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Factors affecting the magnesium nutrition of potatoes (*Solanum tuberosum*)

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SUMMARY

Between 1995 and 1999, eight response experiments tested the effects of magnesium (Mg) fertilizers on the yield of potato crops grown in East Anglia, the Midlands, the West and Southwest of England. In addition, a further six experiments tested the effects of varying nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) supply on the tuber concentrations and uptake of Mg by potato crops. The experiments were done on soils that contained varying amounts of exchangeable Mg and K but were still typical of soils used for potato production.

In the eight response experiments, use of Mg fertilizer had no effect on total tuber fresh weight yield even though yields were often much larger than the national average yield. Increasing the N supply to the crop was often associated with an increase in the concentration of Mg in leaves and stems. This may have been due to N facilitating Mg uptake or a consequence of N delaying canopy senescence and, thus, delaying the translocation of Mg from haulm to tubers. Compared with the effects of N, varying the Mg and K supply to the crop had small and inconsistent effects on crop Mg uptake. Since the experiments also showed that Ca supply and soil K:Mg ratio had no effect on crop yield and erratic effects on tissue Mg concentration, fertilizer recommendation systems based on ratios of nutrients in the soil cannot be endorsed. When these current experiments and older, published experiments are taken into account there is little justification for applying Mg fertilizer to soils with Mg Indices > 0 and on soils with Mg Index 0 an application of *c*. 50 kg Mg/ha would be sufficient.

INTRODUCTION

For potato crops grown in England and Wales, the basis for Mg fertilizer recommendations is extraction of exchangeable soil Mg with 1 N ammonium nitrate and grouping of the analytical results into Indices for which an amount of Mg fertilizer is recommended (MAFF 1986). The amount of Mg fertilizer recommended for each Index is given in MAFF *Reference Book 209* which was first published in 1973 and is now in its seventh edition (MAFF 2000). The main changes in the Mg recommendations over this time are summarized in Table 1.

It is not clear how the Mg recommendations for each Mg Index were derived but, in part, they were based on several series of experiments that are summarized in Table 2. These experiments show that statistically significant yield increases resulting from use of Mg fertilizers occurred in only 10 of 161 experiments. In addition, in the 10 experiments where responses were found, the optimum Mg application rate was < 50 kg Mg/ha. It is of interest that the increase in the quantity of Mg recommended between the 1st and 2nd Editions of *Reference Book 209* appears to have occurred without the benefit of any experimental studies since the last significant bodies of work were published in 1973. The average yield in Table 2 is 27 t/ha whereas the national average main-crop yield is currently *c*. 48 t/ha (British Potato Council 2000). Irrigation is now more common and changes in cultivations, for instance increased ploughing depths and de-stoning will, ideally, facilitate the supply of nutrients to the crop by increasing the volume of soil that the crop may exploit. Many of the early studies were done with relatively indeterminate varieties such as King Edward and Majestic, however current UK potato production often uses relatively determinate varieties such as Estima, Wilja and Marfona. It is possible, therefore, that recommendations based on this older work may not be applicable to modern potato production.

There are few reliable data that give the distribution of Mg Indices for soils on which the UK potato crop is currently grown or the amount of Mg fertilizer

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Table 1. *Magnesium fertilizer recommendations* (*kg Mg/ha*) *for potatoes in MAFF* Reference Book 209, *1973–2000*

Edition	Year	Soil texture	Soil Mg Index or mg Mg/l 0 0–25	1 26–50	> 1 ⩾ 51
1	1973	Sands	75	40	0
		All other soil types	60	0	0
2	1979	All soil types	100	50	0
3	1983	All soil types	100	50	0
4	1985	All soil types	100	50	0
5	1988	All soil types	100	50	0
6	1994	All soil types	100	50	0
7	2000	All soil types for rotation	91	45	0
		All soil types only for potato crop	45	0	0

used. Data from the Representative Soil Sampling Scheme (Skinner *et al.* 1992) show that *c.* 3% of rotationally cropped land was Index 0 and *c.* 20% was Index 1 and these Indices were more common on light textured soils and in lowland, Eastern and South-Eastern Britain. Using crop survey data and the results from 34000 commercial soil samples Dampney (1994) estimated that 2, 13 and 31% of the English and Welsh potato crops were grown on soil with Mg Indices of 0, 1 and 2 respectively. However, this estimate needs to be treated with caution since, although the number of soil samples was large, they did not constitute a stratified sample and bias is likely. However, it is probable that < 5% of the potato crop is grown on Index 0 soils and *c.* 20% is produced on Index 1 soils. Using planting statistics collected by the British Potato Council (2000) this would equate with *c.* 6000 ha of the English and Welsh crop being planted on Index 0 and *c.* 26000 ha on Mg Index 1 soils. The amount of Mg fertilizer used on the potato crop is not known with certainty. Unpublished data from the Survey of Fertilizer Practice (A. G. Chalmers, personal communication) showed that during the period 1987–91, 6% of the crop received fertilizer that contained Mg (compared with 31% for sugarbeet), 1% of the crop received kieserite ($MgSO_4.H_2O$) and 8% of the crop received a foliar application of Mg.

The early studies, summarized in Table 2, provide limited evidence that K supply has an effect on the Mg nutrition of potatoes and, in turn, on Mg fertilizer requirement and to a certain extent this view is supported by other studies. Several studies have shown that as K application rates increased Mg concentrations in petioles or tubers decreased (Walsh & O'Donohoe 1945; Hossner & Doll 1970; Giroux 1986; James *et al.* 1994). However, conclusive proof that antagonism between K and Mg reduces yield is elusive. Walsh & O'Donohoe (1945), show that in the absence of Mg fertilizer, increasing the K application rate from 105 to 264 kg K/ha decreased tuber yield from 25 to 22 t/ha but did not show if this effect could be alleviated by applying Mg fertilizer. Hossner & Doll (1970) showed that in one experiment (out of two), increasing the K application rate from 200 to 665 kg K/ha increased the Mg requirement by *c.* 56 kg Mg/ha whereas Giroux (1986) found that Mg fertilizers had no effect on tuber yield regardless of K application rate. Although there is little good evidence, some crops are recommended large amounts of Mg fertilizer for the sole reason that they are produced on soils with large K Indices or because large amounts of K are to be applied. For example, Russet Burbank crops grown, under contract to a large processing company, on soils with Mg Indices of 0, 1 or 2 are currently recommended 205, 103 and 51 kg Mg/ha respectively.

The N fertilizer recommendations in the 7th edition of *Reference Book 209* are, in part, dependent on a crop's determinacy group with determinate varieties such as Estima and Wilja having larger N recommendations than relatively indeterminate varieties such as Hermes or Cara. This policy for N has been extrapolated to Mg with many growers and agronomists believing that, for a given soil Mg Index, determinate varieties need more Mg than indeterminate ones. This belief is understandable since observations in potato fields have shown that determinate varieties often show foliar symptoms of Mg deficiency although there is no evidence that their yields are Mg limited. However, there are no published experiments that have specifically tested the Mg requirements of determinate varieties.

The objectives for the work described in this paper were to investigate the effects of Mg fertilizers on the growth and yield of potato crops and to determine the extent to which these effects are modified by N, P, K and Ca supply and by potato variety with the aim of improving existing Mg recommendations for potatoes.

Table 2. *Summary of some UK experiments that have tested the effects of magnesium fertilizers on total tuber yield* (*t/ha*)

Reference	No. of expts	Mg/ha	Experimental details	Average yield	Results
Russell & Garner (1941)	10	0, 25, 39, 48	Variety: nd. Soil Mg Index: nd. No FYM	22	Two statistically significant increases in yield due to Mg and one yield decrease
Russell & Garner (1941)	11	0, 20, 23, 26	Variety: nd. Soil Mg Index: nd. FYM applied	24	No effect of Mg on yield
Russell & Garner (1941)	47	0, 23, 45	Variety: nd. Soil Mg Index: nd	22	Three statistically significant increases in yield due to Mg and two yield decreases
Holmes (1962) – Series 1 and 2	21	0, 30	Varieties: Majestic and King Edward. Soil Mg Index: when stated was 1 or 2. No FYM	29	Three yield increases of *c*. 4 t/ha on soils with Mg indices of 1 or 2
Holmes (1962) – Series 3	9	0, 14, 27, 54	Varieties: Majestic, King Edward, Great Scot and Redskin. Soil Mg Index: 0–3, Mg rates tested in combination with 140, 279 or 326 kg K/ha. No FYM	33	Two statistically significant responses to Mg on soils with Mg Index 0 and 3. One response was independent of K rate, one occurred only at the largest rate
Birch *et al*. (1966)	14	0, 7 (foliar), 27	Varieties: Majestic, Redskin and King Edward. Soil Mg Index: 0–4. Mg rates tested in combination with 112 and 335 kg K/ha	35	No main effects of soil or foliar applied Mg fertilizer. When K applied at largest rate, Mg increased yield at one site
Peeler & Heafield (1966)	2	0, 60, 121	Variety: nd. Citric acid soluble Mg: 180 and 260 mg/kg. Mg rates tested in combination with 104 and 208 kg K/ha	36	No main effects of Mg and no interaction with amount of K
Charlesworth (1967)	1	0, 226	Variety: Majestic. Soil Mg Index: nd. Mg rates tested in combinations with 0 or 106 kg K/ha	30	No significant responses to Mg
Edwards (1967)	12	0, 25, 50	Varieties: Majestic, King Edward, Arran Peak, Arran Pilot, Arran Banner, Red King, Soil Mg Index: 0–2. Mg tested in combination with 53 and 211 kg K/ha	25	No significant responses to Mg
Reith (1967)	2	0, 34	Variety: nd. Soil Mg Index: 0	20	No significant response to Mg
Bolton & Penny (1968)	2	0, 49, 99	Variety: King Edward. Soil Mg Index 0–2	7·1*	Response to Mg – but may have been due to residual effect from earlier applications rather than a response to fresh Mg
Archer *et al*. (1973)	16	0, nd	Variety: nd. Soil Mg Index 0–3	41	No significant response to Mg
Simpson *et al*. (1973)	13	0, 14, 27, 54	Varieties: Arran Banner, Majestic, Redskin and Craigs Royal. Soil Mg Index: nd, but no attempt to select Mg deficient soils. Mg rates tested in combination with 70, 140 and 280 kg K/ha	24	No main effects of Mg. However, on two occasions there was significant response to Mg when K fertilizer was applied
Bolton (1973)	1	0, 112, 224	Variety: King Edward. Soil Mg Index: 0	26	No significant response to Mg

* Dry weight yield.
nd, not determined or not given in the reference.

Table 3. *Site, soil and crop management details*

Expt	County	OS Ref	Variety	P (mg/l)	K (mg/l)	Mg (mg/l)	Mg Index	Sand (%)	Silt (%)	Clay (%)	Crop irrigated	Date of planting	Date of harvest
1	Somerset	ST406145	Estima	32	180	53	2	51	36	13	No	27 Apr 95	22 Aug 95
2	Cambridgeshire	TL429603	Estima	88	168	88	2	55	33	12	Yes	4 Apr 97	8 Sep 97
3	Devon	ST075086	Estima, Hermes	68	21	47	1	71	15	14	No	19 May 98	28 Sep 98
4	Cambridgeshire	TL428601	Estima	52	186	75	2	53	30	18	Yes	11 May 98	13 Oct 98
5	Monmouthshire	SO492132	Estima	13	61	221	4	4	48	48	No	21 May 98	16 Oct 98
6	Somerset	ST529157	Estima	25	36	45	1	65	18	17	Yes	21 Apr 99	3 Sep 99
7	Cambridgeshire	TL427598	Estima	113	911	160	3	74	19	7	Yes	28 Apr 99	5 Oct 99
8	Cambridgeshire	TL427598	Courlan, Hermes	113	911	160	3	74	19	7	Yes	28 Apr 99	5 Oct 99
9	Nottinghamshire	SK653581	Erntestolz	64	148	126	3	87	8	5	Yes	7 May 96	2 Oct 96
10	Cambridgeshire	TL429603	Dovekie, Hermes	88	168	88	2	55	33	12	Yes	3 Apr 97	8 Sep 97
11	Cornwall	SX412543	Estima	8	150	117	3	nd	nd	nd	Yes	18 May 98	16 Sep 98
12	Cambridgeshire	TL428601	Cara, Desiree, Estima, Hermes, Marfona, Maris Bard, Maris Piper, Symfonia	52	186	75	2	53	30	18	Yes	13 May 98	1 Sep 98
13	Cambridgeshire	TL428601	Maris Piper	52	186	75	2	53	30	18	Yes	12 May 98	28 Oct 98
14	Cambridgeshire	TL427598	Maris Piper	113	911	160	3	74	19	7	Yes	28 Apr 99	5 Oct 99

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

MATERIALS AND METHODS

Between 1995 and 1999, eight experiments (referred to in the text and tables as E1 … E8) were carried out which studied the effects of Mg fertilizer on the growth, tuber yield and Mg uptake of potato crops grown on different soil types in England and Wales. In addition, in a further six experiments (E9 … E14) the effects of different N, P, K or Ca fertilizer treatments on the concentration of Mg in the tubers of different potato varieties were also recorded. All experiments were planted by hand into pre-formed ridges or beds. The fertilizer treatments were also applied by hand within 3 days of planting. The fertilizers were then thoroughly incorporated by raking into the top 5 cm of soil. Magnesium fertilizer was always applied in the sulphate form either as kieserite ($MgSO_4.H_2O$; *c.* 16% Mg) or as Epsom salts (also known as bittersalz, $MgSO_4.7H_2O$; *c.* 10% Mg). In one experiment (E8) the effects of foliar Mg (applied as an ethylene diamine tetra-acetic acid complex) were tested. Irrigation was applied to 11 of the 14 experiments and this 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 and generally weed, pest and disease control was adequate in all experiments. The exceptions to this were an experiment in Somerset (E6), where some plots were badly infested with red shank (*Polygonum persicaria*) and an experiment at Cambridge (E13) that was affected by blight (*Phytophthora infestans*) which was controlled by destroying one block of plots with a commercial desiccant. All experiments had a factorial design with between 2 (E13) and 4 replicates and treatments were allocated at random into blocks. Adequate guard rows and discard areas were always used so that harvest areas were representative of the treatments. Details of each experiment are given in Table 3 and Table 4.

At harvest, areas of crop (typically 2 m^2) were dug by hand. For all harvests, all tubers > 10 mm were collected from each plot. The samples were returned to Cambridge, where they were graded and the number and weight of tubers in each 10 mm grade was recorded. Tuber dry matter (DM) concentrations were measured in a *c.* 500 g fresh subsample of tubers, taken from grades with the largest yield (typically 40–50 mm for early harvests and 40–60 mm for final harvest). The tubers were then dried to constant weight at 95 °C. To measure Mg uptake of the foliage, haulm samples were taken from some early harvests. From each harvest area all the haulm was collected and weighed and a *c.* 2 kg subsample was taken. This subsample was split into leaf laminae and stem material and these were then dried to constant weight at 95 °C. The Mg concentration of the dried tubers, leaves and stems was measured using standard methodology (MAFF 1986).

Variates were analysed by analysis of variance and treatment means are stated to be different only if the probability of the differences occurring by chance was less than 5% ($P < 0{\cdot}050$).

RESULTS

All the experiments were carried out on soils that are typically used for potato production in the UK and the soil textures ranged from loamy sand (E9) to silty clay (E5). The response experiments were not particularly biased towards soils with small Mg Indices: two out of eight experiments were carried out on Mg Index 1, three out of eight on Mg Index 2 and the remainder on Mg Index 3 and above.

Table 4. *Details of soil and foliar Mg treatments and experimental designs*

Expt	Soil Mg application (kg Mg/ha)	Levels of N applied	Levels of K applied	Levels of P applied	Levels of Ca applied	Design and number of replicates	Foliar Mg application (kg Mg/ha)
1	0, 30, 60	3	—	—	—	Factorial; 4 blocks	
2	0, 45, 90	3	2	—	—	Factorial; 3 blocks	
3	0, 45, 90	1	4	—	—	Factorial; 3 blocks	
4	0, 45, 90	3	2	—	—	Factorial; 3 blocks	
5	0, 121	1	5	1	—	Factorial; 3 blocks	
6	0, 90	1	5	—	—	Factorial; 4 blocks	
7	0, 45, 90	3	2	—	—	Factorial; 3 blocks	
8	0, 45, 90	2	—	—	—	Factorial; 3 blocks	0·19 × 3 occasions
9	—	1	2 × 3 sources	—	—	Factorial; 4 blocks	
10	—	4	—	—	—	Factorial; 3 blocks	
11	—	1	1	—	—	Factorial; 4 blocks	
12	—	2	—	—	—	Factorial; 3 blocks	
13	—	4 × 3 sources	—	—	2	Factorial; 2 blocks	
14	—	1	—	1	4	Factorial; 4 blocks	

Table 5. *Main effects of soil-applied Mg fertilizers on tuber fresh weight yield > 10 mm (t/ha) for harvests taken 94–160 days after planting (DAP)*

				Soil applied Mg fertilizer (kg Mg/ha)							
Expt	DAP	Variety	Mean	0	30	45	60	90	121	S.E.	D.F.
1	117	Estima	45·8	44·0	47·2		46·1			1·82	16
2	94	Estima	33·0	32·8		33·4		33·1		1·10	34
2	158	Estima	59·0	58·7		59·4		59·0		1·38	34
3	132	Estima	59·6	59·4		59·7		59·7		2·14	46
3	132	Hermes	51·9	51·7		51·4		52·7			
4	98	Estima	37·8	35·7		38·5		39·1		1·97	34
4	155	Estima	55·2	52·9		59·3		53·3		1·67	34
5	141	Estima	53·5	55·1					51·9	1·48	18
6	106	Estima	34·1	32·9				35·3		2·24	25
6	140	Estima	42·9	42·4				43·3		1·38	25
7	105	Estima	56·1	57·1		56·3		54·7		1·61	34
7	160	Estima	78·6	80·6		77·0		78·1		1·75	34
8	159	Courlan	65·1	64·0		64·7		66·6		1·68	33
8	159	Hermes	71·0	71·6		67·2		74·3			

Table 6. *Main effects of rate of nitrogen, magnesium and potassium application on the concentration of magnesium (mg/kg) in leaf, stem and tubers of Estima in E2, 4 and 7. Standard errors are based on 34 residual degrees of freedom*

				kg N/ha			kg Mg/ha			kg K/ha			
Date	DAP	Tissue	Mean	0	150	300	0	45	90	0	332	S.E. for N and Mg	S.E. for K
6 Jun 97	63	Leaf	3480	3317	3617	3506	3261	3633	3544	3493	3467	99	81
		Stem	2939	2494	3200	3122	2706	2967	3144	3015	2863	116	95
		Tuber	1143	1525	956	944	950	994	1483	1304	981	288	236
19 Jun 97	76	Leaf	2748	2128	3217	2900	2533	2778	2933	2952	2544	109	89
		Stem	2611	1672	2994	3167	2389	2628	2817	2837	2385	120	98
		Tuber	943	950	961	917	950	950	928	941	944	14	11
7 Jul 97	94	Leaf	3830	2233	4628	4628	3322	4033	4133	4256	3404	188	154
		Stem	2126	1100	2450	2828	1794	2239	2344	2467	1785	149	121
		Tuber	896	879	913	897	893	893	903	889	903	13	10
8 Sep 97	158	Tuber	1115	1328	1006	1011	1378	1000	967	963	1267	226	185
14 Jul 98	64	Leaf	2716	2503	2892	2752	2413	2676	3058	2743	2688	49	40
		Stem	1791	1492	1819	2063	1501	1789	2083	1804	1779	83	68
		Tuber	954	918	985	960	891	973	999	964	944	31	25
17 Aug 98	98	Leaf	1562	1272	1428	1988	1369	1574	1744	1633	1491	81	66
		Stem	1357	1386	1172	1514	1147	1369	1556	1416	1298	73	60
		Tuber	924	872	941	958	913	912	946	923	924	13	11
13 Oct 98	155	Tuber	865	832	877	886	822	887	886	858	872	18	14
14 Jul 99	77	Leaf	2831	2486	2987	3021	2782	2852	2859	2657	3005	60	49
		Stem	1640	1393	1646	1882	1588	1656	1677	1535	1745	47	38
		Tuber	912	889	922	926	886	919	932	912	912	13	11
9 Aug 99	105	Leaf	2499	2466	2456	2576	2370	2559	2569	2404	2594	85	69
		Stem	1203	1194	1172	1243	1139	1225	1245	1131	1275	49	40
		Tuber	696	667	634	786	699	701	686	696	695	37	30
5 Oct 99	160	Tuber	854	855	839	867	849	838	874	858	850	15	13

Table 7. *Main effects of rate of N fertilizer application on leaf, stem, tuber and total Mg uptake for harvests of Estima crops in E2, 4 and 7. Standard errors* (S.E.) *are based on 34 residual degrees of freedom*

					kg N/ha			
Exp.	Date	DAP	Tissue or total	Mean	0	150	300	S.E.
2	6 Jun 97	63	Leaf	2·03	1·59	2·29	2·22	0·102
			Stem	1·18	0·82	1·34	1·38	0·062
			Tuber	0·51	0·66	0·46	0·43	0·126
			Total	3·72	3·06	4·08	4·03	0·192
2	19 Jun 97	76	Leaf	3·38	1·79	4·31	4·03	0·196
			Stem	2·77	1·16	3·23	3·92	0·186
			Tuber	2·05	2·04	2·09	2·01	0·086
			Total	8·19	4·99	9·64	9·95	0·385
2	7 Jul 97	94	Leaf	4·45	1·74	5·63	5·98	0·396
			Stem	3·87	0·91	4·59	6·11	0·320
			Tuber	4·80	4·20	5·28	4·91	0·174
			Total	13·12	6·84	15·50	17·00	0·730
2	8 Sep 97	158	Tuber	12·62	11·06	12·12	14·69	1·769
4	14 Jul 98	64	Leaf	1·85	1·14	2·27	2·14	0·105
			Stem	1·60	0·85	1·83	2·11	0·111
			Tuber	1·64	1·47	1·84	1·60	0·128
			Total	5·08	3·46	5·93	5·85	0·285
4	17 Aug 98	98	Leaf	1·41	0·77	1·37	2·10	0·122
			Stem	1·49	0·86	1·44	2·17	0·094
			Tuber	7·27	5·10	8·48	8·24	0·408
			Total	10·17	6·73	11·29	12·50	0·525
4	13 Oct 98	155	Tuber	9·32	6·19	10·34	11·43	0·338
7	14 Jul 99	77	Leaf	3·94	3·04	4·29	4·47	0·151
			Stem	3·17	1·95	3·27	4·29	0·162
			Tuber	4·95	4·95	5·09	4·82	0·140
			Total	12·06	9·94	12·65	13·58	0·453
7	9 Aug 99	105	Leaf	2·47	2·47	2·41	2·54	0·168
			Stem	2·37	1·89	2·39	2·82	0·121
			Tuber	7·30	6·76	6·62	8·50	0·440
			Total	12·13	11·13	11·42	13·86	0·473
7	5 Oct 99	160	Tuber	12·75	11·91	13·21	13·15	0·436

Effect of magnesium fertilizers on total (> *10 mm*) *tuber fresh weight yield*

The average fresh weight (FW) yield > 10 mm for the eight response experiments was 53 t/ha (Table 5) and despite including some harvests that were taken relatively early in the season this is *c.* 5 t/ha larger than the current national average yield. The experiments were also accurate since the standard errors (S.E.) for comparing the yields of the Mg treatment were small and averaged *c.* 3% of the mean yield. The only experiment that had a relatively large S.E. was the early harvest from E6, the Estima experiment in Somerset that was affected by weeds. The combination of large yields and relatively small standard errors should increase the probability of detecting yield differences that could be attributed to use of Mg fertilizer. However, in these eight experiments Mg fertilizer had no statistically significant effect on tuber FW yield. Furthermore, in the experiments that tested Mg fertilizers in combination with N fertilizers (E1, 2, 4 and 7) and K fertilizers (E2, 3, 4, 5, 6 and 7) there was no evidence that the application rate of N or K affected the response to Mg (data not shown). In the one experiment where it was tested (E8), foliar applied Mg had no effect on tuber FW yield (data not shown). This result was not surprising since the initial soil Mg Index was 3 and soil-applied Mg also had no effect on yield.

Tissue Mg concentrations and uptake by Estima 1997–99 – effects of Mg, K and N

The main effects of Mg, N and K applications on the concentration of Mg in leaves, stems and tubers of

Table 8. *Effect of rate of nitrogen, potassium, magnesium and calcium fertilizer application and variety on the concentration of Mg in the tuber, tuber dry matter yield > 10 mm and tuber Mg uptake. Standard errors for experiments 3, 13 and 14 are based on 46, 11 and 18 residual degrees of freedom respectively*

				kg K/ha				kg Mg/ha					
Exp.	Variety		Mean	0	145	290	435	0	45	90	S.E. for variety	S.E. for K × Var	S.E. for Mg × Var
3	Hermes	mg Mg/kg	1010	984	1009	1020	1028	1003	1005	1023	13	25	22
	Estima	mg Mg/kg	1033	1051	1016	1029	1034	1056	1017	1025			
	Hermes	t DW/ha	12·2	13·2	10·5	12·2	13·0	12·3	11·9	12·4	0·27	0·55	0·47
	Estima	t DW/ha	11·3	11·7	11·9	10·6	10·9	11·2	11·2	11·4			
	Hermes	kg Mg/ha	12·3	12·9	10·7	12·4	13·3	11·9	11·4	11·7	0·28	0·57	0·49
	Estima	kg Mg/ha	11·6	12·3	12·1	11·0	11·2	12·3	11·9	12·7			

				kg N/ha					
Exp.	Variety		Mean	0	80	160	240	S.E. for variety	S.E. for N × Var
13	Maris Piper	mg Mg/kg	903	885	900	895	930		
	Hermes	mg Mg/kg	996	1005	995	955	1030	31	61
	Courlan	mg Mg/kg	1051	1020	1060	1100	1025		
	Maris Piper	t DW/ha	17·6	12·9	20·2	19·9	17·4		
	Hermes	t DW/ha	13·9	9·6	13·5	13·7	18·9	0·78	1·57
	Courlan	t DW/ha	7·6	3·7	6·2	12·8	7·7		
	Maris Piper	kg Mg/ha	15·9	11·4	18·1	17·8	16·2		
	Hermes	kg Mg/ha	14·0	9·6	13·4	13·0	19·9	1·10	2·20
	Courlan	kg Mg/ha	8·1	3·9	6·6	14·1	7·8		

				kg Ca/ha as gypsum				kg K/ha as KCL	kg K/ha as K_2SO_4	kg Ca/ha as $CaCl_2$	
Exp.	Variety		Mean	0	115	230	1150	443	443	230	S.E.
14	Maris Piper	mg Mg/kg	956	943	969	982	976	869	1020	931	34
		t DW/ ha	19·3	19·2	19·4	18·1	19·7	20·7	19·9	18·5	1·47
		kg Mg/ha	18·5	18·1	18·8	17·8	19·2	17·9	20·2	17·3	1·49

Table 9. *Effect of rate of nitrogen, potassium and phosphorus fertilizer application and variety on the concentration of Mg in the tuber, tuber dry matter yield > 10 mm and tuber Mg uptake. Standard errors for experiments 9, 10, 11 and 12 are based on 15, 14, 24 and 30 residual degrees of freedom respectively*

				kg K/ha		
Exp.	Variety		Mean	166	332	S.E. for K
9	Erntestolz	mg Mg/kg	1283	1294	1273	25
		t DW/ha	13·0	13·3	12·7	0·66
		kg Mg/ha	16·8	17·3	16·3	0·99

				kg N/ha					
Exp.	Variety		Mean	0	80	160	240	S.E. for Variety	S.E. for N × Var
10	Hermes	mg Mg/kg	1067	1033	1100	1133	1000	41	82
	Dovekie	mg Mg/kg	1067	1133	1133	967	1033		
	Hermes	t DW/ha	13·3	10·8	11·7	14·9	15·6	0·51	1·03
	Dovekie	t DW/ha	12·4	9·2	13·5	13·7	13·3		
	Hermes	kg Mg/ha	14·2	11·2	12·8	17·0	15·6	0·70	1·40
	Dovekie	kg Mg/ha	13·0	10·3	15·0	13·2	13·6		

				kg P/ha					
Exp.	Variety		Mean	0	55	110	165	220	S.E. for P
11	Estima	mg Mg/kg	930	961	939	930	910	873	57
		t DW/ha	12·3	10·4	12·2	13·7	14·1	11·5	0·65
		kg Mg/ha	11·5	10·1	11·4	12·9	12·9	10·0	1·23

				Variety									
Exp.	Kg N/ha		Mean	Cara	Desiree	Estima	Hermes	Marfona	M. Bard	M. Piper	Symfonia	S.E. for N	S.E. for N × Var
12	0	mg Mg/kg	814	720	793	820	863	883	860	820	750	28	40
	250	mg Mg/kg	851	783	847	847	983	987	877	770	717		
	0	t DW/ha	7·4	5·1	6·5	7·0	8·3	8·9	8·9	8·2	6·5	0·70	0·99
	250	t DW/ha	11·2	7·7	9·8	13·0	11·4	11·4	11·6	10·4	13·9		
	0	kg Mg/ha	6·1	3·7	5·2	5·8	7·2	7·8	7·6	6·7	4·9	0·67	0·95
	250	kg Mg/ha	9·5	6·0	8·3	11·1	11·2	11·3	10·2	8·0	9·8		

three Estima crops (E2, 4 and 7) are summarized in Table 6. Generally, applying Mg fertilizer increased the concentration of Mg in leaves, stems and tubers of three Estima crops (E2, 4 and 7) are summarized in Table 6. Generally, applying Mg fertilizer increased the concentration of Mg in leaves, stems and tubers, although these effects were not always statistically significant. Use of N fertilizer tended to increase the concentration of Mg particularly in the leaves and stems and the size of the increase was often larger than that obtained by use of Mg. Compared with Mg and N fertilizer, significant effects on leaf or stem Mg concentrations resulting from application of 332 kg K/ha were less frequent and more inconsistent. In E2, use of K fertilizer decreased the Mg concentration of leaves and stems whereas in E7, use of K increased leaf and stem Mg concentration.

The main effects of N applications on leaf, stem, tuber and total Mg uptake for the Estima crops in E2, 4 and 7 are shown in Table 7. With the exception of the tubers in early harvests, use of N significantly increased Mg uptake of most crop tissues. In part, this increase in uptake was a result of N increasing DM yield (data not shown) but also a consequence of the increase in tissue Mg concentration. The largest total uptake was 17 kg Mg/ha in a 300 kg N/ha treatment taken 94 days after planting in E2. This uptake was associated with a total DM yield of 8·93 t/ha. The largest removal of Mg in tubers was *c.* 15 kg Mg/ha in a 300 kg N/ha treatment taken 158 days after planting in E2 and this was associated with tuber fresh and dry weight yields of 74 and 14·5 t/ha respectively. As they had no effect on DM yield, the effects of Mg and K fertilizers on Mg uptake and removal were consistent with their effects on tissue Mg concentration (data not shown).

Tuber Mg concentration and uptake – effects of variety and N, P, K, Mg and Ca supply

The effects of variety and use of N, P, K, Mg and Ca fertilizers on tuber Mg concentration and uptake are shown in Tables 8 and 9. In experiments E3, 9–14, the largest Mg uptake by tubers (19 kg Mg/ha) was found in E14, where the mean tuber dry weight (DW) yield was 19·3 t/ha (91 t FW/ha). In E10, 12 and 13, application of N had little effect on tuber Mg concentration, but by increasing tuber DW yield, often increased Mg uptake. In no experiment did use of P (E11), K (E3, 9 and 14), Mg (E3) or Ca (E13 and 14) fertilizers affect tuber Mg concentration or uptake even though, in some cases, large amounts of these nutrients were applied. In E3, 12 and 13 there were significant varietal differences in tuber Mg concentration. However, these differences may be a consequence of different DM yields rather than differences in the relative abilities of the varieties to assimilate and partition Mg to the tubers.

DISCUSSION

In E1 … 8 there was no requirement for Mg application and this result was obtained despite the experiments having relatively large yields and some being done on soils with small Mg Indices or where large amounts of K fertilizer were applied. Therefore, the conclusion from these results and those summarized in Table 2, is that the potato crop is not particularly responsive to Mg fertilizer. However, there is sufficient evidence from the data collated in Table 2 that statistically significant responses do occasionally occur on soils with small Mg Indices and this still warrants an application of *c.* 50 kg Mg/ha. These results and conclusions are in broad agreement with those obtained by Draycott & Durrant (1970) who, in 53 field experiments, examined the relationship between soil exchangeable Mg and the percentage change in sugar yield when 101 kg Mg/ha was applied. These workers showed that once a soil contained more than *c.* 25 mg Mg/l (i.e. > Index 0) the probability of a yield increase resulting from use of Mg fertilizer was small and that yield increases were more likely if the crop had a poor root system. It would seem that the two arable crops previously considered most likely to benefit from an application of Mg are, in fact, rarely responsive. This conclusion has been accepted by the Ministry of Agriculture, Fisheries and Food and has resulted in a reduction in the amount of Mg recommended for both potato and sugarbeet crops.

In experiments E2, 4 and 7 the increase in leaf and stem Mg concentration that was associated with an increase in N supply was achieved without any significant decrease in tuber Mg concentration (Table 6) and since application of N increased dry matter yield there must have been a large increase in Mg uptake. In part this may be due to the mechanism suggested by Mulder (1956), who in a series of field experiments showed that application of N was associated with an increase in tissue Mg concentration. In addition, Mulder (1956) also showed that foliar symptoms of Mg deficiency were reduced by application of Mg fertilizer but also by application of N. Mulder attributed the beneficial effect of nitrate-N on Mg uptake to an ion-exchange mechanism that facilitated crop uptake of Mg. More recently James *et al.* (1994) found that increasing amounts of N fertilizer also resulted in a small increase in the concentration of Mg in the petioles but did not attribute a mechanism to this effect. The observations of Mg deficiency made by Mulder (1956) could also be explained by the effect of N on canopy persistence. Archer (1985) suggested that Mg deficiency symptoms are often associated with premature senescence and that a response to N was more likely than a response to Mg. Magnesium is considered to be highly mobile within the phloem system (Marschner 1995) and during canopy senescence Mg will be mobilized from the haulm and transported to the tubers. In experiments E2, 4 and 7 Estima crops that received no N started to senesce (estimated from the onset of a significant and systematic decrease in ground cover) in late July or early August. The application of 300 kg N/ha delayed the onset of senescence by 2–3 weeks. Therefore, by delaying the senescence process, application of N is likely to retain Mg in the haulm and delay the onset of the appearance of Mg deficiency symptoms. It is probable that in many situations observation of Mg deficiency is not caused by a lack of Mg per se but by inadequate N supply or other stresses, for instance drought or water logging that will induce premature senescence. This hypothesis also explains why field observations suggest that varieties such as Estima, Marfona and Wilja are apparently more prone to Mg deficiency. These varieties are determinate (determinacy groups 1 and 2 in MAFF 2000) and have a limited capacity to produce sympodial branches and new leaves once they have flowered. Once these varieties are exposed to nutritional or environmental stress they will tend to senesce and this will involve movement of Mg out of the haulm and the appearance of foliar deficiency symptoms. In contrast, with less determinate varieties such as Maris Piper or Cara (determinacy groups 3 and 4 respectively in MAFF 2000) once the stress has been alleviated leaf production recommences and Mg will tend to be retained in the crop canopy.

We have no satisfactory explanation as to why K fertilizer decreased tissue Mg concentration in E2, had little effect in E4 but increased Mg concentrations in E7. Assuming a constant concentration of cation in the soil solution then, from the activity ratio ($aK/\sqrt{aCa+Mg}$; Beckett 1964), addition of K might be expected to reduce the concentration of Mg and Ca in the soil solution and in turn Mg uptake as was found in E2. However, as noted by Addiscott (1974) the anion applied with the K fertilizer would increase the anion concentration in the soil solution and this, in turn, would permit an increase in the total cation concentration so that soil solution concentrations of Ca and Mg may increase. Addiscott (1974) also suggested that whilst K may reduce the passive uptake of Mg (by reducing the concentration of Mg in the soil solution), use of K fertilizer may increase the active uptake of Mg. Experiments E1, 4 and 7 demonstrate that the effects of K supply on the Mg nutrition of the potato crop are complex and that application of K or excess soil K supply did not necessarily result in a reduction in tissue Mg concentration and, more importantly, did not result in a yield reduction. Thus, there is little evidence to suggest that potato crops grown on soils with large K Indices or when large amounts of K are applied necessarily need large amounts of Mg fertilizer.

Several authors (for example Batey 1967; Charlesworth 1967; Hossner & Doll 1970) have claimed that Mg fertilizer recommendations may be improved if the ratio of exchangeable K to Mg in the soil is considered as well as the absolute amount of exchangeable Mg. In experiments E1 … 8, where different rates of Mg fertilizer were tested, the ratio of exchangeable K to exchangeable Mg ranged from 0·3 (E5) to 5·7 (E7 and 8) and despite some of the experiments receiving K fertilizer there were no effects of Mg on tuber yield. In E2, 4 and 7 the K:Mg ratios at the start of the experiments were 1·9, 2·5 and 5·7 respectively, yet for similar sampling times and N application rates there were no consistent effects of soil K:Mg ratio on tissue Mg concentration (Table 6). Indeed, in E7, the experiment with the widest K:Mg ratio, application of 168 kg K/ha increased leaf and stem Mg concentrations. The insensitivity of crop yield and tissue Mg concentration to soil K:Mg ratio and also to Ca supply (E13 and 14; Table 8) suggest that fertilizer recommendation systems based on ratios are unlikely to offer any improvement on those based on defining a sufficiency level (i.e. the MAFF Index system). Draycott & Durrant (1970) showed that the probability of an increase in sugar yield resulting from application of Mg was independent of either soil K:Mg ratio or the amount of Ca in the soil. These conclusions cast doubt on the utility of the base cation saturation ratio (BCSR) system that is currently being promoted for use within UK and is being discussed in the farming press (for example, Crops 2000*a*, *b*). The BCSR system was developed by Bear and co-workers (Bear *et al.* 1945 quoted by Bear & Toth 1948) and states that for optimal plant growth the soil's cation exchange capacity should contain 65% Ca, 10% Mg, 5% K and 20% H. This system was originally developed in New Jersey, but is now widely used for making lime and fertilizer recommendations in the USA. However, since it was first proposed other workers have found that ratios between nutrients have little relevance until they become so extreme that one nutrient becomes deficient (Eckert & McLean 1981; McLean *et al.* 1983). Although our work did not specifically test the BCSR system it would support the conclusion made by McLean *et al.* (1983) who stated 'emphasis should be placed on providing sufficient, but non excessive levels of each basic cation rather than attempting to adjust to a favourable basic cation saturation ratio which evidently does not exist'.

CONCLUSIONS AND RECOMMENDATIONS

In these experiments there was no statistically significant benefit from applying Mg fertilizers even though some of the crops were grown on Mg Index 1 soils or on soils with large amounts of exchangeable K. This conclusion is largely in agreement with the survey of published work (Table 2). Thus, it is suggested that *c*. 50 kg Mg/ha is applied only to Mg Index 0 soils. Since potato crops will remove less than half this amount, some Mg will remain in the soil for the benefit of subsequent crops in the rotation. It is likely that, in many cases, symptoms of Mg deficiency are a result of senescence due to inadequate N or other stresses such as drought, water logging or compaction and these symptoms are more likely in determinate varieties. In these circumstances it is unlikely that remedial action (for instance increasing the Mg supply by using foliar sprays) will be of any benefit. There was some evidence that K supply sometimes had a small, but statistically significant effect on haulm Mg concentration. However, these effects were inconsistent and in no experiment did K supply have any effect on response to Mg fertilizer. There was also no evidence in the current experiments to support fertilizer policies based on K : Mg ratios or on the base cation saturation ratios.

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