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FIELD EXPERIMENTS ON PHOSPHATE FERTILIZERS

A JOINT INVESTIGATION

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This investigation, which involved over 400 field experiments, was carried out jointly by the Soil Chemists of the National Agricultural Advisory Service, the Northern Ireland Ministry of Agriculture, the East of Scotland and West of Scotland Colleges of Agriculture and by the staffs of the Macaulay Institute for Soil Research, and the Welsh Plant Breeding Station. The following workers have been responsible for the field experiments at distant centres: A. Blenkinsop, J. W. Blood, H. T. Cranfield, R. O. Davies, W. M. Davies, H. W. Gardner, R. A. Hamilton, F. Hanley, F. Hunter, T. J. Jenkin, H. T. Jones, J. O. Jones, J. Langmead, A. W. Ling, J. S. V. McAllister, D. N. McArthur, S. McConaghy, W. E. J. Milton, M. N. Nicholson, H. Nicol, J. B. E. Patterson, N. H. Pizer, J. W. S. Reith, E. Roberts, G. W. Robinson, T. H. Rose, A. M. Smith, E. L. Smith, W. R. Smith, (Sir) G. Stapledon, R. Stewart, T. Wallace, T. W. Walker, J. E. Watkin, J. Webber, R. Williams, W. T. H. Williamson. The work was planned and co-ordinated in the Chemistry Department of Rothamsted Experimental Station, which also supplied the special fertilizers needed.

The work described here was planned to test phosphate fertilizers the manufacture of which either needed no sulphuric acid or economized in acid. It had the secondary purpose of attempting to improve the efficiency of phosphate fertilizers. The investigation was initiated in 1940 by the Controller of Chemical Research and Development, Ministry of Supply. At that time a serious shortage of sulphuric acid appeared to be possible which would have interfered with the production of superphosphate. Laboratory, glasshouse, and field experiments on alternatives to superphosphate were carried out from 1941–6. The earlier work was mainly concerned with testing of high temperature phosphates made (at the Building Research Station at Garston) by heating phosphate rock with soda ash and sand; these materials were later given the name 'Silicophosphate'. In the later years of the war-time work the scope of the field investigation was widened. The Chemistry Department at Rothamsted was engaged on other aspects of the general problem of improving the efficiency of phosphate fertilizers and of economizing in sulphuric acid; materials from these investigations were included in field experiments mainly concerned with high-temperature phosphates.

The second phase of the investigation was a result of the world-wide shortage of sulphur which occurred in 1950. The Fertiliser Conference of the Agricultural Research Council initiated a further field investigation to test phosphate fertilizers which economized in sulphuric acid. Experiments were carried out in 1951, 1952 and 1953.

Detailed results of the early work were given by Crowther & Cooke (1951) and by Crowther, Warren & Cooke (1953) in Reports made to the Ministry of Supply. The details of the 1951–3 series of experiments are given (Cooke, 1955) in a Report made to the Agricultural Research Council. The purpose of the present paper is to summarize and correlate the results of both series of experiments in an accessible form. More detailed examination of the results of the field experiments may be made by reference to the Reports listed.

1. DESCRIPTIONS OF THE FIELD EXPERIMENTS

(i) *Choice of experimental sites and crops*

The field experiments were carried out on a variety of crops in England, Wales, Scotland and Northern Ireland. The sites were generally chosen by an Advisory Soil Chemist after an analysis of the soil of a field had shown that the crop proposed was likely to respond to phosphate fertilizer.

The bulk of the 1941–6 arable experiments were on roots as these normally receive fairly heavy dressings of phosphate fertilizers. Swedes were commonly chosen as the test crop since they are most sensitive to a deficiency of soil phosphorus; occasionally turnips were taken instead. In the south and east of England, where swedes often yield badly, potatoes or sugar beet were selected. Potatoes are fairly responsive to phosphate fertilizer. Sugar beet and cereals normally give little response to phosphate on most of the soils on which they are grown. There were, therefore, only a few experiments on these crops. There were a number of observational tests on grassland, especially that being reseeded immediately after ploughing old grass on very acid soils. Experiments on other crops were too few to allow reliable averages to be taken but they served to extend the range of information.

Cropping in the 1951–3 experiments was more restricted. One series of experiments tested rock phosphate, silicophosphate and dicalcium phosphate for swedes and potatoes. In a second series nitrophosphates (made by treating rock phosphate with nitric acid) were tested for swedes, potatoes and grass.

(ii) *Methods of laying down the field experiments*

In most of the experiments on potatoes and roughly half of the experiments on swedes, the crops were grown on ridged land. The general practice was to lay out the experiment after the land had been ridged and to apply the fertilizer dressings in the furrows. In experiments on potatoes, the sets were then planted in the furrows and the ridges were closed to cover seed and fertilizer. In experiments on swedes the ridges were split to cover the fertilizer and the crop was sown on the resulting ridges. In such experiment on swedes and potatoes, the fertilizer was concentrated beneath the seed. For crops grown on the flat and for grass, fertilizers were spread by hand on the appropriate plots. The seedbeds of arable crops were harrowed to work in the manures. Basal dressings of nitrogen and potassium fertilizers were applied uniformly to all plots within each experiment at rates which were considered suitable for the crop and locality.

After sowing, the experimental areas were treated in the same way as the rest of the field, but no further dressings of fertilizers were applied. At harvest, yields of produce from each plot were recorded, samples were taken for determination of the percentages of dry matter and of phosphorus in the crops. In 1941–6 experiments on reseeded grassland, it was not possible to obtain harvest data. The experiments were visited regularly and marks were assigned by eye for establishment of sown species and, later in the season, for the growth of grass. The grass in experiments carried out in 1951–3 was cut at hay or silage stages and yields were measured.

(iii) *Form of the experiments*

Most of the experiments employed Latin Square designs to secure the precision needed to compare different forms of phosphate. A few experiments in 1942 and 1943 used a 75-plot Lattice-Square design. Blocks of randomized plots were laid down where there was not sufficient space for a Latin Square or where the experimenter wished to test other phosphates of local interest. The patterns of the experiments varied from year to year according to the materials and facilities available.

The size of plot generally used in experiments on arable crops varied from 0·025 to 0·01 acre. 0·01 acre plots were used in experiments on grassland.

In all the 1941–6 experiments on arable crops superphosphate was taken as standard but, wherever facilities allowed, Bessemer basic slag and Gafsa rock phosphate were included for comparison. In the later work only two patterns of experiments were used and superphosphate was taken as the standard. All dressings of phosphate fertilizers were applied in terms of their contents of *total* P_2O_5.

In estimating the relative values of two similar fertilizers it is desirable to ascertain what quantities are required to produce comparable yields. The relative yield increases by themselves may be unsatisfactory because crop yields follow the 'Law of Diminishing Returns'. Doubling the amount of the fertilizer dressing does not double the response of the crop and if the first unit is fairly high, the additional response to a second unit may be quite small. For this reason experiments to determine the relative efficiencies of different forms of phosphate fertilizers should be planned so that the dressings of fertilizer give crop yields which fall on the steeply-rising parts of the response curve. To achieve this it may be necessary to test rates of dressing well below those commonly recommended in practice.

To obtain data on the form of the response curves and to find the most efficient range of dressings for comparative field trials a number of experiments were laid down in 1942 with superphosphate at four rates (0·25, 0·50, 0·75 and 1·00 cwt. P_2O_5 per acre) and nine other phosphates each at two rates (0·5 and 1·0 cwt. P_2O_5 per acre). These treatments, with an appropriate number of plots without phosphate, were arranged as 75-plot experiments in the form of three 5 × 5 Lattice Squares. Another series of 1942 experiments had superphosphate at two rates (0·5 and 1·0 cwt. P_2O_5 per acre) and either two or three types of silicophosphate at a single rate (1·0 cwt. P_2O_5 per acre).

Most of the 1942 experiments were on land newly-ploughed from very acid and poor grassland. The combination of inevitable soil irregularities with a large number of experimental treatments gave results of relatively low precision for the individual materials. It was therefore decided to use fewer treatments and to obtain the greatest control of soil irregularities by using Latin Square designs wherever possible. The treatments in later years were: *no phosphate, single rate of superphosphate,* double rate of superphosphate, other materials were generally applied at a rate half-way between the two rates of superphosphate. It was also decided to reduce the rates of dressing below those employed in 1942. Most of the later experiments were of the pattern:

(1) Without phosphate
(2) 0·33 cwt. P_2O_5 per acre as superphosphate
(3) 0·66 cwt. P_2O_5 per acre as superphosphate
(4) 0·50 cwt. P_2O_5 per acre as material *x*
(5) 0·50 cwt. P_2O_5 per acre as material *y*
(6) 0·50 cwt. per acre as material *z*

These rates of dressing were also used in one series of 1951–3 field experiments testing rock phosphate, silicophosphate and dicalcium phosphate. The 1952–3 experiments testing nitrophosphates used the same experimental pattern except that the rates of dressing were reduced still further.

2. STATEMENT OF RESULTS

(i) *Crop yields*

Experiments testing the same kinds of materials at the same rates on the same crop have been gathered together in groups, the centres within the groups being subdivided by the reaction of soil samples (in water) taken before the fertilizers were applied. The following divisions are employed throughout this paper: pH to 5·5, very acid soils; pH 5·6 to 6·5, acid soils; pH 6·6 and over, neutral soils. Tables given here supply the mean values for all experiments in which a given set of treatments is compared. In preparing these averages no account has been taken of the precision of individual experiments. Although the crop responses to superphosphate were significant ($P = 0{\cdot}05$ or greater) in most experiments, significant differences between yields given by different phosphates were much less common. In work of this character the value of any comparison between alternative fertilizers increases with the number of centres and seasons in which the materials have been compared and averages of only a few experiments must be regarded as ill-defined.

(ii) *Phosphorus contents of the crops*

Phosphate manuring often increases the concentration of phosphorus in the dry matter of crops. This effect, which may sometimes be of importance in animal nutrition, was marked in the swedes but not in the potatoes. Samples of the produce were taken from each plot in most of the experiments and were analysed for total phosphorus, generally after bulking together samples from similarly treated plots. For swedes the percentage of P_2O_5 in the roots increased rapidly with increasing amounts of added phosphate and phosphorus uptakes show relatively larger differences between amounts of added phosphate than do the actual yields of roots. For some purposes the phosphorus contents of swedes provide a more sensitive index than the yields, of the amount of added phosphate which was available to crops. The values for phosphorus contents of crops must, however, be used with caution, swedes continue to take up phosphorus from the soil too late in the season to produce proportionate increases in yield. The immediate availability of a phosphate fertilizer, as indicated by the yields, is a more useful practical index than the total phosphorus contents of the crops at harvest.

(iii) '*Superphosphate equivalents*'

It is convenient to express the efficiencies of new phosphate fertilizers in terms of the efficiency of a standard material such as superphosphate. Wherever possible this has been done in the work described here. The superphosphate response curves were plotted and the dressings of P_2O_5 applied (as superphosphate) which would have been required to give yields equal to those given by the other phosphates tested read off. These 'superphosphate equivalent dressings' were expressed as percentages of the amounts of P_2O_5 actually applied by the materials under test. 'Percentage superphosphate equivalents' calculated in this way are stated here for most of the phosphates tested as alternatives to superphosphate. The method is approximate but it is a drastic test of alternative phosphate fertilizers. It cannot be used if the phosphates under test give markedly better yields than superphosphate or if the superphosphate response curve is flat.

RESULTS OF THE FIELD EXPERIMENTS

PART 1. GROUND ROCK PHOSPHATE AND MIXTURES OF ROCK PHOSPHATE WITH SUPERPHOSPHATE

Different batches of phosphates were used in different years of these experiments. Since there is little interest in the performance of particular batches, average analyses of all samples of each kind of phosphate are stated in Table 1.

(1) *Rock phosphates*

Earlier experiments described by Robertson (1922) and by Crowther (1934) demonstrated the value of mineral phosphates for certain soils and crops. Most of these experiments tested the soft North African phosphates, supplies of which were cut off at an early stage in the war. War-time experiments therefore tested harder phosphates from Florida and the West Indian island of Curacao which were imported to replace the North African types. Later in the war supplies of Morocco rock phosphate were imported and this material was tested as there was no British evidence of its value for direct application. In the later experiments carried out in 1951–3, Gafsa rock phosphate from Tunis was again tested for potatoes and swedes to define more closely the conditions under which this very cheap phosphate could replace superphosphate.

(i) *Experiments on swedes*

Forty-two field experiments on swedes were carried out from 1941–6 to compare various rock phosphates with superphosphate. Nine experiments in 1941 tested Gafsa, Curacao and Florida rock phosphates, the results are summarized in Table 2. On the average of the whole group Gafsa and Curacao phosphates gave yields and amounts of phosphorus in the crops similar to those given by half as much phosphorus applied as superphosphate. The outstanding feature of these experiments was that Florida pebble phosphate gave yields which were markedly inferior to those given by the other rock phosphates and by superphosphate. This material was not considered to be worth further testing for direct application.

Table 1. *Analyses of rock phosphates and mixtures used in the field experiments*

	No. of samples	Percentage passing 100 mesh B.S. sieve	Total P_2O_5 (%)	Percentage solubility of P_2O_5: In citric acid	Percentage solubility of P_2O_5: In water	Fluorine* (%)
Rock phosphates from						
Gafsa (1941–6)	6	87	27·3	39	—	3·3 (3)
Gafsa (1951–3)	4	—	30·3	36	—	—
Curacao (1941–5)	4	78	34·6	28	—	0·6 (2)
Florida (1941) (pebble phosphate)	1	92	34·6	25	—	3·7
Morocco (1943–5)	4	79	32·6	32	—	3·6
Mixtures of rock phosphate with superphosphate						
Cold mixture	6	—	25·0	58	38	2·6 (5)
Hot mixture	1	—	25·7	51	49	2·9

* Numbers of samples analysed are given in brackets.

Table 2. *Results of 9 field experiments carried out in 1941 to test rock phosphates for swedes*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
Without phosphate	0·00	13·2	0·152
Superphosphate	0·25	17·0	0·185
	0·50	18·9	0·231
	1·00	19·3	0·271
Rock phosphate			
Gafsa	1·00	18·4	0·237
Curacao	1·00	18·7	0·240
Florida	1·00	16·9	0·190

The average results of all experiments in 1941 and 1942 comparing Gafsa and Curacao phosphates at the same rates of dressing are given in Table 3.

'Percentage superphosphate equivalents' derived from the data given in Tables 2 and 3 by the graphical method described above are stated in Table 4. The centres were divided into two groups: 'very acid soils' (pH 5·5 and below) and 'other soils' (above pH 5·5). On 'very acid' soils Gafsa and Curacao rock phosphates were slightly inferior to superphosphate for swedes, on the group of 'other' soils they were much less efficient.

From 1943 onwards, dressings of phosphate fertilizers were reduced so that the comparisons of different materials might be made on the more sensitive parts of the response curve. Owing to the circumstances of the war Gafsa and Curacao phosphates were no longer imported, but Morocco phosphate was available from 1943 onwards. At the end of the war Gafsa phosphate was again imported and

Table 3. *Average results of 24 field experiments on swedes carried out in 1941–2 to test rock phosphates*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
Without phosphate	0·0	8·9	0·092
Superphosphate	0·5	17·4	0·178
	1·0	18·6	0·223
Rock phosphate			
Gafsa	1·0	18·0	0·203
Curacao	1·0	18·0	0·200

Table 4. *Percentage superphosphate equivalents of rock phosphates derived from mean yields and phosphorus contents of swedes*

	From yields: Very acid soils	From yields: Other soils	From phosphorus in crops: Very acid soils	From phosphorus in crops: Other soils
1941 experiments				
No. of experiments...	4	5	4	5
Gafsa	70	23	84	36
Curacao	100	28	84	41
Florida	29	20	30	20
1941 and 1942 experiments				
No. of experiments...	16	8	16	8
Gafsa	82	34	85	48
Curacao	75	40	80	49

was used in the experiments. Gafsa was tested in the uniform series of experiments carried out from 1951 to 1953, which also tested dicalcium phosphate and silicophosphate; the yields given by these materials are stated here for comparison but they are discussed in detail later in this paper. The average results of each group of experiments on Morocco and Gafsa rock phosphates are given in Table 5.

In 1943–4 Morocco phosphate gave yields and phosphorus contents of swedes roughly similar to those given by two-thirds of the quantity of P_2O_5 applied as superphosphate. Gafsa phosphate was tested in 6 swede experiments (all except one were on very acid soils), it was as effective as two-thirds

Table 5. *Mean yields and phosphorus contents of swedes in experiments testing Gafsa and Morocco rock phosphates*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
1943–4. 9 experiments			
Without phosphate	0·00	10·1	0·081
Superphosphate	0·33	16·0	0·139
	0·66	17·6	0·178
Morocco rock phosphate	0·50	15·6	0·144
1945–6. 6 experiments			
Without phosphate	0·00	6·9	0·048
Superphosphate	0·33	13·8	0·107
	0·66	16·3	0·148
Gafsa rock phosphate	0·50	13·5	0·109
1951–3. 35 experiments			
Without phosphate	0·00	12·0	0·111
Superphosphate	0·33	17·4	0·166
	0·66	19·6	0·202
Gafsa rock phosphate	0·50	18·2	0·175
Dicalcium phosphate	0·50	18·4	0·180
Silicophosphate	0·50	18·2	0·181

as much phosphorus applied as superphosphate. In the larger series of experiments carried out in 1951–3 Gafsa phosphate was only slightly inferior to superphosphate for swedes.

Percentage superphosphate equivalents calculated from the yields given in Table 5 are set out for each series of experiments in Table 6 after grouping the centres by soil reaction.

In the 1943–6 experiments both Morocco and Gafsa phosphates were equivalent to only two-thirds as much phosphorus supplied as superphosphate in experiments on 'very acid' soils. In the much larger series of 1951–3 field experiments Gafsa phosphate was practically equivalent to superphosphate on both 'very acid' and 'acid' soils. There was little difference between yields of swedes given by Gafsa phosphate, dicalcium phosphate and silicophosphate on 'very acid' and 'acid' soils. On the small group of 'neutral' soils dicalcium phosphate was nearly as efficient as superphosphate, silicophosphate was only half as effective and Gafsa phosphate was of very little use. The amounts of phosphorus in the crops distinguished more clearly between the various phosphates. In the early series of experiments, swedes recovered nearly as much phosphorus from Morocco phosphate as from superphosphate on 'very acid' soils and only half as much on 'less acid' soils. In the 1951–3 experiments, swedes recovered less phosphorus from Gafsa phosphate on all classes of soil than from the other materials tested. There are marked differences between the results of experiments on rock phosphate carried out in the two phases of this investigation. Both sets of experiments show that for swedes North African phosphates are only a little less effective than superphosphate on 'very acid' soils. The earlier experiments showed that rock phosphates were of much less value on 'acid' soils (pH values from 5·5 to 6·5), this was not confirmed by the later work.

(ii) *Experiments on potatoes*

Potatoes require easily soluble forms of phosphates. Rock phosphates were tested in only four experiments of the war-time series and even on acid soils they gave much lower yields than superphosphate. Gafsa phosphate was compared with superphosphate and with silicophosphate and dicalcium phosphate in thirty-four experiments in the 1951–3 series. The results are summarized in Table 7.

Percentage superphosphate equivalents for the phosphates tested were derived from the data in Table 7. They are given in Table 8.

Gafsa phosphate was of very little value for potatoes grown on neutral soils, even on acid soils it gave yields similar to those given by only one-third as much phosphate supplied as superphosphate. Both dicalcium phosphate and silicophosphate were much superior to Gafsa phosphate on all classes of soil.

(iii) *Experiments on grassland*

A number of experiments were carried out from 1941–6, largely in the Welsh hills on very acid soils, to compare ground rock phosphates with high-soluble basic slags and with superphosphate for direct reseeding of acid grassland. The effects of the fertilizers were estimated by visual 'scoring' for the degree of establishment of the sown species of grasses and clovers. Initially the results were expressed numerically on an arbitrary scale. The data were used to determine graphically the amounts of P_2O_5 as standard fertilizer (basic slag or superphosphate) which had the same value in establishing the sown species as the dressings of rock phosphate used. These amounts were expressed as percentages of the amount of P_2O_5 actually applied and the data are summarized in Table 9.

In general, rock phosphates gave as satisfactory establishment as amounts of standard materials supplying from one-quarter to one-half as much phosphorus. In seven experiments carried out in 1941 Florida rock phosphate was inferior to Gafsa and Curacao phosphates; in three experiments in 1944 Morocco phosphate was inferior to Gafsa phosphate.

Observations on the grass, which was grazed, were made in subsequent years in many of the experiments. It is relatively easy for a skilled observer to assess visually the success which has been achieved in establishing a sown pasture. Observations on the subsequent behaviour of the herbage and its actual productivity are much more difficult. Management of the grass makes a great deal of difference to the effects of the tested phosphates, in addition selective grazing of the treated plots may give a false impression of growth. The data gathered are discussed later.

Six experiments on acid soils were laid down on permanent grass to compare rock phosphates with Bessemer basic slag. Visual estimates of growth were made. On average of the results of this group of experiments Gafsa rock phosphate gave poorer growth than Bessemer basic slag. Improvement of pasture by Gafsa phosphate was equivalent to the improvement achieved by Bessemer basic slag supplying only 55 % as much phosphorus. Two other experiments on permanent grass on acid soils were cut for hay. Gafsa and Curacao phosphates gave lower yields and phosphorus contents of the crops than Bessemer basic slag supplying only two-thirds as much phosphorus (Table 10).

Table 6. *Percentage superphosphate equivalents of rock phosphates derived from yields and phosphorus contents of swedes*

	From yields				From phosphorus contents			
	Very acid soils	Acid soils	Neutral soils	All soils	Very acid soils	Acid soils	Neutral soils	All soils
1943–4 experiments	(5)	(4)	(—)	(—)	(5)	(4)	(—)	(—)
Morocco phosphate	64	38	—	—	84	58	—	—
1945–6 experiments	(—)	(—)	(—)	(6*)	(—)	(—)	(—)	(6*)
Gafsa phosphate	—	—	—	58	—	—	—	68
1951–3 experiments	(10)	(22)	(3)	(35)	(10)	(22)	(3)	(35)
Gafsa phosphate	91	86	12	86	94	78	18	78
Dicalcium phosphate	97	85	95	89	100	85	77	87
Silicophosphate	90	84	52	86	100	88	61	89

* 5 'very acid' soils, 1 'acid' soil.
Numbers of experiments are stated in brackets.

Table 7. *Mean yields of potatoes (in tons/acre) in experiments carried out from* 1951–3

	Amount of P_2O_5 supplied (cwt./acre)	Very acid soils	Acid soils	Neutral soils	All soils
No. of experiments ...	—	10	15	9	34
Without phosphate	0·00	9·2	9·8	9·1	9·4
Superphosphate	0·33	10·8	10·9	9·9	10·6
	0·66	11·6	11·2	10·3	11·1
Dicalcium phosphate	0·50	11·5	10·9	10·0	10·8
Silicophosphate	0·50	11·2	10·8	9·6	10·6
Gafsa phosphate	0·50	10·3	10·6	9·2	10·1

Table 8. *Percentage superphosphate equivalents of dicalcium phosphate, silicophosphate and Gafsa phosphate for potatoes* (1951–3 *experiments*)

	Dicalcium phosphate	Silico-phosphate	Gafsa phosphate
Very acid soils	122	92	34
Acid soils	62	56	37
Neutral soils	84	30	4
All soils	90	65	30

(2) *Fineness of grinding of rock phosphate*

The Fertiliser and Feeding Stuffs Act requires that the percentage of a sample of mineral phosphate which passes through a 100 mesh British Standard Test Sieve be declared. It is generally accepted that practically all should pass through the prescribed sieve. War-time conditions made it essential that the greatest output should be secured from the grinding mills. Quite small increases in fineness of the product may require disproportionately longer times of grinding, particularly when very hard rock phosphates (such as Curacao) are used. Experiments on swedes and reseeded grass were made to test coarse and fine grindings of rock phosphates. The fine and coarse batches contained approximately 80% and 60% respectively of material which passed the 100 mesh B.S. sieve.

In six swede experiments carried out in 1942 (summarized in Table 11) coarse and fine grindings of Curacao phosphate gave similar yields and similar amounts of phosphorus in the crops, at both rates of dressing. In nine other experiments (also summarized in Table 11) the yields of swedes given by the two grades were very similar; the coarse material gave higher amounts of phosphorus in the crops.

Experiments on establishing reseeded grassland are summarized in Table 12. In a group of 3 experiments carried out in 1942 the coarse phosphate gave better establishment than finer material. In three other experiments carried out in 1944 coarse and fine grindings of Gafsa phosphate gave very similar results but coarse Morocco phosphate was inferior to finer material.

3. *Mixtures of rock phosphate and superphosphate*

If rock phosphate is treated with less sulphuric acid than is needed to make superphosphate, the product merely consists of monocalcium phosphate and unchanged rock. Two commercial processes have been used to make mixtures of rock phosphate and superphosphate.

One method consisted of mixing hot, freshly prepared superphosphate with rock phosphate; the 'Kotka' process used in Finland is similar. In this method some rock phosphate may react with the phosphoric acid and monocalcium phosphate in superphosphate to give dicalcium phosphate. In the second method cold superphosphate was mixed with an equal weight of rock phosphate. Products of this kind have been sold in Northern Ireland under the name 'Semsol'; there is no evidence to suggest that the reaction between the two components goes farther than neutralizing free acid in the superphosphate. Products of the 'Kotka' and

Table 9. *Experiments testing rock phosphate for establishing reseeded grassland on acid soils*

Percentage equivalents of rock phosphate in terms of standard phosphate fertilizers.

Year	No. of expts.	Standard material (=100)	Gafsa	Curacao	Florida	Morocco
1941	7	High-soluble basic slag	37	45	21	—
1942	3	Bessemer basic slag	38	24	—	—
1943	4	Bessemer basic slag	—	—	—	43
1944	3	Superphosphate	34	—	—	23

Table 10. *Experiments on permanent grass testing rock phosphates*

(Mean of 2 experiments)

	P_2O_5 applied (cwt./acre)	Yield of dry hay (cwt./acre)	P_2O_5 in crop (cwt./acre)
Without phosphate	0·00	24·2	0·075
Bessemer basic slag	0·66	27·0	0·102
	1·33	27·9	0·112
Rock phosphates			
Gafsa	1·00	26·8	0·097
Curacao	1·00	25·0	0·092

Table 11. 1942 *experiments on swedes grown on acid soils, testing coarse and fine rock phosphates*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)		P_2O_5 in roots (cwt./acre)	
No. of experiments ...	—	6	9	6	9
Without phosphate	0·00	3·6	8·1	0·025	0·077
Rock phosphates					
Coarse Curacao	0·50	13·8	—	0·123	—
	1·00	15·7	18·4	0·156	0·199
Fine Curacao	0·50	13·7	—	0·118	—
	1·00	16·5	18·2	0·160	0·186
Fine Gafsa	0·50	14·8	—	0·128	—
	1·00	16·4	18·6	0·167	0·192

'Semsol' types might be regarded as 'two-stage' fertilizers, water-soluble phosphorus establishing the crop rapidly and rock phosphate supplying its needs later in the season.

Mixtures of rock phosphate with both hot and cold superphosphate were made and tested in field experiments; the average compositions of the mixtures used are given in Table 1. The results of experiments on swedes are summarized in Table 13 by stating percentage superphosphate equivalents of the two mixtures after grouping the experiments by soil reaction. Six experiments tested both kinds of mixtures and also Morocco rock phosphate, nine experiments tested only the 'Semsol'-type mixture.

Table 12. *Experiments on grassland testing coarse and fine rock phosphates*

(Percentage equivalents of the rock phosphates in terms of standard phosphates, calculated from visual estimates of the establishment of sown species.)

3 experiments in 1942	
Bessemer basic slag (standard)	100
Rock phosphates	
Coarse Curacao	28
Fine Curacao	20
Fine Gafsa	38
3 experiments in 1944	
Superphosphate (standard)	100
Rock phosphates	
Coarse Morocco	19
Fine Morocco	27
Coarse Gafsa	35
Fine Gafsa	34

'Semsol'-type phosphate was slightly more efficient than Morocco rock phosphate on both groups of soils. 'Kotka'-type phosphate gave lower yields than rock phosphate.

Two groups of potato experiments in 1943–5 tested mixtures of Morocco rock phosphate with cold superphosphate. The soils chosen, except one, were acid. The results are summarized in Table 14. 'Kotka'-type phosphate was not adequately tested on potatoes.

The four experiments in 1943 were carried out in Northern Ireland, three being on very acid soils and one on a less acid soil. 'Semsol'-type phosphate produced yields similar to those given by half the quantity of phosphorus applied as superphosphate. Five other experiments carried out in 1945 tested the mixture at lower rates; four experiments were on acid (pH 5·6–6·5) soils in Northern Ireland, one was on a neutral peat soil in England. Yields given by 'Semsol'-type phosphate were markedly inferior to those from superphosphate. Percentage superphosphate equivalents for the mixture were obtained from the mean yields by graphical interpolation within each group of experiments, they were:

	From yields	From P_2O_5 contents
Four experiments in 1943		
'Semsol'-type mixture	48	46
Five experiments in 1945		
'Semsol'-type mixture	46	42

Potatoes made little use of the mineral phosphate component of the mixture in both sets of experiments.

Three experiments on acid soils compared 'Semsol'-type phosphate with superphosphate for reseeding grassland on acid soils. Phosphorus supplied by the mixture had only 82% of the efficiency of phosphorus supplied as superphosphate.

Mixtures of rock phosphate and superphosphate had no advantages in these experiments over equivalent amounts of straight rock phosphate and superphosphate used correctly. Unexpectedly, 'Kotka'-type phosphate was less efficient than the rock phosphate from which it was made. No satisfactory explanation can be offered for this result, it must be regarded as a warning against making such mixtures in this country until detailed laboratory investigations on the reactions involved indicate how more efficient products may be obtained.

Part 2. Silicophosphate

The laboratory investigations, pilot-plant work and full-scale production trials which led to the production of silicophosphate fertilizers have been de-

Table 13. *Experiments on swedes and turnips testing mixtures of rock phosphate with superphosphate*

		Percentage superphosphate equivalents					
			From yields		From phosphorus in crops		
	No. of exps.	Morocco phosphate	'Semsol'-type mixture	'Kotka'-type mixture	Morocco phosphate	'Semsol'-type mixture	'Kotka'-type mixture
Experiments on rock phosphate and mixtures							
Very acid soils	3	82	92	68	92	96	90
Other soils	3	28	42	14	48	38	22
Experiments on the 'Semsol'-type mixture							
Very acid soils	6	—	68	—	—	76	—
Other soils	3	—	41	—	—	38	—

scribed by Lea *et al.* (1951). In the early stages of the work various materials were prepared by the Building Research Station to test alternative processes. Several kinds of silicophosphate were compared in field experiments in 1942, the results have been stated fully by Crowther & Cooke (1951) and comparisons of different kinds of silicophosphate are not discussed here. From 1943 onwards work was concentrated on one kind of process where 100 parts of phosphate rock were heated with 16 parts of soda ash and 8 to 10 parts of sand. All the field experiments summarized here tested products made by this process. The rock phosphates used varied; silicophosphates tested in 1942 and 1943 were made from Curacao and Florida phosphates, Morocco phosphate was used to a limited extent. From 1944 onwards practically all the field experiments tested silicophosphates made from 'Kola concentrate' phosphate. The average analyses of the silicophosphates used in the field experiments are given below. (There was little variation between batches used in different years.)

Table 14. *Experiments on potatoes testing a rock phosphate-superphosphate mixture*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in crop (cwt./acre)
1943 experiments (4)			
Without phosphate	0·00	7·0	0·116
Superphosphate	0·50	10·2	0·167
	1·00	10·8	0·180
'Semsol'-type mixture	1·00	10·1	0·165
1945 experiments (5)			
Without phosphate	0·00	5·0	0·098
Superphosphate	0·33	7·3	0·143
	0·66	8·1	0·155
'Semsol'-type mixture	0·50	6·8	0·131

	Total P_2O_5 (%)	Percentage solubility in citric acid (%)	*F* (%)
1942–6 experiments	32·7	94	0·14
1951–3 experiments	33·4	90	—

(i) *Experiments on swedes and potatoes*

In the 1942 experiments superphosphate was tested as a standard material at three rates of dressing and silicophosphates were tested at the highest rate. In all later work superphosphate was tested at rates supplying 0, 2 and 4 units of P_2O_5 and other materials were tested at the intermediate rate (3 units of P_2O_5).

Eighteen experiments in 1942 and twenty-nine experiments in 1943–6 compared silicophosphate and superphosphate for swedes; in later work thirty-five experiments on swedes were carried out between 1951 and 1953. The results are summarized in Table 15 together with corresponding data from the potato experiments. The potato crops from the 1951–3 experiments were not sampled and analysed to determine uptakes of phosphorus since the earlier work had shown that very little extra information was obtained.

In the 1942 experiments silicophosphate was markedly superior to superphosphate for swedes. In the two later series of experiments there was little difference between yields and phosphorus contents from silicophosphate and from superphosphate supplying the same amounts of P_2O_5. Detailed examination of the data (Crowther & Cooke, 1951) failed to show any reason why silicophosphate was consistently superior to superphosphate for swedes grown in 1942 but not in any of the later years.

For potatoes silicophosphate was consistently inferior to superphosphate both in the small group of experiments carried out in 1942 and in the larger series carried out in 1943–6 and in 1951–3. Yields and phosphorus contents from silicophosphate were roughly equal to those given by only two-thirds as much phosphorus supplied as superphosphate.

Yields and phosphorus contents of the experiments summarized in Table 15 were used to derive the percentage superphosphate equivalents given in Table 16. (The superphosphate response curves obtained in the 1942 swede experiments cannot be extrapolated accurately to the high yields given by superphosphate and the treatment is not approximate for such conditions.) The comparisons were made for silicophosphate supplying 0·5 cwt. P_2O_5 per acre and the experiments were grouped by soil reaction.

For both swedes and potatoes silicophosphate was nearly as efficient as superphosphate on average of the groups of experiments on very acid soils. For swedes silicophosphate was less efficient than superphosphate in the groups of 'acid' and 'neutral' soils in the 1943–6 experiments, this tendency was less marked in the 1951–3 series. The two series of experiments on potatoes are very consistent and show that silicophosphate was much less effective on soils having pH values above 5·5 than on the very acid soils. On the basis of the phosphorus contents of swedes in both series of experiments, silicophosphate was less efficient in the groups of experiments on 'acid' and 'neutral' soils. The phosphorus contents of potatoes do not provide any information which cannot be obtained from the yield data.

(ii) *Experiments on sugar beet and oats*

Four experiments on sugar beet compared silicophosphate and superphosphate supplying equal amounts of total P_2O_5, the average results are summarized in Table 17. Silicophosphate produced slightly higher average yields of sugar beet than superphosphate, although none of the soils used was very acid. It is possible that the sugar-beet crops derived some benefit from the small amount of sodium provided by silicophosphate.

of growth were made. On average silicophosphate gave the same amount of growth as Bessemer basic slag and was much superior to Gafsa rock phosphate and to a low soluble basic slag made by the 'Open Hearth' process with addition of fluorspar. The average 'scores' for growth, expressed as percent-

Table 15. *Average yields and phosphorus contents of swedes and potatoes in field experiments comparing silicophosphate and superphosphate*

	P_2O_5 applied (cwt./acre)	Swedes: Yields (tons/acre)	Swedes: P_2O_5 content of crops (cwt./acre)	Potatoes: Yields (tons/acre)	Potatoes: P_2O_5 content of crops (cwt./acre)
1942 experiments					
No. of experiments ...	—	18		8	
Without phosphate	0·00	5·0	0·046	6·6	0·116
Superphosphate	0·50	14·3	0·124	9·2	0·154
	1·00	16·2	0·166	9·9	0·173
Silicophosphate	1·00	16·8	0·191	9·5	0·157
1943–6 experiments					
No. of experiments ...	—	29		25	
Without phosphate	0·00	9·1	0·079	5·0	0·081
Superphosphate	0·33	13·3	0·122	7·5	0·117
	0·66	14·8	0·153	8·3	0·134
Silicophosphate	0·50	13·8	0·135	7·6	0·119
1951–3 experiments					
No. of experiments ...	—	35		34	
Without phosphate	0·00	12·0	0·111	9·4	—
Superphosphate	0·33	17·4	0·166	10·6	—
	0·66	19·6	0·202	11·1	—
Silicophosphate	0·50	18·2	0·181	10·6	—

Table 16. *Percentage superphosphate equivalents of silicophosphate from field experiments on swedes and potatoes*

	Swedes: No. of expts.	Swedes: From yields	Swedes: From P_2O_5 contents	Potatoes: No. of expts.	Potatoes: From yields	Potatoes: From P_2O_5 contents
1943–6 experiments						
Very acid soils	10	90	102	8	90	98
Acid soils	12	84	95	10	59	60
Neutral soils	7	72	86	7	62	62
All soils	29	83	96	25	71	72
1951–3 experiments						
Very acid soils	10	90	100	10	92	—
Acid soils	22	84	88	15	56	—
Neutral soils	3	52	61	9	30	—
All soils	35	86	89	34	65	—

In five experiments on oats (Table 17) average crop yields were poor but silicophosphate gave a slightly lower mean yield than superphosphate, perhaps because cereals need the rapid start which water-soluble phosphorus provides.

(iii) *Experiments on grassland*

Six experiments were laid down on permanent grass grown on very acid soils and visual estimates

ages of the general mean 'score' are given in Table 18.

Twenty-one trials were carried out from 1942 to 1944, largely in the Welsh hills, to compare silicophosphate with Bessemer basic slag or with superphosphate for establishing reseeded grassland. Practically all the experiments were on very acid soils with pH values below 5·6. The effects of the fertilizers were estimated by visual 'scores' for the

6-2

degree of establishment of the sown species of grasses and clovers. The mean results of twenty-one experiments are summarized in Table 19 by averaging all comparable data. Bessemer slag and silicophosphate gave practically identical establishment of the sown species.

Table 17. *Mean yields in experiments on sugar beet and oats comparing superphosphate and silicophosphate*

	Sugar beet, yields of sugar (cwt./acre)	Oats, yields of grain (cwt./acre)
No. of experiments ...	4	5
Without phosphate	27·5	12·3
Superphosphate	34·3	14·1
Silicophosphate	35·4	13·0

Table 18. *Average results from 6 experiments on permanent grassland testing silicophosphate*

	P_2O_5 applied (cwt./acre)	Average visual 'scores'
Without phosphate	0·00	80
Bessemer basic slag	0·66	101
	1·33	112
Silicophosphate	1·00	107
Gafsa rock phosphate	1·00	102
Low-soluble basic slag	1·00	98

Table 19. *Average results from 21 experiments on establishing reseeded grass on very acid soils*

	Average visual 'scores'
Without phosphate	49
Bessemer basic slag	115
Silicophosphate	114

Table 20. *Average results from 13 experiments on establishing reseeded grass on very acid soils*

	P_2O_5 applied (cwt./acre)	Average visual 'score'
Without phosphate	0·00	51
Superphosphate	0·33	104
	0·66	117
Silicophosphate	0·50	112
Bessemer basic slag	0·50	115

In thirteen of these experiments, summarized in Table 20, silicophosphate and Bessemer slag applied at 0·5 cwt. P_2O_5 per acre were compared with superphosphate applied at two rates of dressing (0·33 and 0·66 cwt. P_2O_5 per acre). Silicophosphate and Bessemer basic slag gave mean scores closely approaching those given by superphosphate at the higher rate. Graphical estimation of the 'percentage superphosphate equivalents' gave the following values:

Superphosphate	100
Silicophosphate	107
Bessemer basic slag	120

On such very acid soils the less soluble and more basic phosphates have some advantage in establishing grass.

Part 3. Dicalcium phosphate

(1) *Basic superphosphate mixtures*

Many of the later experiments of the 1941–6 series were concerned with attempts to improve the practical efficiency of phosphate fertilizers. Wastage may result from using a phosphate fertilizer unsuitable for a particular crop or kind of soil, from using too heavy dressings, or by the reaction of the fertilizer with soil constituents to form compounds which are useless to crops. Water-soluble phosphate reacts with the soil very rapidly, less-soluble forms may remain unchanged in the soil for a longer period. Dicalcium phosphate is not soluble in water and therefore diffuses less rapidly than monocalcium phosphate. This property could be an advantage on soils which convert soluble phosphates to inert forms rapidly.

It is not possible to convert mineral phosphate to dicalcium phosphate directly by using less sulphuric acid than is needed for superphosphate. Instead monocalcium phosphate must first be prepared (as in superphosphate) and then converted to dicalcium phosphate by adding basic material—a process often called 'reversion'. Three products containing dicalcium phosphate were made for testing in the field experiments by mixing slaked lime, a low-grade low-soluble basic slag, and serpentine with superphosphate. There was particular interest in the mixture made with serpentine since it had been claimed in New Zealand (Elliot, 1944), that the mixture was as effective as an equal weight of superphosphate implying that phosphorus in 'reverted' forms was more valuable than water-soluble phosphorus.

The average composition of each material used is stated in Table 21. Details of the preparation of these mixtures are given by Crowther, Warren & Cooke (1953). Approximately one-eighth of the total P_2O_5 in the superphosphate-basic slag mixture was derived from the low-soluble slag used, accordingly the phosphorus present had a lower percentage solubility in citric acid than phosphorus in the other mixtures. Some of the mixtures of superphosphate with serpentine contained considerable amounts of water-soluble phosphorus. Different batches of the mixtures were used in any one year and it is not possible to discuss their behaviour separately.

(i) *Experiments on swedes*

A number of experiments on swedes were carried out, mainly in 1943 and 1944, to test mixtures of superphosphate with basic materials; the results are summarized in Table 22. There were very few experiments on very acid soils (pH below 5·6) and the experiments were therefore divided into groups of centres on acid soils (pH 6·5 and below) and on neutral soils (pH above 6·5). Most of the experiments were in the east of England, average yields were low and frequently phosphate fertilizers gave only small increases in the yields of swedes.

Table 21. *Average analyses of basic superphosphate mixtures used in the field experiments*

	Total P_2O_5 (%)	Percentage solubility in	
		Citric acid	Water
Mixture of superphosphate with			
Basic slag	16·4	73	6
Slaked lime	16·9	84	4
Serpentine	14·7	86	38

The results of sixteen experiments on the mixture of superphosphate with basic slag are summarized in Group I. It was inferior to superphosphate on acid soils and the less sensitive experiments on neutral soils failed to distinguish between the two materials. The results of all experiments on the mixture of superphosphate with lime are summarized in Group II. This mixture gave similar yields to superphosphate on both acid and neutral soils, but superphosphate gave crops containing more phosphorus. Superphosphate-serpentine mixture (Group III) gave lower yields and lower amounts of phosphorus in the crops than superphosphate.

The amounts of superphosphate needed to produce the yields and phosphorus contents given by basic superphosphate mixtures were determined by graphical interpolation. These amounts are expressed in Table 23 as percentages of the dressing of P_2O_5 applied. As the response curves were very flat in groups of experiments on neutral soils, percentage superphosphate equivalents determined by graphical interpolation would have been inaccurate and were not derived. Averaging experiments on all soils, superphosphate-lime mixture had about the same effect on yields of swedes as untreated superphosphate; the mixtures with basic slag and serpentine were less efficient than superphosphate.

There was no evidence from the experiments on swedes that mixing superphosphate with basic materials to form, mainly, dicalcium phosphate improves the efficiency of the phosphorus.

(ii) *Experiments on potatoes*

One group of fourteen experiments compared mixtures of superphosphate with lime and with serpentine against untreated superphosphate; seven other experiments tested the mixture of superphosphate with basic slag. The results are summarized in Table 24.

On acid soils the mixtures with lime and serpentine were approximately equivalent to superphosphate but on neutral soils they were inferior. Superphosphate-basic slag mixture gave lower yields than two-thirds of the quantity of phosphorus applied as superphosphate, both on acid and on neutral soils.

Table 22. *Experiments on swedes testing basic superphosphate mixtures*

	P_2O_5 applied (cwt./acre)	Yields of roots (tons/acre) Acid soils	Neutral soils	All soils	P_2O_5 in roots (cwt./acre) Acid soils	Neutral soils	All soils
Group I							
No. of experiments ...	—	8	8	16	8	8	16
Without phosphate	0·00	10·3	6·6	8·5	0·092	0·063	0·077
Superphosphate	0·33	14·0	8·6	11·3	0·140	0·086	0·114
	0·66	15·2	9·4	12·3	0·180	0·106	0·143
Superphosphate + basic slag mixture	0·50	14·3	9·0	11·7	0·154	0·097	0·125
Group II							
No. of experiments ...	—	5	5	10	5	5	10
Without phosphate	0·00	12·2	8·9	10·6	0·108	0·084	0·096
Superphosphate	0·33	15·5	10·7	13·1	0·152	0·106	0·129
	0·66	16·3	11·0	13·6	0·182	0·124	0·153
Superphosphate + lime mixture	0·50	15·8	11·0	13·4	0·154	0·113	0·134
Group III							
No. of experiments ...	—	7	5	12	7	5	12
Without phosphate	0·00	10·7	8·9	10·0	0·093	0·084	0·089
Superphosphate	0·33	14·6	10·7	13·0	0·146	0·106	0·129
	0·66	15·9	11·0	13·9	0·186	0·124	0·160
Superphosphate + serpentine mixture	0·50	15·1	10·7	13·2	0·155	0·108	0·136

Table 25 gives the percentage superphosphate equivalents of basic superphosphate mixtures for potatoes. In Group I the mixture of superphosphate with serpentine was more efficient than the mixture with lime; both mixtures were more efficient on acid soils (pH values below 6·5) than on neutral soils. On the basis of yields of potatoes, the mixture with basic slag was only half as effective as equivalent superphosphate.

Table 23. *Experiments on swedes testing basic superphosphate mixtures*

(Percentage superphosphate equivalents derived from mean yields and phosphorus contents.)

	No. of experiments	From yields	From phosphorus contents
Mixture of superphosphate with			
Basic slag	16	85	89
Lime	10	95	78
Serpentine	12	75	80

Of the three basic materials used to convert monocalcium phosphate in superphosphate to a water-insoluble form, serpentine gave the most efficient product for potatoes, but it was least efficient for swedes. (Mixtures with basic slag are not strictly comparable with the other mixtures since part of the phosphorus was derived from the low-grade low-soluble slag used.) In some experiments the basic superphosphates gave yields similar to those from untreated superphosphate but there is no evidence of the increase in phosphorus efficiency needed to justify the expense of mixing superphosphate with basic material. The best that may be said for these products is that if they are properly made and are applied to potatoes grown on acid soils they are not inferior to superphosphate. Generally potatoes need highly soluble phosphates on less acid and neutral soils.

(iii) *Experiments on reseeded grassland*

The results of four experiments on reseeded grassland on very acid soils and of one on a neutral soil are summarized in Group I in Table 26. Visual 'scores' for establishment given by basic superphosphate mixtures applied at 0·5 cwt. P_2O_5 per acre were a little higher than the 'scores' given for establishment by dressings of 0·66 cwt. P_2O_5 per acre as superphosphate.

The results of four experiments on very acid soils are also summarized in Group II in Table 26. The mixture of superphosphate with low-grade, low-soluble basic slag gave establishment of sown species similar to that given by Bessemer basic slag.

Table 24. *Experiments on potatoes testing basic superphosphate mixtures*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre) Acid soils	Neutral soils	All soils	P_2O_5 in roots (cwt./acre) Acid soils	Neutral soils	All soils
Group I							
No. of experiments ...	—	7	7	14	6	7	13
Without phosphate	0·00	5·7	6·2	6·0	0·088	0·106	0·097
Superphosphate	0·33	7·7	7·4	7·6	0·120	0·121	0·120
	0·66	8·5	8·4	8·4	0·131	0·142	0·137
Superphosphate + lime	0·50	8·1	7·0	7·5	0·128	0·120	0·124
Superphosphate + serpentine	0·50	8·2	7·7	8·0	0·125	0·127	0·126
Group II							
No. of experiments ...	—	5	2	7	4	2	6
Without phosphate	0·00	5·8	3·1	5·0	0·089	0·048	0·076
Superphosphate	0·33	7·0	4·9	6·4	0·098	0·071	0·089
	0·66	7·6	5·8	7·1	0·108	0·086	0·101
Superphosphate + basic slag	0·50	6·8	4·6	6·2	0·099	0·072	0·090

Table 25. *Experiments on potatoes testing basic superphosphate mixtures*

Percentage superphosphate equivalents

	From yields Acid soils	Neutral soils	All soils	From phosphorus in crops Acid soils	Neutral soils	All soils
Group I						
No. of experiments ...	7	7	14	6	7	13
Superphosphate + lime mixture	91	41	63	108	54	81
Superphosphate + serpentine mixture	107	83	94	90	82	86
Group II						
No. of experiments ...	5	2	7	4	2	6
Superphosphate + basic slag mixture	52	50	52	70	68	70

The basic superphosphates tested gave better establishment than a dressing of untreated superphosphate supplying an equal quantity of phosphorus; it was not possible to extrapolate the superphosphate response curves sufficiently to determine the dressings of superphosphate which were equivalent to the other materials. The numbers of experiments reported here are too few for reliable conclusions but they support the statement by New Zealand workers that mixtures of superphosphate and serpentine may be more efficient than untreated superphosphate for grassland.

Table 26. *Experiments on reseeded grassland testing basic superphosphate mixtures*

(Average visual 'scores' for establishment of sown species.)

	P_2O_5 applied (cwt./acre)	'Score'
Group I		
Without phosphate	0·00	51
Superphosphate	0·33	97
	0·66	111
Mixtures		
Superphosphate + basic slag	0·50	112
Superphosphate + lime	0·50	114
Superphosphate + serpentine	0·50	115
Group II		
Without phosphate	0·00	46
Bessemer basic slag	0·33	104
	0·66	130
Superphosphate + basic slag mixture	0·50	120

(2) *Dicalcium phosphate*

Dicalcium phosphate is usually made on an industrial scale by dissolving phosphate rock in hydrochloric acid and then adding milk of lime to the solution with careful control of the pH. Samples of dicalcium phosphate made in this way were tested in a few of the later experiments of the 1941–6 series and much more extensively in the 1951–3 experiments. (This process does not require sulphuric acid since by-product hydrochloric acid is generally used.) Tests of dicalcium phosphate are important since it is present in ammoniated superphosphates and in fertilizers made by dissolving phosphate rock in nitric acid followed by ammoniation.

The average analyses of the samples of dicalcium phosphate used in the two phases of this work are given in Table 27.

Table 27. *Analyses of samples of dicalcium phosphate used in the field experiments*

	Total P_2O_5 (%)	Percentage solubility in citric acid
1943–6 field experiments	39·8	100
1951–3 field experiments	39·1	99

(i) *Experiments on potatoes*

In the earlier work three field experiments on potatoes tested commercial dicalcium phosphate preparations as well as a mixture of superphosphate with lime. The results are summarized in Table 28.

Table 28. *Mean results of three* 1943–6 *field experiments on potatoes testing dicalcium phosphate*

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
No phosphate	0·00	4·8	0·061
Superphosphate	0·33	7·0	0·100
	0·66	7·7	0·107
Superphosphate + lime mixture	0·50	7·5	0·104
Dicalcium phosphate	0·50	7·5	0·104

The mean yields and phosphorus contents given by both materials were similar to those from an equivalent quantity of superphosphate.

The 'percentage superphosphate equivalents' of the two phosphates tested were:

	From yields	From phosphorus contents
Dicalcium phosphate	102	92
Superphosphate + lime mixture	102	92

In the 1951–3 series thirty-four field experiments on potatoes were carried out to test dicalcium phosphate as well as silicophosphate and Gafsa rock phosphate. The results have been summarized in Table 7 and the percentage superphosphate equivalents stated in Table 8 were derived from the data. Dicalcium phosphate was somewhat more efficient than superphosphate on very acid soils (pH 5·5 and below); on less acid and neutral soils it was inferior to superphosphate.

(ii) *Experiments on swedes*

Dicalcium phosphate was not tested in the 1943–6 field experiments on swedes but thirty-five experiments were carried out in the 1951–3 series. The results, already summarized in Table 5, are stated more fully in Table 29. Percentage superphosphate equivalents derived from these data have already been given in Table 6. Dicalcium phosphate was nearly equivalent to superphosphate for swedes grown on all groups of soils; it behaved quite efficiently in the small group of experiments on neutral soils where silicophosphate and rock phosphate were much less effective.

Dicalcium phosphate dihydrate in powder form could replace superphosphate for many crops on slightly acid or acid soils. It might not be so satisfactory on calcareous soils or for crops which require a rapid start from phosphates drilled near the seed. For these purposes water-soluble phosphates are likely to be best.

Part 4. Nitrophosphates

Several methods of treating phosphate rock with nitric acid have been developed in recent years, processes used commercially have been reviewed by Cooke (1954). When sulphuric acid is replaced by nitric acid in the ordinary superphosphate process, the product contains monocalcium phosphate and calcium nitrate and is too hygroscopic for satisfactory storage and use on the farm. Commercial nitric acid processes differ in the way in which the excess of calcium nitrate is dealt with.

When phosphate rock reacts completely with nitric acid, phosphoric acid and calcium nitrate are formed. After treating this reaction mixture with ammonia, the product contains dicalcium phosphate, ammonium nitrate, and calcium nitrate. Nitrophosphates made by three important processes described below, which use different methods of dealing with surplus calcium nitrate, were tested in experiments carried out in 1951–3.

(1) Addition of soluble sulphate, such as ammonium sulphate, prevents calcium nitrate occurring in the final product since calcium sulphate is precipitated.

(2) Mixtures of sulphuric and nitric acids give reaction slurries containing calcium sulphate, calcium nitrate and monocalcium phosphate. After ammoniation, the resulting fertilizer contains calcium sulphate, ammonium nitrate and dicalcium phosphate.

(3) Calcium nitrate is removed by cooling solutions of rock phosphate in nitric acid, half of the calcium nitrate present being precipitated, removed, and sold as a straight fertilizer. By neutralizing the remaining solution with ammonia, a nitrophosphate is produced which consists of ammonium nitrate and dicalcium phosphate.

The nitrophosphate made by adding ammonium sulphate was produced on pilot-plant scale by the process described by d'Leny (1953). Products made by using a mixture of nitric and sulphuric acids and by removing calcium nitrate were imported from continental countries, they are believed to be part of ordinary commercial production. The compositions of the nitrophosphates tested in the 1951–3 experiments are given in Table 30.

Table 29. *Mean yields of swedes and amounts of phosphorus in the crops in experiments carried out in* 1951–3

	P_2O_5 applied (cwt./acre)	Very acid soils	Acid soils	Neutral soils	All soils
No. of experiments ...	—	10	22	3	35
	Yields of swedes (in tons/acre)				
Without phosphate	0·00	10·3	12·6	13·3	12·0
Superphosphate	0·33	17·2	17·8	15·1	17·4
	0·66	19·9	20·0	15·7	19·6
Dicalcium phosphate	0·50	18·8	18·6	15·5	18·4
Silicophosphate	0·50	18·6	18·5	14·9	18·2
Rock phosphate	0·50	18·6	18·6	13·8	18·2
	Phosphorus in the crops (cwt. P_2O_5/acre)				
Without phosphate	0·00	0·100	0·118	0·101	0·111
Superphosphate	0·33	0·166	0·171	0·128	0·166
	0·66	0·209	0·205	0·151	0·202
Dicalcium phosphate	0·50	0·190	0·183	0·132	0·180
Silicophosphate	0·50	0·190	0·184	0·126	0·181
Rock phosphate	0·50	0·186	0·179	0·109	0·175

Table 30. *Compositions of nitrophosphates used in* 1951–3 *field experiments*

	Rothamsted number	Percentage N			Percentage P_2O_5			Percentage K_2O
		Total	As NH_4	As NO_3	Total	Citric acid soluble	Water soluble	
		Nitrophosphate made by adding ammonium sulphate						
1951	NP 6	12·8	7·3	5·5	15·2	12·6	2·3	0·0
1952	NP 15	14·2	7·5	6·7	14·4	13·6	4·5	0·0
1953	NP 19	14·6	8·4	6·2	14·3	12·8	4·0	0·0
		Nitrophosphate made by mixed nitric + sulphuric acids						
1952	NPK 18	12·1	6·1	6·0	11·9	11·5	0·6	13·0
1953	NPK 44	12·4	6·2	6·2	12·2	12·2	0·8	13·5
		Nitrophosphate made by removing calcium nitrate						
1951	NP 7	20·8	10·6	10·3	20·3	20·1	1·4	0·0
1952	NP 14	19·3	9·7	9·7	20·2	19·7	1·6	0·0
1953	NP 20	20·8	10·7	10·1	17·8	17·2	—	0·0

(1) *Experiments in* 1951

Experiments on swedes, potatoes and grass were carried out from 1951 to 1953. The 1951 experiments were of a different pattern from those carried out in later years. The treatments, arranged in 6 × 6 Latin Squares, were:

(1) No nitrogen or phosphate.
(2) Nitrogen only.
(3) Superphosphate only.
(4) Superphosphate plus nitrogen.
(5) Nitrophosphate made by adding ammonium sulphate.
(6) Nitrophosphate made by removing calcium nitrate.

Phosphate fertilizers were applied at 0·4 cwt. P_2O_5 per acre, nitrogen dressings were adjusted on plots receiving nitrophosphate so that all plots received equal total quantities. Nitrogen fertilizer was added as ammonium sulphate in experiments on potatoes and swedes and as 'Nitro-Chalk' in experiments on grass. The results are stated in Table 31, by averaging all experiments on each crop; there were not sufficient experiments to give reliable averages when the centres were grouped by soil pH.

For potatoes and swedes the two nitrophosphates behaved similarly, giving yields slightly below those given by superphosphate plus ammonium sulphate, but they supplied more phosphorus for the crops. For grass the nitrophosphate made by removing calcium nitrate was slightly superior to the product made by adding ammonium sulphate, both gave yields similar to those given by superphosphate plus 'Nitro-Chalk'.

Table 31. *Mean results of* 1951 *experiments testing nitrophosphates for potatoes, grass and swedes, averaging all experiments on each crop*

	Potatoes	Grass	Swedes
No. of experiments ...	8	10	4
	Crop yields		
	Tubers (tons/acre)	Dry hay (cwt./acre)	Roots (tons/acre)
Without phosphate, without nitrogen	8·3	24·9	10·7
Without phosphate, with nitrogen	9·3	30·8	11·1
With superphosphate, without nitrogen	8·8	27·5	17·8
With superphosphate, with nitrogen	10·5	33·5	19·0
With nitrophosphate made by:			
Adding ammonium sulphate	10·1	32·8	18·7
Removing calcium nitrate	9·8	34·1	18·4
	P_2O_5 in crops (cwt./acre)		
Without phosphate, without nitrogen	0·152	0·125	0·080
Without phosphate, with nitrogen	0·162	0·146	0·075
With superphosphate, without nitrogen	0·162	0·155	0·152
With superphosphate, with nitrogen	0·184	0·174	0·144
With nitrophosphate made by:			
Adding ammonium sulphate	0·175	0·167	0·154
Removing calcium nitrate	0·176	0·179	0·165

(2) 1952 *and* 1953 *experiments*

The experiments carried out in 1952 and 1953 were of a uniform pattern. Superphosphate was tested at 0·3 and 0·6 cwt. total P_2O_5 per acre and three nitrophosphates were each tested at an intermediate rate (0·45 cwt. total P_2O_5 per acre). The dressings of nitrogen and potassium used with the nitrophosphates were adjusted so that all plots of each experiment received equal total quantities.

(i) *Potatoes*

The results of 18 potato experiments are given in Table 32 after averaging all centres on each crop and grouping them by soil reaction. (There were not sufficient experiments on any of the crops testing nitrophosphate to separate the centres into more than two groups of soils; for all crops the division was made at pH 6·5.) The potato crops were not sampled and analysed to determine phosphate uptakes since earlier work had shown that such analyses do not extend the information obtained from experiments on potatoes.

These data were used to derive the percentage superphosphate equivalents for nitrophosphates which are given in Table 33. All three nitrophosphates were inferior to superphosphate for potatoes and they were more effective on acid soils than on neutral soils, in both groups of soils the product made by removing calcium nitrate was inferior to the other nitrophosphates. On the average of all experiments on acid and neutral soils, nitrophosphate made by adding ammonium sulphate gave yields similar to those given by three-quarters as much phosphorus applied as superphosphate; the product made with a mixture of nitric and sulphuric acids was about two-thirds as effective as superphosphate, the product made by removing calcium nitrate was only one-third as effective.

(ii) *Grass*

Twenty experiments on grass were carried out in 1952–3 to test nitrophosphates. The results are summarized in Table 34.

Table 32. *Yields of potatoes (in tons per acre) in 1952–3 experiments testing nitrophosphates, grouping the centres by soil reaction*

	P_2O_5 applied (cwt./acre)	Acid soils	Neutral soils	All soils
No. of experiments ...	—	11	7	18
Without phosphate	0·00	9·7	10·7	10·1
Superphosphate	0·30	10·7	11·3	10·9
	0·60	11·6	12·1	11·8
Nitrophosphate made by:				
Adding $(NH_4)_2SO_4$	0·45	11·0	11·2	11·1
Mixed $HNO_3+H_2SO_4$	0·45	10·7	11·2	10·9
Removing $Ca(NO_3)_2$	0·45	10·2	11·0	10·5

Table 33. *Percentage superphosphate equivalents of nitrophosphates used for potatoes*

	No. of experiments	Nitrophosphate made by: Adding ammonium sulphate	Nitric+sulphuric acids	Removing calcium nitrate
Acid soils (to pH 6·5)	11	88	66	34
Neutral soils (pH 6·6 and over)	7	51	52	20
All soils	18	78	62	33

On the average of fourteen experiments on grass on acid soils and on the average of all twenty grassland experiments, superphosphate supplying 0·3 cwt. P_2O_5 per acre was sufficient for maximum yields. Since the superphosphate yield response curves obtained in these groups of experiments are quite flat, percentage superphosphate equivalents, derived by graphical interpolation for the nitrophosphates tested, may be misleading. On acid soils nitrophosphate made by adding ammonium sulphate was slightly superior to the other nitrophosphates tested. All three kinds of nitrophosphate gave lower average yields of grass than superphosphate supplying two-thirds as much phosphorus.

When the amounts of phosphorus in the herbage (stated in Table 34) were plotted against the amounts of P_2O_5 supplied, the recoveries from superphosphate fell on a normally shaped curve and it was possible to interpolate equivalent dressings of superphosphate for the nitrophosphates tested. Percentage superphosphate equivalents derived from the amounts of phosphorus in the crops are given in Table 35.

These data illustrate the extra information which may be gained from such experiments by analysing the crops to determine the amounts of phosphorus recovered. The yield data do not allow quantitative estimates of the efficiencies of the tested phosphates to be made, but the phosphorus contents of the grass differentiate clearly between superphosphate and nitrophosphates and also between the three nitrophosphates. On the average of all twenty experiments, nitrophosphates made by adding ammonium sulphate and by mixed nitric-sulphuric acids

Table 34. *Yields of grass and phosphorus contents of the herbage in experiments in 1952–3 testing nitrophosphates*

	P_2O_5 applied (cwt./acre)	Acid soils	Neutral soils	All soils
No. of experiments ...	—	14	6	20
		Yields of dry hay (cwt./acre)		
Without phosphate	0·00	48·0	43·2	46·6
Superphosphate	0·30	51·6	46·8	50·2
	0·60	51·5	48·0	50·4
Nitrophosphate made by:				
Adding $(NH_4)_2SO_4$	0·45	51·4	46·4	49·9
Mixed $HNO_3+H_2SO_4$	0·45	50·8	46·2	49·4
Removing $Ca(NO_3)_2$	0·45	50·4	46·1	49·1
		Phosphorus contents of the herbage (cwt. P_2O_5/acre)		
Without phosphate	0·00	0·212	0·176	0·201
Superphosphate	0·30	0·260	0·214	0·246
	0·60	0·282	0·241	0·270
Nitrophosphate made by:				
Adding $(NH_4)_2SO_4$	0·45	0·264	0·208	0·247
Mixed $HNO_3+H_2SO_4$	0·45	0·258	0·209	0·243
Removing $Ca(NO_3)_2$	0·45	0·254	0·200	0·238

Table 35. *Percentage superphosphate equivalents of three kinds of nitrophosphate derived from phosphorus contents of grass*

	No. of experiments	Nitrophosphates made by: Adding ammonium sulphate	Nitric+sulphuric acids	Removing calcium nitrate
Acid soils (pH 6·5 and below)	14	77	64	56
Neutral soils (pH 6·6 and over)	6	53	56	39
All soils	20	70	61	52

supplied only about two-thirds as much phosphorus as was supplied by superphosphate. Nitrophosphate made by removing calcium nitrate was half as effective as superphosphate.

(iii) *Swedes*

Twelve experiments were carried out on swedes in 1952–3 to test nitrophosphates. The results are summarized in Table 36, there were eleven experiments on acid soils (with pH values below 6·5) and one experiment on neutral soil; mean results for all twelve experiments are stated here. Percentage superphosphate equivalents of the three nitrophosphates derived from the data in Table 36 were:

Table 36. *Yields of swedes and amounts of phosphorus in the roots in experiments testing nitrophosphate in* 1952–3

(Mean of 12 experiments.)

	P_2O_5 supplied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
Without phosphate	0·00	12·7	0·122
Superphosphate	0·30	17·2	0·166
	0·60	19·9	0·203
Nitrophosphate made by			
Adding ammonium sulphate	0·45	18·8	0·189
Mixed nitric + sulphuric acids	0·45	18·5	0·188
Removing calcium nitrate	0·45	18·5	0·193

	From yields	From phosphorus in crops
For nitrophosphate made by:		
Adding ammonium sulphate	103	106
Mixed nitric + sulphuric acids	96	104
Removing calcium nitrate	97	114

On the basis of yields, nitrophosphates were roughly equal to superphosphate; the product made by adding ammonium sulphate being slightly superior. Nitrophosphates supplied somewhat more phosphorus to the crops than superphosphate, that made by removing calcium nitrate supplying most.

PART 5. BASIC SLAGS

In the 1941–6 field experiments Bessemer Process basic slag was widely tested both for arable crops and for grassland. For grass it served generally as the standard phosphate fertilizer; it was included in many experiments on arable crops where superphosphate was the standard, partly to serve as a second 'standard' material, and partly to determine the conditions where high-grade, high-soluble basic slags may be substituted for superphosphate.

(1) *Kinds of basic slags*

Crowther & Warren (1934) compared the agricultural values of different kinds of Open-Hearth Process basic slags with special reference to their valuation by chemical tests. They confirmed that the 2 % citric acid test distinguished between slags of high and low availabilities. A few experiments on swedes and reseeded grassland carried out in 1943–4 continued this work by comparing slags of different grades and solubilities in citric acid. The analyses of the materials tested are given in Table 37.

In two experiments on swedes Bessemer Process basic slag was taken as standard and high-, medium- and low-soluble slags were tested. In three other swede experiments superphosphate was taken as standard and Bessemer Process, medium-soluble and low-soluble basic slags were tested. In addition several experiments of each pattern were laid down on reseeded grassland. Six experiments on permanent grass compared low-soluble basic slag, silicophosphate and Gafsa mineral phosphate against Bessemer basic slag as standard. The results of all these experiments are stated fully by Crowther, Warren & Cooke (1953); they are not discussed in detail here since there were too few experiments of any one pattern to provide very reliable conclusions.

(i) *Experiments on swedes*

All five experiments were on soils with pH values below 6·5. On the average of two experiments low-grade, high-soluble slag gave yields similar to those given by Bessemer basic slag; medium-soluble slag was a little inferior; low-soluble slag gave much lower yields of crops containing less phosphorus. In the other three swede experiments, Bessemer

Table 37. *Analyses of basic slags used in* 1941–6 *field experiments*

Process	No. of samples	Fineness through 100 mesh B.S. sieve (%)	Total P_2O_5 (%)	Citric acid solubility (%)	Fluorine (%)
Bessemer	7	90	17·5	88	0·08 (4)*
Open Hearth (high-soluble)	2	89	9·8	88	0·02 (1)
Open Hearth (medium-soluble)	2	87	11·0	58	0·37 (1)
Open Hearth (low-soluble)	4	88	12·8	26	0·79 (3)

* Numbers of samples are stated in brackets.

basic slag, medium-soluble basic slag and superphosphate gave roughly similar yields and similar amounts of phosphorus in the crops, low-soluble basic slag was markedly inferior to superphosphate and to high-soluble slags.

(ii) *Experiments on reseeded grassland*

A number of experiments were laid down in 1943 and 1944 on very acid and acid soils, to compare the value of different basic slags for establishing reseeded grassland. The results are summarized in Table 38, by stating the percentage efficiencies (obtained by graphical interpolation) of the different types of basic slag in terms of standard materials, averaging all experiments in each year.

In the 1943 experiments low-grade, high-soluble basic slag gave better establishment than Bessemer slag; medium-soluble and low-soluble basic slags were inferior. In the 1944 experiments, superphosphate was used as the standard material, Bessemer slag was slightly inferior and medium-soluble slag was nearly equivalent to superphosphate. Low-soluble slag gave poorer establishment than the other phosphate fertilizers.

Table 38. *Percentage efficiencies of different kinds of basic slags used for establishing reseeded grassland*

Seven 1943 experiments	
Bessemer basic slag (standard)	100
Low-grade, high-soluble basic slag	136
Medium-grade, medium-soluble basic slag	83
Medium-grade, low-soluble basic slag	57
Four 1944 experiments	
Superphosphate (standard)	100
Bessemer basic slag	65
Medium-soluble basic slag	82
Low-soluble basic slag	52

The citric acid test is valuable in distinguishing the poorer types of basic slag, Bessemer basic slag was less efficient in the 1944 experiments than would have been expected, but the improvement in establishment given by increasing the dressing of superphosphate from 0·33 to 0·66 cwt. P_2O_5 per acre was small and comparisons made in that region of the response curve are necessarily inaccurate in such a small group of experiments. In 1943 low-grade high-soluble slag was more efficient than Bessemer basic slag: this may be due in part to the greater dressing of lime supplied by the amount of low-grade slag needed to supply a given quantity of phosphorus.

(iii) *Experiments on permanent grass*

Six experiments were laid down on permanent grass and visual estimates of growth were made. The experiments also tested silicophosphate, Gafsa mineral phosphate and low-soluble basic slag. The following relative efficiencies were derived from estimates of growth:

Bessemer basic slag (standard)	100
Silicophosphate	100
Gafsa rock phosphate	70
Low-soluble basic slag	55

Low-soluble basic slag was inferior to Gafsa mineral phosphate and much inferior to Bessemer basic slag and to silicophosphate.

(2) *Bessemer basic slag*

Apart from serving as the standard phosphate fertilizer in many of the reseeding experiments, Bessemer Process basic slag was compared with superphosphate and with other fertilizers in many of the experiments carried out from 1941–6. All experiments on each crop have been grouped together in this section to provide some general conclusions on the value of high-grade high-soluble basic slag.

Table 39. 1942 *swede experiments on Bessemer basic slag*

(Average results of 6 experiments.)

	P_2O_5 applied (cwt./acre)	Yield of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
Without phosphate	0·0	3·6	0·025
Superphosphate	0·5	14·8	0·123
	1·0	16·1	0·165
Bessemer basic slag	0·5	15·0	0·124
	1·0	16·4	0·169

Table 40. *Percentage superphosphate equivalents for Bessemer basic slag, derived from* 1943–6 *swede experiments*

	Very acid soils	Acid soils	Neutral soils	All soils
No. of experiments	5	11	7	23
Percentage superphosphate equivalents				
From yields	112	64	50	75
From P_2O_5 contents	113	72	60	79

(i) *Experiments on swedes*

Six experiments on swedes (five on acid soils) were carried out in 1942, the results are summarized in Table 39. Bessemer basic slag gave slightly higher yields of crops containing more phosphorus than superphosphate.

Twenty-three other experiments on swedes using lower rates of dressing were carried out in 1943–6. The results are summarized in Table 40 by stating percentage superphosphate equivalents obtained by graphical interpolation from the yield data.

On the average of all the experiments Bessemer basic slag was as effective as only three-quarters as much phosphorus applied as superphosphate for swedes. On very acid soils it was more effective than superphosphate but on the neutral and less acid soils it was only as effective as superphosphate supplying from one-half to two-thirds as much phosphorus.

(ii) *Experiments on potatoes*

Eleven experiments on potatoes comparing superphosphate and Bessemer basic slag were carried out from 1943 to 1946. The results are summarized in Table 41 by stating the percentage superphosphate equivalents obtained by graphical interpolation from the yield and phosphorus content data after grouping the experiments by soil reaction.

Bessemer slag gave lower yields of potatoes containing less P_2O_5 than superphosphate on all classes of soils, on the basis of yields it was two-thirds as efficient as superphosphate on very acid soils and little more than one-third as efficient on other soils.

Table 41. *Percentage superphosphate equivalents for Bessemer basic slag, from* 1943–6 *potato experiments*

	Very acid soils	Acid soils	Neutral soils	All soils
No. of experiments	4	5	2	11
From yields	66	36	38	45
From P_2O_5 contents	90	39	48	57

(iii) *Reseeding of grassland on very acid soils*

Thirteen experiments on acid soils compared silicophosphate and Bessemer basic slag with superphosphate. Basic slag gave better establishment than superphosphate in most of the experiments. Graphical interpolation from mean scores for establishment of grasses and clover gave the following percentage superphosphate equivalents:

Superphosphate	100
Silicophosphate	107
Bessemer basic slag	120

Basic phosphates have some advantage over superphosphate in establishing grass on very acid soils.

PART 6. 'TRIPLE' SUPERPHOSPHATE AND CALCIUM METAPHOSPHATE

Calcium metaphosphate from the United States and 'triple' superphosphate from Canada were tested in a few of the early field experiments in 1941 and 1942. The results are stated fully by Crowther *et al.* (1953). The analyses of the materials used are given in Table 42.

'Triple' superphosphate is made by treating rock phosphate with phosphoric acid and usually contains 40–48% P_2O_5; often the proportion of the total phosphorus soluble in water is lower than in ordinary superphosphate but the solubility in 2% citric acid or in neutral ammonium citrate solution is high. Sulphuric acid is not saved by making triple superphosphate unless the phosphoric acid needed is made by a 'dry' (high-temperature) process.

The calcium metaphosphate used in this work was manufactured by the Tennessee Valley Authority from phosphorus prepared in an electric furnace. It is a glass which is attacked by water to form calcium ortho-phosphate; since metaphosphates become water-soluble only slowly they may be 'fixed' to useless forms less rapidly than orthophosphates. A disadvantage of such highly concentrated materials is that it is difficult to distribute small dressings accurately.

Table 42. *Analyses of triple superphosphate and calcium metaphosphate*

	Total P_2O_5 (%)	Percentage solubility in: Citric acid	Water
Triple superphosphate	46·4	85	83
Calcium metaphosphate	63·7	16	—

Table 43. *Mean yields and phosphorus contents of swedes and potatoes in experiments testing 'triple' superphosphate*

	P_2O_5 applied (cwt./acre)	Yields of roots (tons/acre)	P_2O_5 in roots (cwt./acre)
Swedes (4 experiments)			
Without phosphate	0·0	2·5	0·023
Superphosphate	0·5	16·6	0·124
	1·0	19·5	0·180
'Triple' superphosphate	1·0	18·8	0·187
Potatoes (4 experiments)			
Without phosphate	0·0	7·0	0·116
Superphosphate	0·5	10·2	0·167
	1·0	10·8	0·180
'Triple' superphosphate	1·0	11·0	0·188

(1) *'Triple' superphosphate*

Experiments on swedes and potatoes grown on acid soils in Northern Ireland compared superphosphate and 'triple' superphosphate. The results are summarized in Table 43. For both crops 'triple' superphosphate gave roughly the same yields and phosphorus contents as ordinary superphosphate. 'Triple' superphosphate was slightly superior for potatoes and slightly inferior for swedes, both swedes and potatoes grown with 'triple' superphosphate contained slightly more phosphorus than crops grown with ordinary superphosphate.

(2) *Calcium metaphosphate*

Ten experiments on swedes tested calcium metaphosphate. The centres were grouped by soil reaction and the percentage superphosphate equivalents stated in Table 44 were derived from the data by graphical interpolation.

Table 44. *Percentage superphosphate equivalents of calcium metaphosphate derived from* 1941–2 *experiments on swedes*

	Very acid soils	Other soils	All soils
No. of experiments ...	6	4	10
From yields	48	70	52
From phosphorus contents	81	97	88

On the average of all experiments calcium metaphosphate was about half as efficient as superphosphate, it tended to be more efficient on soils having pH values above 5·5 than on very acid soils. On the basis of the amounts of phosphorus taken up by the crops metaphosphate was only a little less efficient than superphosphate.

Part 7

Residual values of phosphate fertilizers

(1) 1941–6 *field experiments*

It was not possible to continue the majority of the field experiments on arable crops after the initial year. At a few centres, where special facilities were available, yields were obtained of the crops grown in the second year. No further dressings of phosphate were applied but basal dressings of nitrogen and potash were given in accordance with local practice. Most of the sites of two-year experiments were in Eastern England on soils where arable rotations are traditional and where phosphate deficiency is not as acute as on many of the soils used in the West and North which had been ploughed from permanent grass. Experiments on reseeded grassland did not present such difficulties. On many sites the experimenter continued to give eye-scores for the growth of grass each year until the experiment was ended, either because the land was ploughed again, or because the farmer wished to apply a dressing of phosphate to the area.

(i) *Experiments on arable crops*

Although cereals predominated, there were other kinds of crop and it is not possible to summarize the yields of any one crop from a worth-while number of experiments. The amounts of phosphorus recovered by both first and second year crops are stated in Table 45, as percentages of the amounts of phosphorus applied, after averaging the results for all appropriate experiments which tested silicophosphate. Superphosphate, silicophosphate and Bessemer basic slag gave almost identical results in both years in seven experiments where the first-year crops were swedes or potatoes. The mean recoveries of phosphorus by the second-year crops from the three forms of phosphate fertilizers were approximately one-quarter of the mean amounts recovered by the first-year crops.

Table 45. *Percentage recoveries of added phosphorus by crops grown in experiments on silicophosphate which were continued for two years*

	First year			Second year		
	Superphosphate	Silicophosphate	Basic slag	Superphosphate	Silicophosphate	Basic slag
Mean (7 experiments)	9	9	8	2	2	2
Mean (9 experiments)	8	8	—	2	2	—
Two-year leguminous crops						
Lucerne	3	1	2	10	6	8
Sainfoin	2	2	—	9	8	—

In one experiment on lucerne and one on sainfoin there were no cultivations after the crop was sown. Cuts of hay were taken in the two years and both crops recovered much more of the added phosphorus in the second year than in the first; lucerne recovered less phosphorus from silicophosphate and basic slag than from superphosphate. Superphosphate and silicophosphate provided approximately the same amounts of phosphorus for sainfoin.

Only two of the 1941–6 experiments which were continued for a second year tested rock phosphates; at both centres the responses in the second year were very small and there were no clear differences between the uptakes of phosphorus from superphosphate and from mineral phosphate.

Five experiments testing mixtures of superphosphate with lime and with serpentine were continued for two years. The mean recoveries of phosphorus by the first- and second-year crops are given in Table 46.

The quantities of phosphorus taken up by second-year crops from all three materials were identical and were only about one-third of the amounts recovered in the first year of the experiments.

There were only small responses to phosphate in the second year of most of the experiments. Many of the soils used were not acutely deficient in phosphorus, and cereals, which were often grown in the second year, do not usually give large responses to phosphate fertilizers. In addition the dressings given in the first year were diluted with soil when the areas were ploughed and cultivated for the second crop. It is possible to argue that phosphate dressings had been fixed to useless forms by the time the second crop was sown, but it is more likely that the inevitable dilution of phosphate with soil by cultivation had reduced the efficiency of the fertilizers added, even for sensitive crops.

Although the evidence is scanty, there is nothing in these experiments to suggest that, for arable crops, there is any material difference in the residual values of superphosphate and of the other phosphate fertilizers tested.

Table 46. *Percentage recoveries of added phosphorus by crops grown in experiments on basic superphosphate mixtures which were continued for two years*

(Mean of 5 experiments.)

	Percentage recovery from		
	Superphosphate	Superphosphate + lime	Superphosphate + serpentine
First-year crops	9	7	9
Second-year crops	3	3	3

(ii) *Experiments on reseeded grassland*

Where sites were available for more than one year marks were given by eye for establishment in the first year and for growth of grass in subsequent years. These data are summarized (as percentages of the mean values for the treatments listed in each experiment) in Table 47.

In six experiments which were continued for three years, superphosphate, silicophosphate and basic slag gave similar scores for initial establishment. In the second and third years silicophosphate and basic slag tended to give progressively better growth of grass than superphosphate. In an earlier section of this paper it was shown that silicophosphate and Bessemer basic slag were approximately equivalent for establishing grassland on acid soils and that both tended to be superior to superphosphate. The superiority of the basic phosphates over superphosphate in promoting growth of grass increased in subsequent years. This may be taken to imply that the extra base retards the fixation of phosphate to inert forms or, alternatively, that the more soluble phosphate is spread more widely in the soil and in consequence, inactivated more rapidly.

A number of the reseeding experiments testing rock phosphates were continued for more than one year. A summary of some of the data obtained is given in Table 47. Four experiments were observed for three years. High-soluble basic slag produced better establishment and growth than Gafsa and Curacao rock phosphates which, in turn, were much superior to Florida rock phosphate. The relative superiority of basic slag over rock phosphate was maintained in these experiments.

Three other experiments were observed for two years. Superphosphate gave better establishment than rock phosphates and Bessemer basic slag in the first year. In the second year Bessemer slag produced best growth, Gafsa phosphate was a little inferior to superphosphate and both materials gave better growth than Morocco phosphate.

Four experiments testing different kinds of basic slag were observed over two seasons and the results are summarized in Table 47. Superphosphate was the standard fertilizer, it gave similar establishment to that given by medium-soluble basic slag and was superior to Bessemer slag and low-soluble basic slag. In the second year Bessemer slag gave slightly better growth than superphosphate and the other basic slags.

Table 47 also sets out a summary of the observations on three experiments testing mixtures of superphosphate with basic materials. Basic superphosphates gave slightly better establishment than untreated superphosphate. In the second year the mixtures of superphosphate with lime and with serpentine gave a little better growth than equivalent superphosphate.

In this work on reseeded grassland the number of centres which were observed for several years were too few to give very reliable averages. They indicate that water-soluble phosphates may have advantages for establishing grass but that, at least on acid soils, more basic phosphates may give better growth than superphosphate in later years. Ground North African rock phosphates were inferior to more soluble phosphates both for establishing grass and for promoting growth in later years; since rock phosphates are cheap they may, however, prove to be economic for improving poor grassland on acid soils.

(2) 1951–3 *experiments*

(i) *Experiments on dicalcium phosphate, silicophosphate and rock phosphate*

Six experiments on potatoes were continued for a second year and cereals were grown. Mean yields of potatoes and of the six cereal crops which followed are given in Table 48.

For first-year potatoes there were only small differences between yields given by superphosphate, dicalcium phosphate and silicophosphate; rock phosphate was inferior to the other materials. For second year cereals silicophosphate was equivalent to superphosphate and both dicalcium phosphate and rock phosphate were slightly inferior.

As the second-year crops gave such small responses to phosphate applied the year before, little importance can be attached to these data.

(ii) *Experiments on nitrophosphates*

A number of the grassland experiments testing nitrophosphates were continued for two years. For six experiments started in 1951 mean yields of hay harvested in the first and second years are given in Table 49 together with the average amounts of P_2O_5 in the herbage. Nitrophosphate made by adding ammonium sulphate gave lower yields and smaller amounts of phosphorus in the herbage than superphosphate plus equivalent nitrogen in the first year, but in the second year was approximately equivalent to superphosphate. Nitrophosphate made by removing calcium nitrate gave approximately the same first-year yields and amounts of phosphorus in the herbage as superphosphate plus equivalent nitrogen, but in the second year this material was somewhat superior to superphosphate and the other nitrophosphate.

Experiments laid down in 1952 and 1953 to test nitrophosphate were of a standard pattern. Three experiments on grassland started in each year were continued for a second year and the mean yields for all six experiments are stated in Table 50. The low rate of superph›sphate gave a higher average yield than the high rate in the first year. With such an

Table 47. *Experiments on direct reseeding of grassland on very acid soils*

(Visual scores for establishment in the first-year and for growth in subsequent years are stated (after averaging all comparable experiments) as percentages of the mean score in each group of experiments.)

Six three-year experiments on silicophosphate

	Year	Without phosphate	Superphosphate		Silico-phosphate	Basic slag
P_2O_5 applied (cwt./acre)	—	0·0	0·33	0·66	0·50	0·50
	1st	59	108	110	107	110
	2nd	74	104	108	108	108
	3rd	77	97	106	108	110

Four three-year experiments on rock phosphates

	Year	Without phosphate	High-soluble basic slag			Rock phosphates: Gafsa	Curacao	Florida
P_2O_5 applied (cwt./acre)	—	0·0	0·5	1·0	1·5	1·0	1·0	1·0
	1st	21	114	134	144	102	109	82
	2nd	17	102	152	186	98	110	62
	3rd	40	113	132	138	97	108	83

Three two-year experiments on rock phosphates

	Year	Without phosphate	Superphosphate		Bessemer slag	Morocco	Gafsa
P_2O_5 applied (cwt./acre)	—	0·0	0·33	0·66	0·50	0·50	0·50
	1st	47	116	116	104	104	110
	2nd	69	104	112	116	97	103

Four two-year experiments on kinds of basic slag

	Year	Without phosphate	Superphosphate		Bessemer slag	Medium-soluble slag	Low-soluble slag
P_2O_5 applied (cwt./acre)	—	0·0	0·33	0·66	0·50	0·50	0·50
	1st	50	109	116	108	113	104
	2nd	75	101	106	112	102	104

Three two-year experiments on basic superphosphate mixtures

	Year	Without phosphate	Superphosphate		Mixtures of superphosphate with: Basic slag	Lime	Ser-pentine
P_2O_5 applied (cwt./acre)	—	0·0	0·33	0·66	0·50	0·50	0·50
	1st	42	96	121	116	112	114
	2nd	68	99	110	105	109	109

irregularly shaped response curve it is impossible to value the nitrophosphates tested quantitatively in terms of superphosphate but that made by removing calcium nitrate gave a lower mean yield than no phosphate at all, while nitrophosphates made with mixed nitric-sulphuric acids and by adding ammonium sulphate increased the yields. The amounts of phosphorus recovered by the grass gave a regularly shaped response curve and it is possible to compare the tested phosphates on this basis. All three nitrophosphates were inferior to superphosphate supplying two-thirds as much phosphorus. Nitrophosphate made by removing surplus calcium nitrate provided less phosphorus for the grass than the other two materials. Second-year cuttings from these experiments gave different results. The phosphates applied the year before had negligible effects on yields but increased the amounts of phosphorus in the herbage regularly; nitrophosphate made by removing calcium nitrate supplied a little more phosphorus than the other two nitrophosphates and was as effective as superphosphate.

Table 48. *Yields of first-year potatoes and second-year cereals in 1951–3 experiments which were continued for two years*

(Averages of 6 experiments.)

	P_2O_5 applied in first year (cwt./acre)	First-year potatoes (tons/acre)	Second-year cereals (cwt./acre)
Without phosphate	0·00	10·7	18·2
Superphosphate	0·33	12·3	19·0
	0·66	12·5	19·2
Dicalcium phosphate	0·50	12·4	18·7
Silicophosphate	0·50	12·3	19·1
Rock phosphate	0·50	11·5	18·7

Table 49. *Mean yields and phosphorus contents of hay from six grass experiments started in* 1951 *and continued in* 1952 *to test nitrophosphates*

	Nitrogen only	Superphosphate + nitrogen	Nitrophosphate made by: Adding ammonium sulphate	Nitrophosphate made by: Removing calcium nitrate
P_2O_5 applied in first year (cwt./acre)	0·0	0·4	0·4	0·4
Mean yields of dry hay (cwt./acre)				
First year	23·8	28·3	26·3	28·3
Second year	32·1	35·3	35·6	36·7
Phosphorus in crops (cwt. P_2O_5/acre)				
First year	0·096	0·140	0·120	0·138
Second year	0·110	0·134	0·131	0·148

Variations in the behaviour of nitrophosphates in these experiments is puzzling. In the experiments started in 1951 that made by removing calcium nitrate was as good as superphosphate in the first year and was superior to superphosphate in later years. Fresh batches of this nitrophosphate were obtained from the manufacturer for the experiments carried out in both 1952 and 1953; they were relatively inactive. In contrast the 1951 batch of nitrophosphate made by adding ammonium sulphate was less active than batches prepared for use in 1952 and 1953. Similar variations between different batches of nitrophosphate made by the same process were observed in the annual experiments described earlier in this paper.

DISCUSSION

(i) *Rock phosphates*

In swede experiments carried out in 1941–2 Gafsa phosphate was roughly three-quarters as efficient as superphosphate on very acid soils but in a few later experiments it was rather less effective. Curacao phosphate and Gafsa phosphate behaved similarly for swedes and for reseeded grass in 1941–2. Florida rock phosphate was tested for both crops in 1941 and was of so little value that it was not used in later years. Very few swede experiments tested both Gafsa and Morocco phosphates but in

Table 50. *Mean yields and phosphorus contents of hay from six experiments on grass started in* 1952 *and* 1953 *and continued for a second year*

	Without phosphate	With superphosphate	With superphosphate	With nitrophosphate made by: Adding ammonium sulphate	With nitrophosphate made by: Mixed nitric + sulphuric acids	With nitrophosphate made by: Removing calcium nitrate
P_2O_5 applied in first year (cwt./acre)	0·00	0·30	0·60	0·45	0·45	0·45
Yields of dry hay (cwt./acre)						
First year	52·1	55·6	53·5	53·7	53·6	51·4
Second year	42·6	42·5	43·7	43·5	42·1	42·6
Amounts of phosphorus in the hay (cwt. P_2O_5/acre)						
First year	0·248	0·294	0·311	0·286	0·287	0·270
Second year	0·190	0·200	0·216	0·205	0·202	0·208

parallel experiments the two materials behaved similarly. Morocco phosphate was slightly inferior to Gafsa phosphate for establishing grass.

In recent field experiments carried out from 1951 to 1953 Gafsa phosphate was nearly as effective as superphosphate for swedes grown on soils having pH values below 6·5. Swedes are now mainly restricted to the north and west of the United Kingdom where most of the soils are acid and the rainfall is often high, in these areas swedes could receive Gafsa rock phosphate instead of superphosphate. Ground rock phosphate is generally much cheaper (per unit of P_2O_5) than superphosphate. Comparisons of rock phosphate and superphosphate for other fodder crops and for grass are needed to determine how far this cheap material can be used to replace more expensive fertilizers.

Ground rock phosphate was useless for potatoes grown on neutral soils; even on acid soils Gafsa phosphate produced yields equivalent to those given by only one-third as much phosphorus applied as superphosphate.

Mixtures of superphosphate with rock phosphate were tested from 1943–6 and gave disappointing results. The 'Semsol'-type mixture, made with cold superphosphate, was satisfactory for swedes grown on very acid soils; for potatoes it was only half as efficient as superphosphate and the mineral phosphate component of the mixture appeared to have little value. A mixture of rock phosphate with hot superphosphate was compared with Morocco phosphate (from which it was made) in a few swede experiments; the mixture was less effective than rock phosphate alone, suggesting that secondary reactions gave products which were less soluble than the untreated apatite. Cold mixtures of superphosphate and mineral phosphate have no special advantage, for crops where they are useful, rock phosphate alone is almost as good, for other crops and on neutral soils the mineral phosphate cannot be regarded as more than a diluent. The hot ('Kotka' type) mixture is an example of an under-acidulated superphosphate; if sulphuric acid supplies are restricted it is more satisfactory to use the quantities available to make reduced amounts of normal superphosphate. The deficiency in supplies of superphosphate must be covered by reducing rates of dressing and by using rock phosphate directly on the soils and crops for which it is suitable.

For grassland sown in wet areas on acid soils rock phosphate may form the bulk of the phosphate manuring provided that a little readily soluble phosphate is applied to the seedbed (or drilled with the seed) to secure satisfactory establishment. Rock phosphates were somewhat inferior to high-soluble basic slag for permanent grass but, if necessary, they could form the bulk of the phosphate applied in areas where soils are acid so that more quickly acting phosphate fertilizers could be reserved for arable crops.

A few of the war-time experiments suggested that it may not be necessary to grind rock phosphates intended for direct application very finely. Coarser grinding would allow greater output from the mills and should cheapen the cost of the phosphate.

(ii) *Silicophosphate*

Field experiments on swedes showed that the silicophosphates tested were superior to equivalent superphosphate in 1942 but not on the average of the experiments carried out in 1943–6 and 1951–3. No clear explanation of this discrepancy can be given. It is likely that the peculiar results of 1942 depended on the predominance in that year of sites on land recently ploughed from acid permanent grassland in the wetter areas. On such soils superphosphate might be expected to diffuse more quickly in the soil and thus give a better start to the young seedlings. On the other hand, on very acid soils, superphosphate may be converted more quickly to inactive forms. By contrast, basic materials liberated in the hydrolysis of silicophosphates and basic slags may retard the reaction of phosphate ions with soil colloids and allow, for a time at least, the formation of unstable basic calcium phosphates available to the plants. Silicophosphate is likely to give similar results to superphosphate for swedes on acid soils but may be somewhat inferior on neutral soils. For potatoes there was little difference between silicophosphate and superphosphate at equivalent rates on very acid soils, but on slightly acid and neutral soils silicophosphate was generally less effective than an equivalent amount of superphosphate. For both permanent and reseeded grassland on acid soils silicophosphate and Bessemer basic slag gave similar results. There were too few experiments on cereals and other arable crops for reliable conclusions to be drawn. The general indications were that superphosphate will give the better results on neutral soils and for crops needing readily soluble phosphate in their earliest stages.

These conclusions, derived mainly from the war-time series of experiments, were fully confirmed by the 1951–3 series. Silicophosphate may be regarded as behaving like a very high-grade, high-soluble basic slag. There is no agricultural justification for producing silicophosphate unless it can be sold more cheaply than superphosphate, since it is only as effective as roughly two-thirds as much phosphorus supplied as superphosphate, on the average of the various crops and soils tested in this work.

(iii) *Dicalcium phosphate and basic superphosphate*

There were not sufficient experiments on 'pure' dicalcium phosphate preparations in the

1943–6 series to allow reliable conclusions to be drawn.

Commercial preparations of dicalcium phosphate were tested extensively in the 1951–3 field experiments. For swedes they were practically as efficient as superphosphate on both acid and neutral soils. For potatoes they were more efficient than superphosphate on very acid soils (having pH values below 5·5) and somewhat less efficient on acid soils (pH values from 5·5 to 6·5) and also on neutral soils. Powdered fertilizers containing dicalcium phosphate dihydrate will be used to best advantage if they are restricted to acid soils.

When superphosphate is mixed with basic materials the products contain dicalcium phosphate. Mixtures of superphosphate with lime have been sold in this country, they should contain mainly dicalcium phosphate unless further reactions produce phosphates with apatite structures. When serpentine (a magnesium silicate) is mixed with superphosphate, dimagnesium and dicalcium phosphates may be formed. To be judged as successful any superphosphate mixture must be consistently more efficient than superphosphate to justify its cost of preparation. On the average of experiments on swedes carried out from 1943 to 1946 none of the products tested was quite as successful as superphosphate; the mixture with lime was nearly as good as superphosphate and was better than the mixtures with basic slag or serpentine. For potatoes superphosphate-serpentine mixture was roughly equal to superphosphate, the mixture with lime was inferior. In a few experiments on reseeded grassland, basic superphosphate mixtures gave rather better establishment than untreated superphosphate. The experiments were too few for reliable conclusions but they suggest that the superiority of super-serpentine mixtures over superphosphate for established grassland, claimed by New Zealand workers, may have a parallel under some British conditions.

The best that may be said for basic superphosphates applied to arable crops is that in some experiments they were not inferior to superphosphate. Many of the experiments were in the eastern counties on neutral or slightly acid soils which are not likely to convert phosphates to inert forms very rapidly. Possibly on very acid soils, rich in iron, dicalcium phosphate preparations may prove superior to superphosphate but such results have not been found in this work. Where the use of water-insoluble phosphate is justified it would be more economic to use basic slag, silicophosphate or mineral phosphate than to convert monocalcium phosphate in superphosphate to dicalcium phosphate. The trifling superiority of the superphosphate-serpentine mixture over untreated superphosphate for reseeded grass on acid hill-land is not sufficient reason for recommending its preparation in this country.

Some of the mixtures of superphosphate with basic materials had low solubilities in 2% citric acid. This may be due to the formation of apatite-like materials; if such reactions occur the mixtures will be less effective than superphosphate. Similar problems arise in the ammoniation of superphosphate for excessive quantities of ammonia lead to products with lowered citric acid solubilities. Ammoniated superphosphates normally contain a considerable proportion of water-soluble ammonium phosphate and in the presence of this active material it is difficult to assess the value of the relatively insoluble products also present. The basic superphosphates prepared in the present investigation had a semi-granular structure. They 'handled' better than superphosphate and did not cake in storage or rot the bags. These advantages are considerable but they would not repay the cost of 'reverting' the superphosphate or compensate for any loss in efficiency.

(iv) *Nitrophosphates*

In general the nitrophosphates tested were inferior to superphosphate, particularly on less acid and neutral soils. Variable results obtained in the different years of these experiments for the same kinds of nitrophosphates suggest that the manufacturing processes used need further investigation, so that stabilized products with consistent performances can be marketed. A tentative conclusion from these experiments is that phosphorus in the better nitrophosphates was, on average, about three-quarters as efficient as water-soluble phosphorus and that it behaves in much the same way as phosphorus in high-soluble basic slag. Although products containing dicalcium phosphate may give better results than superphosphate on very acid soils, such soils should be limed in the interests of full production. As the liming programme in the U.K. becomes more effective, the value of less-soluble forms of phosphate may be reduced. It is not in the interests of farmers, nor is it practicable, to suggest that soils should be under-limed merely to allow the crops to use certain kinds of phosphate fertilizers.

Further work in field and laboratory is needed before newer types of phosphates may be valued by laboratory tests. Of the nitrophosphates tested only recent batches of that made by adding ammonium sulphate contained an appreciable amount of water-soluble phosphorus (about 30% of the total phosphorus present). The products made by using mixed nitric and sulphuric acids and by removing surplus calcium nitrate had high solubilities (over 95%) in 2% citric acid. The batches of material made by adding ammonium sulphate were, on average, less soluble in citric acid; the superior performance of this nitrophosphate may be due, in part, to the relatively high proportion of water-soluble phosphorus.

Phosphate fertilizers with similar solubilities in conventional extracting solutions have behaved very differently in these experiments. The 2 % citric acid test was quite useless for differentiating between active and inactive batches of nitrophosphate made by the same process. The individual batches of nitrophosphate made by removing surplus calcium nitrate were all practically completely soluble in 2 % citric acid; the batch used in 1951 was nearly as efficient as superphosphate for potatoes and grass, that tested in 1952 was of very little value for these crops. Cooke (1954) has suggested that these variations in behaviour of the different batches may be associated with the rates at which the granules break down when moistened. It is possible that inactive batches of nitrophosphate had granules with hardened surfaces. When granular fertilizers are analysed, they are ground finely to secure representative small samples. The analytical data properly refer only to such finely powdered materials since grinding destroys physical properties of the granules which may be agriculturally important.

Work in progress indicates that chemical tests used in other countries to evaluate granulated phosphate fertilizers are not a certain guide to the agricultural value of the materials offered. Manufacturers may be misled in developing new processes by using solubility tests as the sole criterion for control. Other factors such as the physical condition of granulated fertilizers containing insoluble phosphates and the natures of the other salts present may also be important. It is suggested that the development of newer types of phosphates which contain little or no water-soluble phosphate can only be guided by agricultural tests both in glass-houses and in fields.

The field experiments described here emphasize the merits of water-soluble phosphate on most, if not all, classes of land. Although other tests are needed for special classes of phosphate fertilizer, formal simplicity should not be secured at the cost of sacrificing the water-solubility test for superphosphate, ammonium phosphate and mixtures based on them. Newer methods of manufacturing fertilizers are likely to be introduced in the United Kingdom in order to cheapen costs of production and to obtain high-analysis materials with suitable ratios of plant nutrients. Anhydrous ammonia is usually the cheapest form of fixed nitrogen in a large fertilizer works and it may become convenient to ammoniate superphosphate or to make nitrophosphates here. The valuation of granular fertilizers containing dicalcium phosphate may become an increasingly urgent problem as fertilizer consumption increases.

Recently accounts have been published of the results of field experiments carried out in the United States to test nitrophosphates made by several processes. Rogers (1951) summarized the results of experiments in 1948 and 1949 on nitrophosphates made with mixed phosphoric plus nitric acids and with mixed sulphuric plus nitric acids. For maize, cotton and cereals, phosphorus in nitrophosphates was as effective as phosphorus in triple superphosphate or commercial ammoniated mixtures. In most tests, crops were not increased in yield by raising the water-solubility above 10 % (of the total phosphorus). In a few tests with maize on alkaline soils in Iowa and Nebraska a higher degree of water solubility appeared to be important.

Thorne *et al.* (1955) have reported the results of more recent American work on four kinds of nitrophosphates. Most of the products tested passed the 12-mesh U.S. screen and were retained on the 50-mesh U.S. screen. They were compared with triple superphosphate and with commercial ammoniated mixtures. For maize nitrophosphates were as effective as ammoniated-superphosphate mixtures but were inferior to triple superphosphate. For cotton nitrophosphates were superior to triple superphosphate. For vegetables and cereals nitrophosphates compared favourably with equivalent commercial (ammoniated) mixtures. Residual effects were measured on a few soils; they were similar to the residual effects of triple superphosphate. The effect of particle size was investigated, materials which were retained on the 50-mesh sieve but passed the 12-mesh sieve being compared with materials which passed the 40-mesh sieve. Similar yields were obtained from both kinds of nitrophosphate. Thorne *et al.* also investigated the importance of water-solubility. For all crops and fertilizers there was no definite relationship between the water solubility of the phosphorus and relative increases in crop yields. They state that water solubility is most important with crops having restricted root systems and where it is difficult to take up phosphorus fast enough for the needs of the growing crops. Maize growing rapidly, or vegetable crops with limited root range or short growing seasons, often require water-soluble phosphorus. Variations in water solubility did not account fully for observed differences between the materials tested. In some materials anhydrous dicalcium phosphate was a major phase, in others 'apatite-like material' occurred. Thorne and his colleagues conclude that the phosphorus compounds need further investigation: 'any final solution of the problem of quality of phosphate in fertilizers must come from a more complete characterization of the compounds of phosphorus involved as well as from crop response'.

The nitrophosphates used in the United States investigations were generally of powdery character, 'granular' products tested were finer than the granular products commonly made in Europe.

(v) *Basic slags*

A very few experiments on basic slags confirmed the value of the 2 % citric acid test for distinguishing slags of low agricultural value, both for arable crops and for grassland. It is doubtful whether slags with low contents of citric-soluble phosphorus should be described as basic slags. They might more properly be sold as liming materials containing some phosphorus. As most of the experiments were on acid soils, discussion of the value of different basic slags is complicated by the higher liming value of the lower grade materials.

(vi) *Calcium metaphosphate*

Calcium metaphosphate was about half as efficient as superphosphate on the basis of crop yields but gave about the same amounts of phosphorus in the crops as superphosphate. Presumably metaphosphate hydrolyses slowly and extra phosphorus is taken up late in the season when the crop cannot produce a corresponding increase in yield of dry matter. As a rapid start is essential for all crops grown on very phosphate-deficient soils calcium metaphosphate is unlikely to be a successful fertilizer for short-lived arable crops; for established grassland a supply of phosphorus is needed over a long period and the material might be more successful.

(vii) *Residual effects of phosphate fertilizers*

Very few of the arable experiments were continued for more than one year. Where harvest data were obtained in the second year responses were generally small, partly through the normal agricultural practice of following phosphate-sensitive crops by cereals or other crops which give only small responses to phosphate fertilizers. There were no clear indications of differences in the residual values of the different phosphates tested. Many of the experiments on reseeded grassland were observed for several years and marks were assigned for growth of grass. There was a general tendency for the magnitude of the visible effects of phosphate dressings to diminish in later years and for contrasted phosphate fertilizers to give similar amounts of growth. Incomplete as they are, the assessments of residual values in these experiments show that it is generally unjustifiable to claim that prolonged action compensates for the low immediate value of some of the less-soluble forms of fertilizer. Residual effects are generally small and phosphate fertilizers should be used at the time and in the way believed to provide the best immediate effects. Progress is likely to be obtained more quickly from methods for improving the immediate efficiency of phosphate fertilizers than from forms intended to act slowly.

The efficient use of phosphate fertilizers

The outstanding conclusion from these experiments is that it is difficult to produce a phosphate fertilizer which is as good as superphosphate for potatoes and grass grown on all kinds of soils and that none of the materials tested have given as consistently good crops as the same amount of water-soluble phosphate. Improvements in efficiency of phosphate fertilizers are more likely to result from a general reduction in rates of dressing on richer soils and from controlled placement of small quantities near the seed than from the introduction of new forms of phosphate. Water-soluble phosphates are particularly effective on neutral soils, the phosphate may diffuse into the soil a short distance from each particle of fertilizer and build up small pockets of phosphate-rich soil, especially on the surface of structural units. These 'pockets' and surfaces provide an extended area from which the roots may feed. Some less-soluble phosphates may be able to diffuse and form such pockets in acid soils but not in neutral soils. The experiments demonstrate the types of phosphate fertilizer which may be used for different crops. Superphosphate is the most generally satisfactory fertilizer for all purposes, except perhaps for reseeding grassland on very acid soils where the more basic materials have some advantage. Swedes and allied crops on very acid soils make full use of phosphates soluble in 2 % citric acid and also of certain rock phosphates. There is at present no satisfactory chemical test for assessing the value of different kinds of mineral phosphate; it is more useful for farmers and their advisers to know the type of mineral phosphate as shown by the place of origin than to have analytical data.

The series of field experiments summarized here bring out the serious difficulties involved in obtaining reasonably accurate estimates of the relative values of alternative fertilizers, even with a few dozen experiments of modern design. Comparisons between fertilizers have generally to be made on parts of the response curves where they are already flattening out. The alternative materials do not necessarily act at the same rate, and it is therefore possible for them to give differently shaped response curves. The comparative results may vary considerably with the kind of crop, the rate and method of applying the fertilizer, the soil conditions and the weather. In investigations of this kind it is most desirable to have an adequate number of experiments on many kinds of soil in each of several seasons.

SUMMARY

The results of over 400 field experiments testing different kinds of phosphate fertilizers are summarized and are discussed with special reference to the reactions of the soils used. The classifications were: 'very acid' soils—pH below 5·5, 'acid soils'—pH 5·6 to 6·5, neutral soils—pH over 6·5. All comparisons are made in terms of fertilizers supplying the same amounts of total phosphorus.

In war-time experiments Gafsa and Morocco rock phosphates were about two-thirds as efficient as superphosphate for swedes and turnips grown on very acid soils. In 1951–3 experiments on very acid and acid soils Gafsa phosphate was practically equivalent to superphosphate for swedes, but for potatoes it was as effective as only one-third as much phosphorus supplied as superphosphate; on neutral soils Gafsa phosphate was useless. For establishing grassland on acid soils Gafsa and Morocco phosphate were equivalent to about one-third as much phosphorus supplied as high-soluble basic slag. Rock phosphates were somewhat more effective for promoting growth of established grassland but they remained inferior to high-soluble basic slags and to superphosphate. Curacao rock phosphate was roughly equivalent to Gafsa phosphate for swedes and grass. Florida pebble phosphate was much less effective and was judged unsuitable for direct application. Mixtures of rock phosphate with superphosphate were not more efficient than equivalent amounts of the separate components used correctly.

Silicophosphate was practically as effective as superphosphate for swedes grown on very acid and acid soils; it was less efficient on neutral soils. For potatoes silicophosphate was nearly as effective as superphosphate on very acid soils; it was much less efficient on acid and neutral soils. Silicophosphate was roughly equivalent to high-soluble basic slag for grassland.

Mixtures of superphosphate with lime, serpentine, and low-grade basic slag were prepared, most of the water-soluble phosphorus being converted to insoluble forms. In experiments on swedes and potatoes these basic superphosphates were not superior to untreated superphosphate. For establishing grassland on very acid soils, the mixtures were slightly superior to ordinary superphosphate.

Dicalcium phosphate was practically equivalent to superphosphate for swedes on all groups of soils. For potatoes dicalcium phosphate was more efficient than superphosphate on very acid soils, on less acid and neutral soils it was inferior to superphosphate.

Nitrophosphates made by three different processes involving treatment of rock phosphate with nitric acid were tested in the field experiments. A product made by adding ammonium sulphate to the reaction mixture was most successful, perhaps because it contained an appreciable proportion of water-soluble phosphorus. Another product, made by using a mixture of nitric and sulphuric acids, was somewhat less effective; a third nitrophosphate, made by removing surplus calcium nitrate, was least successful. All the nitrophosphates were less efficient than superphosphate for potatoes and for grassland; they were more effective on acid than on neutral soils. For swedes grown on acid soils all three nitrophosphates were equivalent to superphosphate.

A few experiments on swedes and grass grown on acid soils confirmed the use of the 2% citric acid test for distinguishing between basic slags of differing agricultural values. Bessemer Process basic slag was compared with superphosphate in many experiments. On the average of all swede experiments Bessemer basic slag was as effective as only three-quarters as much phosphorus applied as superphosphate, for potatoes it was half as efficient as superphosphate. For both crops Bessemer slag was most effective on very acid soils and less useful on acid and neutral soils.

In a few experiments on potatoes and swedes triple superphosphate was roughly equivalent to ordinary superphosphate. Calcium metaphosphate was less effective than superphosphate for swedes.

Some experiments were continued to compare the residual effects of the tested phosphates. There was no evidence to suggest that superphosphate, silicophosphate, Bessemer basic slag and basic superphosphate mixtures differed in residual values for arable crops. Experiments on reseeded grassland indicated that highly soluble phosphates have advantages for establishing the grass but that the less-soluble phosphates became more effective in later years. Slowly acting nitrophosphates were relatively more effective in the second year than in the first year of experiments on grass.

Conventional solubility tests distinguish between processed phosphate fertilizers in powder form but they may not be satisfactory for valuing granulated fertilizers containing phosphates insoluble in water.

None of the materials tested were as consistently satisfactory for potatoes and grass as equivalent amounts of superphosphate. Water-soluble phosphates are particularly effective on neutral soils. Swedes and allied crops grown on acid soils make full use of citric-soluble phosphates and also of certain rock phosphates.

The war-time experiments were sponsored by the Fertiliser Control of the Ministry of Supply, the later work was carried out under the auspices of the Fertiliser Conference of the Agricultural Research Council. The investigation was made possible by the enthusiastic co-operation of local workers, most of whom are listed at the beginning of this paper, together with members of the staffs of the Chemistry and Statistics Departments of Rothamsted Experimental Station. Acknowledgement is made to the Ministry of Supply, the Agricultural Research Council, to all who have taken part in the work, and to the firms which supplied some of the special fertilizers tested. Both phases of the investigation were carried out under the general supervision and guidance of the late Dr. E. M. Crowther.

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