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Effects of repeated phosphorus fertilisation on field crops in Finland I. Yield responses on clay and loam soils in relation to soil test P values

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In order to update phosphorus (P) fertiliser recommendations for the Finnish clay and loam soils enriched with applied P, the effects of repeated P fertilisation on the yields of cereal and other crops were measured at eight sites over a period of 12–18 years. Yield results of some earlier field studies were also used in calibrating the soil test P values determined by the Finnish acid ammonium acetate method (P_{Ac}). Significant yield responses to P fertilisation were obtained on soils which had low P_{Ac} values or medium levels of P_{Ac} and too low or too high pH values (< 6.0 or 7.5 in water suspension). The mean relative control yield (RCY, yield without applied P divided by yield with sufficient P multiplied by 100) of the eight sites was 94.6% (n = 128, mean P_{Ac} 15.5 mg dm^{-3}) varying from 87% at P_{Ac} 2.8 mg dm^{-3} to 100% at high P_{Ac}. A P_{Ac} level of 5–7 mg dm^{-3} was adequate for cereals, grasses and oilseed rape on the basis of the RCY value of 95% at optimal pH. At this P_{Ac} replacing the amounts of P in the crops (14 kg in 4 t grain) and the fixation of extractable P (about 6 kg ha^{-1} a^{-1}) produced almost maximum yields in favourable seasons and were considered optimal.

Key words: Acid ammonium acetate method, optimal soil test P, soil acidity, soil phosphorus

Introduction

The supply of essential elements to crops to replace the nutrients removed from the soil is an indispensable requirement for efficient and sustainable food production. Inherently and anthropogenically very rich soils can produce large yields for decades without any phosphorus (P) application (Johnston and Poulton 1992, Wechsung and Pagel

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1993). However, a major part of the arable soils of less developed countries have very low soil test P values (Sillanpää 1982). Rather poor soils needing regular fertilisation are not uncommon even in Europe. The availability of P to crops is still insufficient at least in the sandy and silty soils in the northern and eastern parts of Finland (Saarela et al. 1995, Saarela 1998b) and in some Lithuanian soils (Vaishvila et al. 2000).

Coastal clay and loam soils of southern and western Finland have shown to be better sources of P than the silty and sandy soils of the inland regions (Salonen and Tainio 1957, Saarela et al. 1995). In some other northern clay and loam soils the long-term supply of P has remained fairly good. At five sites in central Sweden in 1963–1996 (Carlgren and Mattsson 2001) the mean yield obtained with N (treatment A) was 87% of that with N plus replacement of P and K (treatment C2). The mean latest soil test P value by the ammonium lactate method was 33 mg kg^{-1} (range 13–98 mg kg^{-1}, classes I to IV of five classes). On five soils in southern Sweden, cereals and grasses produced even higher relative yields without applied P and K, while the sugar beet yield dropped to 63%.

The role of P in Finnish agriculture was discussed in a review (Saarela 2002) as an introduction to a project for optimising P fertilisation of crops grown on the soils enriched with P. Soil and crop data and summaries of the results were reported in Finnish (Saarela et al. 1995) and studies on the twenty-four soils of the project were published in English (Saarela et al. 2003, 2004). Eight of the field experiments were conducted on low-silt clay and loam soils, which cover almost one million hectares or about 35% of the cultivated land. Finnish clay and loam soils are mainly used for grain production, while sugar beets, oilseed rape and ley for ensilage, hay and grazing are cultivated in smaller areas on these soils.

In order to update P fertiliser recommendations on the basis of chemical soil tests, the yield responses of crops to repeated P fertilisation in relation to soil test P values at eight clay and loam soils are reported in this paper. The effects of four rates of applied P and the control treatment were recorded for twelve to eighteen successive growth seasons at each site. The annual yield variations in relation to soil properties and weather conditions were studied at three sites, and key points of other sites are discussed. The immediate effect of applied P on the treated crop and the cumulative residual effect of repeated P fertilisation were compared at two sites.

For better reliability and applicability of the results, the soil test P values determined by the Finnish acid ammonium acetate method (P_{Ac}, Vuorinen and Mäkitie 1955) were calibrated by including appropriate other studies in the summaries of results. The yield effects of repeated P fertilisation were mainly examined on the basis of the relative control yield, RCY, and relative yield, RY. Relative control yield is the ratio of the yield obtained without P fertilisation to the yield obtained with sufficient P fertilisation, and RY is the corresponding ratio of the yields obtained with insufficient and sufficient amounts of P.

Results from earlier studies

Yield and soil test data were compiled from twenty-four sites, and the last years were presented separately for four sites (Table 1). In the experiments conducted prior to the late 1960s, cereals and clover-grass ley were grown in rotation with some other crops, fertilisers were spread on the soil and incorporated by harrowing in tilled soils and plant residues were removed. Later, cereals were grown alone or with a few oilseed rape crops in rotation, fertilisers were applied by the placement method and plant residues were returned to the soil; grass was grown in two short-term studies.

The RCY values obtained with repeated P fertilisation showed that most clay and loam soils supplied sufficient P to produce relatively good yields. The yield response to P fertilisation was small even at the medium level of P_{Ac}, if the pH_w value was not lower than 6.0 or unusually high (Table 1). The yield effect of periodical animal manure application on a clay soil in Tammela was

Table 1. Effects of annual P fertilisation, periodical manure application (ref. 1) and initial liming with ground limestone (L) on crop yields and soil test P values (P_{Ac}) in clay and loam soils in Finland.

Location	Soil type	Years	Soil amen-	P kg ha^{-1} a^{-1}		Yield[1]	RCY[2]	Soil P_{Ac}[3]	Soil	Ref[4]
Latitude (N)		(Soil test)	dings	NK	NPK	NPK	NK	NK	pH_w[5]	
Tammela	Clay	1929–53	Nothing	0	18	2600	91	3.4[6]	6.1	1
60˚ 45’		(1953)	Manure	8	26	2710	98	4.6[6]	6.1	
Nakkila	Muddy clay,	1947–54	Nothing	0	24	2550	101	3.7	5.9	2
61˚ 15’	20% OM	(1955)								
	Muddy clay	1947–52	Nothing	0	18	2250	92	4.8	4.9	3
	Muddy clay,	1947–52	Limed	0	18	1920	100	4.8	5.0	3
	rich in OM	1947–52	Manure	5	23	2260	99	4.9	4.9	3
Pori	Muddy clay,	1953–57	Limed	0	18	2350	85	5.2	5.0	3
61˚ 25’	lower in OM	(1953)								
Mietoinen	Muddy clay	1964–73	Nothing	0	18	3380	94	5.0	5.5	4
60˚ 40’		(1973)	Limed	0	18	3580	99	6.1	6.1	
			Limed	0	18	3700	101	8.2	6.9	
Tikkurila	Clay loam	1969–80	Limed	0	25	4140	97	12.8	6.4	5
60˚ 15’		(1980)								
Mietoinen	Clay	1974–92	Nothing	0	44	4050	94	3.6	6.9	6
		1989–92		0	44[7]	3340	87[7]	3.6		
		(1987)		25[7]	44[7]	3340	92[7]	4.8		
Mietoinen	Clay	1974–92	Nothing	0	44	4590	99	9.2	6.7	6
		1989–92		0	44[7]	4690	100[7]	9.2		
		(1987)								
Vihti	Clay loam	1974–85	Nothing	0	30	4440	84	2.1	5.4	7
60˚ 20’		1981–85		0	31	4440	74	3.0		
		(1985)								
Vihti	Clay loam	1975–85	Nothing	0	30	4790	92	1.7	6.0	7
		1981–85		0	31	4600	87	2.9		
		(1985)								
Hausjärvi	Loam	1978–95	Nothing	0	35	2560	86	20.0	7.5[5]	8
60˚ 45’		(1995)								
Jokioinen	Clay (site 8	1982–84	Nothing	0	60	4760	97	14.9	6.4	9
60˚ 50’	in this study									
Mietoinen	Clay	1983–86	Nothing	0	50	5770	90	4.3	5.9	6
		(grass)								
Jokioinen	Clay	1991–93	Nothing	0	36	6420	95	3.5	5.8	10
		(grass)								
Jokioinen	Clay	1991–96	Limed with	0	91	5560	72	0.9	6.1	11
			8 t ha^{-1} 1993							
Mietoinen	Clay	1991–98	Mean of	0	16	4560	94	5.2	6.6	12
			limings							
Jokioinen	Clay	1994–98	As above	0	49	4300	93	3.6	6.3	12
			Deep ploug-	0	49	4370	93	3.1	6.3	
			ing (32 cm)							
Jokioinen	Clay (site 8	1994–98	Nothing	0	23	4540	96	30.5	6.5	12
	in this study		Limed	0	23	4610	96	43.0	6.9	

[1] Yield unit: 1.0 kg cereal grain, 0.5 kg rapeseed or 1.0 feed unit grass equivalent to 1.0 kg barley grain
[2] Relative control yield. Yield with NK devided by the yield with NPK expressed in per cent
[3] mg P dm^{-3} soil
[4] References: 1 = Salonen and Tainio 1956, 2 = Salonen and Tainio 1957, 3 = Salonen 1963, 4 = Jaakkola et al. 1977, 5 = Experiments conducted by Göthe Larpes, 6 = Unpublished experiments conducted by Jaakko Köylijärvi 7 = Yli-Halla 1989, 8 = Jaakkola et al. 1997, 9 = Saarela 1989 and 1991, 10 = Hakkola 1998, 11 = Saarela 1998a, 12 = Saarela et al. 2000 and unpublished results from site 8 of this study
[5] Soil pH measured in water suspension.The pH_w value of Hausjärvi was derived from the pH value 7.0 measured in 0.01 M $CaCl_2$.
[6] The P_{Ac} values of Tammela were approximated from those extracted in 0.01 M HCl (Keränen et al. 1963).
[7] Residual effects of previous P fertilisation

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remarkably good (ref. 1 in Table 1). The supply of P and possible indirect effects of animal manure were sufficient for maximum yields in clover-grass ley and other cereals, but not for winter rye and rutabaga. One manuring supplied sufficient P in a shorted study on a muddy clay soil in Nakkila (ref. 3). The amounts of P applied in manure were roughly similar to those nowadays transferred from the soil to the straw, which were removed up till the early 1970s and later in Hausjärvi (ref. 8), but returned to the soil in other recent studies.

The young muddy Litorina soils found at Nakkila and Mietoinen (ref. 4 in Table 1) probably supplied significant amounts of P from below the plough layer. The two heavy glacial clays in Mietoinen (ref. 6) were located close to the sites 1 and 3 of this study (Saarela et al. 2003). Soil acidity was clearly detrimental for P availability in the unlimed muddy clay in Mietoinen. Exceptionally high pH was an obvious reason for the exceptional results in Hausjärvi, in accordance with the relatively poor availability of P at high pH and P_{Ac} (Aura 1978). The decline of the quadratic pH-correction equation at very high pH values (Saarela 1992) also implied that the availability of P in relation to P_{Ac} is poor at excessive pH. The removal of plant residues in contrast to other recent experiments is another possible reason for the untypical yield responses in Hausjärvi.

The control plots not fertilised with superphosphate received little or no fertiliser sulphur. However, the field studies conducted in Southern Finland (Korkman 1973) suggest that the low grade potassium fertilisers used in the oldest experiments and the acid rain since the 1960s probably supplied sufficient sulphur to the crops.

Material and methods

Experimental soils

The eight clay and loam soils of this study (Table 2, Fig. 1) include three types of mineral soils: i) glacial clay and clay loam containing 30% or more clay (soils 1, 3, 7 and 8), ii) glacial loam with 12–30% clay (soils 2 and 5) and iii) the younger Litorina sediments or muddy clay (soils 4 and 6). The glacial soils which contain 12–30% clay, but relatively little fine silt, belong to the Finnish soil types fine sand and very fine sand, sometimes specified as clayey. The experiments on silt loam and silty clay loam soils will be published later together with the results from sandy soils.

A summary of the P status and other characteristics of the clay and loam and soils studied earlier (Saarela et al. 2003, 2004) is presented in Table 2. Some additional soil test P values determined in an international comparison of chemical methods (Saarela et al. 1996) are also presented. The ammonium lactate P values (Egnér et al. 1960) are medium (41–80) or high according to Swedish calibration, while some of the calcium lactate P values are rather low according Estonian calibration (medium = 31–61). The values for resin P (van Raij 1998) are all high according to Brazilian ratings for agriculture (high = 41–80). The $CaCl_2$

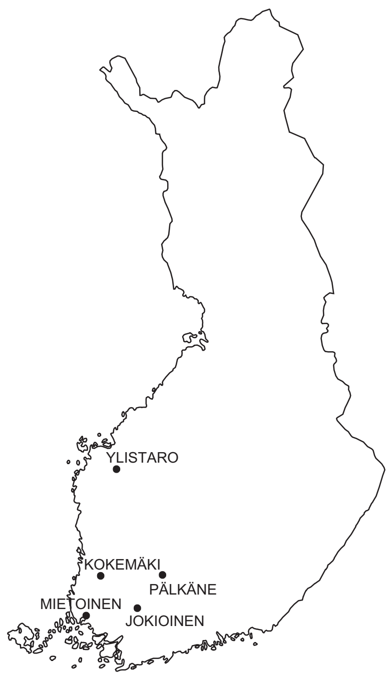

Fig. 1. Location of the experimental sites.

Table 2. Soil characteristics and P status of the plough layer at each experimental site in clay and loam soils with "low" (CLP1) "high" (CLP2) and mean (CLPM) concentration of P extractable in acid ammonium acetate (P_{Ac}).

No/	Location Group	OC % 1)	Clay, %	pH_w 2)	CATS3) cmol(+) dm^{-3}	Total P $g\ kg^{-1}$	P saturation, % 4)	Sorption index 5)	Soil test P values, P_x 6), where x = Ac	w60	Olsenm	Al	Cal	$CaCl_2$	res
1	Mietoinen	1.9	74	6.5	21.0	1.04	6.2	0.63	3.9	4.6	33	66	22	0.2	99
2	Pälkäne	2.3	12	5.6	6.3	0.89	6.4	0.67	4.4	5.7	26	29	13	0.3	49
3	Mietoinen	2.1	59	6.2	15.3	1.19	7.4	n.d.	5.5	5.4	38	59	35	(0.5)	86
4	Ylistaro	6.9	27	5.4 2)	5.3	1.31	6.2	2.35	5.8	1.6	62	80	50	0.4	77
1–4	**CLP1**	**3.3**	**43**	**5.9**	**12.0**	**1.11**	**6.5**	**1.21**	**4.9**	**4.3**	**39**	**59**	**30**	**0.4**	**78**
5	Mietoinen	1.7	24	5.7	7.2	0.91	9.5	0.29	8.9	5.0	41	64	35	0.7	75
6	Kokemäki	8.1	25	5.7	10.5	1.41	8.8	0.95	9.1	9.8	82	136	72	0.7	123
7	Mietoinen	2.1	35	5.8	10.0	1.29	12.0	0.26	14.1	29.9	71	107	65	0.6	156
8	Jokioinen	2.7	43	6.6 2)	18.3	1.61	n.d.	0.16	56.6	33.0	101	240	131	5.2	446
5–8	**CLP2**	**3.7**	**32**	**6.0**	**11.5**	**1.33**	**10.1**	**0.42**	**22.2**	**19.1**	**74**	**137**	**76**	**1.8**	**200**
1–8	**CLPM**	**3.5**	**37**	**5.9**	**11.8**	**1.22**	**8.0**	**0.76**	**13.6**	**11.7**	**56**	**98**	**53**	**1.1**	**139**

1) Organic carbon

2) At site 4 soil pH increased to 5.7 after liming with 5 t ha^{-1} in 1985
In the limed plots at site 8 soil pH increased to 7.0

3) CATS = sum of extractable Ca, K and Mg measured by the acid ammonium acetate method (Saarela et al. 2003)

4) Amm. fluoride and sodium hydroxide extractable P divided by acid oxalate extractable Al and Fe (Saarela et al. 2003)

5) Sorption of 0.2 g P kg^{-1} soil in 0.005 M $CaCl_2$ in one week divided by the final solution P concentration, $(g\ kg^{-1})\ (mg\ dm^{-3})^{-1}$ (Saarela 1992)

6) P_{w60} = water extraction, ratio1:60 by volume, P_{Olsenm} = modified Olsen P mg kg^{-1}, P_{Al} = ammonium lactate extraction by SLU, Sweden, mg P kg^{-1} (S. Engblom), P_{Cal} = calcium lactate extraction by ERIA, Estonia, mg P kg^{-1} (L. Kevvai), P_{CaCl2} = 0.01 M $CaCl_2$ extraction by WAU, Netherlands, mg P kg^{-1} (S. van der Zee), P_{res} = resin extraction by IA, Brazil, mg P dm^{-3} (B. van Raij)

method introduced by Houba et al. (1990) extracted little P from most Finnish mineral soils indicating a low content of dissolved phosphate in soil solution, or a low intensity of soil P, in agreement with P_w. The modified (20% higher) Olsen P values are high in accordance with their quantitative character (Saarela et al. 2003).

Treatments and cropping

The treatments consisted of five annual phosphorus applications including the control and four rates of P: 0, 15, 30, 45 and 60 kg P ha^{-1} in 4–5 m by 12–20 m plots. Initial liming with 10 t ha^{-1} in ground limestone applied in 1980 was included in experiment 8 as another factor in the whole plots which included the five P fertilisation treatments. The whole study area of this site was treated with the same liming agent at 4 t ha^{-1} in the autumn of 1993. The main experimental plants were spring barley, spring wheat and oats, while oilseed rape, winter wheat, winter rye, perennial ley and peas were also grown in irregular rotations (Table 3). Cereals and oilseed rape were harvested with a plot combine and grasses with a plot harvester equipped with a weighing system. The crops were weighed immediately or after drying, the moisture percentage at weighing was determined gravimetrically and the dried samples were analysed for total P and other macronutrients.

The P rates were applied as single (1977–1987) or triple superphosphate (8.7 or 20% P). To cereals, rapeseeds and peas the P fertiliser was placed

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Table 3. Crop succession and rates of nitrogen fertilisation (N, kg ha^{-1}) applied at the experimental sites 1–8 in the crop years 1977–1994.

Exp.	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91 [1)]
1	sw [2)]	sw	bar	bar	oat	oat	bar	sw	oilr	bar	sw	sw	*bar**	*sw*	*bar* [1)]
	100	100	100	100	100	100	100	100	100	100	100	110	110	110	110
2		bar	oat	bar	sw	oat	bar	sw	oat	fail	bar	sw	oat	sw	
		55	55	55	55	55	55	55	55	55	55	55	55	55	
3	pea	pea	pea	sw	oat	pea	sw	sw	sw	oilr	bar	sw			
	50	50	50	50	83	50	50	100	100	100	100	100			
4	oat	oat	oat	oat	oat	oat	oat	oat	oat	bar	oilr	bar	grl	grl	grl
	55	55	55	55	55	55	55	55	55	55	55	55	150	150	150
5	bar	oat	sw	oat	oat	bar	sw	bar	oat	sw	bar	sw	*bar**	*oat*	*bar* [1)]
	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83
6		bar	bar	bar	oat	oat	bar	fail	bar	oat	bar	oat	sw		
		53	53	41	41	41	41	41	41	41	41	41	60		
7		rye	rye	ww	rye	ww	rye	bar	rye	ww	rye	ww	rye		
		124	124	124	124	124	124	124	124	124	132	132	130		
8				bar	bar	bar	ww	oat	oilr	sw	bar	sw	*bar**	*grcl*	*grcl* [1)]
				100	100	100	160	100	110	110	90	90	60	100	230

[1)] Exp. 1: 92 oilr, 93 sw, 94 sw, 115N each year; Exp. 5: 92 sw, 93 oat, 94 oils, 92N each year;
Exp. 8: 92 grl 200N, 93 ww 170N, 94 sw 120N;
Underlining indicates splitting of the plots with NK and NPK fertilisations
Italicising indicates withdrawal of the P application rates 30 and 60 kg ha^{-1} from the year marked with *
(15 and 45 kg ha^{-1} continued).
[2)] Crop abbreviations: sw = spring wheat, bar = spring barley, oilr = oilseed rape (spring turnip rape), grl = grass ley, rye = winter rye, ww = winter wheat, grcl = grass clover ley. fail = a crop failure caused by a treatment error (exp. 2 in 1986) or omitted harvesting of a lodged cereal crop (exp. 6 in 1984)

with hoe coulters in narrow bands or rows to a depth of 8 cm with a row distance of 12.5 or 15 cm before sowing. To ley the P fertiliser was broadcast at the beginning of the growing season. In order to measure the residual effects of previously applied P, the P rates 30 and 60 kg ha^{-1} were withdrawn beginning in the tenth (site 8) or thirteenth (sites 1 and 5) year. During one or three final years the plots were split with NK and NPK fertilisation (Table 3). Both fertilisers supplied exactly the same amounts of N, and the minor differences in K and other nutrients were considered negligible. The mean amount of P applied in the NPK fertiliser was 20 kg ha^{-1} (variation 16–25 kg P ha^{-1}, exact amounts given by Saarela et al. 1995).

The use of compound fertilisers allowed us to apply several nutrients and the seeds in one operation by the combined fertiliser and seed drilling technique employed on most Finnish farms. The fertiliser was then placed with narrow hoe coulters (<15 mm wide) in the middle of every second 12.5 cm wide spaces of the seed rows drilled with shoe coulters. The distance of two adjacent fertiliser rows was thus 25 cm, and the horizontal distance of fertiliser and seed rows was 6.2 cm. A Finnish ammonium nitrate granulated with a mixture of ground dolomite, "Oulunsalpietari", was used as the single N fertiliser, and a high-grade KCl fertiliser was used as the K source.

When superphosphate was applied to the four treatments by the placement method, the control was usually drilled in the same way without any fertiliser distribution. The K fertiliser was placed across the P fertiliser rows to the depth of 5 (to avoid loosening of clay) to 8 cm as basal fertilisation at 60 kg K ha^{-1} in each year. The N fertiliser

Table 4. Monthly mean temperature (° C) and precipitation (mm) at Jokioinen, southwestern Finland (60° 52' N, 23° 27' E) during the growing seasons 1977–1994 with the means of the period 1961–1990 (Finnish meteorogical institute).

	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92 [1)]
Temperature, ° C																
May	8.7	9.8	10.5	7.0	11.2	8.5	11.0	12.6	8.6	10.5	7.6	11.4	10.4	9.3	7.2	11.4
June	13.9	14.1	15.5	16.4	12.8	11.2	13.3	13.1	13.2	16.3	12.1	16.5	15.4	14.4	12.1	15.7
July	14.2	14.5	14.2	16.2	16.2	16.4	16.6	14.8	15.3	16.2	14.8	19.0	16.3	15.2	16.6	16.0
August	13.7	12.8	15.2	13.9	13.5	15.6	15.0	13.8	15.5	12.9	11.7	14.1	13.7	15.0	16.2	14.3
Precipitation, mm																
May	49	11	21	20	19	71	44	66	43	52	38	44	41	22	29	7
June	43	73	27	131	115	25	84	113	41	11	81	25	30	20	69	25
July	82	54	156	36	104	84	41	91	55	65	68	128	85	85	55	47
August	54	101	112	76	88	111	58	69	119	110	83	79	92	90	92	107

[1)] 1993 temperature 13.3, 11.4, 15.6, 12,9 ° C, precipitation 1, 56, 107 and 136 mm for May, June, July and August
1994 temperature 7.8, 12.1, 19.0, 15,1 ° C, precipitation 34, 66, 1 and 54 mm for May, June, July and August
1961–90 temperature 13.3, 11.4, 15.6, 12,9 ° C, precipitation 1, 56, 107, 136 mm for May, June, July and August

was applied with the combidrill during the same passing as the seeds and drilled across the P fertiliser rows to a depth of 8 cm. The amounts of N applied each year are given in Table 3. The combidrill was equipped with narrow press wheels which compacted the seed rows while leaving the fertiliser rows totally uncompacted. To ley single N and K fertilisers were broadcast separately for each cut, except on the rich clay soil (8) K was applied only in spring. To winter cereals most of the N fertiliser was broadcast in spring.

Normal autumn ploughing was employed as the only method of primary cultivation. Seedbed was prepared by two or three passes with a S-pine harrow. Particularly in clay fields in spring, the soil was not loosened to deeper than the seeds were drilled. Spring sowing was normally done between the 10th and 25th of May. Weeds in cereals and insects in oilseed rape were controlled chemically. Early barley varieties were harvested with a plot combine during the first or middle weeks of August and other crops one to three weeks later. Winter cereals were sown at the end of August or early September and combined about fifty weeks later. Leys were cut two or three times in a growing season.

A summary of the weather conditions at Jokioinen during the experimental period is presented in Table 4. The seasons 1981 and 1987 were exceptionally cool and the early summer of 1982 was cool and dry. Precipitation in early summer is critical for growth and is usually less than optimal, particularly in the southern and south western coastal regions. Most of the seasons in the early and middle years of the study had an average or higher precipitation, but the seasons 1979, 1982, 1986, 1988–1990 were rather dry. The growing season of 1992 was warm and very dry.

Testing and presenting results

The five P fertilisation treatments were arranged in randomised blocks with four replicates. The effects of liming were studied at site 8 in four additional blocks which included the five fertilisation treatments as subplots (Saarela et al. 2003). Differences between the treatments were tested by analysis of variance for each year and for the whole study period and its parts. The multi-factorial experiments with the NK and NPK fertilisation in the subplots (final three years on soils 1 and 5) were

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tested by using the treatment means as independent variables and the two experiments as replicates. Relationships between the yield effects of applied P and the chemically estimated supply of P from the soils were examined graphically by RCY/P_{Ac} plots.

Results and discussion

Yields at eight sites

A summary of the cumulative yields presented in Fig. 2 shows that the yield responses were relative small and not found on soils which had high soil test P values measured with P_{Ac}. In addition to the chemically estimated availability of P, other properties of the individual soils, crop species and weather conditions also had an impact on the effects of applied P. The relatively modest yields and their small responses to P fertilisation on the physically favourable loam soil 2 in Pälkäne resulted from bad lodging of oats in 1979 and barley in 1983 (cultivar Otra) and 1987 (Silja). In 1983 and 1987 the insignificant response was not larger than 150 kg ha^{-1}, but in a stiffer barley cultivar (Pomo) grown in 1978 and 1980 the significant yield effect of P was 450 kg ha^{-1}.

The loam soil 6 in Kokemäki which was rich in organic matter did not respond to P fertilisation in spite of a medium P_{Ac} value. The early growth was sometimes visually weaker in the control. Other chemical methods produced relatively higher P values in agreement with the good bioavailability of P (Table 2). The winter cereals grown on the rich but acid soil 7 produced generally rather mod-

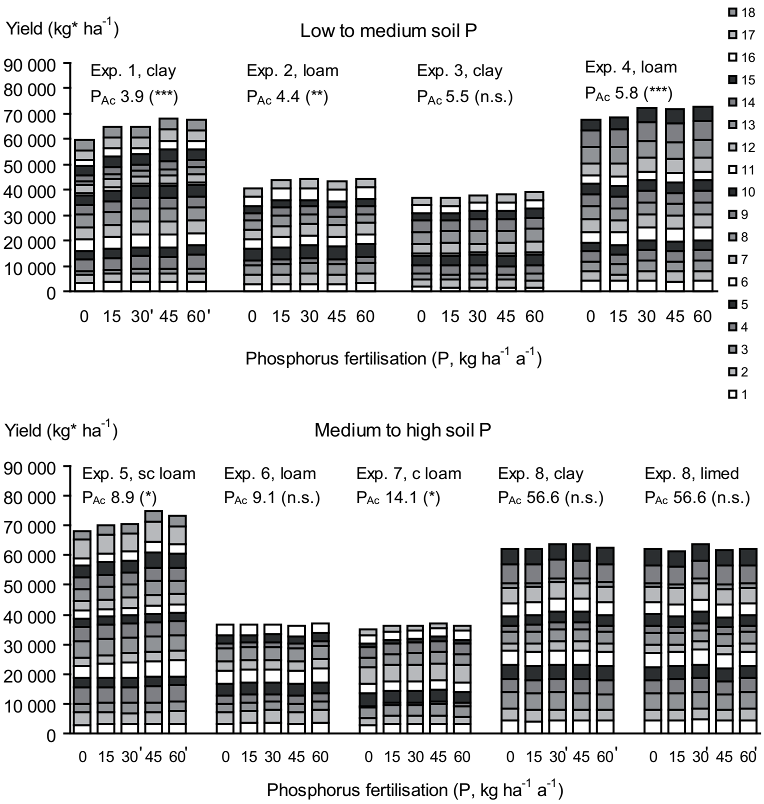

Fig. 2. Effects of different amounts of repeated annual P fertilisation on cumulative yield on eight clay and loam soils in southern and western Finland over 12–18 successive seasons. White sub-bars from bellow indicate the 1st, 6th, 11th and 16th years. 30' and 60' indicate residual effects of previous fertilisation in the last six years. Yield unit (kg*) = 0.5 kg rapeseed, 1.0 kg cereal grain or 1.0 feed units of grass equivalent to 1.0 kg barley grain. Asterisks (*, **, ***) indicate significant effect of P fertilisation (F) at P = 0.05, 0.01 and 0.001, respectively, n.s = not significant.

est yields, particularly in relation to the total amounts of N applied at sowing and in spring (Table 3).

The clay soil of experiment 8 in Jokioinen had been used for growing of sugar beet and it was therefore limed and fertilised heavily (Table 2). As typical Finnish clay, its aggregate structure resisted gentle rain but not heavy showers, after which the soil mass was exposed to rapid evaporation and hardening. When that occurred at a critical time during the early season, the crop suffered from poor rooting and drought. The high concentration of extractable P in the surface soil supplied P abundantly when moist, resulting in exceptionally high concentrations of P in the grain crop (0.50% in dry matter, usual 0.40%). However, drying of the enriched surface soil and the poor availability of P in the subsoil (Saarela et al. 1995, 2003) caused temporary P deficiencies in the crops during long dry periods.

The importance of soil depth enriched with nutrients was demonstrated in the UK (McEwen and Johnston 1979). Finnish soils are saturated with water in the spring, but a thin layer of the clay surface is rapidly dried through evaporation. The drying front remains sharp during the early summer and reaches the bottom of the enriched plough layer in the middle of June, during a critical stage in spring cereals (Elonen and Kara 1972, Saarela et al. 2000). Each additional centimetre in the depth of the clay soil enriched with P prolongs the supply of P from the surface soil by about one day during the dry periods common in Finland during early summer. The theoretical benefits of deepening the soil enriched with P were confirmed experimentally by field studies (Saarela et al. 2000).

Yield variation at three sites

The heavy clay soil of experiment 1 in Mietoinen had relatively low content of organic C and extractable P and a nearly neutral pH (Table 2), which is considered optimal for most crops. The small grain yields of barley in 1979 and of spring wheat in 1987 did not depend on P fertilisation (Fig. 3). The short barley cultivar (Eero) suffered from the dryness of early summer in 1979 and the spring wheat in 1987 from the extremely cold and rainy season, which prevented its normal ripening. In contrast, in the years 1989 and 1990, the modest yields of the same crops responded relatively well to P fertilisation. An increasing trend of the yield differences is obvious on this soil. The annual application of 15 kg P ha^{-1} and the final P_{Ac} 3.6 mg dm^{-3} were insufficient for maximal yields of barley, spring wheat and oilseed rape (yield unit 0.5 kg ha^{-1}).

The Litorina soil of experiment 4 in Ylistaro had a low concentration of water extractable P and a strong capacity to sorb applied P (Table 2), but its subsoil appeared to be relatively rich in P (Saarela et al. 2003). Typical for Litorina profiles, the soil was well drained and physically favourable for rooting. Oats grown continuously in the first nine years produced stable yields and responded to P fertilisation only in the fifth and sixth years, 1981 and 1982, which were cold during the critical early development in June (Table 4). In the warm season of the tenth year (1986) for an unknown reason, barley produced slightly but statistically significantly smaller grain yields with P fertilisation than without.

A probable reason for the good performances of oats in relation to the soil test P values of the surface soil at site 4 was the contribution of the subsurface layers in supplying P to crops. In accordance with the low concentration of water extractable P in the soil, pot-grown barley and oats produced almost no grain on the surface soil if no P was applied (Saarela 1992, Saarela et al. 2003). During the last five of the 15 years a continuous positive response to P fertilisation was measured at site 4 (Fig. 3). The rich but acid subsoil seemed to be less beneficial for barley and timothy. The small yield response in the non-mycorrhizal plant turnip rape in 1987 suggested that the symbiotic mechanism was not exceptionally important in this soil.

The rather acid loam soil in experiment 5 was a mixture of clay and sand with only 11% fine silt (2–20 µm). The soil was physically fairly favourable for growth, but the low content of organic matter obviously weakened its drought resistance. This soil had a high content of oxalate extractable

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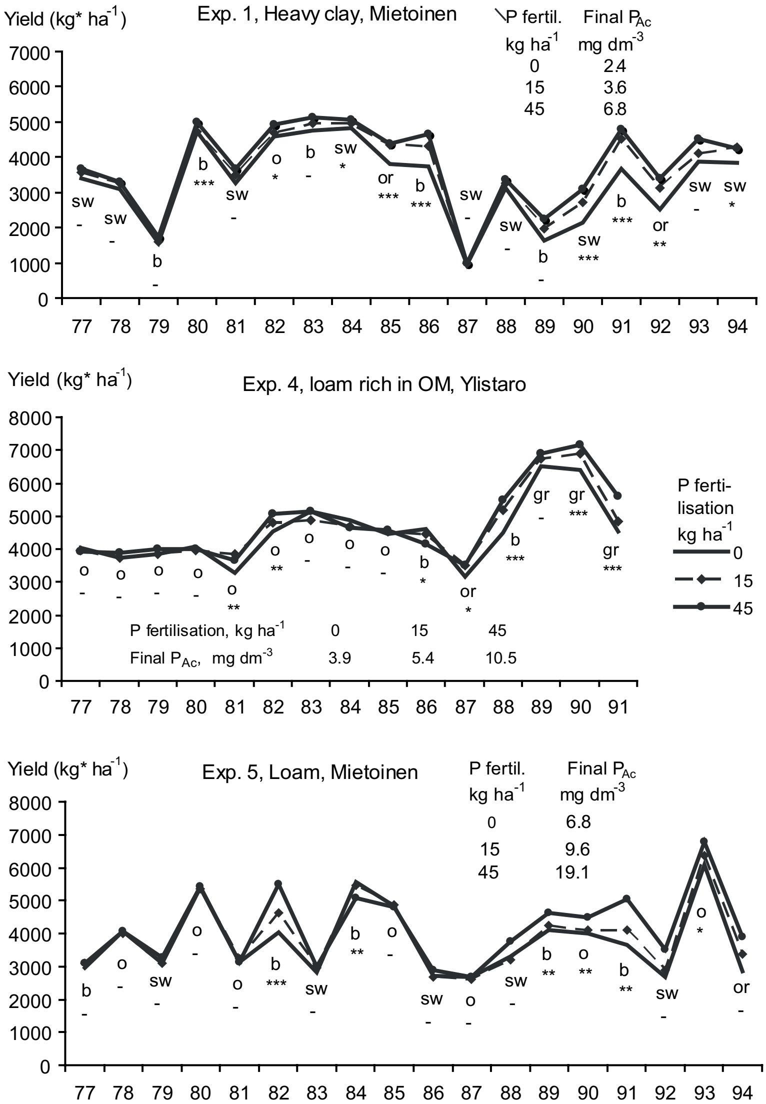

Fig. 3. Annual variation in yields with three amounts of repeated P fertilisation on three soils. Yield unit (kg*) = 0.5 kg rapeseed, 1.0 kg cereal grain or 1.0 feed units of grass equivalent to 1.0 kg barley grain. sw = spring wheat, b = barley, o = oats, or = oilseed rape. Asterisks (*, **, ***) indicate significant effect of P fertilisation (F) at P = 0.05, 0.01 and 0.001, respectively, – = not significant.

Fe in relation to Al (Hartikainen 1989), which is more typical for more fine-textured soils (Kaila 1963). The high Fe/Al ratio and low content of organic matter were possible reasons for the efficient improvement of the availability of P by liming as typical for clay soils (Saarela et al. 2000, 2003). This soil performed relatively well in the pot experiment, not only with liming but also without.

Grain yields and their responses to P fertilisation varied widely and irregularly at site 5 (Fig. 3). Sharp peaks occurred with the moderately acid-sensitive barley cultivars grown in the cool and dry seasons in 1982 (Suvi) and 1991 (Ida). As a more acid-tolerant crop, oats performed relatively well in this acid soil. As the mean of six years, RCY was 96% in oats, but 90% in barley and spring wheat in eleven years. No increases in oat yields by applied P were found until the fourteenth experimental year in 1990 (Fig. 3). The highest grain yield in this site was obtained in the 17th year when 192 kg P ha^{-1} had been removed from the soil by the previous sixteen crops. Then the grain yield grown without P fertilisation was 6.08 t ha^{-1} and contained 20.7 kg P ha^{-1}.

Effects of residual and freshly applied P

The yield responses to P fertilisation were roughly similar for the first two periods of six years, while sharp drops in the RCY values were found later on soils 1, 4 and 5 which contained low or medium amounts of extractable P (Table 5). The residual effects of previous P fertilisation studied on soils 1 and 5 in years 13–18 can be directly compared to the effects of continuous P fertilisation. During the final three years the earlier treatments were continued with the NK fertilisation and the NPK fertilisation formed an additional factor. As mean of soils 1 and 5 for the years 13–18, the yield response to continuous fertilisation with 45 kg P ha^{-1} was 800 kg ha^{-1}. As per cent of this, the residual effect of annual P application repeated 12 times was 30 and 68% with the P rates 30 and 60 kg ha^{-1}, respectively. The corresponding effect of continuous fertilisation with 15 kg P ha^{-1} was 50% or 400 kg ha^{-1}.

A summary of the results obtained with similar amounts of N and 0 or 20 kg P ha^{-1} with NK and NPK is presented in Fig. 4 as means of the experiments 1 and 5. The NPK fertiliser was almost equally efficient with the residuals of 30 and 60 kg P ha^{-1} as with the control treatment. The compound fertiliser produced maximum yields with residual P applied at 60 kg ha^{-1} but not at 30 kg ha^{-1}. Continuous use of 45 kg ha^{-1} sufficed for maximum yields without any supplement. The poor effect of NPK together with the 15 kg P ha^{-1} applied as superphosphate was possibly an exceptional result, which contradicts with the corresponding responses on the sandy soils 11 and 15 of this project (Saarela et al. 1995).

The decline of yields with large amounts of residual P showed the importance of continuous P fertilisation for sustainable plant production even in relatively rich soils. After twelve years the total amounts of P applied with the rates 30 and 60 kg ha^{-1} were 360 and 720 kg ha^{-1}, and after fifteen years the residuals had aged for three to fifteen years. Since the amounts of P removed with the harvested crops varied little with P fertilisation, the corresponding differences in P balance (P fertilisation minus P removal in crops) between these treatments and the control were almost as large as the difference in P fertilisation or 350 and 710 kg ha^{-1}. In relation to the total amounts of residual P accumulated in the soil, the yield responses were rather small in the final years of the experiments. On the other hand, normal annual fertilisation did not entirely compensate for the deficient supply of P from the soils impoverished by reduced fertilisation.

The short-term efficiency of the NPK-P, applied in accordance with general Finnish farming practice, was possibly poorer than usual because of the dry seasons. The loose fertiliser rows may dry up rapidly and remain practically rootless for weeks, and then the P of the fertiliser is almost totally unavailable. The normal placement of P, about 8 cm, may be too deep in wet and cold soils, as also found by Dibb et al. (1990). Roots should grow close to the fertiliser rows, because applied P remains within a 25 mm wide band for several months (Saarela and Saarela 2000). Rolling the whole soil surface or compacting the fertiliser rows with press wheels has been found to facilitate their rapid rooting and promote P uptake and growth during the dry early seasons typical in Finland.

Yield response and soil P_{Ac}

The supply of nutrients to crops is universally estimated on the basis of chemical soil tests. The P values determined by the Finnish acid (pH 4.65) ammonium acetate method (P_{Ac}) used since the 1950s, have predicted the availability of soil P fairly well in moderately and weakly acid soils (Keränen et al. 1963, Saarela 2002). In this study, each soil was tested every third seasons during the experimental period (Saarela et al. 2004). The P_{Ac} values are presented as means of the whole experimental period and the two (1–6 years and 7–12

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Table 5. Soil test P values (P_{Ac}, mg dm^{-3}) and relative yields (RY) during two or three periods at each site and the means of two groups of soils with “low” (sites 1 – 4) and "high" (sites 5 – 8) initial levels of (P_{Ac}). Values with residual P after withdrawn P fertilisation are presented in parantheses.

Site No	Crop years	Soil P_{Ac} by P rates (kg ha^{-1} a^{-1}) 0	15	30	45	60	RY by P rates (kg ha^{-1} a^{-1}) 0	15	30	45	60	Relative value 100 = kg[1] ha^{-1}	Sign[3] effects
1	1 – 6	3.1	3.6	4.6	4.4	5.4	90	94	99	98	100	3770	3
	7 – 12	3.1	4.0	5.6	6.0	7.5	91	98	98	100	100	3910	4
	13 – 18	2.3	3.6	(4.3)	6.7	(6.9)	78	93	(87)	100	(96)	3710	4
	1 – 18	**2.8**	**3.7**	**(4.9)**	**5.7**	**(6.6)**	**87**	**95**	**(98)**	**100**	**(100)**	**3800**	**11**
2	1 – 6	3.9	4.6	4.1	4.6	4.3	93	98	101	98	100	3670	3
	7 – 12	3.0	4.5	5.9	7.0	7.8	92	103	100	100	100	3660	3
	1 – 12	**3.5**	**4.5**	**5.0**	**5.8**	**6.1**	**93**	**100**	**101**	**99**	**100**	**3670**	**6**
3	1 – 6	4.7	5.4	6.8	5.8	6.5	94	97	100	98	100	2530	2
	7 – 12	5.8	6.5	8.3	9.0	11.1	94	93	96	99	100	3910	0
	1 – 12	**5.3**	**5.9**	**7.6**	**7.4**	**8.8**	**94**	**95**	**98**	**99**	**100**	**3220**	**2**
4	1 – 6	5.0	5.2	5.9	6.0	6.7	95	98	102	99	100	4130	2
	7 – 12	4.6	5.9	6.9	7.9	9.2	98	99	100	100	100	4600	3
	13 – 15	3.6	5.1	6.8	8.5	10.1	88	93	97	100	100	7860	2
	1 – 15	**4.6**	**5.5**	**6.5**	**7.2**	**8.3**	**95**	**97**	**100**	**100**	**100**	**5060**	**7**
1 – 4	**1 – 18**	**3.9**	**4.8**	**(6.0)**	**6.5**	**(7.4)**	**92**	**97**	**(99)**	**99**	**(100)**	**3980**	**26/57**
5	1 – 6	7.7	8.6	8.7	10.6	10.1	93	96	97	99	100	4110	1
	7 – 12	7.1	8.7	9.9	13.2	14.4	98	97	99	100	100	3690	(1)
	13 – 18	6.6	9.2	(9.4)	16.4	(13.0)	82	88	(87)	100	(93)	4720	4
	1 – 18	**7.1**	**8.8**	**(9.7)**	**13.4**	**(12.5)**	**91**	**94**	**(97)**	**100**	**(98)**	**4180**	**5**
6	1 – 6	9.1	9.2	8.8	9.8	9.5	98	100	100	98	100	3380	0
	7 – 12	7.8	8.9	9.9	11.1	12.8	103	99	100	99	100	3050	0
	1 – 12	**8.5**	**9.0**	**9.3**	**10.4**	**11.0**	**100**	**100**	**100**	**99**	**100**	**3340**	**0**
7	1 – 6	12.5	13.3	13.8	14.4	15.3	92	97	99	102	100	2930	0
	7 – 12	10.2	11.7	12.8	14.5	17.0	95	97	99	100	100	3200	2
	1 – 12	**11.3**	**12.5**	**13.3**	**14.5**	**16.1**	**93**	**97**	**99**	**101**	**100**	**3060**	**2**
8	1 – 6	55.6	66.4	58.6	72.0	52.6	100	99	101	101	100	4630	0
	7 – 12	37.4	47.7	49.4	56.7	49.0	95	97	102	103	100	4690	0
	13 – 15	30.9	41.2	(39.0)	59.3	(39.5)	99	96	(99)	100	(102)	4570	0
	1 – 15	**43.4**	**53.9**	**(51.1)**	**63.3**	**(48.6**	**98**	**98**	**(101)**	**101**	**(100)**	**4640**	**0**
8L[2]	1 – 6	57.5	51.2	71.3	58.5	73.2	99	100	103	99	100	4540	0
	7 – 12	46.9	44.3	69.3	63.5	70.2	105	99	104	101	100	4570	0
	13 – 15	42.5	40.3	(61.5)	63.3	(63.6)	94	95	(98)	100	(98)	4670	1
	1 – 15	**50.2**	**46.2**	**(69.7)**	**61.5**	**(70.3)**	**100**	**99**	**(103)**	**100**	**(100)**	**4580**	**1**
5 – 8	**1 – 18**	**24.8**	**26.9**	**(31.5)**	**33.8**	**(32.9)**	**96**	**97**	**(100)**	**100**	**(100)**	**4040**	**8/71**
1 – 8	1 – 6	17.7	18.6	20.3	20.7	20.4	95	98	100	99	100	3770	11/54
	7 – 12	14.1	15.9	20.0	21.2	22.3	97	98	100	100	100	3940	12/53
	13 – 15	13.5	16.0	(19.6)	25.3	(28.1)	86	92	(96)	100	(100)	4850	11/21
	1 – 18	**15.5**	**17.1**	**(20.1)**	**21.6**	**(22.0)**	**95**	**97**	**(100)**	**100**	**(100)**	**4010**	**34/128**

[1] 1.0 kg grain, 0.5 kg rapeseed or 1.0 feed units of grass equivalent to one kg barley grain
[2] initial liming with 10 t ha^{-1} ground limestone in 1980
[3] number of years with significant effect at P = 0.05 (negative effects in parentheses)

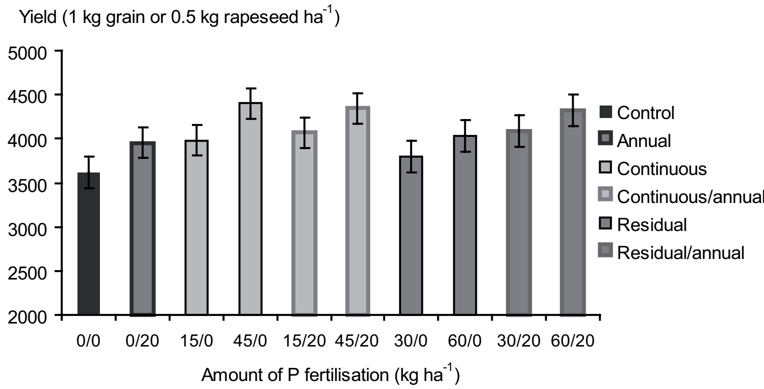

Fig. 4. Effects of continuous (years 1–18), residual (withdrawn from year 13) and annual P fertilisation (20 kg ha^{-1}) on yields in crop years 16–18, means from sites 1 and 5. Error bars are based on treatment means at each site and show the confidence intervals at P = 0.05.

years) or three (13– years) periods together with the corresponding RY values (Table 5).

The results of other field studies on clay and loam soils (Table 1) were summarised with the respective data of this study (Table 5). The combined data allows the relationships of the yield responses and the P_{Ac} values for different types of soil to be examined (Fig. 5). The sugar beet yields reported by Brummer (1959) show the essential differences between crops in P requirement. The large yield responses of sugar beet at the medium level of P_{Ac} are in agreement with the Swedish results obtained in sugar beets and other crops grown in rotation in the same plots (Carlgren and Mattsson 2001).

In agreement with earlier studies (Sippola 1980, Saarela 1992), the P_{Ac} value required for optimal yields depended on the pH of the soil (Fig. 5). Exceptionally high pH, at which the acetate method produces too high and unreliable values (Saarela 1992, Jaakkola et al. 1997) was associated with a large response to P fertilisation. Large responses to applied P were frequently measured at low pH values, and even the moderately weak acidity common in Finnish soils (Mäkelä-Kurtto and Sippola 2002) was detrimental. The rather strongly acid soil 2 in Pälkäne (pH 5.6), which appeared less toxic than typical at this pH and suffered from lodging, was probably untypical and should not be extrapolated for cereals other than oats. All the other acid mineral soils having a normal content of organic matter produced smaller RY values than were obtained at optimal pH. In strongly acid mineral soils, extractable P was poorly available even to oats (Saarela 1992). The detrimental effects of low pH values on P availability are probably largely biological and caused by dissolved aluminium.

All the Litorina soils plotted in Fig. 5 were better sources of P than the glacial soils. The high content of organic matter in the surface layer of the inherently deep soils was a possible reason for their good supply of P. However, the results of pot experiments and field studies from site 4 and other soils emphasise the importance of the lower part of soil profile. Deepening and diluting a glacial clay by deep ploughing improved the availability of P during dry periods and gave additional evidence of the role of the depth of the enriched soil (Table 1).

In the present study, the estimated optimal amount of repeated P fertilisation increased after twelve experimental years because of the sharp increase of the yield responses. The sharp decrease of RY with decreasing P_{Ac} (Fig. 5) and the changes of these values during the study period agreed fairly well at site 1 (Table 5) and also in the two soils studied by Yli-Halla (1989) (ref. 7 in Table 1). At site 4 the large final yield effect of P fertilisation originated from the more requiring crops, barley and timothy in stead of oats (Table 3), and no significant changes in the responses were found in the soils 2 and 3 which were rather low in P_{Ac}. The decline of barley yields caused by insufficient P

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fertilisation appeared to be rather sharp in some acid silty and sandy soils (Saarela et al. 1995) and not entirely explained by chemical soil tests.

The results from clay and loam soils summarised in Fig. 5 show the typical relationships between RY and the soil P_{Ac} value fairly exactly for sufficiently limed soils. The fundamental reason for the good fit is the primary importance of the intensity factor of soil P status for the supply of P from Finnish mineral soils (Saarela 1992) and a sufficient reliability of the acetate method in indicating it. The intensity character of the acetate method was shown by a close correlation of the P_{Ac} values with water extractable P (Uusitalo and Jansson 2002). In recent unpublished studies the values of P_{Ac} and water extractable P correlated especially closely in the weakly acid fine-textured soils in which Fe is a major sorption agent (Kaila 1963).

A good dependence between soil test P values and yield responses requires that both of them are reproducible and reliable parameters, and a high correlation coefficient requires that the supply of P to crops is insufficient. The relatively precisely determined and narrow response range to soil P_{Ac} at optimum pH is largely attributable to the long-term yield responses. As shown by Munk and Rex (1990), the yield effects obtained by short-term field experiments are not reliable indications of the availability of P in the soil and the optimal amount of long-term P fertilisation. When the pH is optimal, the acetate method appeared to be suitable even for precision fertilisation of P, while the same method is inaccurate at too low and too high pH.

Sufficient level of P_{Ac}

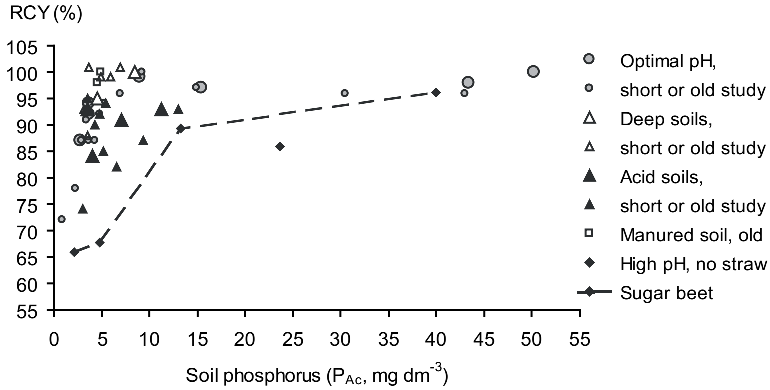
At some sites the yield responses to P fertilisation were large enough to allow the requirement of P fertilisation and the corresponding P_{Ac} values to be derived from the response curves. As much as 45 kg P ha^{-1} and a final P_{Ac} value of 19.1 mg dm^{-3} was required for maximum yields in the acid loam at site 5. In the acid clay loam in Vihti (Yli-Halla 1989), 30 kg P ha^{-1} was sufficient, though the final P_{Ac} value was not higher than 4.3 mg dm^{-3}. Large amounts of P were required at optimal pH in soil 1 because of its low initial P_{Ac} value and strong buffering for P (Fig. 1, Table 5), but the final P_{Ac} value was not higher than 6.7 mg dm^{-3} at 45 kg P ha^{-1} which was sufficient. The best effect with the lowest rate of P (15 kg ha^{-1}) was obtained in the loam soil at site 2, where maximum yield was achieved at P_{Ac} 4.5 mg dm^{-3}.

The yields obtained with different rates of repeated P fertilisation (Fig. 2, Table 5) indicate that the amounts of P similar to those of the harvested yield do not suffice for maximal yields if the P_{Ac} value is low and the yield responses large. This statement is true even though the P fertiliser was applied by the placement method. The increased mycorrhizal contribution studied in soil 1 (Kahiluoto et al. 2001) also seemed to be insufficient to compensate for the declining availability of P as detected by the chemical test. Soil test P (STP) values that are too low should be increased by applying larger amount of P than is removed with the harvested crops and fixed in the soil. Adequate P status should then be maintained by continuous fertilisation.

Replenishment of the P taken up by the crop and lost by fixation probably suffice for optimal long-term yields when the control treatment produces about 95% of the maximum yield obtained with large amounts of P fertilisation (RCY = 95%). The loss of extractable P caused by fixation to the soil in the 0.23 m deep plough layer was variable and slow at low level of P_{Ac}, on average 6 kg P ha^{-1} at P_{Ac} 5.0 mg dm^{-3} (Saarela at al. 2004). Cereal grain contains about 3.5 kg P in a tonne or 14 kg in 4 t (Saarela et al. 1995). Cereal straw contains about 6 kg P ha^{-1} but is usually returned to the soil. The low leaching of P from Finnish soils has a negligible effect on soil P status. The annual requirement of P for maintaining adequate P status is thus 20 kg ha^{-1} at the typical yield level of 4.0 t ha^{-1}.

At optimal soil pH, RCY was 95% at P_{Ac} 5–7 mg dm^{-3} (Fig. 5). Deep Litorina soils and deepened glacial soils occurred in the lower end of this range and typical glacial clay and loam soils in the upper end. Values of P_{Ac} which are one or two units higher than are sufficient by the common placement fertilisation may be required if the immediate ef-

Fig. 5. Dependence of relative control yield, RCY (yield without P fertilisation divided by the yield with sufficient P fertilisation) on extractable soil P. Large markers denote current conventional cultivation methods and means of 11 or more crop years (Tables 1 and 5). Small markers present old results, residual periods or other short studies. Sugar beet yields from Brummer's (1959) study.



fect of applied P is impaired by less favourable date or method of fertilisation, as is typical for manure. Even a small difference in P_{Ac} is significant according to the amounts of applied or removed P required to change the P_{Ac} value. At P_{Ac} 5.0 the mean buffer capacity derived from the field experiments was 133 kg P ha^{-1} per unit P_{Ac} (Saarela et al. 2004). The balance difference of 710 kg P ha^{-1} and final P_{Ac} values of 2.4 and 5.2 mg dm^{-3} at the residual P rates 0 and 60 kg ha^{-1} correspond to the buffer capacity of 710/2.8 = 254 kg ha^{-1} per unit P_{Ac}.

The acid ammonium acetate soil test is a modification of the Morgan test, and the P_{Ac} values of mineral soils closely correlate with the Morgan P values (Saarela et al. 2004). Because Morgan P is 0.7 times P_{Ac}, the critical P_{Ac} range at optimal pH (5–7 mg dm^{-3}) is equal to the Morgan P range of 3.5–5 mg kg^{-1}. These values correspond to the lower end of the optimal range of Morgan P in the north eastern parts of the United States, from 4 to 7 mg kg^{-1} (Jokela et al. 1998). In strongly acid glacial soils the adequate P_{Ac} value was much higher and more variable.

Application of results

The soil test P values of cultivated Finnish soils were rapidly increasing during the 1970s as a result of the general balance surplus of soil P caused by abundant fertilisation. The target range of P_{Ac} for cereals and leys was 6–15 mg dm^{-3} in clay soils and 10–25 mg dm^{-3} in coarser soils including glacial loams. A large P surplus was assumed to be necessary to maintain sufficient P availability in the acid soils of Finland. Small amounts of P were recommended up to the excessive P_{Ac} value of 200 mg dm^{-3}, and even in richer soils after a three years period of exhaustive cropping. The field experiments establish from the 1960s (Table 1) and the first results of this project summarised annually and reported in Finnish showed the possibilities to reduce the amounts of P fertilisation on the soils which had high P_{Ac} values. Farmers were advised to check the amounts of applied P by means of soil tests.

The interpretation of the chemical soil test P values was revised on the basis of the Finnish report of these results (Saarela et al. 1995). The estimated optimal amounts of P are even maximal amounts allowed by the Agri-Environmental Program, which is an essential part of farm income (Koikkalainen and Lankoski 2004). The target range of P_{Ac} for clay soils is 6–12 mg dm^{-3} for the clays rich in organic matter and 7–14 mg dm^{-3} for the typical clays containing 6–3% organic matter. For loam soils, which were ranked in the same category with silts and sands, the target range of P_{Ac} is 10–18, 12–20 and 13–22 mg dm^{-3} at > 6, 6–3 and < 3% organic matter.

Within the target ranges the amount of annual P fertilisation, in kg ha^{-1}, is 10 for oats, 15 for wheat, rye and rapeseed, 18 for barley and 20 for leys cut at least twice a season. These amounts are allowed for average yields and must be reduced with lower yields and may be increased with higher yields. As an environmentally important restriction in the fertilisation based on chemical soil testing, no fertiliser P is allowed to be used at P_{Ac} >40 mg dm^{-3} in clay soils and >50 mg dm^{-3} in loam soils. The upper limits were derived from the equilibrium phosphate concentrations (EPC) determined for heavily enriched soils (Yli-Halla et al. 1997).

Conclusions

The level of soil P_{Ac} which gives a long-term RCY value of 95% was considered to be a relevant basis for P fertilisation recommendations. At optimal soil pH this RCY value was achieved at P_{Ac} 5–6 mg dm^{-3} in the Litorina soils and in the well-aggregated deep glacial clays, and at P_{Ac} 6–7 mg dm^{-3} in the typical glacial clays and loams. At this P_{Ac} the application of an amount of P equal to that in the harvested crop will increase the relative yield from 95% to almost maximum in most years, when the fertiliser is applied by the common placement method. In other words, the P status of the soil is optimal at this level of P_{Ac}.

The narrow range of optimal P_{Ac} established in this study resulted from two essential requirements: i) the acid ammonium acetate soil testing method was reliable in predicting the supply of P to crops from the moderately and weakly acid soils rich in sorption active Fe, and ii) the yield responses which were integrated over the long study periods levelled the untypical results of individual years caused by variable weather conditions and other reasons. The different P requirements and yield responses of individual species and varieties were also partly levelled.

The optimal P_{Ac} value (5–7 mg dm^{-3}) correspond to the lower end of the present target range for clay soils, but is slightly lower than the present target for loam soils. In acid soils (pH 5.6–6.0 in mineral soils) the same target P_{Ac} is probably sufficient for oats, but not for other crops grown without proper liming. In still more acid soils the availability of P is poor even for oats and other moderately acid-tolerant crops. The smaller apparent P requirement of oats obtained during the first years of this project was probably largely caused by the better tolerance to soil acidity of this crop and should not be extrapolated to adequately limed soils.

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SELOSTUS

Vuosittain toistetun fosforilannoituksen vaikutus Suomen peltokasvien satoon I. Savi- ja hiuemailla saadut sadonlisäykset

Into Saarela, Yrjö Salo ja Martti Vuorinen

Maa- ja elintarviketalouden tutkimuskeskus

Useimmilla pelloilla 1940-luvulla alkanut runsas fosforilannoitus on parantanut Suomen viljelymaiden alun perin heikkoa kykyä luovuttaa kasveille fosforia. Etelä-Suomen ja länsirannikon savi- ja hiuemaat ovat kuitenkin osoittautuneet paremmiksi fosforin lähteiksi kuin sisämaan hiesuiset ja karkeat maat. Viiden vuosittain annetun fosforimäärän vaikutuksia viljojen ja muiden kasvien satoon tutkittiin 12–18-vuotisilla kenttäkokeilla savi- ja hiuemailla.

Tutkimukset osoittivat, että Suomen savien ja hiukeiden fosforivarat riittävät useiksi vuosiksi suhteellisen hyvien satojen tuottamiseen. Suuret fosforilannoituksella saadut sadonlisäykset ovat todennäköisiä vain pelloilla, joiden viljavuusanalyysin P-luku on huono, pH-luku liian alhainen tai pH on poikkeuksellisesti liian korkea. Myös maan huonosta rakenteesta ja kuivumisesta johtunut tehoton ravinteiden otto lisää fosforilannoituksen tarvetta. Ilman fosforilannoitusta saatu sato (maan P-luku 15,5 mg/dm^3) oli keskimäärin 94,6 % riittävällä fosforilla saadusta sadosta (4000 kg tai ry/ha) vaihdellen 87 %:sta maan P-luvulla 2,8 mg/dm^3 100 %:iin P-luvulla 50 mg/dm^3. Runsasmultainen, liejuinen hiue tuotti täyden sadon myös maan P-luvulla 8,5 mg/dm^3. Riittävästi kalkituilla mailla saatiin ilman fosforilannoitusta 95 % runsaalla fosforilannoituksella saadusta sadossa, kun maan P-luku oli 5–7 mg/dm^3. Korjatun sadon fosforisisältöä (14 kg 4 viljatonnissa) ja uuttuvan fosforin keskimääräistä pidättymistä (6 kg/ha) vastaavalla sijoituslannoituksella (20 kg/ha P) tällainen maan fosforitila riitti edullisina kasvukausina lähes täyteen satoon. Maan P-luku 5–7 mg/dm^3 arvioitiin pitkällä tähtäyksellä optimaaliseksi. Liejusaville sekä syvä- ja runsasmultaisille aitosaville riitti vaihteluvälin alapää, muille saville ja hiukeille tarvittiin alueen yläpäätä vastaava P-tila.