Journal of Agricultural Science, *Cambridge* (2001), **137**, 379–395.
DOI: 10.1017/S0021859601001526 *Printed in the United Kingdom*

Effects of soil- and foliar-applied phosphorus fertilizers on the potato (*Solanum tuberosum*) crop

M. F. ALLISON*, J. H. FOWLER AND E. J. ALLEN

Cambridge University Farm, *Huntingdon Road*, *Girton*, *Cambridge*, *CB3 0LH*, *UK*

(*Revised MS received 23 May 2001*)

SUMMARY

Twenty-two field experiments in England, done between 1986 and 2000, tested the effects of phosphorus (P) fertilizers on number of tubers and tuber yield in *Solanum tuberosum*. Applying P fertilizer resulted in statistically significant increases in tuber yield in six experiments and the optimal P application rate ranged from *c*. 90 to 180 kg P/ha. Statistically significant increases in yield in response to application of P fertilizers were found only in soils that contained < 26 mg Olsen-P/l (< Index 3) and appeared to be associated with increases in ground cover. Statistically significant increases in the number of tubers in response to application of P fertilizer were found only in soils that contained < 16 mg Olsen-P/l (< Index 2) and appeared to be associated with an increase in ground cover by the time of tuber initiation (*c*. 5–6 week after planting). Each tonne of tuber fresh-weight yield was, on average, associated with removal of 0·39 kg P but regression analysis showed that this value increased as soil Olsen-P increased. Re-analysis of published data showed that whilst the probability of a response to P fertilizer and the optimum P application rate may have been overestimated, some statistically significant responses to P fertilizer did occur when Olsen-P was > 26 mg/l. The absence of yield responses on P Index 3 soils found in the current experiments was attributed to increased use of irrigation that may have increased the availability of soil P. Re-interpretation of data from long-term experiments showed that the agronomic benefits of increasing soil P status by applying more P than is removed by harvested crop parts, are small. Since large P residues, estimated by Olsen-P or degree of soil P saturation, are associated with desorption of P and consequent loss to drainage water it is inadvisable to increase soil P above Index 3. For these reasons, no P fertilizer is recommended for Index 4 soils, an amount equivalent to replacement is recommended for Index 3 soils but up to 110–130 kg P/ha should be applied to Index 0 soils. Applications of foliar P had no effect on number of tubers or tuber yield and this practice cannot be recommended.

INTRODUCTION

The 1998 British Survey of Fertilizer Practice (Fertilizer Manufacturers Association 1998) showed that, on average, second early and maincrop potatoes receive 80 kg P/ha and that potatoes receive more phosphorus (P) fertilizer than any other arable, vegetable, fruit or grassland crop. These large P applications reflect the widespread and longstanding view that potatoes are responsive to P fertilizers even on soils that contain moderate to large P reserves (Cooke 1982; Archer 1985). Within England and Wales, the most widespread fertilizer recommendations are those published by the Ministry of Agriculture, Fisheries and Food (MAFF) in *Reference Book 209* which base the recommendations for P on soil analysis (MAFF 1994) using sodium bicarbonate as the extractant (Olsen *et al*. 1954; MAFF 1986). The results are grouped into Indices on which the recommended amount of P fertilizer is based. The first edition of *Reference Book 209* was published in 1973 with the sixth edition published in 1994. During this period the main changes to the P fertilizer recommendations have been the elimination of recommendations that distinguished between organic and mineral soils and an overall increase in the amount of P fertilizer recommended (Table 1).

The relationship between soil P status and fertilizer P recommended is based on many series of published experiments (e.g. Boyd & Dermott 1964; Birch *et al*. 1967; Archer *et al*. 1976; Webber *et al*. 1976; Farrar & Boyd 1976; Johnson & Zemroch 1981) and on several studies by the Agricultural Development and

* To whom all correspondence should be addressed. Email: m.allison@farm.cam.ac.uk

Table 1. *Evolution of phosphate fertilizer recommendations for maincrop potatoes (kg P/ha) in MAFF* Reference Book 209

			Bicarbonate extractable P (mg/l) and soil P Index					
			0–9	10–15	16–25	26–45	46–70	> 71
Edition	Year	Soil type	0	1	2	3	4	> 4
1	1973	Mineral	135	110	95	85	55	–
		Fen – light and loamy peats	110	110	85	85	85	–
		Fen – peat loams	135	135	110	110	110	–
		Fen – light and medium silts	135	110	85	55	40	–
		Fen – heavy silts	165	135	110	85	70	–
2	1979	Mineral	155	130	110	90	45	–
		Peaty, organic, moss and warp	155	130	110	90	90	–
3	1983	Mineral	155	130	110	90	45	–
		Peaty, organic, moss and warp	155	130	110	90	90	–
4	1985	Mineral	155	130	110	90	45	–
		Peaty, organic, moss and warp	155	130	110	90	90	–
5	1988	Mineral	155	130	110	90	45	–
		Peaty, organic, moss and warp	155	130	110	90	90	–
6	1994	All soil types	155	130	110	90	45	0

Advisory Service (ADAS) and commercial organizations that have not been formally published. Many of the early experiments had a 3^3 factorial design with limited replication and experimental errors were usually estimated from higher order interactions. The relevance of these early experiments to current P fertilizer recommendations is questionable. The yields of these early experiments, whilst similar to national average yields of the period, are smaller than current yields which reflect changes in farming practice, particularly use of irrigation. For example, British Potato Council crop statistics (British Potato Council 2000) show that *c*. 24% of the national crop area was irrigated in 1976 compared with 54% in 1999. The maintenance of soils at small moisture deficits may make nutrients more available and may reduce the response to fresh P fertilizer (Simpson 1962; Harris 1985). It is also increasingly recognized that, given good soil conditions, the potato crop may exploit a large volume of soil, for example Allen & Scott (1992) showed that potatoes may produce fibrous roots to a depth *c*. 120 cm. Furthermore, since the work of Boyd & Dermott (1964) there has been a change in the soil texture on which the national crop is produced. The increase in the availability of irrigation has resulted in a greater use of lighter-textured soils since these have a greater flexibility in timing of cultivations and harvesting and are particularly suited to the production of processing potatoes.

An earlier paper (Allison *et al*., 2001) showed that in respect of the requirement for K in potatoes, many of the published studies appeared to overestimate fertilizer K requirement. Many potato growers also feel that current P recommendations are too large and support for this view comes from a variety of sources. A review by Edwards *et al*. (1997) compared published P fertilizer recommendations for maincrop potatoes grown on soils containing defined amounts of Olsen extractable P from several countries. For Index 0 soils the amount of P recommended varied from 35 kg P/ha (Denmark) to 153 kg P/ha (England and Wales). Similarly, for Index 3 soils, 87 kg P/ha would be recommended in England and Wales compared with 0 (Italy) or 10 kg P/ha (New Zealand). Information from the British Survey of Fertiliser Practice and the British Potato Council (British Survey of Fertiliser Practice 2000; British Potato Council 2000) shows that whilst the amount of P applied to maincrop potatoes has decreased, yields have increased.

Within the UK potato industry there is also a widespread belief that increasing the P supply to the potato crop will increase the progeny tuber population, and this effect is independent of any effect on yield. A consequence of this perception is that seed and early potato crops (where many small tubers are normally required) are, for a given soil P Index, recommended a similar amount of P fertilizer to maincrop potatoes even though their yields may be much smaller. Similarly, commercial contracts for Russet Burbank destined for processing into French fries (where larger tubers are required), prohibit production on land with P Indices > 3 so as to avoid excess number of tubers. The experimental evidence to support these practices is scant. Early studies by Hanley *et al*. (1965) and Berryman *et al*. (1973) state that application of P fertilizer increased the number of tubers but neither present data. A review by Perrenoud (1983) and quoted by Harris (1992), states that use of P fertilizers increased the number of tubers

Table 2. *Site, soil and crop management details*

Expt	County	OS Grid	Sand (%)	Silt (%)	Clay (%)	P (mg/l)	P Index	K (mg/l)	Mg (mg/l)	Variety	Date of planting	Date of harvest	Crop irrigated
1	Cambridgeshire	TL428601	53	30	18	–	4	–	–	Estima	12 May 86	9 Sep 86	Yes
2	Cambridgeshire	TL425602	58	26	16	–	3	–	–	Estima	27 Apr 87	30 Sep 87	Yes
3	Norfolk	TL985832	87	6	7	33	3	95	43	Estima	10 May 89	20 Sep 89	Yes
4	Norfolk	TG386111	57	30	13	27	3	142	55	Estima	30 Mar 89	2 Sep 89	Yes
5	Norfolk	TG386083	71	20	9	45	3	86	42	Estima	28 Apr 89	13 Sep 89	No
6	Norfolk	TG196243	61	33	6	59	4	340	52	Estima	28 Mar 89	16 Aug 89	Yes
7	Norfolk	TF585233	61	23	16	22	2	200	> 250	Estima	24 May 89	23 Aug 89	No
8	Lincolnshire	TF415213	30	40	30	11	1	223	195	Estima	19 May 89	26 Sep 89	No
9	Lincolnshire	TF455333	38	50	12	30	3	192	68	Estima	8 May 89	5 Sep 89	No
10	Suffolk	TM336542	89	7	7	40	3	93	55	Estima	4 May 89	30 Aug 89	Yes
11	Cambridgeshire	TL435600	78	11	11	80	5	336	75	Estima	4 May 89	1 Sep 89	Yes
12	Nottinghamshire	SK698578	89	9	5	28	3	152	153	Record	19 Apr 93	16 Aug 93	Yes
13	North Yorkshire	NZ171064	nd	nd	nd	16	2	61	158	Record	10 May 93	17 Aug 93	No
14	Hampshire	SU645574	39	43	18	8	0	115	54	Pentland Dell	12 May 94	3 Oct 94	No
15	Hampshire	SU640572	20	44	36	32	3	462	37	Russet Burbank	14 May 94	3 Oct 94	Yes
16	Berkshire	SU827659	7	16	77	57	4	94	42	Shepody	11 Apr 94	19 Jul 94	Yes
17	Suffolk	TM364448	86	9	5	25	2	67	76	Maris Bard	18 Mar 94	21 Jun 94	Yes
18	County Durham	nd	nd	nd	nd	nd	2	nd	nd	Lady Rosetta	25 Apr 95	11 Sep 95	No
19	Cornwall	SX412543	nd	nd	nd	8	0	150	117	Estima	18 May 98	16 Sep. 98	Yes
20	Gloucestershire	SO727157	24	41	35	8	0	103	587	Nadine	28 May 99	13 Oct 99	No
21	Herefordshire	SO633260	71	15	14	45	3	260	96	Maris Peer	18 May 00	1 Sep 00	Yes
22	Cheshire	SJ426579	30	36	34	14	1	93	421	Estima	26 May 00	20 Sep 00	Yes

Particle size of sand, 2·00–0·63 mm; silt 0·63–0·002 mm; clay < 0·002 mm. nd, not determined.

but a review by O'Brien *et al.* (1998*a*) could find few published reports on the effects of nutrients, other than N, on tuber initiation. Recently, Jenkins & Ali (2000) found that application of P fertilizer to potato crops growing on P Index 1 soils was associated with an increase in the number of tubers at final harvest but no effect of P fertilizers occurred on an Index 3 soil. It is of concern that management decisions such as location of production and fertilizer policy are based on such limited and inconclusive evidence and this situation needs to be remedied.

A survey of the 1991 potato crop by the Potato Marketing Board (now the British Potato Council, BPC) showed that *c.* 15% of the potato area received applications of foliar P in addition to soil-applied P fertilizers. Early studies showed that foliar P was efficiently taken up by the potato crop but had little effect on tuber yield (Prasad & Brereton 1970). However, within the UK much of the commercial interest in foliar application of P was stimulated by studies done by ADAS (e.g. MAFF, 1979, 1980, 1981, 1982). These experiments and more recent studies by Lewis & Kettlewell (1992) and Kilpatrick (1993) used maincrop varieties and soils with P indices ranging from 0 to 4 for testing factorial combinations of soil and foliar-applied P. In these experiments there were no significant effects of foliar P on number of tubers or tuber yield. Despite the paucity of evidence to support use of foliar P, its use has become common, increasing variable costs of production with little or no benefit.

The work described in this paper investigates the response of potato crops to soil-applied P fertilizer when grown on soils with different amounts of extractable P under current commercial management conditions. In a limited number of experiments the effects of foliar-applied P were also tested in combination with soil-applied P. The objective of this work was therefore, to establish whether current P fertilizer recommendations are justified and, if needed, to suggest modifications to them.

MATERIALS AND METHODS

Twenty-two experiments (referred to in the text and Tables as E1 … E22) were done between 1986 and 2000 that tested the effects of P fertilizers on the growth and yield of potato crops grown on different soil textures in England. All experiments were hand planted into pre-formed ridges or beds. Within 3 days after planting, the soil-applied fertilizer treatments were broadcast, by hand, onto the surface of the ridges or beds. The fertilizers were then thoroughly incorporated into the top 5 cm of soil by raking. In all experiments triple super phosphate (20% P) was used as the source of P. Six experiments (E1, 2, 12, 13, 19 and 20) also tested the effects of foliar-applied P on growth and yield. Irrigation was applied to 14 of the 22 experiments and the irrigation was scheduled using a commercial scheduling system (Stalham *et al.* 1999) to ensure that limiting soil moisture deficits were not exceeded. Crop protection chemicals were applied according to best commercial practice. The experimental design varied from experiment to experiment, but in all cases treatments were allocated at random into blocks or main plots and each treatment was replicated at least three times. Details specific to each experiment are given in Table 2 and Table 3.

At harvest, an area of at least 2·0 m^2 was dug by hand from each plot and the harvested areas were always guarded by unharvested rows and plot-ends. The number of stems (main and secondary) was recorded and all tubers > 10 mm were collected. The tubers were returned to Cambridge where they were graded and the weight and number of tubers in each 10 mm size grade was recorded. Tuber dry matter (DM) concentrations were measured in a subsample of tubers (*c.* 500 g), taken from the size grades with the largest yield (usually 40–60 mm). The subsample was then dried to constant weight at 95 °C. The concentration of P in the dried tubers was measured using standard methods (MAFF 1986). All variates were analysed by analysis of variance and treatment means are stated to be significantly different only if the probability of the differences occurring by chance was less than 5% ($P < 0·050$). Some experiments also tested the effect of other nutrients applied in factorial combination with the P treatments (Table 3). Whilst the main effects of these treatments were sometimes statistically significant, there were few statistically or agronomically significant interactions between treatments. Therefore, for simplicity, only the main effects of the P treatments have been presented in the Tables.

RESULTS

Eighteen experiments were done on soils with a P index of 3 or less and where large amounts of P fertilizer are currently recommended. The coefficients of variation (CV) for total (> 10 mm) tuber fresh weight (FW) yield in these experiments were generally small. Ten experiments had CVs ⩽ 10% and only two (E1 and 14) had CVs > 15%. More importantly, the standard errors (S.E.) for the effect of P on tuber yield were also small (*c.* 3% of the mean yield). Therefore, these experiments provide a sensitive test of the effects of P on the yield of the potato crop. The mean total fresh weight of all experiments was *c.* 45 t/ha, which is similar to the current national average yield. Exceptionally small yields were found in two experiments (E14 and 18) that suffered from soil compaction and drought stress respectively and the results from these two experiments should be treated with caution. Generally, yields smaller than the national average yield (48 t/ha) were associated with short growing seasons and/or lack of irrigation.

Table 3. *Details of soil and foliar P treatments and experimental design*

Expt	Levels of soil P (kg P/ha)	Levels of K	Levels of N	Design and number of replicates	Date of foliar P treatments	Foliar treatment
1	0, 55, 110	1	1	Factorial; 4 blocks	27 Jun 86 or 21 Jul 86	Unsprayed, 0 (water), 2·2 or 4·4 kg P/ha as commercial product
2	0, 55, 110	1	1	Factorial; 4 blocks	26 Jul 87	Unsprayed, 0 (water), 2·2 or 4·4 kg P/ha as commercial product
3	50, 100	3	5	Factorial; 3 blocks	–	–
4	50, 100	2	5	Factorial; 4 blocks	–	–
5	50, 100	3	5	Factorial; 3 blocks	–	–
6	0, 50	2	5	Factorial; 4 blocks	–	–
7	50, 100	2	5	Factorial; 4 blocks	–	–
8	50, 100, 150	2	5	Factorial; 3 blocks	–	–
9	50, 100	2	5	Factorial; 4 blocks	–	–
10	50, 100	3	5	Factorial; 3 blocks	–	–
11	0, 50	2	5	Factorial; 4 blocks	–	–
12	0, 45, 90, 135	1	1	Factorial; 6 blocks	2 Jun 93	6·6 kg P/ha as mono ammonium phosphate
13	0, 45, 90, 135	1	1	Factorial; 6 blocks	21 Jun 93	6·6 kg P/ha as mono ammonium phosphate
14	0, 90, 180	4	1	Factorial; 3 blocks	–	–
15	0, 45, 90	4	1	Factorial; 3 blocks	–	–
16	0, 45, 90	4	1	Factorial; 3 blocks	–	–
17	0, 45, 90	3	1	Factorial; 4 blocks	–	–
18	0, 45, 90, 135, 180	2	1	Factorial; 3 blocks	–	–
19	0, 55, 110, 165, 220	1	1	Unbalanced factorial; 4 blocks	11 Aug 98	6·6 kg P/ha as mono ammonium phosphate
20	0, 65, 135	4	1	Factorial; 3 blocks	13 Jul 99	6·6 kg P/ha as commercial product
21	0, 45, 90, 135, 180	1	1	4 blocks	–	–
22	0, 45, 90, 135	4	1	Factorial; 3 blocks	–	–

Table 4. *Main effects of basal P application on tuber FW yield > 10 mm (t/ha)*

			kg P/ha						
Expt	Variety	Mean	0	45	90	135	180	S.E.	D.F.
12	Record	56·8	56·3	56·4	56·1	58·2		1·09	34
13	Record	42·1	40·0	40·7	44·0	43·8		1·08	35
14	Pentland Dell	22·0	21·0		21·2		23·9	0·85	22
15	Russet Burbank	30·7	30·0	32·2	29·8			1·47	22
16	Shepody	42·5	42·7	41·9	42·8			1·18	21
17	Maris Bard	39·0	38·4	39·7	38·9			1·73	24
18	Lady Rosetta	22·1	22·0	20·8	22·1	22·8	22·7	0·95	17
21	Maris Peer	41·3	41·2	37·8	41·2	43·8	42·7	2·07	12
22	Estima	40·2	31·9	39·3	42·3	47·2		1·32	30
Expt	Variety	Mean	0	55	110	165	220	S.E.	D.F.
1	Estima	63·4	62·9	63·7	63·7			0·97	69
2	Estima	73·7	71·5	74·5	75·1			1·52	43
19	Estima	61·2	52·7	61·0	68·1	69·4	56·4	4·17	24
Expt	Variety	Mean	0	65	135			S.E.	D.F.
20	Nadine	36·3	34·9	35·9	38·0			1·79	46
Expt	Variety	Mean	0	50	100	150		S.E.	D.F.
3	Estima	42·8		42·6	42·9			0·83	58
4	Estima	58·2		58·8	57·6			1·28	57
5	Estima	41·5		41·7	41·3			0·63	58
6	Estima	64·1	64·6	63·7				0·90	57
7	Estima	35·2		34·0	36·5			0·62	57
8	Estima	34·2		31·6	35·2	35·7		0·56	58
9	Estima	30·0		29·1	30·9			0·71	57
10	Estima	53·5		53·2	53·9			0·86	58
11	Estima	54·1	54·7	53·6				0·83	57

Conversely, large yields were generally associated with long growing seasons and use of irrigation.

Main effects of soil-applied P on tuber yield and number of tubers

Soil-applied P fertilizer had a significant effect ($P < 0{\cdot}050$) on tuber FW yield in only six experiments (Table 4; E7, 8, 13, 14, 19 and 22). This may be an underestimate since some experiments (E3–5, 9 and 10) did not have a P0 treatment, but in these experiments, the optimum rate of P must have been less than the smallest P application rate tested (50 kg P/ha). The optimum rate of P application was defined as the smallest P application rate above which there was no statistically significant increase in yield and this was estimated from examination of treatment means and the corresponding t statistic multiplied by the S.E. The reasons for using this method, as opposed to the estimation of the optimal P application rate by curve fitting, have been described in an earlier paper (Allison *et al*., 2001). For E7, only two rates of P were tested and, in consequence, an optimal P application rate could not be estimated. For the remaining sites (E8, 13, 14, 19 and 22) the optimum P application rate varied from *c*. 90 kg P/ha (E13) to *c*. 180 kg P/ha (E14), although the results from E14 must be viewed with caution since the largest yield increase was associated with application of the final increment of P fertilizer and the yields were very small. Compared with treatments that received no P fertilizer the FW yield response to the optimum P application ranged from 3 t/ha (E14) to 16 t/ha (E19). Statistically significant yield responses were found at two of the three Index 0 sites, at both Index 1 sites and at half of the Index 2 sites. There were no yield responses for soils with P Indices $\geqslant 3$. Thus, for soils with small amounts of Olsen extractable P (soil P Index 0 and 1) or with large amounts of P (Index 3 or above) the Olsen method was reasonably reliable at predicting the probability of a significant yield increase in response to applied P. However, for Index 2 soils, which may account for *c*. one-fifth of the national potato area (Skinner & Todd 1998) the Olsen method was much less reliable.

Soil-applied P fertilizer had a significant effect on

Table 5. *Main effects of basal P application on the number of tubers > 10 mm (000/ha)*

			kg P/ha						
Expt	Variety	Mean	0	45	90	135	180	S.E.	D.F.
12	Record	796	793	775	786	831		19·5	34
13	Record	635	579	637	656	666		24·0	35
14	Pentland Dell	313	294		301		344	12·5	22
15	Russet Burbank	487	481	501	480			17·2	22
16	Shepody	389	389	394	384			13·9	21
17	Maris Bard	435	416	431	458			21·3	24
18	Lady Rosetta	525	553	502	527	536	506	18·0	17
21	Maris Peer	772	779	729	741	774	839	27·4	12
22	Estima	362	325	366	369	388		13·5	30
Expt	Variety	Mean	0	55	110	165	220	S.E.	D.F.
1	Estima	693	689	684	707			13·7	69
2	Estima	435	433	437	435			9·7	43
19	Estima	437	396	436	453	470	455	23·5	24
Expt	Variety	Mean	0	65	135			S.E.	D.F.
20	Nadine	418	422	413	419			16·9	46
Expt	Variety	Mean	0	50	100	150		S.E.	D.F.
3	Estima	528		528	529			10·2	58
4	Estima	584		587	581			12·5	57
5	Estima	487		486	488			7·1	58
6	Estima	534	532	536				8·3	57
7	Estima	406		395	417			7·7	57
8	Estima	355		337	364	365		7·6	58
9	Estima	630		623	636			10·7	57
10	Estima	538		534	541			8·1	58
11	Estima	804	803	806				13·9	57

Table 6. *Main effects of foliar P applications on tuber FW yield > 10 mm (t/ha)*

				kg P/ha					
Expt	Variety	Mean	Unsprayed	0	2·2	4·4	6·6	S.E.	D.F.
1	Estima	63·4	64·6	62·2	63·5	63·5		1·12	69
2	Estima	73·7	76·6	71·8	74·2	72·2		1·76	32
12	Record	56·8	57·1				56·4	0·77	34
13	Record	42·1	42·8				41·5	0·76	35
19	Estima	60·6	63·2				58·0	2·56	15
20	Nadine	36·3	35·8				36·7	1·46	46

the number of tubers > 10 mm in only three experiments (E8, 14 and 22) and the increase was only *c*. 30–40 000 tubers/ha (Table 5). Fertilizer P had a significant effect on the number of tubers only at those sites where soil P fertilizer had an effect on tuber FW yield and where the P Index was 0 or 1. The increase in the number of tubers > 10 mm due to application of basal P fertilizer was mainly due to an increase in the number of tubers > 10 mm per stem. However, in one experiment (E22) the effect of basal P on the number of tubers per stem was not significant and in another experiment (E8) basal P fertilizer also had a small but significant effect on the number of stems (data not shown).

Table 7. *Main effects of foliar P applications on number of tubers > 10 mm (000/ha)*

				kg P/ha					
Expt	Variety	Mean	Unsprayed	0	2·2	4·4	6·6	S.E.	D.F.
1	Estima	693	694	679	689	712		15·8	69
2	Estima	435	452	430	419	438		11·2	32
12	Record	796	793				800	13·8	34
13	Record	635	643				626	17·0	35
19	Estima	428	435				422	13·4	15
20	Nadine	418	402				435	13·8	46

Table 8. *Main effects of basal P application on P removal by tubers at harvest (kg P/ha)*

			kg P/ha						
Expt	Variety	Mean	0	45	90	135	180	S.E.	D.F.
14	Pentland Dell	10·9	9·4		10·7		12·8	0·42	22
15	Russet Burbank	10·1	8·7	10·8	10·9			0·41	20
16	Shepody	23·3	21·9	23·6	24·3			1·10	21
Expt	Variety	Mean	0	55	110	165	220	S.E.	D.F.
19	Estima	20·3	15·5	18·4	22·6	25·8	24·0	1·80	24
Expt	Variety	Mean	0	50	100	150		S.E.	D.F.
3	Estima	21·6		21·0	22·2			0·55	58
4	Estima	21·8		21·5	22·2			0·56	57
5	Estima	17·9		17·7	18·1			0·29	58
6	Estima	24·9		24·6	25·2			0·55	57
7	Estima	9·4		8·4	10·3			0·23	57
8	Estima	11·8		9·7	12·5	13·2		0·29	58
10	Estima	23·5		21·6	25·3			0·55	58

Main effects of foliar P on tuber yield and number of tubers

The effects of foliar-applied P on tuber FW yield and number of tubers were tested in six experiments (E1, 2, 12, 13, 19 and 20). Foliar-applied P had no effect on FW yield or number of tubers in any experiment (Table 6, Table 7). This was despite two of the experiments being done on P Index 0 soils and all experiments included treatments that had received no soil-applied P fertilizer.

Phosphate removal in tubers

The removal of P in tubers at harvest was measured in 11 experiments (Table 8). Application of P fertilizer significantly increased P removal in six experiments (E7, 8, 10, 14, 15 and 19). Increases in P removal were always associated with an increase in the P concentration of the tuber DM and in four experiments (E7, 8, 14 and 19) P removal was also increased by increases in DM yield (data not shown). Regression analysis of P removal on yield showed that each tonne of FW yield was associated with 0·39 ($\pm$0·015) kg P. The regression was significant ($P < 0{\cdot}001$) and explained 65% of the variation in phosphate removal. The Potash Development Association (1997) suggests a value of 0·44 kg P/t FW (equivalent to 1·0 kg P_2O_5/t) to calculate P removal for the purpose of replacement P applications. The regression equation was then modified to examine the effects of soil P Index on the relationship between P removal and tuber FW yield. The five levels of soil P index (0–4) were added as factors to the regression and five lines, with separate slopes fitted for each level of soil P Index (GENSTAT 5 Committee 1993). Including soil P Index in the regression, resulted in a small but statistically significant increase in the percentage of the variance accounted for by the regression ($r^2 =$ 74%) and showed that for crops grown on P Index 0 soils, each tonne of FW yield was associated with 0·36 kg P compared with 0·45 kg P for crops grown on P Index 4 soils.

Table 9. *Summary of experiments contributing towards RB209. Soil P Indices are based upon Olsen-P except for Series 2 (ammonium acetate/acetic acid) and Series 3 (exchange resin). Yields are average, total yields except for Series 7 and 8 which are ware yields. Experiments were done on maincrop (MC) or early (E) potato crops and were not irrigated except for some experiments in Series 3*

Series	Reference	No. of expts	Location	No. of sites with P Index 0	1	2	3	4	Yield t/ha	P rates kg P/ha	Basic experimental design and potato type	
1	Boyd & Dermott (1964)	124	England & Wales			Mainly 2/3			25	0–55	Single replicate of 3N × 3P × 3K	MC
2	Berryman *et al.* (1973)	18	Lincolnshire	0	2	3	4	9	36	0–135	Single replicate of 3N × 3P × 3K	MC
3	Holmes & Turner (1976)	5	Dyfed	0	0	0	1	4	19	0–135	Five replicates of 5P	E
4	Archer *et al.* (1976)	16	Cumbria	0	2	4	⇐10⇒		41	0–220	Single replicate of 2N × 6P × 2K	MC
5	Farrar & Boyd (1976)	16	Herefordshire	0	4	6	6	0	42	45–135	Single replicate of 3N × 3P × 3K	MC
6	Webber *et al.* (1976)	26	Yorkshire	0	0	7	16	3	35	30–165	Single replicate of 3N × 3P × 3K	MC
7	Evans (1979)	7	Dyfed	0	1	2	2	2	19	25–135	Four replicates of 5P	E
8	Johnson & Zemroch (1981)	32	Humberside	3	7	13	8	1	53	30–195	One sixth replicate of 6N × 6P × 6K	MC

DISCUSSION

These studies have shown that there are few soils currently in potato production where crops are responsive to fresh P fertilizer and the optimum P application was usually much smaller than currently recommended. In addition, there was little evidence that potato crops grown on soils that contain moderate amounts of P (> 26 mg Olsen-P/l or > Index 2) responded to P fertilizer. Our results suggest that excessive amounts of P fertilizer are currently recommended and applied and that urgent revision of the current recommendations is needed. There also appear to be differences between our results and the historic data upon which the current recommendations are based.

Reinterpretation of data from published annual experiments

Current P fertilizer recommendations are based on the results of several series of experiments done between the 1950s and 1970s; the main features of these experiments are summarized in Table 9. Many of the experiments were of a factorial design with a single replicate and P0 treatments were often in subsidiary plots that were not part of the main factorial design. In these experiments errors were often estimated from higher order interactions or from deviations from fitted cubic polynomial curves and optimum P applications were often derived from response curves or taken to be the P application that gave the largest numerical yield. Both methods are likely to overestimate the optimum application rate. Boyd (1970) showed that a 'split line' model with a steeply rising linear portion and then an abrupt change to an almost horizontal, linear portion adequately described the effects of nutrients on yield. Assuming the optimum application rate is the one that gave the largest yield will give undue weight to the result that has the largest positive deviance from the horizontal portion of Boyd's model. Thus, the optimum calculated by this method is likely to be too large and subject to considerable error. Fitted curves are influenced by all values and, if the largest numerical yield is found at the largest rate of fertilizer application, this will inflate the optimum rate despite the absence of any other evidence to suggest that this yield differs from smaller values. In many cases fitting curves to estimate the optimal rates of application is also subject to large error. For example, Neeteson & Wadman (1987) fitted curves to the results of 98 nitrogen response experiments on potatoes and found the optimum was dependent on the type of curve fitted and, in the majority of cases, the confidence limit for the optimum N application rate was > 300 kg N/ha. This source of error is compounded if in calculation of economic optima, large potato value to fertilizer cost ratios are used which, in many cases, result in almost any increase in yield paying for the fertilizer required (Johnson & Zemroch 1981).

The largest series of experiments was done by Boyd & Dermott (1964), but the relevance of these experiments to modern potato production is doubtful: the yields were relatively small; some experiments were done on heavy clay soils which are no longer used for potato production and the rates of P tested were much less than those currently recommended. Of more relevance is that Boyd & Dermott (1964) showed that yield increases as a consequence of applying P fertilizer were, on average, smaller on free-draining soils than on soils where the drainage was impeded. From the data in their paper it is not possible to ascertain whether an association between drainage class and soil Olsen-P could explain these results. It is also possible that root systems were larger on the free-draining soils and this reduced the reliance on fertilizer P. Re-examination of the data shown by Berryman *et al.* (1973) shows that statistically significant responses to P fertilizer happened in seven experiments (out of 18) and in all cases the optimum amount of P (defined as the smallest P application above which there was no statistically significant increase in yield) was *c.* 25 kg P/ha. The probability of a significant yield increase in response to application of P fertilizer was reasonably well associated with measurement of soil P by ammonium acetate/acetic acid and some responses were found on Index 3 and 4 soils. However, the data from this series of experiments cannot easily be used to formulate or test recommendations where soil P was measured using the Olsen method. From response curves, Holmes & Turner (1976) calculated that the economic optimum rate of P was *c.* 120 kg P/ha. These workers costed P at £0·73/kg P and valued potatoes at £50/t. However, typical current values would be £0·64/kg P and £70/t (Nix 1999) and using these values the optima would be beyond the range of P fertilizer rates tested. Using the published treatment means and least significant differences, we calculated that the actual optima were probably in the range 35–90 kg P/ha and that, on occasion, responses may be found on soils with P Indices of 3 or 4. In their conclusions, Archer *et al.* (1976) implied that for soils that contained little Olsen-P an application of 110 kg P/ha was needed, but for soils containing more P ($\geqslant$ Index 3) a smaller insurance application was appropriate. Re-analysis of the data presented by Farrar & Boyd (1976) showed that there were statistically significant $P \times N$ interactions. When given the optimal amount of N, there were no significant responses to P fertilizer on Index 3 soils. For soils with P Indices 1 and 2, there were no responses to P fertilizer if the previous crop had been grass but if it had not been grass then *c.* 90 kg P/ha was required. The effect of previous cropping may be due to differences in N supply but may also be due to improved soil structure following grassland allowing the potato crop better access to soil P which minimized the reliance on fertilizer P. Significant $N \times P$ and $P \times K$ interactions were found in some of the experiments of Webber *et al.* (1976) and when these were taken into account the optimal P application rates were *c.* 65 kg P/ha in 1966, *c.* 90 kg P/ha in 1967/68 and *c.* 110 kg P/ha in 1969–71. This increase in optima over time was likely to be a consequence of the increase in the fertilizer rates tested rather than larger fertilizer requirements. In addition, some of the optima may be large since some experiments were done on shallow soils (< 45 cm) that would have impeded rooting. Evans (1979) recommended that *c.* 135 kg P/ha be applied to early potato crops since numerically, the largest yields were associated with the largest P applications. However, inspection of means and standard errors from these experiments suggest that for soils with P Indices 1 to 4 the optimal P applications were *c.* 135, 90, 110 and 25 kg P/ha respectively. Johnson & Zemroch (1981) defined the optimum P application as the "dressing above which further manuring would be uneconomic" and this was calculated from a ratio of kg ware yield value to kg P cost of 11·5. Using linear, quadratic or Mitscherlich type curves optima of between 110 and > 195 kg P/ha were estimated for 14 experiments (out of 32). Confidence limits for these optima were not given but the authors state that in some cases it was 'almost impossible to estimate an optimum dressing'. When we reanalysed their data by examining the published treatment means and standard errors, it was found that in 19 experiments the optimum P dressing was < 30 kg P/ha (the smallest rate tested) and for many of these it was probably 0. For all three Index 0 sites the optimal P application was *c.* 65–155 kg P/ha, for the Index 1 and 2 sites that showed response to P the optimum was *c.* 65–100 kg P/ha. For the two (out of eight) Index 3 sites where crops responded to P, the optimum was *c.* 65 kg P/ha.

Reanalysis of these 244 published experiments shows that, in many cases, the probability of a response to P fertilizer has been overstated and the optimum P dressing has been overestimated. The current experiments confirm this but there have been changes in soil types used for potatoes and increased use of irrigation since the original experiments were carried out. The use of irrigation has allowed increased use of sands and loamy sand textured soils particularly for processing potato crops although there are no precise survey data that quantify this trend. Compared with sands and loamy sand textured soils, clays and clay loam textured soils have a greater ability to fix applied P in forms that are less readily available to plants (Conesa *et al.* 1982). In consequence, addition of a given amount of P fertilizer will tend to give a larger increase in Olsen-P on a sand textured soil than on a clay textured soil. For example, long-term

Table 10. *Effect of historical P applications on soil Olsen-P and tuber FW yield (t/ha) with and without fresh P fertilizer. Adapted from Johnston et al. (1970), Johnston & Warren (1970) and Johnston & Powlson (1994). nd, not determined*

	Agdell 1959/1960		Exhaustion Land 1957/1958		Woburn 1960–1962	
Historic P (kg P/ha)	0	1000	0	1410	0	1570
Olsen-P (mg/kg)	4	13	4	12	18	42
	Yield (t/ha)		Yield (t/ha)		Yield (t/ha)	
0 P/ha	12	30	13	21	35	41
14 kg P/ha	18	33	29	26	35	39
28 kg P/ha	nd	nd	32	28	nd	nd
56 kg P/ha	25	38	33	33	38	43

experiments on the Exhaustion land at Rothamsted (a loam/silty loam textured soil) and at Woburn (a sandy loam textured soil) showed that application of similar amounts of P fertilizer resulted in a larger increase in Olsen-P at Woburn than on the Exhaustion Land (Johnston *et al.* 1970; Johnston & Warren 1970; Johnston & Powlson 1994). For P Indices where responses are likely, the optimum P application may be less on lighter textured soils than on heavier and the benefits of incorporating relatively simple soil properties into P fertilizer recommendations has been demonstrated within a Scottish advisory system (Reith *et al.* 1987). Similarly, studies in Australia have shown that taking account of oxalic acid/ammonium oxalate extractable iron and aluminium (Colwell & Esdaile 1968) or P buffering capacity (Helyar & Spencer 1977) increased the precision of soil P tests based on bicarbonate extraction. In summary, these older experiments have shown that responses to P fertilizer are most likely to occur on Index 0, 1 and 2 soils and statistically significant responses may sometimes occur on Index 3 soils, but other factors such as supply of N or K, soil texture or soil compaction may be important in determining the probability of a yield response and the optimum amount of P fertilizer required.

Responses to P in long-term fertilizer experiments

At soil P Indices 0–4 (0–70 mg P/l), the current P recommendations apply more P to the soil than is removed by the potato crop so as to increase the P status of the soil. Our experiments and the older experiments discussed earlier have examined the effect of fresh P fertilizer in annual experiments. However, this type of experiment cannot measure the effects of historic P inputs on crop response to fresh P fertilizer. In addition, in annual experiments there is the possibility that site and season effects will be confounded with the effects of soil P. The problems of confounding may be removed or reduced in long-term fertilizer experiments that permit the testing of the effects of a range of soil P analysis at one site and in one season. There have been several studies that have attempted to quantify the combined effects of P removal (in harvested crop parts) and P inputs (in fertilizers or organic manures) on soil extractable P and the yield response of subsequent potato crops to fresh fertilizer P. Eagle (1974) tested the effects of freshly applied fertilizer P and soil residual P in a long-term rotational experiment done near King's Lynn, Norfolk between 1960 and 1970. At the start of the experiment the soil P was *c.* 19 mg P/l (measured after extraction with ammonium acetate/acetic acid) and, at this stage, P fertilizer had no statistically significant effect on tuber yield. However, by 1970 the extractable P in the plots that had received no P fertilizer had decreased to *c.* 10 mg P/l and the tuber yields in these plots were significantly smaller than in those plots that had received at least 50 kg P/ha per 5-year rotation. However, it could not be determined whether the increases in yield were due solely to the P fertilizer applied to the potato crop or the larger soil P reserves due to the P fertilizer that had been applied earlier in the rotation.

Studies at Rothamsted, Woburn and Saxmundham have also attempted to relate yield responses to fresh fertilizer P to previous manuring history and soil P status. The results from these experiments need to be interpreted carefully since, in many cases, due to constraints arising from earlier experimental designs, the P fertilizer treatments could not be fully randomized or adequately replicated. Between 1959 and 1962 experiments were done at Rothamsted on Agdell field and the Exhaustion land and at Woburn on the permanent wheat and barley experiments. These experiments are described by Johnston & Warren (1970) and results are given by Johnston *et al.* (1970) and Johnston & Powlson (1994). At all sites there were large yield penalties if fresh P fertilizer was omitted from soils that had small P residues (Table 10). However, once fresh P fertilizer was applied at *c.* 28–56 kg P/ha the yield differences between plots

Table 11. *Effect of Olsen-P on mean (1969–74) potato FW yield response (t/ha) to fresh P fertilizer at Saxmundham, Suffolk. Adapted from Johnston et al. (1986) and yields of field experiments (Rothamsted Experimental Station 1969–74)*

	Olsen-P (mg/kg)							
kg P/ha	4	7	17	27	30	34	39	48
0	21	31	38	39	40	44	43	44
27	32	36	42	42	42	45	44	47
55*	32	40	40	43	45	42	43	43
82	36	40	44	44	46	44	45	44

* Mean of 1969–72 only.

Table 12. *Effect of Olsen-P on mean, 1968–69, potato FW yield (t/ha) when no fresh P was applied and on mean 1971–72 response (t/ha) to fresh P fertilizer at Stackyard, Woburn. Adapted from Johnston et al. (1976)*

	Olsen-P (mg/kg)					
P applied	16*	20	23	31	37	S.E.
0 kg P/ha	31	34	35	39	36	1·21
	Olsen-P (mg/kg)					
	18*	21	26	34	43	S.E.
0 kg P/ha	32	34	38	41	39	1·31
82 kg P/ha	38	41	42	41	38	

* Duplicated treatments, when comparing these treatments use S.E. × 0·707.

with small or large residues were small and probably non-significant. Johnston *et al.* (1976) got similar results from their study at Woburn using plots from the Continuous Wheat and Barley experiment. In 1967, the main-plots were split and P treatments (0, 82, 164, 328 and 492 kg P/ha) used to create subplots with different values for Olsen-P. In 1969 and 1970 potato crops were grown without further addition of P fertilizer. The average tuber yield of these crops was 35 t/ha and once Olsen-P was *c.* 30 mg P/kg there was no further increase in yield (Table 11). In the next phase of the experiment the subplots were divided: one half receiving no P and the other 82 kg P/ha prior to planting of the potato crops grown in 1971 and 1972. For the plots receiving no fresh P fertilizer, a soil Olsen-P of *c.* 30 mg P/kg resulted in the largest yield. The results also suggest that a P application of 82 kg P/ha is sufficient to attain full yield potential on soils with Olsen-P values of 18. More recently, Johnston *et al.* (1986) reported the results of a long-term P experiment on a sandy clay soil at Saxmundham, Suffolk. This experiment superimposed P fertilizer treatments on main plots where previous use of organic manures and fertilizer had resulted in soil Olsen-P ranging from 4 to 48 mg P/kg. The data presented by Johnston *et al.* (1986) suggested that, in the absence of fresh P fertilizer, tuber yields were reduced if Olsen-P is < 30–35 mg P/kg (Table 12) and regression analysis by Johnston *et al.* (1986) showed that, on average, at an Olsen-P of 25 mg/kg tuber yields were within 1 t/ha of the maximum.

From their data Johnston *et al.* (1970) concluded that there was a yield benefit from growing potatoes on soils with large P residues but this benefit was site dependent. From the Exhaustion Land experiments Johnston *et al.* calculated that the yield benefit from historic applications of 1410 kg P/ha could be matched by a fresh application of only 6 kg P/ha. In contrast, at Agdell and Woburn, plots with the larger P residues were always associated with larger yields irrespective of the size of fresh P applications. However, inspection of these data shows that yield benefits were unlikely to be statistically significant and for the Agdell and Woburn experiments the amount of fresh P fertilizer applied may have been much less than the optimum. Cooke (1979) also noted that the benefits from P residues are largest where poor soil structure hinders the mobility of phosphate and reduces root–fertilizer contact. It is our view that, collectively, the results from these long-term fertilizer experiments suggest that on soils with small Olsen-P values (< 15 mg P/l, P Index < 2) the yield potential of potato crops will not be limited as long as sufficient fresh P fertilizer is applied. In many cases a relatively small amount of P fertilizer will constitute a sufficiency although the exact amount needed may vary according to soil type and its capacity to fix P. Therefore, there appears to be little or no long-term benefit from a fertilizer policy designed to increase P reserves by applying more than is removed by a crop or crop rotation.

Allison *et al.* (2001) suggested that the response to K fertilizer may be modified by use of irrigation and this had implications for the interpretation of early studies of potato crop nutrition where irrigation had not been used and for the interpretation of soil analysis results. In our experiments, statistically significant responses to P fertilizer were found on soils with P Indices 0, 1 and 2. Half of the responsive P index 0 and 1 sites were unirrigated and neither of the responsive Index 2 sites received irrigation. It is therefore possible that use of irrigation may modify a crop's response to P fertilizer. There have been few experiments that have investigated the effects of water supply on P nutrition, however, Simpson (1962) found that P uptake was increased more by irrigation than by application of 60 kg P/ha. Harris (1985) reviewed the effects of water supply on the availability of N, P and K, and concluded that use of irrigation will improve the availability of P to the potato crop and might reduce the fertilizer P requirement, although Johnston *et al.* (1986) showed that in a dry season the response to P fertilizer was smaller than that in wetter seasons. Increasing the soil moisture content will decrease the path length over which nutrients have to diffuse to the root and this results in a reduction in the concentration of P in the soil solution needed to maintain diffusive supply (Barraclough 1986). However, as noted by Barraclough, other factors such as mycorrhizal infection, length of root hairs or the solubilization of P by root exudates are important. It is also known that root extension makes a major contribution to plant access of P. Studies on P uptake by spring wheat showed that in the later stages of growth, between 30 and 40% of the P uptake was from below 30 cm (Marschner 1995). In uncompacted soil conditions potatoes can root to > 1 m (Allen & Scott 1992) and recent work by Stalham & Allen (2001) has shown, during the initial expansion phase, fibrous roots extend at *c.* 1·2 cm/day and that use of irrigation tended to increase the total root length. It is therefore probable that use of irrigation may facilitate diffusion to the roots, but more importantly, may increase the ability of the root system to scavenge P from the soil profile thus reducing P fertilizer requirement.

A possible criticism of the current study is that the method of P fertilizer application (shallow incorporation into the ridges or beds above the seed tuber after planting) may have reduced the probability of a significant response by reducing the availability of the applied P. Although we did not test the effects of method of application, our data suggest that application method did not bias the results. The current experiments show that statistically significant increases in FW yield in response to P fertilizer occurred in six out of 22 experiments. However, Table 8 shows that in the six out of the eleven experiments where it was measured, application of P fertilizer increased P availability and uptake even though this was not always associated with increases in yield. Furthermore, the occasions where P application did not increase crop P uptake were generally associated with soils that already contained moderate amounts of Olsen-P (*c.* > 35 mg P/l) and where addition of fertilizer P was unlikely to significantly increase the amount of P available to the crop. In addition, if our method of P fertilizer resulted in limited availability this should have been most noticeable in unirrigated ridges or beds yet yield responses to P fertilizers tended to be associated with sites that received no irrigation. Thus, these results suggest that the method of P application had little or no effect on the probability of a response to P fertilizer.

In summary, the published data show that P fertilizer is needed for soils with small P Indices (0 or 1) and that relatively large application rates may be required so that yield potential is not lost. Not all P Index 2 experiments showed significant responses to P fertilizer, but when they did occur application rates of *c.* 65 kg P/ha were needed. Many experiments were done on P Index 3 soils, and there was little good evidence to support the current large application rates recommended for these sites.

Use of the Olsen-P method to predict response to P fertilizer

Boyd (1965) examined the relationship between soil P, measured by several different methods and the response of potatoes to P fertilizer. Overall, Olsen-P explained 37% of the total variation in response to P fertilizer and was judged to be the best method even though it performed poorly on fen peat soils. However, if soil groups were separated (for instance silt and warp soils or sandy loam soils) the amount of variation explained was increased to *c.* 50%. Archer *et al.* (1976) found that *c.* 75% of the variation in response to P fertilizer could be explained by Olsen-P. However, Johnson & Zemroch (1981) found that at high P levels, soil P Index was not a good predictor of the probability of a response to fresh fertilizer P as was found in our experiments. Using data collected for the Representative Soil Sampling Scheme, Skinner & Todd (1998) estimated that *c.* 20% of the potato crop is produced on soil with ADAS P Index 2. Our data, and those of Johnson & Zemroch (1981) suggest that on these soils it is not possible to use Olsen-P as a reliable predictor of the fertilizer P requirement. Boyd (1965) also acknowledged these problems yet Olsen-P values alone are still widely used to determine fertilizer applications. Edwards *et al.* (1997) recognized the shortcomings of the Olsen method and suggested that it may be improved by including soil properties such as pH, texture, carbonate content or P sorption capacity. Cropping factors such as depth of rooting or use of irrigation may also prove to be important factors in an improved fertilizer recommendation system.

Effects of P supply on DM accumulation and number of tubers

Monteith (1977) suggested that crop growth could be analysed in terms of the amount of radiation absorbed by the leaf surface and the efficiency with which the absorbed radiation is converted into DM. For the few crops that responded to P fertilizer only in E22 was it possible to measure ground cover on a *c.* fortnightly basis. These data show that from 10 July (45 days after planting, DAP) P fertilizer caused a significant

Table 13. *Effect of basal P applications on angular transformed ground cover per cent, days after planting (DAP) to 50% emergence and season-long, integrated ground cover (% days) for E22. Standard errors are based on 30 degrees of freedom*

Date	DAP	Mean	kg P/ha				S.E.
			0	45	90	135	
20 June	25	12	13	12	12	12	0·7
22 June	27	13	13	13	13	12	0·8
30 June	35	27	27	25	27	27	0·7
10 July	45	36	34	35	37	38	0·8
13 July	48	48	42	48	50	52	1·2
22 July	57	57	47	55	62	65	1·8
12 August	78	67	60	68	70	71	1·6
25 August	91	64	58	65	67	66	1·5
15 September	112	61	54	62	65	63	1·3
Days to 50% emergence		25	24	25	25	25	0·32
Integrated ground cover		5399	4669	5360	5760	5808	113

increase in crop ground cover and resulted in a significantly larger season-long integrated ground cover (Table 13). This suggests that the increase in ground cover and radiation absorbtion observed in this experiment is the mechanism by which P fertilizer may increase yield. Studies by Jenkins & Ali (1999) also showed that yield increases due to use of P fertilizer was a result of increased radiation interception rather than any effect on conversion efficiency.

O'Brien *et al.* (1998*b*) showed that the number of tubers produced per mainstem was positively correlated with the quantity of radiation absorbed by the crop during the first week of initiation. Firman *et al.* (1991) and O'Brien *et al.* (1998*b*) showed that, under normal circumstances, tuber initiation occurs 2–3 weeks after 50% emergence and lasts for *c.* 2–7 days. Therefore, for P fertilizer to increase the number of tubers it must increase the amount of radiation absorbed by increasing ground cover and this effect must occur *c.* 3 weeks after 50% emergence. The Estima crop in E22 reached 50% emergence 25 DAP and P fertilizer had no effect on emergence (Table 13). The time course of tuber initiation was not measured in E22 but it may be assumed that it started *c.* 45 DAP and this coincides with the increase in ground cover as a result of P application. Although we cannot be certain, it is assumed that in the other experiments where P increased yield and the number of tubers (E8 and 14), the effects of P on crop ground cover occurred at the time of tuber initiation, whereas in the experiments where P increased yield but not the number of tubers (E7, 13 and 19) the effects on ground cover were too late to effect tuber initiation. Likewise, for foliar P products to increase yield they must increase ground cover and, in turn, radiation absorbtion. In order to increase number of tubers, use of foliar P must increase ground cover and radiation absorbtion by the time of tuber initiation (*c.* 6 weeks after planting). Thus, foliar P needs to be applied within 5 to 6 weeks of planting to allow sufficient time to affect crop ground cover. The work by Prasad & Brereton (1970) showed that once applied to the leaf surface, foliar P might be absorbed efficiently, although a glasshouse study by Lewis & Kettlewell (1992) showed that absorbtion of P through the leaf surface could be affected by factors such as formulation of the foliar P product, potato variety, temperature, humidity and plant water status. Of greater importance, is that early in the season crop ground covers are small and variable, for example, unpublished data from experiments at Cambridge University Farm show that between 35 and 42 days after planting, crop ground covers may range from 2 to 32%. Hence, most of the foliar P will not be intercepted by the crop canopy but will end up on the soil. In our experiments the foliar P treatments were applied using a knapsack sprayer and despite this, in two experiments (E2 and 19), the foliar P treatments could not be applied early in season due to rain and were applied later than recommended. Similar problems are likely to be found in commercial practice. Use of foliar products will also add to the variable costs of production. Apart from the cost of the products themselves (*c.* £35/ha), the cost of application may be *c.* £7/ha (Nix 1999) and will use personnel at a busy time of year. Combining the foliar P sprays with other agrochemicals could reduce application costs, but costs will still be incurred for little or no discernable benefit. In conclusion, our data (Table 5, Table 6 and Table 7) and those of other workers (Prasad & Brereton 1970; Lewis & Kettlewell 1992; Kilpatrick 1993) and, indeed, the ADAS studies of the mid-1970s do not show any evidence to justify the use of foliar P applications to increase tuber yield or the number of tubers.

Environmental considerations for fertilizer P recommendations

Currently, for soil with P indices of 3 or 4, P fertilizer application rates for maincrop potatoes are *c.* 65 and 20 kg P/ha in excess of that removed by average yielding crops. Hence, P will tend to accumulate in soil used to produce potatoes. Our data and the review of published work show that significant yield increases in response to application of P fertilizer are highly unlikely at Index 3 or 4 and therefore these recommendations cannot be supported. Furthermore, there is evidence that application of P fertilizers to soils already rich in P may result in environmental damage. Studies, using plots from the Broadbalk Experiment at Rothamsted, have related soil Olsen-P with the concentration of P in water draining from plots that had received different P inputs (Heckrath *et al.* 1995). In soils containing *c.* 57 mg Olsen-P/l (Index 4), the concentration of total P in the drainage water was relatively small (0·03–0·23 mg/l) and independent of the quantity of Olsen-P. However, when Olsen-P was $>$ 60 mg/l the concentration of P in the drainage water was positively correlated with Olsen-P and, in one season increased to *c.* 2·5 mg P/l when the Olsen-P was *c.* 100 mg /l. The general utility of the Rothamsted work has to be established since it was done at a single site and loss of P in drainage water is likely to be affected by soil type (Hooda *et al.* 1997) but it demonstrates that loss of P in drainage water may occur at soil P Indices common within UK potato production. Studies by Catt *et al.* (1998) on a range of soil types and Olsen-P values (16–60 mg P/l) showed that most P was lost by surface runoff during erosion events. However, drainage losses could be significant (0·04–0·74 kg P/ha/year) and in these studies factors such as soil stability and particle size distribution affected the amount of P lost. More recent work by Hooda *et al.* (2000) compared, on a range of UK soils, the correlation of different methods of assessing soil P status with the amount of P desorbed from soils that could then be lost in drainage water. Olsen-P was reasonably well correlated ($r^2 =$ 0·72) with P desorption and the regression showed that P may be desorbed once Olsen-P was $>$ 20 mg/l (Index 2). However, Hooda *et al.* (2000) showed that P desorption was better correlated ($r^2 = 0·94$) with the ratio [P] × 100 %/[Aluminium + Iron] using acidified ammonium oxalate-oxalic acid as an extractant and these workers showed that below 10 % saturation little or no P was desorbed. These studies suggest that application of P fertilizer to soils with P Indices $>$ 3 may increase the risk of P loss to drainage water and provide further support for our view that application of P fertilizer should be omitted on these soils.

CONCLUSIONS AND RECOMMENDATIONS

In the 22 experiments carried out there was no evidence that P fertilizers increased yield when the initial soil P Index was 3 or 4. However, there was some evidence in the literature that statistically significant increases in yield in response to application of P fertilizer may occur at Index 3. Unequivocal reasons for this difference between our data and historic data sets are not known but may be due to increased use of irrigation, increased use of lighter textured soil or other agronomic factors. Therefore, on Index 3 soils we recommend that *c.* 20–35 kg P/ha be applied to reduce the possibility for potential loss of yield. Since this application is similar to that removed by an average potato crop, enrichment of soils with P will be minimized and this will reduce the risk of P loss in the longer term. There were statistically significant responses to P on half the Index 2 soils and for these soils a P application rate of 65–90 kg P/ha appeared to be sufficient. At Index 1 and 0, statistically significant responses to P fertilizer were much more likely and applications of *c.* 90–110 kg P/ha on Index 1 soils and 110–130 kg P/ha on Index 0 soil appear to be needed. On soils with P Indices 0, 1 and 2 more P will be applied than is removed in the tubers and therefore a surplus of P is created which is available to other crops in the rotation. An integrated study of the P nutrition of a rotation of crops is now needed.

Re-examination of published data from long-term field experiments suggest that when given an adequate amount of fresh P fertilizer, potato crops grown in P deficient soils have similar yield potentials to those grown in soils with large P residues. Therefore, the benefits of building up soil P reserves may have been overstated.

Our experiments have shown for crops that are responsive to P fertilizer, that increases in yield may be explained by increases in crop ground cover and that P fertilizer does not affect the number of tubers independently of yield. Irrespective of initial soil P index or the amount of basal P fertilizer applied, there was no evidence that use of foliar P increased tuber yield or the number of tubers and this practice cannot be recommended.

For soil with P Indices 0, 1 or $\geqslant$ 3, Olsen-P was a satisfactory predictor of the probability of a response to fresh P fertilizer. However, for soil with P Index 2 (*c.* 20 % of the national crop) the Olsen-P method was much less reliable. This study has identified several areas where future research could make significant improvements to P fertilizer recommendations. Studies are needed to assess the effect of such factors as soil moisture content and soil physical conditions on the uptake of P and the probability of yield responses to P fertilizer. Due to long and widespread use, the reliance on the Olsen method is likely to continue for the foreseeable future. However, studies may show that additional information such as soil series or basic soil properties may help improve the reliability of the Olsen method, particularly on Index 2 soils. Future P fertilizer recommendations may then resemble earlier recommendations (Table 1) in that both Olsen-P and other soil factors modify them.

This work was funded by Cambridge University Potato Growers Research Association and the co-operation and enthusiasm of the many growers who allowed experiments on their fields is gratefully acknowledged as is the assistance of the team at CUF. The authors also thank Mark Stalham, Paddy O'Brien and Murray Hogge for providing data and site details and Bill Ridgman for suggesting improvements to an earlier draft of this paper.

REFERENCES

ALLEN, E. J. & SCOTT, R. K. (1992). Principles of agronomy and their application in the potato industry. In *The Potato Crop – The Scientific Basis for Improvement*, Second Edition (Ed. P. M. Harris), pp. 816–881. London: Chapman & Hall.

ALLISON, M. F., FOWLER, J. H. & ALLEN, E. J. (2001). Responses of potato (*Solanum tuberosum*) to potassium fertilizers. *Journal of Agricultural Science, Cambridge* **136**, 407–426.

ARCHER, F. C., VICTOR, A. & BOYD, D. A. (1976). Fertilizer requirements of potatoes in the Vale of Eden. *Experimental Husbandry* **31**, 72–79.

ARCHER, J. (1985). *Crop Nutrition and Fertiliser Use*. Ipswich: Farming Press Ltd.

BARRACLOUGH, P. B. (1986). The growth and activity of winter wheat roots in the field: nutrient inflows of high-yielding crops. *Journal of Agricultural Science, Cambridge* **106**, 53–59.

BERRYMAN, C., BATEY, T., CALDWELL, T. H. & BOYD, D. A. (1973). Manuring of potatoes on fen soils in Holland, Lincolnshire. *Journal of Agricultural Science, Cambridge* **80**, 269–281.

BIRCH, J. A., DEVINE, J. R., HOLMES, M. R. J. & WHITEAR, J. D. (1967). Field experiments on the fertilizer requirements of maincrop potatoes. *Journal of Agricultural Science, Cambridge* **69**, 13–24.

BOYD, D. A. (1965). The relationship between crop response and the determination of soil phosphorus by chemical methods. II. In *Soil Phosphorus Technical Bulletin No. 13. Proceedings of a conference organized by the Soil Chemists of the National Agricultural Advisory Service October 1962*, pp. 94–102. London: HMSO.

BOYD, D. A. (1970). Some recent ideas on fertilizer response curves. *Proceedings of the 9th Congress of the International Potash Institute, Antibes 1970*, pp. 461–473.

BOYD, D. A. & DERMOTT, W. (1964). Fertilizer experiments on maincrop potatoes 1955–1961. *Journal of Agricultural Science, Cambridge* **63**, 249–263.

BRITISH POTATO COUNCIL (2000). *Potato Statistics in Great Britain 1995–99*. Oxford: British Potato Council.

BRITISH SURVEY OF FERTILISER PRACTICE (2000). *British Survey of Fertiliser Practice: Fertiliser Use on Farm Crops 1999*. London: the BSFP Authority. ISBN 0 85310 085 3.

CATT, J. A., HOWSE, K. R., FARINA, R., BROCKIE, D., TODD, A., CHAMBERS, B. J., HODGKINSON, R., HARRIS, G. L. & QUINTON, J. N. (1998). Phosphorus losses from arable land in England. *Soil Use and Management* **14**, 168–174.

COLWELL, J. D. & ESDAILE, R. J. (1968). The calibration, interpretation, and evaluation of tests for the phosphorus fertilizer requirements of wheat in northern New South Wales. *Australian Journal of Soil Research* **6**, 105–120.

CONESA, A. P., FARDEAU, J. C. & SIMON-SYLVESTRE, G. (1982). Phosphorus and sulphur. In *Constituents and Properties of Soils* (Eds M. Bonneau & B. Souchier), pp. 443–457. London: Academic Press.

COOKE, G. W. (1979). Some priorities for British soil science. *Journal of Soil Science* **30**, 187–213.

COOKE, G. W. (1982). *Fertilizing for Maximum Yield*, Third Edition. London: Granada.

EAGLE, D. J. (1974). Long term phosphate manuring experiment on a silt soil. *Experimental Husbandry* **26**, 28–36.

EDWARDS, A. C., WITHERS, P. J. A. & SIMS, T. J. (1997). Are current fertiliser recommendation systems for phosphorus adequate? *Proceedings of the Fertiliser Society No. 404, 11 December 1997, Cambridge*. York: The Fertiliser Society.

EVANS, C. (1979). Effects of phosphate fertilisers on yield of early potatoes. *Experimental Husbandry* **35**, 19–23.

FARRAR, K. & BOYD, D. A. (1976). Experiments on the manuring of maincrop potatoes on soils of Ross series. *Experimental Husbandry* **31**, 64–71.

FIRMAN, D. M., O'BRIEN, P. J. & ALLEN, E. J. (1991). Leaf and flower initiation in potato (*Solanum tuberosum*) sprouts and stems in relation to number of nodes and tuber initiation. *Journal of Agricultural Science, Cambridge* **117**, 61–74.

GENSTAT 5 COMMITTEE (1993). *GENSTAT 5, Release 3 Reference Manual*. Oxford: Clarendon Press.

HANLEY, F., JARVIS, R. H. & RIDGMAN, W. J. (1965). The effects of fertilizers on the bulking of Majestic potatoes. *Journal of Agricultural Science, Cambridge* **65**, 159–169.

HARRIS, P. M. (1985). Irrigation and the fertilizer requirement of the potato crop. In *Irrigating Potatoes – United Kingdom Irrigation Association Technical Monograph No. 2* (Eds M. K. V. Carr & P. J. C. Hamer), pp. 25–40. Silsoe College: UK Irrigation Association.

HARRIS, P. M. (1992). Mineral nutrition. In *The Potato Crop – The Scientific Basis for Improvement*, Second Edition (Ed. P. M. Harris), pp. 162–213. London: Chapman & Hall.

HECKRATH, G., BROOKES, P. C., POULTON, P. R. & GOULDING, K. W. T. (1995). Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk Experiment. *Journal of Environmental Quality* **24**, 904–910.

HELYAR, K. R. & SPENCER, K. (1977). Sodium bicarbonate soil test values and the phosphate buffering capacity of soils. *Australian Journal of Soil Research* **15**, 263–273.

Holmes, M. R. J. & Turner, J. T. (1976). Phosphate requirements of early potatoes. *Experimental Husbandry* **30**, 116–121.

Hooda, P. S., Moynagh, M., Svoboda, I. F., Thurlow, M., Stewart, M., Thomson, M. & Anderson, H. A. (1997). Soil and land use effects on phosphorus in six streams draining small agricultural catchments in Scotland. *Soil Use and Management* **13**, 196–204.

Hooda, P. S., Rendell, A. R., Edwards, A. C., Withers, P. J. A., Aitken, M. N. & Truesdale, V. W. (2000). Relating soil phosphorus indices to potential phosphorus release to water. *Journal of Environmental Quality* **29**, 1166–1171.

Jenkins, P. D. & Ali, H. (1999). Growth of potato cultivars in response to application of phosphate fertiliser. *Annals of Applied Biology* **135**, 431–438.

Jenkins, P. D. & Ali, H. (2000). Phosphate supply and progeny tuber numbers in potato crops. *Annals of Applied Biology* **136**, 41–46.

Johnson, E. W. & Zemroch, P. J. (1981). The manuring of maincrop potatoes on warp soils. *Experimental Husbandry* **37**, 94–109.

Johnston, A. E. & Warren, R. G. (1970). The value of residues from long-period manuring at Rothamsted and Woburn. 3. The experiments made from 1957 to 1962, the soils and histories of the sites on which they were made. *Rothamsted Annual Report for 1969, Part 2*, 22–38.

Johnston, A. E. & Powlson, D. S. (1994). The setting up, conduct and applicability of long-term, continuing field experiments in agricultural research. In *Soil Resilience and Sustainable Land Use* (Eds D. J. Greenland & I. Szabolcs), pp. 395–421. Wallingford: CAB International.

Johnston, A. E., Warren, R. G. & Penny, A. (1970). The value of residues from long-period manuring at Rothamsted and Woburn. 4. The value to arable crops of residues accumulated from superphosphate. *Rothamsted Annual Report for 1969, Part 2*, 39–68.

Johnston, A. E., Mattingly, G. E. G. & Poulton, P. R. (1976). Effect of phosphate residues on soil P values and crop yields. 1. Experiments on barley, potatoes and sugar beet on sandy loam soils at Woburn. *Rothamsted Annual Report for 1975, Part 2*, 5–35.

Johnston, A. E., Lane, P W., Mattingly, G. E. G., Poulton, P. R. & Hewitt, M. V. (1986). Effects of soil and fertilizer P on yields of potatoes, sugar beet, barley and winter wheat on a sandy clay loam soil at Saxmundham, Suffolk. *Journal of Agricultural Science, Cambridge* **106**, 155–167.

Kilpatrick, J. B. (1993). Effects of foliar applications of mono-ammonium phosphate grown at three levels of seedbed phosphate. *Annals of Applied Biology* **122** (*Supplement 14, Tests of Agrochemicals and Cultivars*), 106–107.

Lewis, D. J. & Kettlewell, P. S. (1992). A comparison of broadcast and placed liquid fertiliser for potatoes. *Aspects of Applied Biology* **33**, 29–35.

Marschner, H. (1995). *Mineral Nutrition of Higher Plants*, Second Edition. London: Academic Press.

Ministry of Agriculture, Fisheries and Food (1979). *ADAS Experiments and Developments in the Eastern Region 1978/79*, pp. 200–205. Cambridge: ADAS.

Ministry of Agriculture, Fisheries and Food (1980). *Crop Nutrition and Soil Science 1979*. (*Reference Book 253*(*79*)), 25. London: HMSO.

Ministry of Agriculture, Fisheries and Food (1981). *Crop Nutrition and Soil Science 1980*. (*Reference Book 253*(*80*)), pp. 21–22. London: HMSO.

Ministry of Agriculture, Fisheries and Food (1982). *Crop Nutrition and Soil Science 1981*. (*Reference Book 253*(*81*)), pp. 41–42. London: HMSO.

Ministry of Agriculture, Fisheries and Food (1986). *The Analysis of Agricultural Materials* (*Reference Book 427*), Third Edition. London: HMSO.

Ministry of Agriculture, Fisheries and Food (1994). *Fertiliser Recommendations for Agricultural and Horticultural Crops. Reference Book 209*, Sixth Edition. London: HMSO.

Monteith, J. C. L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London* **281**, 277–294.

Neeteson, J. J. & Wadman, W. P. (1987). Assessment of economically optimum application rates of fertilizer N on the basis of response curves. *Fertilizer Research* **12**, 37–52.

Nix, J. (1999). *Farm Management Pocketbook*, Thirtieth Edition. Wye, Kent: Wye College Press.

O'Brien, P. J., Allen, E. J. & Firman, D. M. (1998*a*). A review of some studies into tuber initiation in potato (*Solanum tuberosum*) crops. *Journal of Agricultural Science, Cambridge* **130**, 251–270.

O'Brien, P. J., Firman, D. M. & Allen, E. J. (1998*b*). Effects of shading and seed tuber spacing on initiation and number of tubers in potato crops (*Solanum tuberosum*). *Journal of Agricultural Science, Cambridge* **130**, 431–449.

Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular No. 939*. United States Department of Agriculture.

Perrenoud, S. (1983). *Potato: fertilizers for yield and quality. International Potash Institute Bulletin No. 8*. Basel: International Potash Institute.

Potash Development Association (1997). *Phosphate and Potash Removal by Crops*, leaflet 10/97. Laugharne: PDA.

Prasad, M. & Brereton, A. J. (1970). A comparison of the effects of foliar-applied and soil-applied phosphatic fertilisers on crop yields. *Irish Journal of Agricultural Research* **9**, 401–414.

Reith, J. M. S., Inkeson, R. H. E., Scott, N. M., Caldwell, K. S., Ross, J. A. M. & Simpson, W. E. (1987). Estimates of soil phosphorus for different soil series. *Fertiliser Research* **11**, 123–142.

Simpson, K. (1962). Effects of soil moisture tension and fertilizers on yield, growth and phosphorus uptake of potatoes. *Journal of the Science of Food and Agriculture* **13**, 236–248.

Skinner, R. J. & Todd, A. D. (1998). Twenty five years of monitoring pH and nutrient status of soils in England and Wales. *Soil Use and Management* **14**, 162–169.

Stalham, M. A., Allen, E. J. & Gaze, S. R. (1999). *Irrigation scheduling and efficient use of water in potato crops. Research review for 1999/2*. Oxford: British Potato Council.

Stalham, M. A. & Allen, E. J. (2001). Effect of variety, irrigation regime and planting date on depth, rate, duration and density of root growth in the potato (*Solanum tuberosum*) crop. *Journal of Agricultural Science, Cambridge* **137**, 251–270

Webber, J., Boyd, D. A. & Victor, A. (1976). Fertilizers for maincrop potatoes on magnesian limestone soils: experiments in Yorkshire 1966–71. *Experimental Husbandry* **31**, 80–90.