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Responses of potato (*Solanum tuberosum*) to potassium fertilizers

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SUMMARY

Between 1989 and 1999, 33 experiments tested the effects of potassium (K) fertilizer on the yield and quality of potatoes. The experiments were done on a range of soil types and used varieties and management conditions common to modern commercial production. The average yield in these experiments was 48 t/ha. Nearly half of the experiments were done on soils that had exchangeable K values < 120 mg/l (MAFF Indices 0–1) but use of K fertilizer resulted in statistically significant increases in fresh weight yield in only seven experiments. Generally, soil exchangeable K was a poor predictor of the probability of a yield response. Potassium fertilizer caused an increase in dry weight yield in only four experiments and these experiments were characterized by the absence of irrigation, soils with small amounts of exchangeable K and use of determinate varieties. Re-examination of published data supported the findings in the current work: potatoes are not particularly responsive to K fertilizer and the optimal K application rate is rarely > 170–210 kg K/ha. When applied at the optimal rate, the effects of K fertilizer on tuber dry matter concentration were nonsignificant. Exceeding the optimal K application rate caused occasional reductions in tuber dry matter concentrations particularly if potassium chloride (KCl) was used. In the two experiments where it was tested, application rate and form of K had no effect on crisp fry-colour. The effect of K fertilizer on tuber K concentration was measured in 21 experiments and on average each tonne of fresh weight yield was associated with 4·2 kg K. The range in values was large, 2·8–5·7 and related to soil exchangeable K.

For fertilizer recommendations based solely on the probability of a significant yield response to K fertilizer it is suggested that no more than 210 kg K/ha be applied even on soils with < 120 mg exchangeable K/l. For fertilizer recommendations based on crop K removal, an uptake value of 4·8 kg K/t fresh weight (FW), as has been suggested, would be adequate, although errors in the estimation of yield may lead to over or under application of K. Since there was little evidence to support fertilizer policies that apply more K than is removed by the crop a fertilizer recommendation system based primarily on the probability of a yield response would be more than sufficient.

INTRODUCTION

The British potato crop is produced on *c.* 140000 ha of land, of which *c.* 9% are first early potatoes and 91% second early and maincrop potatoes (British Potato Council 2000). The first early crop receives an average 180 kg K/ha whilst the second early and maincrop receive an average of 229 kg K/ha (British Survey of Fertiliser Practice 1998). There is, however, large variation in the amounts of potassium (K) fertilizer applied to the potato crop. Earlier survey data show that 40% of maincrop potatoes receives > 250 kg K/ha and 6% receives > 330 kg K/ha (British Survey of Fertiliser Practice 1996). A survey of the economic performance of potato production (Claydon 1995) showed that when grouped according to net margin, the top 20% of growers of maincrop processing potatoes used *c.* 350 kg K/ha compared with 210 kg K/ha used by the top 20% of maincrop ware growers. The total amount of K fertilizer used on the British potato crop amounts to *c.* 32000 t K per annum which at a current price of *c.* 23 pence/kg K for KCl (Nix 1999) gives a total cost of K fertilizer of *c.* £7·4 million per annum.

Within England and Wales, the amount of K fertilizer recommended for all crops is based on an Index system with the Indices related to the quantity of 1N ammonium nitrate exchangeable K within the plough layer (Ministry of Agriculture, Fisheries and

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Table 1. *K fertilizer recommendations (kg K/ha) for second early and maincrop potatoes in MAFF fertilizer Reference Book 209*

			Soil K Index or mg K/l				
Edition	Year	Soil texture	0 0–60	1 61–120	2 120–240	3 241–400	4 401–600
1	1973	Sands, loamy sands and sandy loams	260	210	210	160	—
		Others mineral soils	260	210	160	105	—
		Fen, light and loamy peats	260	210	210	160	—
		Fen, peaty loams	260	210	160	105	—
		Fen, light and medium silts	260	210	160	130	—
		Fen, heavy silts	210	160	105	75	—
2	1979	All mineral and organic soils	290	250	210	125	85
3	1983	All mineral and organic soils	290	250	210	125	85
4	1985	All mineral and organic soils	290	250	210	125	85
5	1988	All mineral and organic soils	290	250	210	125	85
6	1994	All mineral and organic soils	290	250	210	125	85

Food (MAFF) 1986). The amount of K fertilizer recommended for each Index is given in Reference Book (RB) 209. This book was first published in 1973 and is now in its sixth edition although the recommendations for potatoes have not changed since the second edition was published in 1979 (Table 1). The derivation of the K recommendations for potatoes within RB 209 is not clear. Before the formation of the National Agricultural Advisory Service (NAAS) in 1946, soil chemists in different parts of the country were autonomous and had their own methods of soil analysis. Many of these chemists joined NAAS and continued to use extractants for soil K and make fertilizer recommendations particular to their region. In 1963, the NAAS soil chemists held a conference on soil K and magnesium (MAFF 1967*a*) and this led to the standardization of soil analytical methods and fertilizer recommendations.

The experimental evidence for the fertilizer recommendations in the first edition of RB 209 is not clear, but relied on published and unpublished data from the UK, mainland Europe and the United States of America (MAFF 1967*b*). In part they were based on the reinterpretation of old K response experiments (Boyd 1961) and on studies between the tuber yield response to K fertilizer and soil exchangeable K (Boyd & Dermott 1964; Eagle 1967). Boyd & Dermott published results of 124 experiments, on a range of soil types, which tested in factorial combination N (50, 100 and 150 kg N/ha), P (0, 27 and 55 kg P/ha) and K (0, 78 and 156 kg K/ha). In these experiments, the average tuber fresh weight yield was only 25 t/ha and the average yield increase to K in these experiments was also small (2·4 t/ha when 78 kg K/ha was applied and a further 0·6 t/ha when the second 78 kg K/ha increment was applied). Eagle measured soil exchangeable K in a 71 experiment subset of these data and fitted a Mitscherlich curve to data of the relationship between tuber yield response to applied K and soil exchangeable K. Whilst the relationship was statistically significant, the correlation coefficient was only $-0{\cdot}23$ (Fig. 1). A similar study by Birch *et al*. (1967) tested the effects of N (0–200 kg N/ha), P (0–88 kg P/ha) and K (0–223 kg K/ha) on the variety Majestic in 51 experiments. In these experiments there was a significant relationship between tuber yield response to K fertilizer and soil K (analysed by extraction with 1% citric acid) but it accounted for only 20–25% of the variance. Average second early and maincrop tuber yields in Great Britain have now increased to *c*. 48 t/ha (British Potato Council 2000). Thus, current fertilizer recommendations for application of fertilizer K in England and Wales are based on the series of experiments with comparatively small yields; use a relationship between yield response to K and soil exchangeable K that is weak; and, in many cases, recommend amounts of K far larger than those tested by earlier workers.

The effect of K on the potato crop extends beyond simply yield to tuber characteristics that influence quality for both processing and table use. There is general acceptance that tuber dry matter (DM) concentration is reduced when K is applied and the decrease in DM is often larger for equivalent amounts of K supplied as chloride compared with sulphate (Cowie 1943; Perrenoud 1993). Tuber DM concentrations are particularly important for potato crops destined for crisping or chipping. Crisping crops with small DM concentrations tend to absorb more oil during frying which increases processing costs (Storey & Davies 1992). Many growers produce potatoes, under contract, for processing into chips (French fries) and as part of the contract these growers are often obliged to apply large amounts of K in the belief that these large K applications will reduce tuber bruising. Furthermore, it is thought that large

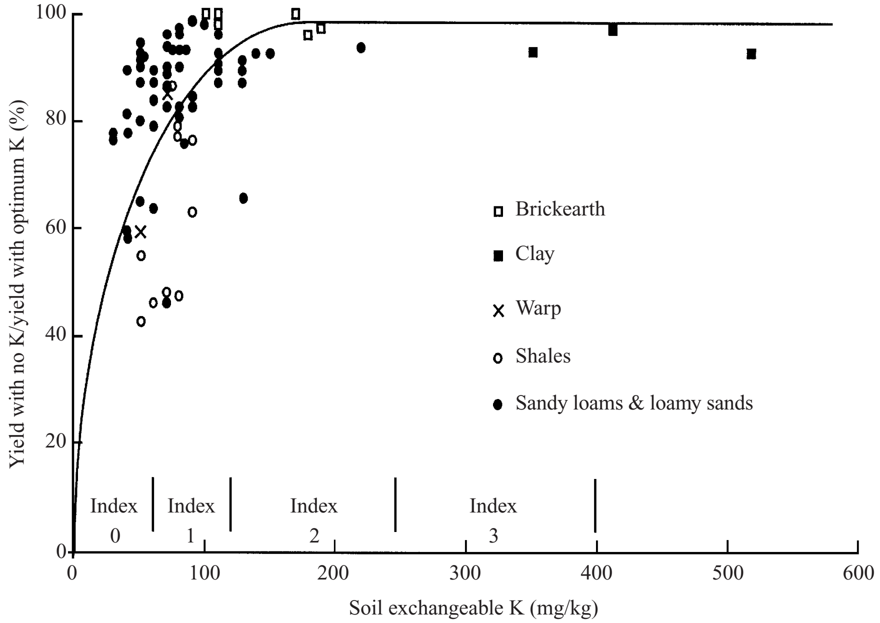

Fig. 1. Relationship between yield response to K fertilizer and soil exchangeable K. Redrawn from Eagle (1967).

applications of K fertilizer will help improve the colour of the final, fried product (Zehler *et al.* 1981; Perrenoud 1993). It is therefore of considerable importance to growers that sufficient K is applied to achieve economic optimum yields and acceptable quality for the end use.

Depending on the intended market a grower may currently be advised to use very different amounts of K as advisors and some manufacturers have produced their own recommendations whose justification is also absent. For example for a 48 t/ha crop of maincrop ware potatoes grown on a K Index 2 soil, MAFF would recommend 210 kg K/ha, a typical crisping contract would suggest 125 kg K/ha, whereas a crop for French fry production may be recommended 330 kg K/ha. Not surprisingly there has been considerable confusion amongst growers and inevitably the K recommendation system used in England and Wales has come under review. It is proposed that the amount of K fertilizer recommended will, in part, be related to the amount of K removed in the tubers at harvest. A removal value of 4·8 kg K/t tubers has been suggested (equivalent to 5·8 kg K_2O/t, Potash Development Association 1997). A benefit of this new system is that it does not rely on imprecise relationships between crop response to K fertilizer and soil K status, and as a replacement method should, by definition, maintain the soil at its existing K status. However, this method requires the prediction of yield. It is also known that the concentration of K in tubers is variable (for example Harris (1992) gives a range of 3·7–5·4 kg K/t tubers) nor is it certain whether there is a simple linear relationship between crop K removal and fresh weight yield. For instance, recent studies with sugarbeet (Milford *et al.* 2000) have shown that as the root yield increased so did the variability of the concentration of K in the root and this variability was related to soil exchangeable K.

In 1989, due to these large discrepancies in approach and increasing confusion in K recommendations, a series of experiments began to test the effects of K fertilizer on the potato crop. The objectives of these experiments were to investigate the effect of K supply on crop growth, tuber yield and tuber dry matter concentration; the relationship between tuber yield response to K fertilizer and soil K index; the relationship between crop K removal and tuber yield; and to suggest modifications to existing K recommendations to ensure effective use of K fertilizer.

MATERIALS AND METHODS

Between 1989 and 1999, 33 experiments (referred to in the text and tables as E1 … E33) were done that tested the effects of K fertilizers on the growth, tuber yield and K removal of potato crops grown on different soil types in England and Wales. Apart from E2, 5 and 32 which were machine planted, experiments were planted by hand into pre-formed ridges or beds. Within 3 days after planting, the fertilizer treatments were broadcasted, by hand, onto the surface of the ridges or beds. The fertilizers were then thoroughly incorporated into the top 5 cm of soil

Table 2. *Site, soil and crop management details. Particle size of sand, 2·00–0·63 mm; silt, 0·63–0·002 mm; clay, < 0·002 mm. n.d. = not determined*

Expt	County	OS Grid	Sand (%)	Silt (%)	Clay (%)	P (mg/l)	K (mg/l)	K Index	Mg (mg/l)	Varieties	Date of planting	Date of harvest	Crop irrigated
1	Cambridgeshire	TL427598	74	19	7	113	911	6	160	Estima	28 Apr 99	5 Oct 99	Yes
2	Herefordshire	SO594205	69	16	15	14	36	0	45	Maris Piper	20 May 99	11 Oct 99	Yes
3	Gloucestershire	SO694145	19	54	27	14	56	0	199	Estima	21 May 99	13 Oct 99	No
4	Somerset	ST529157	65	18	17	14	36	0	45	Estima	21 Apr 99	3 Sep 99	Yes
5	Gloucestershire	SO727158	24	41	35	8	103	1	587	Nadine	28 May 99	13 Oct 99	No
6	Cambridgeshire	TL427598	74	19	7	113	911	6	160	Hermes, Saturna, Dovekie, Courlan	16 Apr 99	4 Oct 99	Yes
7	Cambridgeshire	TL428601	53	30	18	52	186	2	75	Estima	11 May 98	13 Oct 98	Yes
8	Devon	ST075086	71	15	14	68	21	0	47	Estima, Hermes	19 May 98	28 Sep 98	No
9	Monmouthshire	SO492132	4	48	48	13	61	1	221	Estima	21 May 98	16 Oct 98	No
10	Cambridgeshire	TL429603	55	33	12	88	168	2	88	Estima	4 Apr 97	8 Sep 97	Yes
11	Nottinghamshire	SK653581	87	8	5	64	148	2	126	Erntestolz	7 May 96	2 Oct 96	Yes
12	Somerset	ST406145	51	36	13	36	180	2	76	Estima	27 Apr 95	22 Aug 95	No
13	Hampshire	SU645574	39	43	18	8	115	1	54	Pentland Dell	12 May 94	3 Oct 94	No
14	Hampshire	SU640572	20	44	36	32	462	4	37	Russet Burbank	14 May 94	3 Oct 94	Yes
15	Berkshire	SU827659	7	16	77	57	94	1	42	Shepody	11 Apr 94	19 Jul 94	Yes
16	Somerset	ST398165	35	47	18	38	87	1	32	Lady Rosetta, Record, Shepody, Hermes	9 May 94	18 Aug 94	Yes
17	County Durham	NZ093134	n.d.	n.d.	n.d.	n.d.	n.d.	2	n.d.	Lady Rosetta, Erntestolz	16 May 94	6 Sep 94	No
18	Cambridgeshire	TL425602	50	32	18	108	726	5	149	Record	25 Apr 94	23 Sep 94	Yes/No
19	Suffolk	TM364448	86	9	5	25	67	1	76	Shepody, Russet Burbank	18 Mar 94	5 Aug 94	Yes
20	Suffolk	TM364448	86	9	5	25	67	1	76	Maris Bard	18 Mar 94	21 Jun 94	Yes
21	North Yorkshire	NZ171064	n.d.	n.d.	n.d.	16	61	1	158	Record, Panda, Atlantic, Hermes	11 May 93	28 Sep 93	No
22	Nottinghamshire	SK698578	89	9	5	28	152	2	153	Record, Panda, Atlantic, Hermes	20 Apr 93	20 Sep 93	Yes
23	Norfolk	TL985832	87	6	7	33	95	1	43	Estima	10 May 89	20 Sep 89	Yes
24	Norfolk	TG386111	57	30	13	27	142	2	55	Estima	30 Mar 89	2 Sep 89	Yes
25	Norfolk	TG386083	71	20	9	45	86	1	42	Estima	28 Apr 89	13 Sep 89	No
26	Norfolk	TG196243	61	33	6	59	340	3	52	Estima	28 Mar 89	16 Aug 89	Yes
27	Norfolk	TF585233	61	23	16	22	200	2	> 250	Estima	24 May 89	23 Aug 89	No
28	Lincolnshire	TF415213	30	40	30	11	223	2	195	Estima	19 May 89	26 Sep 89	No
29	Lincolnshire	TF455333	38	50	12	30	192	2	68	Estima	8 May 89	5 Sep 89	No
30	Suffolk	TM336542	86	7	7	40	93	1	55	Estima	4 May 89	30 Aug 89	Yes
31	Cambridgeshire	TL435602	78	11	11	80	336	3	75	Estima	4 May 89	1 Sep 89	Yes
32	Nottinghamshire	SK666582	n.d.	n.d.	n.d.	64	272	3	234	Hermes, Dovekie, Courlan	13 Apr 99	6 Sep 99	Yes
33	Cheshire	SJ426579	n.d.	n.d.	n.d.	14	93	1	421	Estima	26 May 00	20 Sep 00	Yes

Table 3. *Experimental treatments and designs. Treatments or main plots were allocated at random into blocks. Subplots (sp) were allocated at random into main plots (mp). –, not included as a treatment*

Expt	Levels of K	Sources of K	No of varieties	Levels of N	Levels of P	Levels of Mg	Design and number of replicates
1	2	1	1	3	–	3	Factorial; 3 blocks
2	4	1	1	–	–	–	Split plot; K sp in lime (3 levels) mp in 4 blocks
3	5	1	1	–	–	–	4 blocks
4	5	1	1	–	–	2	Factorial; 4 blocks
5	4	1	1	–	3	–	Factorial; 3 blocks
6	3	3	4	–	–	–	Factorial; 3 blocks
7	2	1	1	3	–	3	Factorial; 3 blocks
8	4	1	2	–	–	3	Factorial; 3 blocks
9	5	1	1	–	–	2	Factorial; 3 blocks
10	2	1	1	3	–	3	Factorial; 3 blocks
11	2	3	1	–	–	–	Factorial; 4 blocks
12	3	1	1	3	–	–	Factorial; 3 blocks
13	4	1	1	–	3	–	Factorial; 3 blocks
14	4	1	1	–	3	–	Factorial; 3 blocks
15	4	1	1	–	3	–	Factorial; 3 blocks
16	4	1	4	–	–	–	Factorial; 3 blocks
17	4	1	2	–	–	–	Factorial; 3 blocks
18	4	1	1	–	–	–	Split plot; K sp in irrigation (4 levels) mp in 4 blocks
19	3	1	2	–	–	–	Split plot; K sp in planting date (2 levels) mp in 3 blocks
20	3	1	1	–	3	–	Factorial; 4 blocks
21	4	2	4	–	–	–	Factorial; 3 blocks
22	4	2	4	–	–	–	Factorial; 3 blocks
23	3	1	1	5	2	–	Factorial; 3 blocks
24	2	1	1	5	2	–	Factorial; 4 blocks
25	3	1	1	5	2	–	Factorial; 3 blocks
26	2	1	1	5	2	–	Factorial; 4 blocks
27	2	1	1	5	2	–	Factorial; 4 blocks
28	2	1	1	5	2	–	Factorial; 3 blocks
29	2	1	1	5	2	–	Factorial; 4 blocks
30	3	1	1	5	3	–	Factorial; 3 blocks
31	2	1	1	5	2	–	Factorial; 4 blocks
32	2	3	3	–	–	–	Split plot; K treatments in variety mp in 2 blocks
33	4	1	1	–	4	–	Factorial; 3 blocks

by raking. The exception to this was E32 where the fertilizer treatments were spread by machine at planting. To ensure uniform emergence and subsequent crop development potassium sulphate (K_2SO_4, 42% K) was normally used except where experiments were designed to compare different forms of K fertilizer. Irrigation was applied to 21 of the 33 experiments. The irrigation was scheduled using a commercial scheduling system so that limiting soil moisture deficits were not exceeded (Stalham *et al.* 1999). Crop protection chemicals were applied according to best commercial practice. The experimental design varied from experiment to experiment, but in all cases the treatments were allocated at random into blocks or main plots and, with the exception of E32, each treatment was replicated three or four times. Adequate guard rows and discard areas were always used so that harvest areas were representative of the treatments. Details, specific to each experiment, are given in Table 2 and Table 3.

At harvest, areas of crop (typically 2 m^2) were dug by hand and all tubers > 10 mm were collected. The samples 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 500 g fresh weight subsample of tubers, taken from grades with the largest yield (generally 40–60 mm), which were then dried to a constant weight at 95 °C. The total K concentration in the dried tuber samples was measured using standard methodology (MAFF 1986).

The effect of K fertilizer on fry colour was measured in E6 and 32. At final harvest, a subsample of tubers (*c.* 5 kg, 40–80 mm size grade) was taken from each plot and fried using standard commercial protocols of a large crisp company (Frito–Lay Europe, Africa and Middle East). Assessment of crisp colours were made using a Hunter Lab (Model D25-DP9000, Kirstol Ltd, Stalybridge, Cheshire) which expresses crisp colour in terms of three values: L, a and b. The L

Table 4. *Main effects of rate of application of K on potato tuber (> 10 mm) fresh weight yield (t/ha)*

			kg K/ha						
Expt	Variety	Mean	0	85	170	250	330	S.E.	D.F.
1	Estima	78·6	76·4				80·7	1·43	34
7	Estima	55·2	56·8				53·6	1·36	34
10	Estima	59·0	58·6				59·4	1·13	34
11	Erntestolz	64·0			65·2		62·8	2·97	14
12	Estima	43·1	42·7		43·4		43·3	1·75	16
14	Russet Burbank	30·5	28·6	31·1	29·5	32·9		1·70	22
16	Combined varieties	40·7	38·4	40·2	42·0	42·4		1·38	30
17	Combined varieties	34·0	34·4	34·6	33·4	33·5		1·71	21
18	Record	58·6	63·1	57·7	55·5	58·2		2·26	24
19	Combined varieties	36·5	35·8	34·5	37·8	38·0		1·32	28
20	Maris Bard	34·4	35·3	35·4	32·4			1·86	24
21	Combined varieties	66·8	63·4	67·5	67·7	68·5		1·07	62
22	Combined varieties	67·0	66·5	67·6	68·4	65·4		1·39	62
			0	105	210	310	415		
3	Estima	66·6	53·3	65·4	74·2	69·7	70·2	3·51	12
4	Estima	42·9	39·8	44·0	43·9	44·5	42·1	2·18	25
9	Estima	53·5	41·2	54·5	54·5	59·3	57·8	2·35	18
23	Estima	42·8		42·4	43·3	42·6		1·01	58
24	Estima	58·2		58·4	58·0			1·28	57
25	Estima	41·5		41·5	41·6	41·4		0·77	58
26	Estima	64·1		63·0	65·3			0·90	57
27	Estima	35·2		34·7	35·8			0·62	57
28	Estima	34·2		34·2	34·2			0·45	58
29	Estima	30·0		30·1	29·9			0·71	57
30	Estima	53·6		54·1	53·2	53·6		1·04	58
31	Estima	54·1	52·8	55·5				0·83	57
			0	125	250	375	500		
2	Maris Piper	36·4	32·6	36·6	39·0	37·4		2·41	27
5	Nadine	36·3	26·7	35·4	41·1	41·8		2·06	46
6	Combined varieties	51·7	48·1	54·2	52·9			2·01	46
13	Pentland Dell	22·0	20·8	20·0	24·1		22·9	0·99	22
15	Shepody	42·7	42·1	42·6	42·7		43·3	1·44	21
33	Estima	40·2	36·9	40·2	42·7	40·9		1·32	30
			0	145	290	435			
8	Combined varieties	55·8	58·2	53·2	55·0	56·7		1·75	46

value is the percentage of light reflected from the crisp. The a value expresses the red or green attribute of the crisp while the b value expresses the yellow or blue attribute of the crisp.

Variates were analysed by analysis of variance using the GENSTAT statistical package and treatment means are stated to be significantly different only if the probability of differences occurring by chance were less than 5% ($P < 0{\cdot}050$). Some experiments tested the effects of other factors in combination with the potassium treatments (Table 3). Whilst the main effects of some of these treatments were sometimes statistically significant, there were few significant interactions between treatments. Therefore, for simplicity, the data presented in the tables have been averaged over the other factors.

RESULTS

In most cases, the sites for the experiments were selected using results of soil analysis and of the 33 experiments, *c.* 50% were done on soils with K Indices of 0 or 1. This compares with an estimate made by Dampney (1994) which showed that 33% of the English and Welsh potato crop was produced on land with K Indices 0 or 1. Therefore, our experiments were biased towards those soils where responses were

Table 5. *Optimum K application rate and yield at the optimum calculated from exponential plus linear and two straight line models*

Expt	Curve fitted	r^2	Optimum K rate (kg K/ha)	Yield at optimum (t FW/ha)
3	Exponential + linear	46·6	265 ± 60·6	72 ± 2·9
3	Two straight lines	49·1	178 ± 54·7	74 ± 3·3
5	Exponential + linear	35·1	328 ± 55·8	42 ± 4·8
5	Two straight lines	35·1	201 ± 65·8	41 ± 3·0
9	Exponential + linear	53·2	Could not be estimated – curve still rising	
9	Two straight lines	45·9	260 ± 63·6	60 ± 3·3

Table 6. *Effect of rate and source of K application rate on potato tuber* (> *10 mm*) *fresh weight yield* (*t/ha*)

				kg K/ha						
Expt	K source	Mean	S.E.	0	85	170	250	330	S.E.	D.F.
11	KCl	59·8				61·3		58·3		
	K_2SO_4	68·8	3·64			70·5		67·1	5·15	14
	KNO_3	63·5				64·0		63·1		
21	KCl	68·8	1·07	65·6	68·6	69·6	71·6		2·15	62
	K_2SO_4	64·7		61·1	66·4	65·9	65·4			
22	KCl	65·9	0·98	67·9	64·6	68·3	63·0		1·96	62
	K_2SO_4	68·0		65·1	70·6	68·6	67·8			
				0	125	250				
6	KCl	51·8	1·64	46·4	56·0	52·8			2·84	46
	K_2SO_4	51·7		49·8	52·4	52·9				
32	KCl				46·1					
	K_2SO_4	45·6			45·4	43·7			1·85	23
	KNO_3				47·2					

considered to be most likely. The experiments were generally accurate and for all experiments, the mean coefficient of variation (CV) for tuber fresh weight yield was 13·0% and small CVs (⩽ 10%) were found in 12 experiments (E1, 3, 9, 10, 15, 22, 25, 26, 28, 30, 31 and 32) whereas large CVs (⩾ 16) were found in only four experiments (E2, 5, 6 and 14). More importantly, standard errors (S.E.) for comparing the effects of K fertilizer were generally small. Thus, these experiments have provided a sensitive test of the effects of K on the potato crop.

Tuber fresh weight yields and response to K fertilizers

The average tuber yield (> 10 mm) for all experiments was 48 t FW/ha (Table 4), which is similar to the current national average for second early and main-crop yield. The smallest yield was for a Pentland Dell crop grown in 1994 (E13), which yielded 22 t/ha, whilst the largest was for an Estima crop grown in 1999 (E1), which yielded 79 t/ha. The small yield for the Pentland Dell crop was due to drought stress over a prolonged period and results from this experiment must be treated with caution. Similarly, soil compaction reduced the yield of a Russet Burbank crop grown in Hampshire (E14). Experiments with average yields that were smaller than the national average were generally associated with short growing seasons and absence of irrigation. Conversely, those experiments with yields larger than the national average were generally irrigated and had long periods of growth.

Statistically significant increases in fresh weight yield due to the application of K fertilizer were obtained in only seven experiments (E1, 3, 5, 9, 13, 31 and 33). This may be an underestimate since some experiments (E11, 23–30) did not include a K0 treatment, but in these experiments the optimum rate of K was always less than the smallest rate tested (105–170 kg K/ha).

The optimal K application rate was defined as the smallest K application rate above which there was no statistically significant increase in yield i.e. the change

Table 7. *Main effects of rate of application of K on potato tuber* (> *10 mm*) *dry weight yield* (*t*/*ha*)

			kg K/ha						
Expt	Variety	Mean	0	85	170	250	330	S.E.	D.F.
1	Estima	14·90	14·56				15·23	0·280	34
7	Estima	10·71	10·90				10·43	0·277	34
10	Estima	11·73	11·81				11·65	0·695	34
11	Erntestolz	12·97			13·21		12·72	0·679	14
12	Estima	9·53	9·42		9·17		9·89	0·362	16
14	Russet Burbank	6·73	6·26	6·75	6·48	7·44		0·357	22
16	Combined varieties	10·11	9·55	10·07	10·32	10·49		0·368	30
17	Combined varieties	8·54	8·48	8·85	8·47	8·38		0·329	21
18	Record	13·40	14·61	13·15	12·69	13·14		0·536	24
19	Combined varieties	8·79	8·69	8·60	8·98	8·88		0·324	28
20	Maris Bard	8·15	8·47	8·34	7·65			0·377	24
21	Combined varieties	14·79	14·21	15·14	15·05	14·77		0·322	62
22	Combined varieties	15·37	15·39	15·88	15·79	14·43		0·376	62
			0	105	210	310	415		
3	Estima	13·19	10·95	13·03	14·60	13·58	13·78	0·737	12
4	Estima	8·60	8·24	8·97	8·89	8·76	8·16	0·414	25
9	Estima	11·19	8·20	11·59	11·16	12·70	12·28	0·515	18
23	Estima	7·99		7·98	8·07	7·91		0·213	58
24	Estima	11·59		11·56	11·62			0·260	57
25	Estima	8·75		8·86	8·82	8·57		0·169	58
26	Estima	12·22		12·11	12·34			0·215	57
27	Estima	7·27		7·20	7·35			0·137	57
28	Estima	7·40		7·41	7·39			0·121	58
29	Estima	6·39		6·40	6·39			0·162	57
30	Estima	10·80		11·06	10·61	10·74		0·257	58
31	Estima	11·38	11·15	11·61				0·233	57
			0	125	250	375	500		
2	Maris Piper	7·66	6·92	7·70	8·50	7·53		0·635	27
5	Nadine	6·36	4·41	6·28	7·29	7·45		0·349	46
6	Combined varieties	11·00	10·43	11·50	11·06			0·466	46
13	Pentland Dell	5·04	4·79	4·68	5·48		5·24	0·217	22
15	Shepody	9·48	9·60	9·44	9·33		9·54	0·333	21
33	Estima	8·77	8·21	8·87	9·06	8·95		0·307	30
			0	145	290	435			
8	Combined varieties	11·74	12·45	11·21	11·41	11·90		0·385	46

in yield caused by additional K was smaller than the *t* statistic multiplied by the S.E. For Experiments E3, 5, 9 and 33 this was estimated by examination of means and S.E.s since this method was probably as accurate and objective as fitting curves to the data by a least squares method. For example, when data from E3, 5 and 9 were fitted to an exponential plus linear model (Dyke *et al.* 1983) or a 'bent-stick' model (Boyd 1970) it was shown that neither model fitted the data well and accounted for only *c.* 50% of the variation in yield (Table 5). In one case (E9) the exponential plus linear model could not estimate an optimum since the response curve was still rising. It was evident that the optimal K application rate was also dependent on which model was chosen. Thus, the optima estimated by the 'bent-stick' model were *c.* 100 kg K/ha smaller than those estimated by the exponential plus linear model and these optima were also much smaller than the amount of K fertilizer currently recommended. In consequence model selection will introduce subjectivity into the estimation of optima. It is also likely that optima derived from models are no more accurate than those derived from examination of means. In E3, 5 and 9 the K fertilizer was applied in increments of 105–125 kg K/ha and, in practice, these increments correspond to the accuracy with which the optima may be estimated. However, the determination of the optimum K application rate from curve fitting was no more accurate since for these experiments the average

Table 8. *Effect of rate and source of K on potato tuber* (> *10 mm*) *dry weight yield* (*t/ha*)

				kg K/ha						
Expt	K source	Mean	s.e.	0	85	170	250	330	s.e.	d.f.
11	KCl	11·67	0·831			11·97		11·37	1·176	14
	K_2SO_4	14·52				14·72		14·31		
	KNO_3	12·72				12·95		12·48		
21	KCl	15·01	0·228	14·53	15·24	15·29	15·00		0·455	62
	K_2SO_4	14·47		13·90	15·04	14·80	14·54			
22	KCl	14·96	0·266	15·47	14·96	15·66	13·74		0·531	62
	K_2SO_4	15·78		15·31	16·80	15·92	15·11			
				0	125	250				
6	KCl	10·84	0·364	10·16	11·69	10·66			0·630	46
	K_2SO_4	11·16		10·69	11·32	11·45				
32	KCl				9·94					
	K_2SO_4	9·89			9·85	9·45			0·428	23
	KNO_3				10·32					

s.e. of the optima was ±60 kg K/ha. Examination of the yields and s.e.s in E3, 5 and 9 suggest that above a certain value, the tuber yield is independent of applied K and the observed variation in yield is caused mainly by randomly distributed error. However, fitting a model to such data assumes that incremental increases in K application correspond absolutely to incremental changes in tuber yield throughout the whole of the response curve. The estimation of the optimum K rate is therefore likely to be largely controlled by the magnitude of the errors in yield measurement at and above the optimum. Thus, for these data, estimation of optimum derived from fitted curves were likely to be no more objective or accurate than estimates made from simple inspection of means and s.e.s, and therefore the latter approach was used. The optimum K application rate could be defined in only five of these experiments and ranged from *c.* 105 kg K/ha (E9) to *c.* 250 kg K/ha (E13). The large optimal K application rate for E13 is probably an aberrant value since, unlike the other responsive sites, there was no yield increase from the first increment of K. Compared with treatments that received no K, the increase in tuber FW yield when the optimum amount of K was applied ranged from *c.* 4 t/ha (E13) to *c.* 21 t/ha (E3).

Soil K index was a poor predictor of the probability of a yield response to K fertilizers. Four experiments were done on Index 0 soils where responses to K fertilizer were most likely, but in only one experiment did the crop respond to K fertilizer. Eleven experiments were done on Index 1 soils but yield responses were obtained in only four experiments. Significant increases in yield were also obtained on one Index 3 site (out of three experiments) and on one Index 6 site (out of two experiments).

Five experiments (E6, 11, 21, 22 and 32) compared the effect of application rate and form of K on tuber yield (Table 6). At these sites, there were no main effects of rate of K application on tuber fresh weight yield. However, at one site (E21), use of KCl increased yield by an average of *c.* 4 t/ha when compared to use of potassium sulphate (K_2SO_4). There were no significant interactions between K application rate and form.

Tuber dry matter yield

Potassium fertilizer had a significant effect on DM yield in five experiments (Table 7). In Experiments E3, 5, 9 and 13 application of K caused a significant increase in DM yield and the optimal K application rate ranged from *c.* 105 kg K/ha (E9) to *c.* 250 kg K/ha (E13). Compared to the K Index 0 treatment, the largest increase in DM yield was 3·7 t/ha in E9. In E22, the largest K rate tested (250 kg K/ha) reduced DM yield when compared to smaller application rates. However, the size of this effect was larger with KCl than with K_2SO_4 and in this experiment the yields with KCl were, on average, 0·8 t/ha smaller than with K_2SO_4 (Table 8).

Tuber dry matter concentrations

Potassium fertilizer had a significant effect on tuber DM concentration in 10 experiments (Table 9). In two of these (E5 and 14) the tuber DM concentration was increased by an average 0·9 g DM/100 g FW when K was applied. In the remaining experiments (E2, 4, 6, 19, 21, 22, 25 and 33) tuber

Table 9. *Main effects of rate of application of K on potato tuber dry matter concentration* (*g DM/100 g FW*)

			kg K/ha						
Expt	Variety	Mean	0	85	170	250	330	S.E.	D.F.
1	Estima	19·0	19·1				18·9	0·16	34
7	Estima	19·6	19·5				19·6	0·13	34
10	Estima	20·0	20·1				19·8	0·25	34
11	Erntestolz	20·2			20·2		20·2	0·32	14
12	Estima	22·1	22·1		22·4		21·8	0·21	16
14	Russet Burbank	21·8	21·9	21·6	22·4	22·4		0·19	22
16	Combined varieties	24·7	25·0	24·2	24·8	25·0		0·45	30
17	Combined varieties	23·1	22·7	23·4	23·4	23·0		0·54	21
18	Record	22·9	23·0	22·6	23·0	22·8		0·31	24
19	Combined varieties	24·1	24·3	24·8	23·7	23·4		0·27	28
20	Maris Bard	20·9	21·2	20·8	20·6			0·22	24
21	Combined varieties	22·2	22·5	22·5	22·4	21·6		0·20	62
22	Combined varieties	23·0	23·2	23·5	23·1	22·1		0·32	62
			0	105	210	310	415		
3	Estima	19·8	20·5	20·0	19·7	19·5	19·6	0·33	12
4	Estima	20·1	20·7	20·4	20·3	19·7	19·4	0·23	25
9	Estima	22·1	22·1	22·2	22·7	22·4	22·3	0·32	18
23	Estima	18·7		18·8	18·6	18·6		0·19	58
24	Estima	20·0		19·9	20·0			0·26	57
25	Estima	21·2		21·5	21·3	20·8		0·18	58
26	Estima	19·1		19·3	19·0			0·18	57
27	Estima	20·7		20·8	20·5			0·18	57
28	Estima	21·6		21·6	21·5			0·15	58
29	Estima	21·3		21·2	21·3			0·16	57
30	Estima	20·2		20·4	20·0	20·0		0·23	58
31	Estima	21·0	21·1	20·9				0·23	57
			0	125	250	375	500		
2	Maris Piper	22·7	23·1	22·8	23·2	21·7		0·36	27
5	Nadine	17·5	16·5	17·7	17·8	17·9		0·21	46
6	Combined varieties	21·3	21·8	21·2	21·0			0·21	46
13	Pentland Dell	23·0	23·0	23·1	22·8		23·0	0·22	22
15	Shepody	22·4	22·9	22·5	22·1		22·0	0·59	21
33	Estima	21·8	22·3	22·0	21·2	21·8		0·25	30
			0	145	290	435			
8	Combined varieties	21·2	21·5	21·5	20·9	21·0		0·28	46

DM concentrations were reduced by 0·7–1·4 g DM/100 g FW but these reductions only occurred at the largest K application rates. At the optimal K application rate for crop yield, K caused no significant decrease in tuber DM concentration in any experiment.

In five experiments (E6, 11, 21, 22 and 32) the effect of form of K was studied. In three of these experiments (E6, 11 and 21) use of potassium chloride reduced tuber DM concentration when compared with potassium sulphate (Table 10). At these sites, the average reduction in tuber dry matter was *c.* 1·4 g DM/100 g FW. However, in all five experiments there was no effect of form at the optimal application rate for yield since this was zero.

Concentration of K in tubers and K removal

In the 21 experiments where it was measured the unweighted, mean K concentration was 4·27 kg K/t tuber FW and ranged from 2·79 to 5·73 kg K/t tuber FW (Table 11). The form of K fertilizer had no effect on tuber K concentration (Table 12). The quantity of K removed in the tubers, when averaged over treatments, ranged from 93 to 368 kg K/ha (Table 13). Potassium application rate significantly increased K removal in nine experiments (E1, 2, 3, 5, 10, 13, 25, 26 and 30). In three experiments (E3, 5 and 13), the increase in the quantity of K removed by the tubers was primarily due to K fertilizer increasing the tuber

Table 10. *Effect of rate and source of K on potato tuber dry matter concentration (g DM/100 g FW)*

				kg K/ha						
Expt	K source	Mean	S.E.	0	85	170	250	330	S.E.	D.F.
11	KCl	19·5	0·39			19·5		19·5	0·55	14
	K_2SO_4	21·0				20·9		21·2		
	KNO_3	20·1				20·4		19·8		
21	KCl	21·9	0·14	22·2	22·2	22·1	21·1		0·29	62
	K_2SO_4	22·6		22·7	22·8	22·6	22·2			
22	KCl	22·7	0·22	22·8	23·2	23·0	21·9		0·45	62
	K_2SO_4	23·2		23·5	23·8	23·3	22·3			
				0	125	250				
6	KCl	21·1	0·17	22·0	20·9	20·3			0·30	46
	K_2SO_4	21·6		21·6	21·5	21·7				
32	KCl	21·7			21·6	21·6			0·21	23
	K_2SO_4				21·7					
	KNO_3				21·9					

Table 11. *Main effects of rate of application of K on concentration of K in potato tubers (kg K/t FW)*

			kg K/ha						
Expt.	Variety	Mean	0	85	170	250	330	S.E.	D.F.
1	Estima	3·96	3·91				4·01	0·055	34
7	Estima	4·11	4·01				4·21	0·061	34
10	Estima	4·34	4·15				4·53	0·058	34
11	Erntestolz	5·73			5·72		5·73	0·069	15
14	Russet Burbank	3·89	3·83	3·81	3·96	3·96		0·083	20
17	Combined varieties	5·12	4·95	5·00	5·28	5·26		0·099	21
18	Record	5·39	5·25	5·34	5·52	5·45		0·073	24
			0	105	210	310	415		
3	Estima	3·14	2·80	3·10	3·27	3·28	3·29	0·115	12
23	Estima	4·18		4·05	4·26	4·22		0·055	58
24	Estima	4·21		4·18	4·24			0·049	57
25	Estima	4·28		4·04	4·33	4·48		0·050	58
26	Estima	4·27		4·23	4·32			0·033	57
27	Estima	3·98		3·96	3·99			0·037	57
28	Estima	4·62		4·63	4·61			0·069	58
30	Estima	4·06		3·81	4·03	4·35		0·051	58
			0	125	250	375	500		
2	Maris Piper	3·69	3·33	3·50	3·87	4·07		0·097	27
5	Nadine	2·79	2·56	2·73	2·90	2·96		0·045	46
6	Combined varieties	4·86	4·90	4·85	4·84			0·047	46
13	Pentland Dell	4·26	4·16	4·35	4·19		4·31	0·072	22
15	Shepody	4·89	4·65	4·67	5·07		5·16	0·257	21
			0	145	290	435			
8	Combined varieties	3·97	3·83	3·98	3·98	4·11		0·072	46

dry weight yield. In the remaining experiments, the increase in uptake was mainly due to an increase in the concentration of K in the tuber dry matter (data not shown). In the two experiments where it was tested (E6 and 11) K form had no significant effect on tuber K uptake (Table 14).

Table 12. *Effect of rate and source of K on concentration of K in potato tubers* (*kg K/t FW*)

				kg K/ha						
Expt	K source	Mean	S.E.	0	85	170	250	330	S.E.	D.F.
11	KCl	5·63				5·72		5·55		
	K_2SO_4	5·78	0·085			5·68		5·87	0·120	15
	KNO_3	5·77				5·76		5·79		
				0	125	250				
6	KCl	4·87	0·038	4·94	4·84	4·84			0·066	46
	K_2SO_4	4·86		4·87	4·97	4·84				

Table 13. *Main effects of rate of application of K on K uptake by potato tubers* (*kg K/ha*)

			kg K/ha						
Expt	Variety	Mean	0	85	170	250	330	S.E.	D.F.
1	Estima	311	298				318	7·6	34
7	Estima	225	226				224	6·3	34
10	Estima	252	239				265	5·3	34
11	Erntestolz	368			375		361	18·8	14
14	Russet Burbank	117	109	118	118	123		6·6	20
17	Combined varieties	189	185	190	191	192		7·2	21
18	Record	312	330	309	300	312		11·5	24
			0	105	210	310	415		
3	Estima	210	146	202	243	228	230	14·6	12
23	Estima	178		170	183	180		7·2	58
24	Estima	243		242	245			6·4	57
25	Estima	175		165	177	183		5·3	58
26	Estima	273		265	281			6·0	57
27	Estima	140		138	142			2·8	57
28	Estima	158		159	157			5·1	58
30	Estima	216		204	211	232		7·7	58
			0	125	250	375	500		
2	Maris Piper	136	110	129	151	154		11·0	27
5	Nadine	101	69	97	119	126		5·8	46
6	Combined varieties	249	234	261	252			9·4	46
13	Pentland Dell	93	86	87	101		98	3·5	22
15	Shepody	208	194	199	216		224	12·9	21
			0	145	290	435			
8	Combined varieties	220	221	209	218	232		6·8	46

Fry colour

In Experiments E6 and E32 neither the source nor the rate of K application had any effect on fry colour which in both cases would have been acceptable to European consumers. In E6, the overall mean values for L, a and b were 63·6, 27·7 and 1·61 respectively, whilst for E32 the L, a and b values were 68·8, 27·5 and −1·65 respectively.

DISCUSSION

It is generally believed (for example Cooke 1982; Archer 1985) that potatoes show large responses to potassium fertilizer and this justifies large inputs of potassium even on soils that contain moderate amounts of exchangeable potassium. Our results have shown that even on soils considered to have small potassium reserves the probability of a significant

Table 14. *Effect of rate and source of K on K uptake by potato tubers* (*kg K/ha*)

Expt	K source	Mean	S.E.	kg K/ha					S.E.	D.F.
				0	85	170	250	330		
11	KCl	340	22·3			357		323	31·6	15
	K_2SO_4	397				401		394		
	KNO_3	367				368		366		
				0	125	250				
6	KCl	249	7·7	227	268	252			13·3	46
	K_2SO_4	248		240	253	252				

response to potassium is small and on responsive sites the optimum application rate was normally < 170 kg K/ha. This suggests that much fertilizer K is applied unnecessarily and that current recommendations require urgent revision. There is a clear difference between the results of the current experiments and previously published results. The experiments produced greater yields yet showed few responses to applied K. The causes of the increasing yields and their significance for nutrient use must be established.

The re-interpretation of historic data using the same criteria as our own is difficult because in many cases standard errors are not quoted or the data have been averaged across regions, soil types or soil potassium status. Boyd & Dermott (1964) do not quote S.E.s for individual experiments but state that the average S.E. was *c.* 12% of the mean yield. Using this as the criterion, examination of their data shows that, in many cases, there was no significant increase in yield in response to potassium fertilizer. Where responses were present, the response was generally to the first 78 kg K/ha and not thereafter. Similarly, for the 38 experiments quoted by Birch *et al.* (1967) the yield response to the first increment (74 kg K/ha) of potassium was 3·4 t/ha. For subsequent K applications the yield responses were only 0·7 and 0·5 t/ha. Standard errors are not quoted, but it is unlikely that yield responses < 1 t/ha would be statistically significant. Birch *et al.* (1967) also grouped yield responses by soil citric acid extractable potassium. From these data economic optimal application rates of 223, 179 and 46 kg K/ha were calculated for soils with < 70, 70–200 and > 200 mg K/kg respectively. However, re-examination of their response curves bearing in mind that changes in yield of < 1 t/ha are unlikely to be significant suggest much smaller optima. Thus, for soil citric acid extractable K of < 70, 70–200 and > 200 mg K/kg the optimal K applications are more likely to be *c.* 150, 75 and 0 kg K/ha respectively. The study by Eagle (1967), does not give the optimum K application rate, but this work shows that even at K Index 0 the yield response to potassium fertilizer may be small or nonsignificant. More recent studies (Archer *et al.* 1976; Farrar & Boyd 1976; Webber *et al.* 1976) have also been used to justify large K applications, but closer examination of the means and S.E.s in these experiments suggest that the optimal K application has been over estimated. These 58 experiments tested N, P and K fertilizers in factorial combination. The average yield was *c.* 40 t/ha and since the experiments had limited replication, S.E.s were estimated from higher order interactions, additional replicated treatments or deviations from fitted cubic polynomials. Farrar & Boyd (1976) showed that on soils with K indices of 0 or 1, the average tuber yield increase when 94, 188, and 281 kg K/ha was applied was 2·8, 0·9 and –0·2 t/ha. On soils with K Index 2, the yield increases were < 1 t/ha and on an Index 4 soil, yields were decreased when K was applied. Thus, only on Index 0/1 soils was K fertilizer needed and the optimum rate was *c.* 94 kg K/ha. Similarly, Archer *et al.* (1976) found an average 5 t/ha yield increase when 156 kg K/ha was applied, but the yield increase from the subsequent 78 kg K/ha was only 0·7 t/ha. These workers also found that topsoil exchangeable K explained only 50% of the variation in the yield response to the first increment of K fertilizer. Webber *et al.* (1976) found an average 1·9 t/ha yield increase resulting from an application of 83 kg K/ha compared to controls receiving no K fertilizer. However, when 166 or 249 kg K/ha was applied the yield increases were only 0·5 and 0·4 t/ha respectively. Thus, notwithstanding relatively low yields by current standards, these older experiments do not support the use of amounts of K fertilizer which are currently recommended and do not allow the conclusion that potatoes are particularly responsive to K.

It seems that earlier work has often set the optimal K dressing at the application rate that resulted in the largest yield and this results in large optima. However, it would appear that if historic data are interpreted using similar criteria to our own and due consideration is given to the errors associated with yields found in experiments, the conclusions drawn from all sets of data, old and current, are similar. Thus our studies and historic studies show that topsoil exchangeable K is a poor predictor of the probability of a response to potassium fertilizer and when responses do occur they may be achieved with modest application rates ($<$ 170 kg K/ha) which are smaller than current recommendations.

Many of the earlier experiments are characterized by relatively small average tuber yields (for example 25 t/ha in Boyd & Dermott (1964) and 30 t/ha in Birch *et al.* (1967)). However, British Potato Council statistics (British Potato Council 2000) show that these yields are similar to the national average yields of that time (for example the average yield for 1960–64 was 23 t/ha) and that national yields have since doubled. This increase in yield is due to a number of factors including improvements in pest, disease and weed control. However, a major factor is the increased use of irrigation and British Potato Council statistics show that 24% of the national crop area received irrigation in 1976 compared with 54% in 1999. Whilst resulting in increased yields, the maintenance of fields at relatively small soil water deficits may also aid K supply to roots. For example, Van der Paauw (1958) examined the relationship between the number of rainless days (May–July) on the size of the response to K fertilizer and found a reasonable correlation between response and rainless days ($r^2 = 0{\cdot}71$; $P < 0{\cdot}001$). Thus, the response to K fertilizer was larger under dry conditions. Van der Paauw attributed this effect to the small availability of soil K in dry conditions thereby increasing the response to K fertilizer. However, a major function of K within the plant is osmotic regulation (Marschner 1995) and it is therefore possible that the larger yield response to K in dry conditions is due to enhanced tolerance of water stress. More recent work by Asfary *et al.* (1983) showed that irrigated potato crops had larger tuber K concentrations than unirrigated, presumably due to increased availability of K. Studies of nutrient inflows in winter wheat (Barraclough 1986) showed that, because of the decrease in diffusion path length, increasing the volumetric soil water content from 0·15 to 0·33 cm^3/cm^3 would permit a tenfold decrease in the soil solution K concentration without affecting K uptake. Thus, irrigated potato crops could meet their K requirements at smaller concentrations of K in the soil solution than unirrigated crops. Use of irrigation would thus tend to reduce the probability of a response to K fertilizer and to reduce the optimum fertilizer application rate. A component of the work by Asfary *et al.* (1983) and by Barraclough (1986) is that crops may get some of their nutrient requirement from soil layers below plough depth ($>$ 25 cm). Asfary *et al.* (1983) measured fibrous roots at 90 cm depth and Allen & Scott (1992) showed that, in good soil conditions, potato crops may root to 1–1·5 m. In consequence, the potato crop will take up some K from soil layers where the amount of exchangeable K is not normally measured. Since the amount of subsoil exchangeable K is smaller than top soil exchangeable K (*c.* 40% in our experiments) and rooting density decreases with depth, the contribution of subsoil K to crop K uptake is likely to be relatively small. However, sufficient K may still be provided from the subsoil to significantly reduce the probability of a yield response to K fertilizer even though this may be indicated on the basis of top soil analysis. In principle, changes in crop management can explain increases in yield and there appears to be little difference between the current results and older experiments.

A possible criticism of the current study is that the method of K application (shallow incorporation into the ridges or beds above the seed tuber after planting) may have reduced the probability of a significant yield response by reducing K availability. Other workers (e.g. Boyd & Dermott 1964; Webber *et al.* 1976) have suggested that the method of application may affect the response to K fertilizer, however, our own data suggest that application method did not bias the results. The current experiments show that statistically significant FW yield increases in response to the broadcast application of K were found in only seven experiments. However, the data in Tables 11–14 show that in several experiments the fertilizer K was available and taken up by the crop although this was not always associated with an increase in yield. In addition, the occasions where K application did not increase K uptake were generally associated with large soil K Indices ($>$ mid Index 2). Moreover, the statistically significant increases in DW yield in response to K application were associated with sites that received no irrigation and if our method of fertilizer application reduced the availability of K this effect should have been most noticeable in unirrigated ridges. As with other nutrients (N and P) there is a need for corroborative data from experiments using commercial times and methods of application.

The net effect of K fertilizer on tuber fresh weight yield results from the relative effects on dry weight yield and tuber DM concentration. In these experiments, K application increased tuber DM yield in only four experiments, but we have no data to suggest how these yield differences were created. Monteith (1997) proposed that crop growth should be analysed in terms of the amount of radiation absorbed by the leaf surface and the efficiency with which the absorbed radiation is converted to DM but there are few data in the literature investigating the effects of K on radiation absorption or conversion efficiency. Results from pot experiments (Watson & Wilson 1956) and field experiments (Gunasena & Harris 1968; Dyson & Watson 1971) are inconclusive. Compared to unfertilized controls, the effects of K fertilizer on leaf area index and tuber yield were generally small and inconsistent and the effects on conversion efficiency were not measured. Likewise, these papers cannot be used to support the widely held opinion that K increases yield by increasing leaf area index (and therefore radiation absorption) in the latter part of the season. Our work would also contradict this opinion. In the few experiments where K increased DW yield (E3, 5, 9 and 13) the experiments were planted relatively late (mid- to late May) and, with the exception of E13, used determinate varieties such as Estima or Nadine. Thus, in the current experiments, effects of K were found in relatively short growing seasons and in varieties whose canopies would not be expected to persist for much more than *c.* 100 days. Although it was not measured, it is probable that in the current experiments K increased yield by increasing leaf area index relatively early in the season.

With the exception of E13, all experiments where K significantly increased dry matter yield were located near Ross on Wye, Herefordshire. These experiments were characterized by small values of soil exchangeable K (Index 0 or 1), absence of irrigation, use of a determinate variety and large values for soil exchangeable Mg (Index 4 or above). The effects of water supply on K nutrition have been discussed earlier but the choice of variety may be very important. Studies at Cambridge University Farm (quoted by Allen & Scott 1992) have demonstrated that determinate varieties such as Estima tend to produce shallower fibrous root systems than indeterminate varieties such as Cara. It is possible that in E3, 5 and 9 the determinate varieties Estima and Nadine were relatively shallow rooting and could not fully exploit subsoil reserves of K, thereby increasing their response to freshly applied K fertilizer. The large amounts of soil exchangeable Mg at experiments E3, 5 and 9 may have contributed to the increase in dry matter yield when K was applied. Several workers (Edwards 1967; Dampney 1994) have suggested that large amounts of soil Mg may inhibit K uptake and increase yield response to applied K, although this was not demonstrated conclusively. In one experiment (E9), extra magnesium was applied (120 kg Mg/ha as Epsom salts) to investigate its effects on potato yield and crop response to K fertilizer. The supplemental Mg application did not reduce tuber yield even when no K fertilizer was applied nor did it affect the optimal K application rate. These results suggest that Mg has relatively little effect on crops response to K fertilizer even at small K:Mg ratios. Our data suggest that the probability of a significant DM yield increase when K fertilizer is applied is only partly dependent on soil K index. Other factors such as depth and extent of rooting, soil moisture and K requirement for osmotic control also appear to be important. For these reasons K index alone is a poor predictor of likely response to K as found in our work and also by Eagle (1967) and Birch *et al.* (1967).

For those experiments in which a significant yield response to applied K fertilizer was found, K had no statistically significant effect on tuber DM concentration when given at the optimum rate. Other workers have also found the effects of K fertilizer to be relatively small. For instance, Birch *et al.* 1967 showed that, on average, increasing the K application rate from 0 to 223 kg K/ha decreased tuber DM concentration from 22·0 to 21·1 g DM/100 g FW but this effect was significant in only half of the experiments. Dickins *et al.* (1962) compared the effect of different rates of KCl and K_2SO_4 on tuber yield and DM concentration. Use of KCl reduced tuber DM concentration in 11 out of 16 experiments compared with only three reductions when K_2SO_4 was used. In contrast to our experiments, these workers found that reductions in DM concentration occurred at application rates below those needed for maximum tuber yield.

In the UK, K fertilizer is recommended for some processing crops grown on soils with large K Indices and where no yield response is expected in order to reduce the incidence of bruising (internal black spot) and to improve the fry colours of crisps. In our experiments, we did not assess the effects of K application rate or form of K on internal bruising and the literature on this subject is inconsistent. For instance, Dwelle *et al.* (1977) have shown that application of K in excess of that needed for maximum yield had no effect on the incidence of tuber bruising. Conversely, more recent Australian work (Maier *et al.* 1986) indicated reductions in tuber bruising with K applications in excess of those needed to attain maximum yield although this was found at one site which had only 40 mg/l of soil exchangeable K. Recent studies in the UK (Hole *et al.* in press) have demonstrated that increasing the amount of K applied sometimes had a small effect on the severity of tuber bruising. When reductions in bruising occurred, these were achieved at the K application rate needed for maximum yield and there was no benefit from applying more.

In the two experiments where it was tested (E6 and 32) K source and K rate had no effect on crisp fry colour. Review articles by Zehler *et al.* (1981) and Perrenoud (1993) quote work which indicates that applying K fertilizer results in improved chip and crisp colour and, compared to controls receiving no K, K_2SO_4 is more effective than KCl. However, in both studies the largest improvements in colour were obtained with the first increment of K and applying more K did not significantly improve chip colour. Studies by Kunkel & Holstad (1972) have shown that whilst application of K fertilizer resulted in statistically significant improvements in crisp colour these were too small to be of practical significance. Harrison *et al.* (1982) showed that once sufficient K had been applied to maximize yield there was no further

Table 15. *Effect of residual and fresh fertilizer K on potato tuber yield* (*t FW/ha*). *Adapted from Johnston & Powlson* (*1994*)

Site	K applied in build up phase (kg K/ha)	Soil exchangeable K and K Index		kg K/ha applied in test phase		
		mg K/kg	K Index	0	125	210
Rothamsted	0	83	1	17·1	31·1	
	c. 5070	111	1	27·6	36·7	
Woburn	0	61	1	32·9	44·2	
	c. 3260	84	1	41·2	47·2	
Saxmundham	0	113	1	28·8		39·6
	c. 3740	166	2	43·1		44·0

improvement in chip fry-colour. Collectively, these data show that addition of K in excess of that required for yield in order to improve tuber quality is likely to be ineffective and thus this practice will waste fertilizer and cannot be recommended.

A component of the current K fertilizer recommendations is to apply more K fertilizer than is removed by crops so that, over time, soil K will increase. The justification for this policy was a series of experiments which indicated that tuber yields were smaller in soils with small K reserves compared to soils with larger K reserves irrespective of the amount of K fertilizer applied. The results of three of these experiments (Johnston *et al.* 1970; Johnston 1987; Johnston & Powlson 1994) are summarized in Table 15. However, due to problems with the experimental design in these studies, conclusions that support a policy of increasing soil K reserves are difficult to make. At Rothamsted, two unreplicated strips (1 and 7, in the Exhaustion Land Experiment) were given a total of 0 or 5070 kg K/ha over a 45-year period. Microplots were placed on these strips that tested the effects of fresh K fertilizer. At Woburn, a similar approach used Plots 7, 8 and 9 of the Permanent Wheat and Barley Experiments and these plots received 0, 3185 or 3330 kg K/ha over an 83-year period. It is interesting to note that despite large differences in the amounts of K applied to the soil in these long term experiments the effect on soil exchangeable K was relatively small (Table 15). At Rothamsted and Woburn the microplots were 13 and 10 m^2 respectively and the experiments at Rothamsted were hand planted and thus should have provided an accurate assessment of plot yield. However, since both of these experiments were unrandomized and unreplicated, it is not possible to test if the yields were statistically different or to associate, with any confidence, yield differences to K treatments. A similar problem is found with the study at Saxmundham, which used a design that was neither fully replicated nor randomized. A further and very important problem with these experiments was noted by Cooke (1979) who concluded that the apparent benefits of residual K over fresh K are greatest when poor soil conditions prevent good root growth and close contact between root and fertilizer K and hinder mobility of K in the soil solution. It is likely that in these long-term experiments soil conditions were such that fertilizer-derived K was not readily available to the crop and this over emphasized the benefits of residual K.

Other works on the benefits of residual K are no more conclusive. Studies by Ralph & Ridgman (1981), on clay soil at Otley, Suffolk, compared fresh K fertilizer (0–180 kg K/ha) with K fertilizer (124–996 kg K/ha) that had been applied in the previous ten years. This experiment showed that the presence or absence of K residues had no effect on tuber yield when fresh K fertilizer was given at the optimum application rate (*c.* 120 kg K/ha). A further study by Ridgman & Jones (1986), on a clay soil at Cambridge, showed that fresh K fertilizer (0–180 kg K/ha) had no effect on tuber yield. However, crops grown in plots with K residues (from 1000 kg K/ha applied in the previous 2 years) had slightly larger yields than those crops grown in the absence of K residues.

Our studies did not compare freshly applied K fertilizer with residual K, but they have demonstrated that large yields may be obtained in the absence of fertilizer on Index 0 soils (for example, E3 and 8 yielded > 50 t/ha). Furthermore, they have also shown that responses may be achieved with relatively small applications of K. There is little compelling evidence that shows the benefits of residual K or supports a fertilizer policy designed to increase soil exchangeable K. For many growers it is not practical to increase soil K reserves since they grow their crops on rented land. The exact proportion of the national crop grown on land rented for 1 or 2 years is not known. However, estimates made by British Potato Council field staff suggest that typically 15–30% of the crop is grown on rented land, but this value may be > 80% in some areas. Furthermore, on sandy soils with small cation exchange capacities it is not possible to increase soil exchangeable K above certain limits. For example, Archer (1985) suggests that a realistic upper limit for sandy soils is *c.* 100 mg K/l (Index 1)

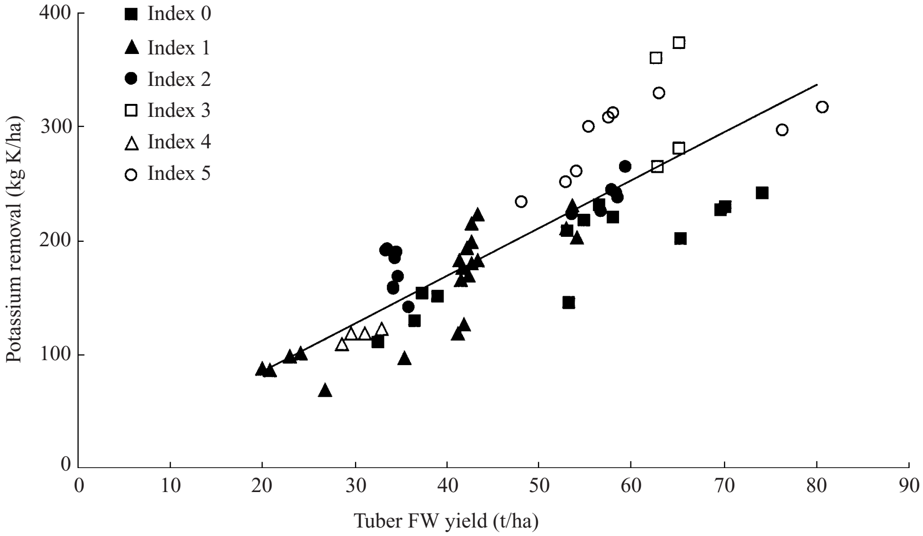

Fig. 2. Relationship between K removal and potato tuber fresh weight yield for soils for varying K index. Regression line is for all data.

whilst for loamy sands it is 150 mg K/l (lower Index 2). On these soil types large applications will lead to K leaching. Therefore, it can be concluded that response or replacement based policies would appear to be more than adequate.

Within the 21 experiments where it was measured, the addition of K fertilizer resulted in a statistically significant increase in tuber K concentration in only eight experiments. Increases in tuber K concentration were only found in crops grown on soils that had exchangeable K < 200 mg/l, however, small quantities of soil exchangeable K did not guarantee a significant increase in tuber K when K fertilizer was applied. These data show, that for crops grown on soils with > 200 mg K/l (i.e. above mid Index 2), application of K fertilizer is unlikely to increase tuber K concentration.

The suggested new K fertilizer recommendations assume that each tonne of tuber fresh weight yield will remove 4·8 kg K. Our data (Table 11) suggest that the average K concentration is smaller (*c.* 4·3 kg K/t) and is quite variable. Recent studies with sugarbeet (Milford *et al.* 2000) have shown from experimental plots and from factory tarehouse data that, for similar yields, crops grown on soils with large K Indices remove more K than crops grown on soils with smaller K Indices. Our data show that K uptake and tuber fresh weight yield are related but there was much unexplained variation (Fig. 2). For instance, a crop yielding 42 t/ha could remove between *c.* 115 and 230 kg K/ha. Simple, linear regression analysis showed that K removal and tuber FW yield were related and this regression was significant ($P < 0{\cdot}001$) and explained *c.* 70% of the variation in tuber K removal (Table 16). The regression was then modified to examine the effects of soil K Index on the relationship between K removal and tuber yield. The six levels of soil K Index (0–5) were added as factors to the regression and six lines with separate slopes were fitted for each level of soil K Index (GENSTAT 5 Committee 1993). Including soil K Index caused a significant improvement ($P < 0{\cdot}001$) in the regression, reduced the amount of unexplained variation and increased r^2 to 82% (Table 16). This modified regression showed that, with the exception of one experiment grown on an Index 4 soil (E14, a Russet Burbank crop grown on compacted soil), increasing the soil K Index increased the amount of K removed in each tonne of tubers. Predictions formed from these regressions showed that a 48 t/ha crop grown on an Index 0 soil would remove 167 (±7·1) kg K/ha compared with 240 (±11·1) kg K/ha for a crop grown on an K Index 3 soil. Dampney (1994) estimated that *c.* 70% of the potato crop grown in England and Wales was produced on soils with K Indices of 1 and 2. For these soils, our data would suggest a K removal of *c.* 4·3 kg K/t is appropriate and this value is reasonably consistent with the published value of 4·8 kg K/t. For K Index 0 soils, a replacement value of 4·8 kg K/t would return slightly more K than is removed by the crop.

Fertilizer recommendations based on the amount of K expected to be removed by a potato crop rely on a prediction of yield to be made at the time of fertilizer application, possibly several months before the crop is planted. In these circumstances, growers will have to estimate future yields based on the past performance of potato crops within their farming

Table 16. *Regression parameters for K removed (kg K/ha) on potato tuber FW yield (t/ha), r^2 is amount of variation explained by the regression when the effect of soil K Index was omitted (Regression 1) or was included as six lines of different slope (Regression 2)*

	r^2	F
Regression 1 averaged across all soil K Indices K removed = 4·22 ± 0·096 FW yield	70	< 0·001
Regression 2, including soil K Index as a factor K removed = 3·49 ± 0·147 FW yield Index 0 K removed = 4·09 ± 0·218 FW yield Index 1 K removed = 4·45 ± 0·227 FW yield Index 2 K removed = 5·00 ± 0·274 FW yield Index 3 K removed = 3·83 ± 0·505 FW yield Index 4 K removed = 4·70 ± 0·217 FW yield Index 5	82	< 0·001

systems. However, studies at Cambridge University Farm have shown that even for irrigated crops grown in a similar way each season, the variation in yield is large. The average (1993–1999) yield for crops of Estima was 60 t/ha, but the range was from 43 to 74 t/ha. Similarly, the average yield for crops of Cara was 65 t/ha with a range of 55–78 t/ha. A consequence of the variability in fresh weight yield and K removal per tonne of fresh yield is that, in a particular season, the amount of fertilizer applied based on expected offtake is unlikely to be equivalent to the amount actually removed by the crop and the discrepancy will not be measured.

CONCLUSIONS

The experiments reported in this paper have shown that the probability of a significant increase in tuber FW yield resulting from application of K fertilizer is small, even on soils that have small amounts of exchangeable K. Where responses did occur, the optimum K application rate was always $\leqslant 210$ kg K/ha. These conclusions are in agreement with data published earlier when these data are subject to the same analytical criteria as our own. Other workers (Eagle 1967; Birch *et al.* 1967; Archer *et al.* 1976) have also found that soil exchangeable K was a poor predictor of the probability of a response to K fertilizer. A possible reason for this is that other management practices, for instance use of irrigation and varietal choice appear to be important in determining the likelihood of a significant DM yield response to K fertilizer. These aspects of K nutrition of potatoes need further study. For crops that were responsive to K fertilizer, when applied at the optimum rate, the effect of K fertilizer on tuber DM concentration was not significant. However, when applied at rates larger than the optimum, the DM concentrations were reduced, particularly when KCl was used.

For fertilizer recommendations that are driven solely by the probability of a significant yield response to the applied K it is suggested that no more than 170–210 kg K/ha be applied even on soils with K Indices of 0 or 1. For replacement based fertilizer recommendations a value of *c.* 4·3 kg K/t multiplied by the FW yield would appear to be appropriate. However, estimation of yield before the crop is planted is problematic and could lead to over or under application of K fertilizer but more likely the former. In situations where a yield response to K fertilizer is not expected, the replacement K could be applied after the crop is harvested when the yield, and possibly the K concentration of the tubers, is known. The philosophy of applying more K than is removed by crops, in order to increase the K status of the soil and increase the yields of subsequent crops is not supported by the available data and this practice cannot be justified. Furthermore, for many growers who produce their crops on land rented for one or two seasons such a policy is not feasible.

Our studies on potatoes and those of Milford *et al.* (2000) on sugarbeet have shown that the two arable crops considered to have a large K fertilizer requirement are, in most cases, now unresponsive. Currently, cereals and oil seed rape are considered relatively unresponsive to K fertilizer and when grown on soil with K Index 2 the K fertilizer recommended is for maintenance of soil reserves rather than for yield response (Archer 1985). The amount of K fertilizer recommended for cereals and oil seed rape grown on soils with K Indices 0 or 1 is relatively modest when compared to potatoes. However, it is probable that there is potential to reduce this K input further and studies are needed to test this hypothesis in rotations of crops using modern, high yielding varieties grown using current production methods.

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