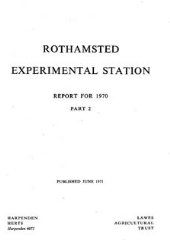
Rothamsted Experimental Station Report for 1970 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

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PART 2

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Long-term Liming Experiments at Rothamsted and Woburn

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Long-term Liming Experiments at Rothamsted and Woburn

J. BOLTON

Introduction

Few experiments on the Rothamsted and Woburn farms have been specifically designed to study the effects of liming on crop yields, although both soils are naturally acid and liming has been an integral part of crop husbandry for centuries. Only the permanent grass plots (Park Grass) of the 'classical' experiments include liming treatments. However, liming has been necessary on the permanent wheat (Broadbalk) and barley (Hoosfield) experiments at Rothamsted, and on the Classical cereal plots at Woburn, partly because some fertilisers, especially ammonium sulphate, acidified the soil.

Description of the experiments. In 1962 two liming experiments were started on very acid soils at both Rothamsted (Sawyers) and Woburn (Stackyard), with plots given 0, 2, 4 and 6 tons/acre of ground chalk ($<\frac{1}{8}$ in. mesh; 47% N.V.). Interactions of liming with cumulative annual phosphate and potassium dressings were studied by including superphosphate (0·5 cwt P_2O_5/acre) and potassium chloride (1·0 cwt K_2O/acre) treatments in 4×2^2 factorial designs. There were two replicates giving a total of 32 plots at each site. In autumn 1962 a further 2 tons/acre limestone was given to the plots initially given 6 tons/acre at Rothamsted, and 0·75 and 1·5 tons/acre were given to the plots at Woburn already given 4 and 6 tons/acre.

Both fields had for many years been 'reserved sites' where lime and fertilisers were withheld, to provide soils and experimental sites acid and deficient in phosphate and potassium.

Crops

Spring tick beans (1962–64). 'Gartons 30B' was sown in 1962 and 1963 and 'Gartons Pedigree' in 1964 at 200 lb/acre in rows 21 in. (1962 and 1963) and $10\frac{1}{2}$ in. (1964) apart. Simazine (1·0 lb a.i./acre) was used each year at both sites to kill weeds. Winter beans planted in autumn 1963 at Woburn were so severely damaged by birds that spring beans were resown in early 1964, with a repeated dose of simazine.

Spring barley (1965–67). The variety Maris Badger was used each year in both experiments, sown at 156 lb/acre. Basal nitrogen fertilisers were as follows:

	Cwt N/acre	
	Rothamsted	Woburn
1965	0·50 N/C	0·50 N/C
1966	0·50 N/C	0·50 S/A; 0·50 N/C*
1967	0·75 N/C	0·62 S/A; 0·38 S/A*

N/C = 'Nitro-Chalk' 21% N; S/A = Ammonium sulphate 21% N; * = topdressed.

Potatoes (1968). The variety Majestic was grown with basal dressings of 1·5 cwt N/acre at Rothamsted and 2·0 cwt N/acre at Woburn, given as 'Nitro-Chalk' before planting

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Analytical methods

Soils. Surface soil (0–9 in.) was taken from all plots each autumn except in 1965. The samples were air-dried and sieved (<2 mm). The pH was determined in 1 : 2·5 soil : water suspensions, stirred, left for one hour, then measured using a glass electrode and Pye 'Dynacap' meter. Figure 1 gives mean values of the pHs during the experiments.

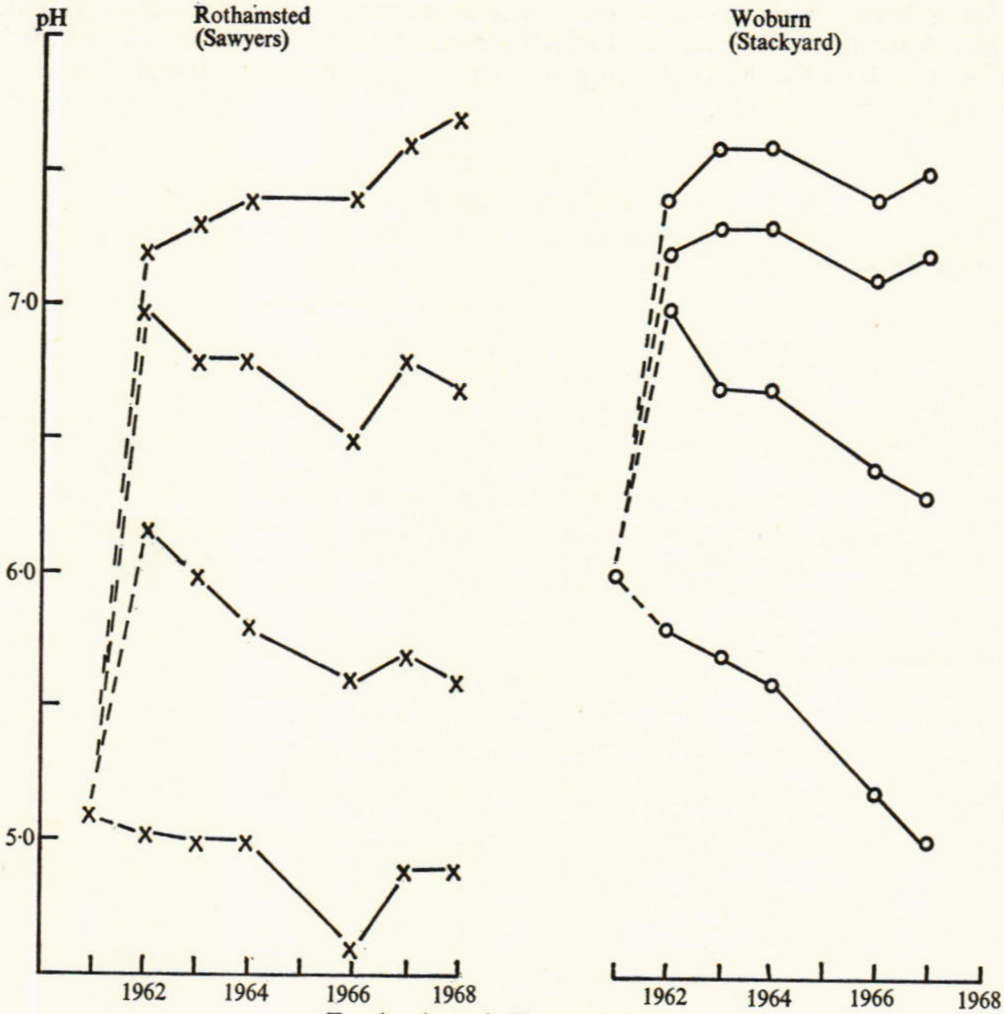

FIG. 1. Annual pH measurements.

The 1967 samples were analysed for exchangeable cations by leaching 2 g of air-dried soil with 75 ml of *N* ammonium acetate at pH 7, using the tube method of Metson (1956). December 1968 samples from the Rothamsted experiment were used to measure 'available' phosphate soluble in 0·5*M* sodium bicarbonate (Olsen *et al.*, 1954).

Crops. The beans grown during 1962–64 were not analysed. Samples of barley grain were analysed each year for the major cations, and, for two years, manganese. Oven-dried grain was ground <0·5 mm and sub-samples were ashed at 450°C for 3 hours.

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The ash was extracted with *N* HCl, and K, Na and Ca measured in the extract by emission and Mg and Mn by atomic-adsorption flame spectrometry. Similar analyses (except Mn) were made on oven-dried potato slices, ground <0·5 mm from each plot.

Results

I. Crop yields

Spring beans. Yields of beans from these experiments were discussed by Moffatt (1967). A summary of the results (Table 1) shows that the optimum pH in both experiments was about 6·8. Responses to potassium were larger than to phosphate and increased in successive crops.

TABLE 1

Yields of spring beans

(cwt grain/acre at 85% D.M.)

Rothamsted—Sawyers

		Limestone tons/acre				
		0	2	4	8	S.E.
Mean yields	1962	12·3	16·0	20·3	18·6	±1·51
	1963	10·7	20·7	23·0	22·5	±1·21
	1964	14·7	19·0	19·8	17·1	±1·26
Response to P	1962	−0·7	−2·5	−1·7	+2·2	±3·01
	1963	+0·8	−3·7	+1·0	+2·8	±2·43
	1964	−0·7	−2·4	+0·2	+1·8	±2·53
Response to K	1962	−2·9	+1·6	+2·5	−0·2	±3·01
	1963	+0·5	+3·2	+2·2	+3·4	±2·43
	1964	−1·0	+4·8	+4·5	+4·8	±2·53

Woburn—Stackyard

		Limestone tons/acre				
		0	2	4·75	7·5	S.E.
Mean yields	1962	14·8	19·0	19·1	22·0	±0·86
	1963	12·4	17·5	16·5	16·5	±0·84
	1964	19·1	16·5	13·0	13·2	±0·57
Response to P	1962	+3·5	−0·4	−0·6	+0·6	±1·73
	1963	+2·5	+3·4	−1·0	+2·3	±1·69
	1964	+1·9	+0·4	+1·2	+1·7	±1·16
Response to K	1962	−0·1	−0·1	−2·2	−3·6	±1·73
	1963	+1·7	+6·4	+3·6	+2·7	±1·69
	1964	+5·0	+7·5	+4·1	+5·0	±1·16

An anomalous result in the final year at Woburn was that liming significantly lessened yields and most grain was obtained from the unlimed plots (pH 5·0). This may have resulted from simazine damaging plants differentially on soils at different pHs. Simazine hydrolyses faster and is adsorbed more strongly in acid than neutral soils and liming has been observed to increase the toxicity of simazine to other crops (Burnside & Behrens, 1961). In 1964, a double dressing (2 lb a.i./acre) was applied, one to the winter crop that failed, another to the spring crop. We now know that 2 lb/acre a.i. of simazine can severely damage bean crops at Woburn (Johnston & Briggs, 1970). Soil samples taken after ploughing from each plot (in November, when the yields were known) were sown

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with mustard, which is sensitive to simazine. The mustard grew equally well in soil from all plots, so the simazine-damage hypothesis was not proven.

There was some evidence that in the same year, simazine damaged the beans at Rothamsted. The crop was shorter at intervals across the plots corresponding exactly to the boom width of the sprayer, indicating damage where the spray from successive swathes across the plots overlapped.

Spring barley. Except from the unlimed plots grain yields were reasonable, exceeding 30 cwt/acre. However they diminished during the three years especially on the most acid plots and without phosphate fertiliser (Table 2). At both Rothamsted and Woburn, the

TABLE 2

Yields of spring barley

(cwt grain/acre at 85% D.M.)

Rothamsted—Sawyers

		Limestone tons/acre				
		0	2	4	8	S.E.
Mean yields	1965	25·9	41·8	41·7	41·3	±3·07
	1966	21·7	35·1	38·0	38·2	±2·31
	1967	11·5	34·5	33·6	30·8	±2·53
Response to P	1965	+3·4	+1·2	+1·3	+1·1	±4·34
	1966	+6·5	+2·4	+2·7	+2·4	±3·27
	1967	+7·6	+7·5	+12·4	+13·8	±3·58
Response to K	1965	−7·4	−1·8	−2·0	−1·2	±4·34
	1966	−7·1	+2·9	+1·2	+4·4	±3·27
	1967	−1·6	+0·5	+6·2	+8·4	±3·58

Woburn—Stackyard

		Limestone tons/acre				
		0	2	4·75	7·50	S.E.
Mean yields	1965	38·0	39·7	42·2	42·4	±0·34
	1966	36·9	39·5	41·0	40·9	±0·45
	1967	29·0	33·5	34·7	35·0	±1·07
Response to P	1965	+4·9	+1·7	+2·1	+2·3	±0·48
	1966	+4·0	+0·8	+1·7	+2·1	±0·63
	1967	+11·8	+8·2	+2·8	+4·7	±1·52
Response to K	1965	−1·0	+0·9	−0·4	−0·5	±0·48
	1966	+0·5	+1·4	−0·2	+0·7	±0·63
	1967	+2·3	+2·6	+4·4	+1·3	±1·52

largest yields (39–43 cwt/acre grain) were from plots with soil pH 6·5–7·5. Without phosphate, yield was largest at pH 7 at Woburn but in two of the years at Rothamsted the best yield was at pH 5·7. The phosphate response increased over the three years because yields without phosphate decreased more than with phosphate. If yields from successive barley crops declined because root-attacking fungi became more prevalent, it seems that applying phosphate lessens their effects.

The experimental errors (Table 2) were much larger at Rothamsted than at Woburn, and an attempt to explain some of the large differences (1 ton/acre) between replicate plots at Rothamsted is described in part III of this paper. Details of liming and fertiliser effects on soil and crop compositions are described in part II.

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Potatoes. In contrast to barley and beans, the yields of potatoes were not affected by soil pH at either site. However, responses to phosphate and potassium fertilisers differed with different dressings of lime (Table 3). At Woburn, the phosphate response was larger

TABLE 3

Yield of potatoes in 1968

(tons fresh tubers/acre)

Rothamsted—Sawyers

	Limestone tons/acre				
	0	2	4	8	S.E.
Mean yield	9·2	10·4	10·7	9·9	±0·70
Response to P	+3·22	+1·76	+1·27	+3·51	±1·40
Response to K	+0·60	+3·89	+4·82	+5·32	±1·40
Interaction PK	+2·17	+3·40	+0·90	−1·40	±1·40
Yield from PK plots	12·2	14·9	14·2	13·6	±1·40

Woburn—Stackyard

	Limestone tons/acre				
	0	2	4·75	7·50	S.E
Mean yield	10·7	10·3	9·6	9·8	±0·36
Response to P	+4·91	+1·83	+2·90	1·97	±0·72
Response to K	+4·03	+6·54	+6·46	+6·37	±0·72
Interaction PK	+1·40	0·00	+1·89	+1·35	±0·72
Yield from PK plots	15·8	14·5	15·2	14·6	±0·72

in unlimed than limed plots and in both experiments the response to potassium was least in the most acid plots, because liming decreased yields when potassium was not given. A similar 'lime-induced potassium deficiency' has been observed with other crops (Adams & Pearson, 1967), and can be explained by liming increasing the proportion of potassium adsorbed on the exchange complex and decreasing the concentration of potassium in soil solution. Potassium ions can displace adsorbed calcium from cation exchange sites on the soil more easily than aluminium, which is the predominant exchangeable ion in acid soils (Black, 1968).

Total yields of tubers from plots given both phosphorus and potassium were similar at Rothamsted and Woburn, and were unaffected by liming (Table 3).

The percentage of ware potatoes (1·5 in. riddle) at Rothamsted was slightly increased by potassium fertiliser, from 94·3 to 97·6%. Plant numbers were unaffected by the treatments. At Woburn also, the only statistically significant effect on the proportion of ware tubers was an increase from 92·8 to 97·4% by potassium.

Effects of fertilisers on the composition of the tubers are discussed later. Experimental errors were larger at Rothamsted than at Woburn, as they were in the previous barley crops, probably for similar reasons.

A noticeable feature of both experiments at harvest was that stoloniferous grasses (mainly *Agrostis gigantea* Roth) were extensive in the very acid plots. The infestation closely followed the plot boundaries. However, some of the most infested plots yielded 8–11 tons/acre of tubers. The sites of both experiments were fallowed in 1969 to control the grass weeds by cultivation.

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Discussion. The pHs giving largest yields of barley and beans broadly confirm previous work. Gardner and Garner (1953) stated that below pH 5·6 both crops grew badly. Adams and Pearson (1967) tabulated maximum pH values at which responses to lime had been observed in southern U.S.A. and Puerto Rico. For barley this was pH 6·0, for potatoes 5·0, consistent with my results. However, there is no 'optimum' pH for each crop under all conditions. Growing plants in nutrient solutions showed long ago that the hydrogen-ion concentration of the growing medium (or soil solution) is '*per se*' unimportant. It is interactions between acids and the soil itself that affect the composition of the soil solution and, consequently, crop nutrition. The most important primary causes of poor growth in acid soils are toxicities of aluminium and manganese and deficiencies of calcium, phosphorus and molybdenum, and it is the relative importance of these in each combination of crop and soil that must be determined (Adams & Pearson, 1967). The most useful results from the experiments described here were on the interactions of liming with phosphorus and potassium nutrition of the crops, especially the phosphorus nutrition of barley and its possible effect on root disease damage, and on potassium nutrition of the potatoes.

There is now ample evidence that different varieties of crop plants, especially of cereals, differ in their response to liming and soil pH. Neenan (1960) showed that some varieties of wheat and barley tolerate much aluminium in the soil and others much manganese. Ikeda *et al.* (1965) suggested a connection between 'acid-soil resistance' and the capacity of barley varieties to withstand phosphorus deficiency, and evidence for this is discussed in part III of this paper.

II. Composition of the crops and soil

Spring barley. Fertilisers usually affect the composition of cereal grain less than straw and in both experiments most observed differences were small. Liming increased phosphorus and magnesium but, unexpectedly, not the calcium concentrations in the grain. The largest effect of liming was on the manganese content, especially in the most acid plots (Fig. 2). Rothamsted barley contained about 6 ppm more manganese than Woburn, with each amount of liming.

Potassium fertilisers slightly increased potassium and decreased sodium in the grain; these are effects observed in most crops, especially in leaves. Potassium fertilisers also increased manganese in the grain (Fig. 2).

Appendix Table A summarises the effects of liming, phosphate and potassium additions on grain composition.

Potatoes. The composition of potato tubers is more sensitive than that of cereal grains to the nutritional status of the soil and the treatments applied gave larger effects (Appendix Table B).

Liming, which increased phosphorus and calcium concentrations in the tubers in both experiments, decreased potassium, especially at Woburn. Sodium and magnesium concentrations were unaffected.

Potassium fertilisers greatly increased per cent potassium in the tubers and, in contrast to leaves of plants, also increased the magnesium content, from 0·06 to 0·08%. They also decreased phosphorus in the tubers.

The only effect of superphosphate was to increase the phosphorus content slightly.

Analyses of the soils. Appendix Table C gives analyses of the soils. Exchangeable sodium and magnesium were unaffected by liming or the other fertilisers. Exchangeable

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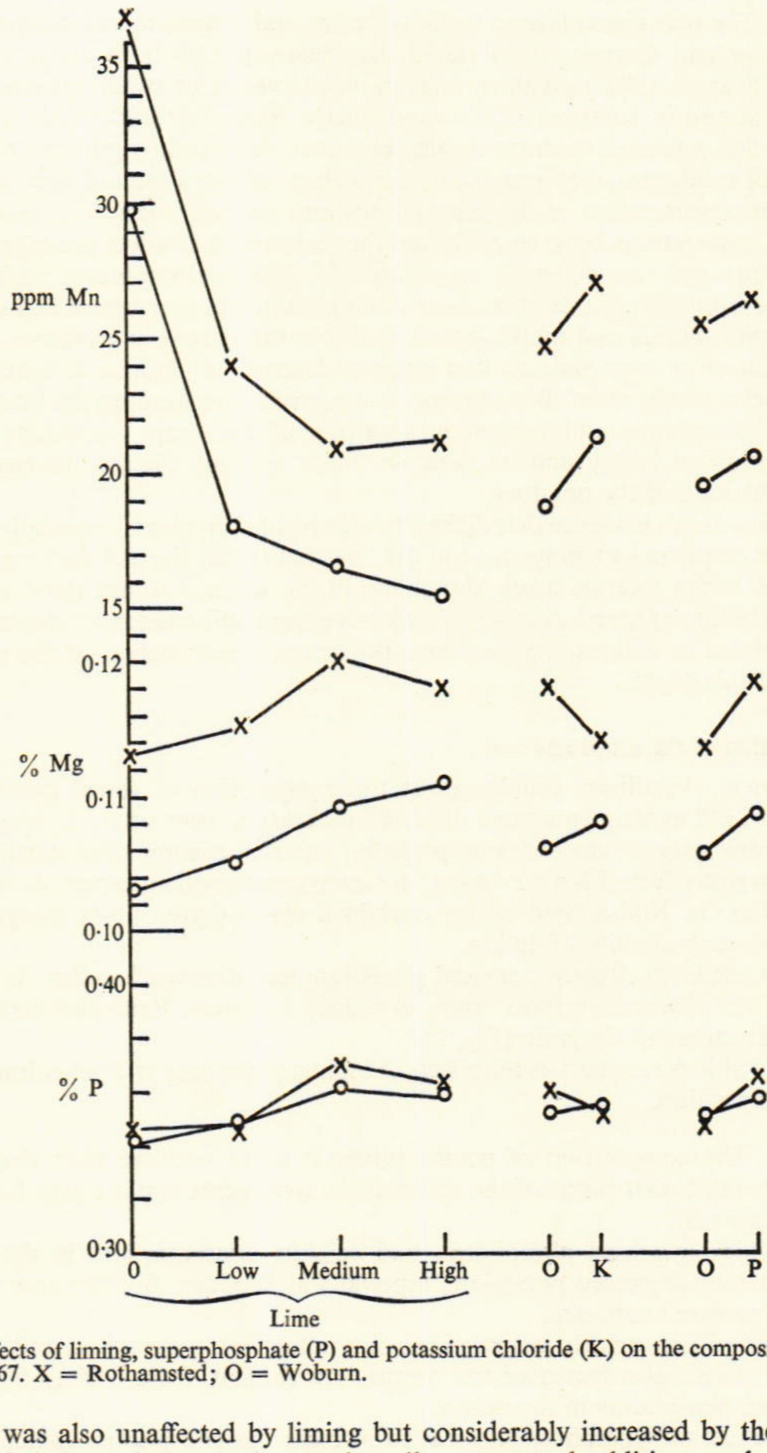

FIG. 2. Effects of liming, superphosphate (P) and potassium chloride (K) on the composition of barley grain, 1965–67. X = Rothamsted; O = Woburn.

potassium was also unaffected by liming but considerably increased by the potassium fertilisers. A balance between changes in soil content and additions and removals of potassium in fertilisers and crops cannot be drawn, because the bean and barley straws were not weighed or analysed.

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Increases in exchangeable calcium in the top 9 in. of the soil were less than the amounts of calcium given as limestone. Apparent lime losses relative to the unlimed plots for each amount of limestone (Table 4) increased as the initial dressing increased

TABLE 4

Estimated annual losses of limestone from the topsoils

(cwt $CaCO_3$/acre)

Rothamsted—Sawyers

	Limestone added, tons/acre				
	0	2	4	8	Mean
1. Using increases in exch. Ca over nil in 1967	—	0·70	1·10	7·15	2·98
2. Using pH changes and pH-exch. Ca graphs	1·95	3·90	1·45	−3·68	1·82

Woburn—Stackyard

	Limestone added, tons/acre				
	0	2	4·75	7·5	
1. Using increases in exch. Ca over nil in 1967	—	1·42	5·55	10·70	5·89
2. Using pH changes and pH-exch. Ca graphs	4·28	6·82	0·00	−0·52	2·64

from 0·7 to 7·2 cwt/acre/annum in the heavier Rothamsted soil and from 1·4 to 10·7 cwt/acre/year in the more sandy Woburn soil. However, these are over-estimates of lime losses because they are based on calcium soluble in *N* ammonium acetate, which dissolves only a proportion of limestone in soils. Unchanged limestone particles were seen in sieved soil from all the limed plots.

A different method of estimating calcium losses from the soil used pH measurements and the relationship between soil pH and exchangeable calcium from the 1967 soil analyses. Graphs of pH changes during the experiments (Fig. 1) show that, with the largest dressing of limestone, the pH at Rothamsted increased with time and that limestone was still reacting with the soil after six years. At Woburn the pH changed little, but had there not been an excess of undissolved limestone, the exchangeable calcium and pH should have become less. This shows that there was still some limestone able to neutralise acidity in the plots in 1968, six years after the dressings were given. Without limestone, acidity increased faster each year at Woburn than at Rothamsted, partly because from 1966 ammonium sulphate was used instead of 'Nitro-Chalk'. This change was made to create a wider range of pHs at Woburn.

Relating changes in pH with the different limings to linear regressions of pH on exchangeable calcium, gives the estimated calcium losses shown in Table 4.

The 'available' phosphate in the Rothamsted soils is discussed in part III.

Discussion. These and other estimates of annual lime losses from different soils and cropping systems (Gardner & Garner, 1953) provide only a rough guide to the need for further liming. Losses of cations by leaching depend not on the amount of drainage *per se* but on losses of the anions, nitrate, sulphate, chloride and bicarbonate. It is therefore the balance between additions and losses of these anions, derived from natural sources or fertilisers, that determine losses of lime and other cations from soils. The type of crop grown, method of husbandry—e.g. whether cereal straw is removed or burnt, amount and type of fertiliser used, and the pattern and amount of rain, are all factors

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affecting lime losses from soils. Because of these variables, regular measurements of soil pH best indicate when further limestone is needed.

III. Causes of heterogeneity in the Rothamsted experiment. A major problem on research farms is to maintain uniformity in fields so that trials can be suitably sited. However, by their nature, experiments create non-uniformity because, to minimise errors, different treatments are given to small areas of land (plots) in close proximity to each other (blocks). The difficulties caused by superimposing fertiliser experiments were shown in the results from the Rothamsted liming experiment.

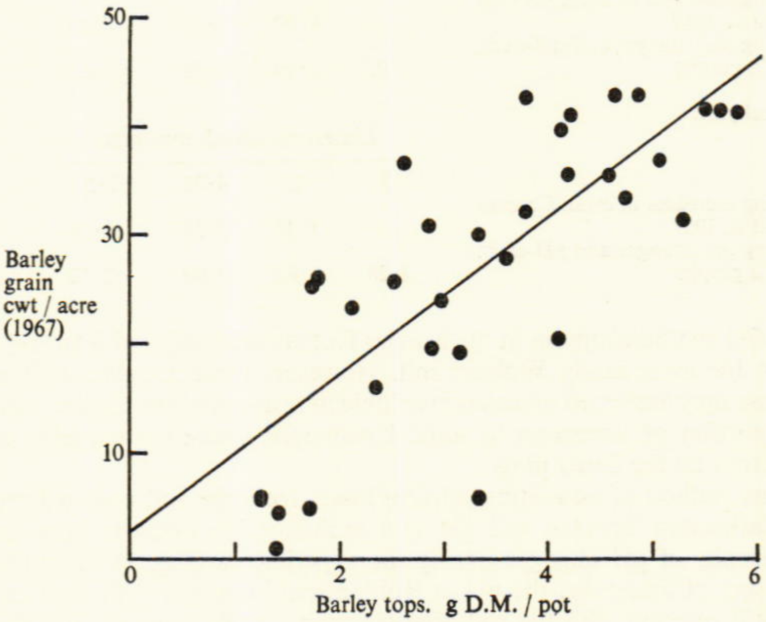

FIG. 3. Relationships between barley yields in the field (grain) and in pots (tops) for each plot of the Rothamsted experiment. (r = 0·77***).

The mean yields and composition of the barley crops already summarised and discussed disguise large differences between duplicate plots, especially those not given lime. In several pairs of plots differences in yield were more than 1 ton/acre of grain in the final crop of barley. To study the reasons for these differences, soil from each plot was cropped with barley in the glasshouse.

Fresh, undried soil (sieved $<$6 mm) from each plot was sown with barley (var. Deba Abed) in pots in the glasshouse. Duplicate pots of 2 kg soil were used for each field plot. Basal dressings of 100 mg N/pot were given as ammonium nitrate ten days after sowing. After three months the plants were cut at soil level, dried, weighed and analysed.

Yields of dry matter harvested from the pots were related to grain yields in the field in 1967 (Fig. 3), showing that differences in the field reflected inherent soil properties rather than positional effects, differences in drainage or stoniness—all of which had been considered possible. Therefore, the next step was to identify the factors responsible for differences between the plots, especially of duplicates of a single treatment that differed in the field.

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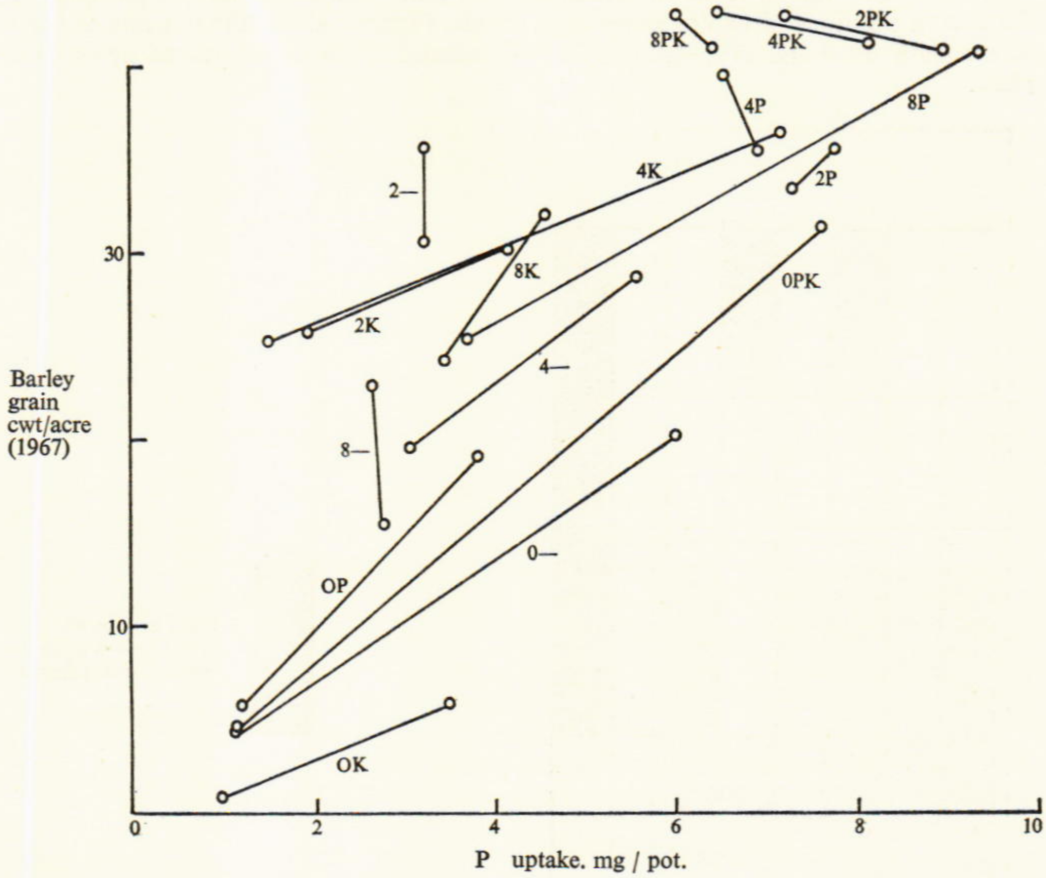

FIG. 4. Relationships between barley yields and P uptake in pots for duplicates of each treatment (numbers = tons/acre limestone; P = superphosphate; K = potassium chloride).

Analyses of barley plants from the pots showed that concentrations of phosphorus in the dry matter most consistently followed the yield differences. Plotting total phosphate uptake in pots against yield of grain in 1967 (Fig. 4) showed that, for each pair of plots, the most P was taken up from the plots that gave most grain in the field, providing this was less than 35 cwt/acre. This was especially so with the seven pairs of plots that differ in yield by more than 7·5 cwt grain/acre (these were the major cause of large coefficients of variation and standard errors in the field experiment). The close correlation between P uptake by the barley in pots and the grain yield in the field ($r = 0{\cdot}804$), confirmed that the differences in yield were associated with the phosphorus nutrition of the barley.

Analyses of soil samples taken in December 1968 (a separate set from those used for the pot experiment) for 'available' phosphate, using the sodium bicarbonate method of Olsen *et al.* (1964), showed large differences between duplicate plots, mostly associated with differences in barley yield. However, there were two anomalies which are discussed later.

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The next step was to relate the distribution of plots with dissimilar soil phosphate to the known positions of two previous experiments. Figure 5 shows the position of these, one made in 1959 and 1961 and one in 1960, relative to the superimposed new experiment.

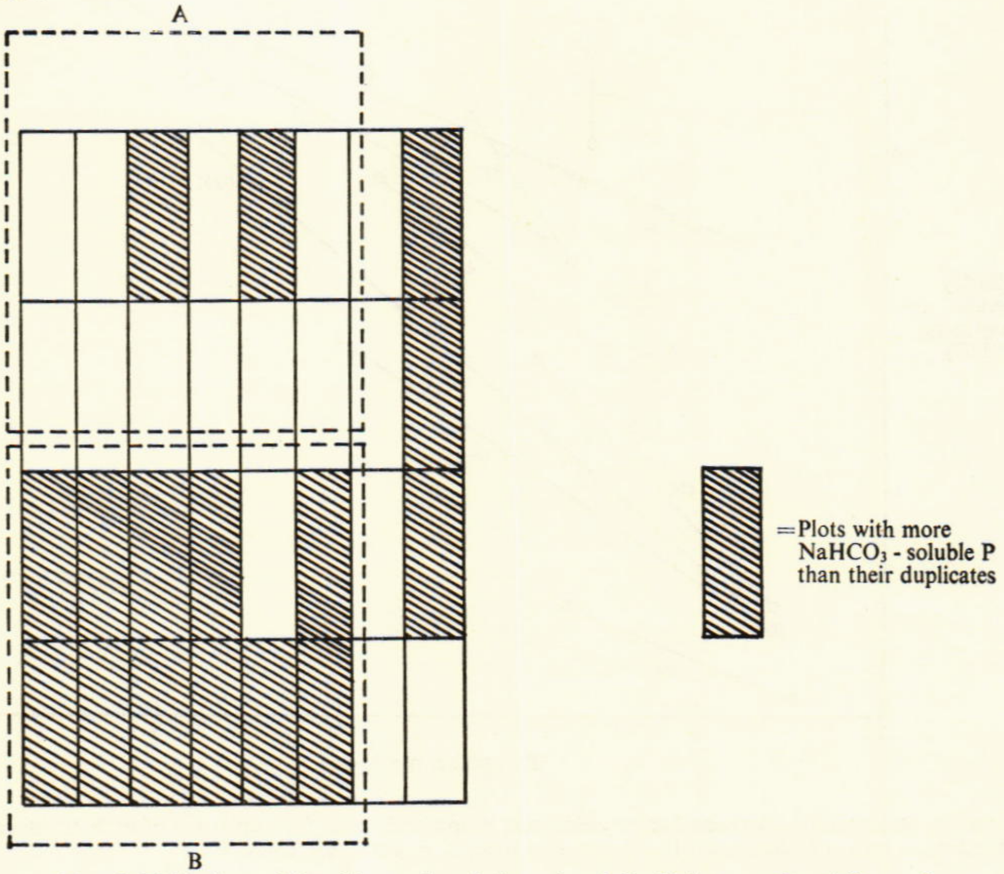

FIG. 5. Field plans of the old experiments (– – –) and the liming experiment (———).

Experiment A testing different forms of K fertiliser on potatoes received a basal dressing of 0·75 cwt P_2O_5/acre in 1960. Some plots received 1·25 and 2·5 cwt K_2O/acre, others none. The same experiment made on site B in 1959 and 1961 was given a total basal dressing of 1·75 cwt P_2O_5/acre, and 0, 2·5 or 5·0 cwt K_2O/acre.

Figure 5 shows that 11 of the 12 plots sited on experiment B contained more 'available' P than their partners. Five of these were among the seven pairs the individuals of which differed in yield by more than 7·5 cwt/acre. This seems to indicate that residual P from the old experiment B could be one cause of large errors in the liming experiment 7 years later.

Discussion. Although the experiments and soil analyses show differences in phosphorus nutrition, it seems improbable these should have such large effects on yield without some other factor operating. The grain yields described in Part I show that the response to superphosphate increased each year especially on the most acid plots, because yields declined without phosphate. The major cause of yield decline in successive cereal crops is the 'take-all' fungus (*Ophiobolus graminis*). Restriction of root growth by this pathogen

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would limit uptake of phosphate more than other nutrients because diffusion over short distances around the root is more important for phosphate uptake than for other nutrients, much of which can be supplied by 'mass-flow' in the transpiration stream (Barber, 1962). Therefore the effect of phosphorus deficiency in the third barley crop could have been accentuated by fungal root pathogens.

TABLE 5

Yield, soil and barley shoot compositions for each pair of unlimed plots

Treatment	Plot Nos.	Soil pH (1966)	$NaHCO_3$-P in soil (ppm)	Exchange-able Ca in soil mg/100 g	Barley yield 1967 cwt/acre	D.M. Barley shoots g/pot	P uptake mg/pot
None	10	4·7	13·0	95	4·1	1·41	1·13
	26	4·8	25·0	123	20·1	4·10	5·99
Superphosphate	1	4·6	19·0	95	5·8	1·23	1·19
	20	4·6	30·0	118	19·1	3·15	3·81
KCl	2	4·5	12·0	95	5·8	3·33	3·50
	29	4·6	22·6	68	0·9	1·42	0·97
KCl plus superphosphate	5	4·5	28·2	80	4·7	1·72	1·12
	23	4·7	23·4	105	31·4	5·23	7·64

Another factor to be considered is the effect of acid soils on phosphorus movement within the plant. The largest difference (26·7 cwt/acre of grain) in yield in 1967 was between plot 5 and plot 23 both given P and K fertiliser but not lime. Table 5 shows that there was more P soluble in $NaHCO_3$ in the soil of plot 5, which yielded poorly, than in plot 23, but P uptake by the barley plants in pots and the %P were considerably less. The main differences between these plots were in exchangeable calcium and pH. Plots 2 and 29 gave similar anomalous results. The more acid soil probably contains more exchangeable aluminium, which can immobilise phosphate in or around roots (Wright, 1943) and induce phosphorus deficiencies in the shoots. Ikeda *et al.* (1965) postulated a relationship between the ability of barley varieties to grow in acid soils and their ability to withstand phosphorus deficiency. My results confirm that barley is very sensitive to factors affecting the movement of phosphorus into the shoots.

Phosphate nutrition was the main factor associated with the large differences in barley yield between duplicate plots in the field experiment. Residues from phosphate dressings given to previous experiments, and differences in acidity between unlimed plots, were major causes of these differences, which in the third barley crop were probably accentuated by 'take-all'.

Summary

The optimum pH for growing spring beans and barley on Rothamsted and Woburn soils was between 6·5 and 7·0, providing phosphate and potassium fertilisers were given. Yields of potatoes were similar at all pH values above 5·0 when phosphate and potassium were sufficient, but when potassium was not given the more acid soils grew larger crops. Yields of beans were increased more by cumulative dressings of potassium than of phosphate (P and K interacted positively). Barley yields were increased more by phosphate than potassium. Potatoes responded most to phosphate on the unlimed soils, whereas response to potassium was largest at pH 7.

Liming decreased manganese, increased phosphorus and magnesium but did not affect calcium concentrations in the barley grain. It increased phosphorus and calcium

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and decreased potassium in the potato tubers. Potassium fertilisers increased the potassium and magnesium concentrations in the potatoes.

Annual lime losses from the soils could not be accurately measured but estimates by two different methods showed they were about 2·5 cwt/acre/annum. The largest amount of limestone continued to increase the pH of Rothamsted soil six years after it was applied.

Large differences in barley yield between replicate plots in the Rothamsted experiment caused unacceptable experimental errors. Similar differences in yields of dry matter of barley grown in pots of soil from each field plot were related to phosphorus uptake. Fertiliser residues from old experiments were one cause of the inconsistency in yield. Accurate recording of the position and treatments given to all plots is essential when fields are re-used for experiments.

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APPENDIX TABLE A

Composition of barley grain

(Mean of three years)

Rothamsted—Sawyers

	Limestone tons/acre 0	2	4	8	Mean	K effect	P effect
	% in D.M.						
K	0·532	0·494	0·510	0·501	0·509	+0·015	−0·002
P	0·346	0·347	0·371	0·363	0·357	−0·008	+0·017
Ca	0·050	0·046	0·046	0·049	0·048	+0·001	0·000
Na	0·019	0·013	0·013	0·015	0·015	−0·006	−0·001
Mg	0·113	0·115	0·120	0·118	0·116	−0·004	+0·005
	ppm in D.M.						
Mn*	37·0	24·0	20·9	21·2	25·9	+2·5	+1·0

Woburn—Stackyard

	Limestone tons/acre 0	2	4·75	7·5	Mean	K effect	P effect
	% in D.M.						
K	0·471	0·465	0·471	0·474	0·470	+0·028	−0·001
P	0·341	0·349	0·361	0·358	0·353	+0·003	+0·006
Ca	0·044	0·044	0·046	0·045	0·045	0·000	0·000
Na	0·010	0·009	0·009	0·009	0·009	−0·004	−0·001
Mg	0·103	0·105	0·109	0·111	0·107	+0·002	+0·003
	ppm in D.M.						
Mn*	29·8	18·0	16·5	15·4	20·0	+2·5	+1·1

* Two years only.

APPENDIX TABLE B

Composition of potato tubers (1968)

Rothamsted—Sawyers

	Limestone tons/acre 0	2	4	8	Mean	K effect	P effect
	% in D.M.						
K	1·72	1·57	1·57	1·57	1·61	+0·71	+0·02
Ca	0·033	0·046	0·042	0·052	0·043	−0·002	+0·002
Mg	0·067	0·066	0·067	0·065	0·066	+0·022	−0·003
P	0·16	0·19	0·21	0·21	0·19	−0·03	+0·02
	ppm in D.M.						
Na	62	65	64	61	63	−4	0

Woburn—Stackyard

	Limestone tons/acre 0	2	4·75	7·5	Mean	K effect	P effect
	% in D.M.						
K	1·64	1·53	1·44	1·42	1·51	+0·67	−0·02
Ca	0·028	0·030	0·031	0·035	0·031	0·000	0·000
Mg	0·072	0·067	0·064	0·067	0·068	+0·022	−0·004
P	0·19	0·19	0·21	0·21	0·20	−0·03	+0·01
	ppm in D.M.						
Na	52	54	52	52	53	−4	−2

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APPENDIX TABLE C

Soil analyses (September 1967)

Rothamsted—Sawyers

	Limestone tons/acre 0	2	4	8	Mean	K effect	P effect
pH	4·91	5·66	6·68	7·59	6·21	−0·03	+0·04
Exchangeable K (mg/100 g)	10·9	10·7	10·7	10·7	10·8	+9·0	−0·5
,, Na ,,	1·2	2·5	2·6	2·6	2·2	+0·2	−0·2
,, Ca ,,	97	151	207	272	182	−6	+10
,, Mg ,,	3·1	3·0	3·4	3·0	3·1	−0·2	−0·1
$NaHCO_3$-P* (ppm)	21·6	20·0	22·8	23·4	28·5	−0·1	+12·3

Woburn—Stackyard

	Limestone tons/acre 0	2	4·75	7·5	Mean	K effect	P effect
pH	5·03	6·26	7·21	7·53	6·51	−0·10	−0·09
Exchangeable K (mg/100 g)	8·8	8·2	7·8	7·6	8·1	+7·2	−0·4
,, Na ,,	0·9	0·9	1·2	1·2	1·0	−0·1	−0·1
,, Ca ,,	86	132	174	212	151	−10	0
,, Mg ,,	1·3	1·2	1·1	1·1	1·2	0·0	0·0

* Soil sampled in December 1968.

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