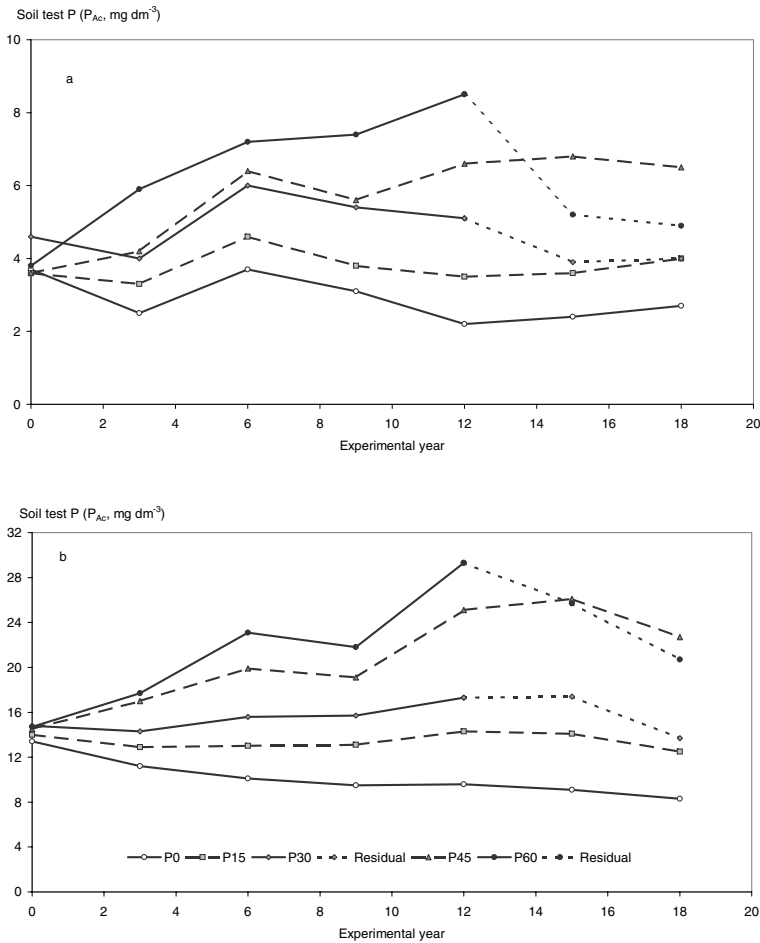

Soil test P (P_{Ac}, mg dm^{-3})

Fig. 5. Soil test P values determined by the acid ammonium acetate method with five rates of annual P fertilisation in clay soil at Mietoinen (Exp. 1, a) and in sandy loam soil at Maaninka (Exp. 15, b).

down to the depth of 40–60 cm, where P_{Ac} values were 2.0 and 3.4 mg dm^{-3} for the P fertilisation rates 0 and 45 kg ha^{-1} (Saarela et al. 1995). The sharp increase in STP as response to P application has been found in several Histosols in Finland (Salonen and Tainio 1957, Saarela and Sippola 1990, Puustinen et al. 1994).

Even if the subsoil studies may have been affected by mixing of the subsoil samples with some of the topsoil, the differences between deep peat soils and mineral soils were large and reliably established. The rapid and deep effect of P fertilisation in peat soils agreed with the generally poor availability of P in newly cleared peat

soil (Salonen and Tainio 1957), which means that a major part of the soluble P in the subsoil must originate from applied fertilisers.

Leaching studies were performed on Carex peat soil at the same site as the experiment 19 of this study (Huhta and Jaakkola 1993). Although the P_{Ac} values at the depth of 0.2–0.7 m were as low as 2–3 mg dm^{-3}, the leaching of soluble P in the drainage water was considerable, almost one kg ha^{-1} y^{-1}. The risk of leaching of P through the soil to the drainage pipes because of a high degree of P saturation in the bulk soil is greatest in the weakly humified Histosols which contain little inorganic compounds capable to sorb P (Kai-

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la 1959). In raised bogs the amounts of P leached may be even hundred times larger than in mineral soils, as stated by Finck (1992) and measured in drainage water by Kuntze and Scheffer (1979).

Final vs. initial P_{Ac} values at zero P balance

The P_{Ac} values for the zero balance, at which the applied P fertiliser exactly replaced the P offtake in harvested crops, were interpolated from the values of P_{Ac} measured from the final soil samples. These final P_{Ac} values at zero P balance were plotted with the initial values of the same test (Fig. 6). The amounts of P applied in seeds, up to one kg ha^{-1} y^{-1}, which were probably not much larger than the leaching and erosion losses, were not included in the balance calculations. The correlation between the final and initial values was equally good with the linear equation y = 0.694x + 1.4, R^2 = 0.963 as with the polynomial curve shown in the figure, but the polynomial curve is probably more accurate with very low STP values because of its smaller intercept.

The final value obtained from the polynomial function at the initial mean, 13.1 mg dm^{-3}, was 11.3 mg dm^{-3}, which represents a decrease of

14% in 12 years. The decrease was about 10% at the mean P_{Ac} of the poorer soil groups, 5 mg P dm^{-3}, and 19% at the mean of the richer soils, 25 mg P dm^{-3} (Table 4). Model calculations indicate that the balance surplus required to prevent the slow decline in P_{Ac} increases with the initial value. The amount of applied P required to change the P_{Ac} value by one unit decreased with P_{Ac}, but the relative change was larger in the decline of extractable P with time. The annual surplus in the P balance should have been 6 kg ha^{-1} in the poorer soil groups and 15 kg ha^{-1} in the richer groups, on average 10 kg ha^{-1}, to prevent the slow decreases of the concentration of soil P extracted with acid ammonium acetate (Table 4). In the twelve weakly acid to neutral Swedish soils investigated by Carlgren and Mattsson (2001) the requirement of surplus P for preventing any decrease in ammonium lactate extractable P (P_{Al}) was roughly similar than required in this study for maintaining P_{Ac}. However, the loss of P_{Al} appeared to have decreased with time and even ceased during the later part of the experimental period of almost 30 years.

Little change in P_{Ac} was recorded for 16 of the 24 soils if P offtake was compensated with fertiliser application (Fig. 6). Similar results were previously obtained by Jaakkola et al. (1977 and unbublished soil test data). Liming with 10
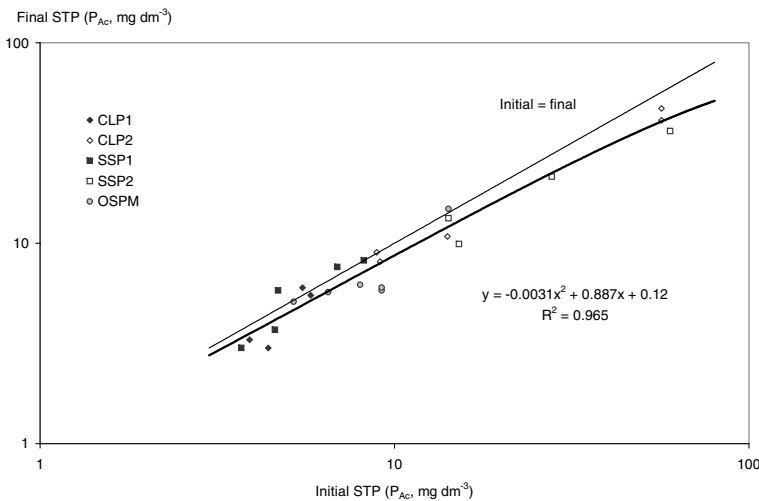

Fig. 6. Final and initial soil test P (STP) values for the experimental soils (22 sites, of which two with and without liming). The final values were determined after 9–15 experimental years and extrapolated for the P fertilisation rate of each soil at which the P balance is zero. Letters CL, SS, and OS in the soil groups denotes clay/loam soils, silty/sandy soils and organic soils, respectively.

t ha^{-1} of ground limestone from pH$_w$ 5.3 to 5.5 had little effect on the extractability of P in the clayey Carex peat at site 22. In the P-rich and almost neutral clay soil (8) heavy liming, from pH$_w$ 6.6 to 7.0, on the contrary, enhanced fairly efficiently the extraction of P by acid acetate, as usual in Finnish clay soils (Jaakkola et al. 1977, Saarela and Sippola 1990, Saarela et al. 2000). Weak or even negative effects of liming on the extractability of P are typical for Finnish organic soils, while particularly the P$_{Ac}$ values increase sharply in mineral soils when the pH$_w$ values raise over 6.5 (Lakanen and Vuorinen 1963, Jaakkola et al. 1977). The smaller changes in P$_w$ than in P$_{Ac}$ resulting from heavy liming (Saarela and Sippola 1990) show that the danger of P leaching is not increased with pH as sharply as the increase in the P$_{Ac}$ values suggest.

Fixation of extractable P in acidic and initially rich soils

At the lower medium level of extractable P, the largest reduction of extractable P was recorded for the clayey Carex peat at site 22, which was highly infertile in 1949 (Saarela et al. 2003). In addition to the better-known chemical fixation, the accumulation of organic P as a result of biological fixation of soluble phosphate occurring in certain organic soils (Kaila and Missilä 1956, Kaila 1961), is a further possible explanation for the loss of acetate extractable P in this particular field. The large amounts of Fe and Al in the heavy clay (350 g clay dm^{-3} soil) previously applied to this soil (Saarela et al. 2003) perhaps weathered quickly in the new acidic and humic medium and phosphate was fixed unusually efficiently even chemically.

The decrease of P$_{Ac}$ was substantial in an acid clay loam (7) and a silty clay loam (16), which had a somewhat better than average initial P status. In addition to replacement of the offtake of 18.8 kg P ha^{-1}, an annual balance surplus as high as 30 kg P ha^{-1} was required in soil 16 to maintain its initial STP value unchanged. This field

was cropped for seven years with ley grasses using heavy nitrogen dressings (Saarela et al. 1995), which were the most probable reason for the exceptional acidification of this soil from pH$_w$ 6.5 to 6.1 (Sillanpää and Rinne 1975). According to a long-term incubation experiment carried out by Lakanen and Vuorinen (1963), this increase in acidity is sufficient to explain most of the observed drop in P$_{Ac}$.

In conflict with most of the soils of this study but in a reasonable agreement with several equally acid fine to medium-textured soils, the fixation of extractable P appeared to be rather strong in two clay loam soils (31–37% clay) in Southern Finland (60.20 N) studied by Yli-Halla (1989). At zero P balance, initial P$_{Ac}$ values of 5.4–6.0 mg dm^{-3} decreased to 3.2–3.8 mg dm^{-3}, or by 40%, in 11–12 years. In addition to the rather strong initial acidity (pH$_w$ 5.4–6.0) and its gradual increase with applied ammonium compounds (Yli-Halla 1989), other reasons for the unusual sharp drop in extractable P in these soils seem to have been the low P saturation indices (4.4–5.2%) in relation to the initial P$_{Ac}$ values and a substantial mixing of the unanalysed but usually poorer subsurface soil with the topsoil, which had been probable as a result of the deeper than average ploughing practised at the experimental farm. According to recent investigations by Peltovuori (2002), the P$_{Ac}$ values of mixtures were accurately predicted by the mass-weighted average values of their components, while the P$_w$ values were lower because of the efficient sorptive material in the subsurface soil.

A general decrease of very high STP values can be postulated from the final values of the richest soils of this study, in agreement with the values for another rich soil (Jaakkola et al. 1997). Mixing of the topsoil with some of the less fertile subsurface soil, as implied by the changes in total P, probably had a substantial influence even on the trend of final P$_{Ac}$ as a function of the initial values (Fig. 6). This kind of mixing was observed to a significant extent in one of the two very rich fields (8). The effects of the mixing may increase with initial STP because of the parallel increase in the gradient in total P (Fig. 1);

the group SSP2 is untypical because of the naturally rich soil 15 (Saarela et al. 2003). Leaching of soluble P was probably a minor reducer of extractable P pools even in this kind of soils as indicated by the sharp decreases in the P_{Ac} values with depth (Saarela et al. 1995, 2003). Enormous amounts of secondary inorganic P as determined in the profiles of some soils (Peltovuori et al. 2002) also support the possibility that the main cause of the losses of soluble P is its fixation and not leaching.

Stratification of broadcast P in ley

As stated above, an increase of the depth of the fertile soil by mixing with subsoil was an obvious reason for the lower than estimated final concentration of total P and the STP values for the topsoils. Deep ploughing to the dept of 30–35 cm increases the yields markedly in coarse sandy soils and somewhat also in clay and clay loam soils, but would decrease the yields in unstable silty soils (Håkansson et al. 1998, Saarela et al. 2000). Deep ploughing or other deep incorporation techniques, which would improve the supply of P to plants during the dry periods in early summer typical in Finland (Saarela et al. 2000) and reduce the concentration of soluble P in the surface exposed to leaching (Peltovuori 2002), should be considered as a multipurpose technique in the agro-environmental management of P in cultivated soils.

The apparent balance within the total soil volume certainly includes spatial variation

caused by localised entry and removal of phosphate. Fertiliser P when drilled to the soil have been found to be enriched only within a limited height and width (Aura 1967). Normal rates of placed P are fixed within 10–15 mm distance from the fertiliser bands and occupy less than 1% of the topsoil in very high concentrations (Saarela and Saarela 2000). When P fertiliser is broadcast on mineral soil and left on the surface, as is usually done in leys, applied P is retained by a thin layer of the uppermost soil and reaches readily very high concentrations within the limited soil volume (Hänninen and Kaila 1960, Haygarth et al. 1998). After a few years of annual dressings, which supplied a total of 50–78 kg P ha^{-1} on two silt loam soils, Hänninen and Kaila (1960) measured two to four times higher concentrations of "P in soil solution" for the uppermost 25 mm thick layer than for the next 50 mm.

The assessment of the stratification of extractable P in ley at the four sites (Table 5) indicated that 200 kg P ha^{-1} broadcast on clay soil (close to site 1 of this study) was retained by the uppermost 25 mm thick layer for four seasons; in silt loam (11) and clayey peat (22) some of the applied P was leached to the next layer (25–50 mm); in a sandy peat soil (21) which sorbed phosphate anions exceptionally weakly, the enrichment extended to the depth of 50–100 mm. In agreement with the studies by Hänninen and Kaila (1960), the results prove that normal rates of surface-applied P are retained by a thin, about 15–25 mm thick layer of the typical mineral soil of Finland which sorbs phosphate anions effectively. The concentration of extractable P in this

Table 5. Concentration of soil P extractable in acid ammonium acetate (P_{Ac}, mg dm^{-3}) at various depths and the calculated mean for the whole plough layer (0–20 cm) in the control soils and in the soils topdressed annually with 50 kg P ha^{-1} for four years (Saarela 1992b). These experiments were conducted at the same sites as four of the 24 long-term experiments (Saarela et al. 2003)

| Soil type | Site | Control fertilisation (no P) | | | P application 4 * 50 kg ha^{-1} | | |
		0–2.5 cm	10–20 cm	0–20 cm	0–2.5 cm	10–20 cm	0–20 cm
Clay	1	3.8	3.2	3.3	22.6	4.0	6.3
Silt loam	11	7.2	8.1	7.8	24.4	8.3	10.6
Sandy peat	21	3.0	4.0	3.5	24.5	4.1	7.5
Clayey mull	22	4.9	5.3	4.9	14.0	5.5	6.8

layer raises to a level several times higher than the mean for the whole plough layer measured by normal sampling. The effect of P fertilisation was three to five times greater in the 2.5 cm thick surface layer than in the 20 cm deep topsoil, which means that three ley years correspond to more than then years of the conventional cultivation including annual ploughing. Although the conventional sampling prevented any analytical proof, the status was certainly similar in the leys of the long-term experiment, in which the highest rate of P fertilisation was even higher than in the short-term experiment in ley.

Since no more than 2 cm of the uppermost soil is exposed to leaching by surface runoff (Sharpley 1985), the transfer of surface-applied P to streams and lakes is not properly predicted by any soil tests based on the samples obtained from the whole plough layer in the usual manner. For environmental purposes the enriched surface should be assessed separately by means of samples obtained form a thin layer of the surface soil, and fairly frequent tests are required for assessing the rapid changes in potentially transportable P. Much less frequent sampling is sufficient for measuring the slow and fairly well predictable changes in the STP values of soils which are regularly homogenised by a deep primary tillage.

Summary and conclusions

The changes of total P and soil test P values caused by different rates of repeated P fertilisation were monitored for 22 diverse Finnish soils enriched with large amounts of accumulated fertiliser P. Several chemical soil testing methods were compared at 19 sites and the Finnish ammonium acetate method was employed at three additional sites. The differences in total P between the fertilisation rates of 15 and 45 kg P ha^{-1} observed by chemical analysis in the topsoil layer accounted for 65% of the calculated balance surpluses during the experimental peri-

od of 9 to 15 years. Because of the P gained by soil exchange between adjacent plots and probably saved with more efficient utilisation of the deeper soil layers in the area not fertilised with P, the recovery percentage of applied P was lower between the smallest rate and the control.

Modified Olsen P (P_{Olm}) accounted for 9.7% (0.058 mg kg^{-1})/(kg ha^{-1}) of the balance differences between the P application rates of 0 and 45 kg ha^{-1}, and the recoveries were similar in all types of soil and even at individual sites almost independent of their P status. With acetate and water extraction methods (P_{Ac} and P_w) the corresponding mean recoveries were 3.5 and 4.7% (0.0159 and 0.0214 mg dm^{-3})/(kg ha^{-1} in P balance), but they increased steeply with increasing initial STP values for both methods. P_{Olm} indicated mainly the capacity factor of soil P status, while the more sensitive P_{Ac} and P_w values appeared to predict primarily the intensity factor of P status in acidic mineral soils. The P surpluses up to 500 kg ha^{-1} were insufficient to rise the STP values any more than required for optimum yields in the poorest soils which efficiently fixed applied phosphate.

At zero P balance, when the P offtake by harvested crops was replaced with fertilisation, most of the initially low and medium P_{Ac} values remained unchanged during the experimental period. Considerable losses of extractable P were found in initially acidic and acidified fine-textured soils, in one clay-amended organic soil formerly poor in extractable P, and in all soils which were initially rich in extractable P. Direct observations and indirect estimations from the changes in the concentration of total P suggested that some unplanned mixing of the poorer subsurface soil with the topsoil by ploughing decreased the P values for the final samples for all methods.

The decrease in the trend values of the final P_{Ac} at zero balance as a function of the initial values was 10% at 5 mg P dm^{-3} and 19% at 25 mg dm^{-3}. These decreases corresponded to 70 and 190 kg ha^{-1} of applied P during the experimental period and annual balance surpluses of 6–15 kg ha^{-1} (mean 10 kg ha^{-1}). These amounts of ferti-

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liser P were required in addition to the offtake in harvested crops to completely prevent the decrease in STP and maintain the P status of soil as estimated by the acetate method.

The results suggest that the slow and regular changes of the P status in Finnish mineral soils can be assessed accurately enough by relatively infrequent soil tests when the topsoil is frequently homogenised with deep primary tillage. Extending the agro-environmental soil testing program to the subsoil depth appeared highly relevant to the deep peat profiles which are poor in the minerals capable to retain soluble phosphate. The effect of broadcast application of P on the STP values of ley soil was much greater in the 2.5 cm thick surface layer than in the whole 20–25 cm deep topsoil. Testing a thin layer of the enriched soil surface for extractable P by means of separate environmental samples seems to be necessary for accurate estimation of the risk of increased P leaching after repeated application of P on the soil surface, as is usually done in leys.

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AGRICULTURAL AND FOOD SCIENCE

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SELOSTUS

Pitkäaikaisen fosforilannoituksen vaikutus Suomen peltojen fosforitilaan.
2. Kemiallisten testien muutokset suhteessa fosforitaseeseen sekä aikaisemmin ja koevuosina lisätyn fosforin multaussyvyyteen

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Fosforilannoituksella tehostetaan kasvintuotantoa ja turvataan välttämättömän kasvutekijän jatkuva saanti kestävän maatalouden vaatimusten mukaisesti. Hyvien satojen edellyttämän maan fosforitilan saavuttamiseen ja ylläpitoon tarvittavaa lannoitusta tutkittiin pitkäaikaisilla kenttäkokeilla 22 koepaikalla ominaisuuksiltaan vaihtelevilla mailla, joihin oli edellisinä vuosikymmeninä kertynyt runsaasti fosforia. Viiden vuosittain annetun fosforimäärän (0, 15, 30, 45 ja 60 kg ha^{-1}) vaikutuksia maan fosforitilaan tutkittiin useilla kemiallisilla menetelmillä 9–15 koevuoden jälkeen, ja analyysituloksia verrattiin pellon fosforitaseeseen. Nurmelle levitetyn fosforin kerrostumista tutkittiin neljällä koepaikalla.

Fosforilannoituksen koko kyntökerroksessa aiheuttamat maan fosforipitoisuuden keskimääräiset erot prosentteina fosforitaseesta olivat asetaattitestillä 3,5 % (0,0159 mg P dm^{-3} maata)/(P-taseen ero 1 kg ha^{-1}), vesiuutolla 4,7 % (0,0214 mg P dm^{-3})/(kg P ha^{-1}) ja Olsenin menetelmällä 9,7 % (0,058 mg P kg^{-1})/(kg P ha^{-1}). Mailla, jotka pidättivät liukoista fosforia tehokkaimmin, enimmillään yli 500 kg ha^{-1} sadoissa poistuneita suuremmat fosforimäärät eivät riittäneet nostamaan asetaatti- ja vesiuutolla määritettyjä fosforipitoisuuksia enempää kuin hyvään kasvuun tar-

vittiin. Alussa korkeat asetaattiuuttoisen fosforin pitoisuudet pienenivät hitaasti fosforilannoituksen ollessa yhtä suuri kuin fosforin poistuma sadoissa, mutta pienet alkupitoisuudet eivät muuttuneet ilman erityistä syytä kuten maan happamoitumista ja niukkafosforisen jankon sekoittumista kyntökerrokseen. Asetaattimenetelmän mukaan lannoitefosforia tarvittiin maan fosforitilan ylläpitoon keskimäärin noin 10 kg ha^{-1} enemmän kuin sadoissa poistui.

Tulosten mukaan syvällä perusmuokkauksella homogenisoitujen kivennäismaiden fosforitilan hitaat ja säännölliset muutokset voidaan määrittää riittävän tarkasti ja luotettavasti suhteellisen harvoin tehtävillä viljavuustutkimuksilla. Maatalouden ympäristönsuojelua varten turvemaiden liukoisen fosforin pitoisuus tulisi määrittää myös muokkauskerrosta syvempää. Pintalannoitettujen nurmien ohut pintakerros rikastui paljon nopeammin kuin koko kyntökerros. Jos fosforia levitetään maan pinnalle toistuvasti ilman välillä tehtävää kunnollista multausta, huuhtoutumisriskin luotettava arviointi edellyttää pintaa pitkin valuvan veden huuhtoman maan tutkimista erikseen ohuesta pintakerroksesta otetuttujen maanäytteiden avulla.