Cooke, G. W. and Widdowson, F. V. 1959. Field experiments on phosphate fertilizers. A joint investigation. *The Journal of Agricultural Science.* 53 (1), pp. 46-63.

FIELD EXPERIMENTS ON PHOSPHATE FERTILIZERS A JOINT INVESTIGATION

CO-ORDINATED BY G. W. COOKE AND F. V. WIDDOWSON

Chemistry Department, Rothamsted Experimental Station, Harpenden, Herts

This investigation involved over ninety field experiments and was carried out jointly by the Soil Chemists of the National Agricultural Advisory Service, the Northern Ireland Ministry of Agriculture, the East of Scotland College of Agriculture and the Macaulay Institute for Soil Research. The following workers were responsible for the field experiments: A. Blenkinsop, J. W. Blood, C. S. Harper, J. O. Jones, J. S. V. McAllister, M. N. Nicholson, J. B. E. Patterson, N. H. Pizer, J. W. S. Reith, E. Roberts, T. H. Rose, A. M. Smith, J. E. Watkin, J. Webber and R. Williams. The work was planned and co-ordinated in the Chemistry Department of Rothamsted Experimental Station, which also supplied the special fertilizers used. The results of the individual field experiments were analysed in the Statistics Department at Rothamsted by J. H. A. Dunwoody.

Experiments comparing different kinds of phosphate fertilizers which economized in sulphuric acid were initiated by the Agricultural Research Council's Conference on Fertilisers in 1951. The results of the first three years' work have been described by Cooke (1956). In 1954 the experiments were replanned to continue and extend those aspects of the work which appeared most important. In the 1951–53 field experiments nitrophosphates made by three different processes were tested, a product made by the process described by d'Leny (1953) (involving the addition of ammonium sulphate during manufacture) proved superior to products made on the continent by removing calcium nitrate or by the use of mixed nitric and sulphuric acids. Tests on nitrophosphate made (in England) by d'Leny's process were continued, but the nitrophosphates made in other countries were not tested in the experiments described here. Ammoniation of superphosphate was carried out on pilot-plant scale by Angus (1953), who described the results of agricultural tests on the materials made. This method allows ammonia, which is a cheap source of nitrogen, to be introduced into compound fertilizers. Other advantages of ammoniation are that it leads to more concentrated compound fertilizers, improves their physical characteristics, eliminates acidity and so prevents rotting of bags, and allows nitrates to be incorporated in granular compound fertilizers. Since industrial developments in this country may lead to the production of surplus ammonia which could be used to ammoniate superphosphate, examples of the kinds of fertilizers which might be produced were tested in these experiments. As both nitrophosphates and ammoniated superphosphate contain dicalcium phosphate, pure dicalcium phosphate dihydrate was tested in all the experiments as a second standard material. Ground rock phosphates gave good results for certain crops on acid soils in earlier field experiments; tests on Gafsa rock phosphate were continued in the 1954–57 experiments to define more closely the crops and soils for which this fertilizer (which is much cheaper than processed phosphate fertilizers) may be used. In addition, comparisons were made of ordinary rock phosphate, such as is used for direct application, with batches of the same phosphate which had been ground much more finely than is customary. (Claims have been made in other countries that rock phosphates ground so that practically all passes the 300-mesh sieve are much more effective than coarser materials.)

The full results of the experiments summarized here are given (Cooke & Widdowson, 1958) in a *Report Presented to the National Agricultural Advisory Service's Conference of Soil Chemists*. More detailed examination of the results of individual experiments may be made from the *Report*, a limited number of copies of which are available for distribution.

DESCRIPTIONS OF THE FIELD EXPERIMENTS

(i) *Experimental sites and crops*

Two types of field experiments were carried out in 1954–57. In both types three materials were tested at an intermediate rate of dressing (0·45 cwt. P_2O_5/acre) and were compared with ordinary superphosphate applied at single and double rates (0·3 and 0·6 cwt. P_2O_5/acre). The first group of experiments tested materials which were suitable for use on arable crops: dicalcium phosphate, nitrophosphate and an ammoniated compound fertilizer. Potatoes, swedes, or barley were grown in most of the experiments which were carried out at centres in all parts of the country. Experiments of a second type tested dicalcium phosphate and coarsely and finely ground rock phosphate; the crops were generally grass, swedes, or kale, most of the centres were on acid soils in the wetter parts of the country where rock phosphates are likely to be active fertilizers. For both types of experiments the sites were 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.

(ii) *Form of the experiments*

The treatments used in the two types of experiments were:

Type I experiments

(1) Without phosphate.
(2) 0·3 cwt. P_2O_5/acre as superphosphate.
(3) 0·6 cwt. P_2O_5/acre as superphosphate.
(4) 0·45 cwt. P_2O_5/acre as dicalcium phosphate dihydrate.
(5) 0·45 cwt. P_2O_5/acre as nitrophosphate.
(6) 0·45 cwt. P_2O_5/acre as ammoniated fertilizer.

Type II experiments

(1) Without phosphate.
(2) 0·3 cwt. P_2O_5/acre as superphosphate.
(3) 0·6 cwt. P_2O_5/acre as superphosphate.
(4) 0·45 cwt. P_2O_5/acre as dicalcium phosphate dihydrate.
(5) 0·45 cwt. P_2O_5/acre as 'coarse' Gafsa rock phosphate.
(6) 0·45 cwt. P_2O_5/acre as 'fine' Gafsa rock phosphate.

In both types of experiments the six treatments were arranged in a Latin Square design. Individual plots within the experiments were 0·0167–0·010 acre in size; the larger size being generally used in experiments on arable crops and the smaller size in experiments on grassland.

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

Nearly all of the potato experiments were planted in the furrows of ridged land. The phosphate fertilizers tested were generally spread along the bottoms of the furrows, the basal nitrogen and potassium fertilizers being spread over the whole surface of the ridges to prevent any risk of damage to sprouting through an excessive amount of soluble salts being in contact with the seed after planting. After applying fertilizers, seed was planted in the furrows and the ridges were split back to cover seed and fertilizer, phosphate fertilizers were therefore concentrated near to the seed. A few of the experiments on potatoes were planted by machines working from flat land and at these centres the fertilizers were broadcast on the flat before planting (this procedure mixes fertilizer with much of the soil in the ridge).

In most of the swede experiments the fertilizers were broadcast on the flat, ridges were then drawn (this process concentrates the fertilizers under the centre of the ridge) and the swedes were sown on the ridges. In a few swede experiments fertilizers were placed in the furrows of ridged land and the ridges were then split to form the final ridges on which the seed was sown; this method also concentrates fertilizers under the seed. In a few other experiments swede seed was sown on flat land after fertilizers had been broadcast and harrowed in.

In the kale experiments seed was generally sown on ridges, the fertilizers being broadcast before the ridges were set up. For barley the fertilizers were broadcast and harrowed into the seedbed before sowing. In the grass experiments fertilizers were broadcast before growth started in spring.

Basal dressings of nitrogen and potassium fertilizers were applied to all plots at rates which were suited to the crop and the locality. In the Type I experiments the amounts of basal fertilizers were adjusted to allow for the nutrients other than phosphate which were supplied by the nitrophosphate and the ammoniated fertilizers tested. All plots of each experiment received the same total quantity of nitrogen and potassium.

After sowing the experimental areas were treated in the same way as the rest of the fields but no further dressings of fertilizers were applied. At harvest yields of each plot were recorded. From most of the experiments on all crops except potatoes samples were taken for determination of the percentages of dry matter and of phosphorus in the crops. The grass experiments were cut at hay or silage stages, generally about three months after the fertilizers were applied. Other crops were harvested at a normal stage of maturity.

(iv) *Fertilizers tested*

Ordinary powdered superphosphate was used as the standard in all the experiments, separate batches were obtained by experimenters for each local group of centres in each year, and analyses of the actual materials used are not stated here. Analyses of the other phosphate fertilizers tested are given in Table 1.

Chemically pure dicalcium phosphate dihydrate was used in all the experiments; the three batches used were very similar. The nitrophosphate used was made in 1953 on pilot-plant scale by the process described by d'Leny (1953); batches were drawn from a large stock for each year's work. The ammoniated fertilizer tested in 1954 was a lightly ammoniated powdered superphosphate (containing about 2 % N). In 1955 and 1956 a granulated NPK compound fertilizer was tested which was

Table 1. *Analyses of phosphate fertilizers used in the field experiments*

Year	Rothamsted numbers	N (%) Total	N (%) As NH_3	N (%) As NO_3	P_2O_5 (%) Total	P_2O_5 (%) Citric sol.	P_2O_5 (%) H_2O sol.	K_2O (%)	Fineness (% passing B.S. sieve) 100 mesh	Fineness (% passing B.S. sieve) 300 mesh
				Dicalcium phosphate dihydrate						
1954	P 639	—	—	—	41·4	41·3	0·3	—	—	—
1955	P 643	—	—	—	41·0	41·0	0·3	—	—	—
1956	P 647	—	—	—	42·4	42·2	0·3	—	—	—
				Nitrophosphate						
1954	NP 22	14·3	8·6	5·7	14·0	12·4	4·7	—	—	—
1955	NP 24	14·1	8·5	5·6	13·7	12·2	4·5	—	—	—
1956	NP 25	14·1	8·5	5·6	13·6	12·4	4·7	—	—	—
				Ammoniated fertilizer						
1954	NP 23	2·1	2·1	—	17·4	16·6	12·3	—	—	—
1955	NPK 49	11·4	11·4	—	11·0	10·7	6·1	14·7	—	—
1956	NPK 50	11·4	11·4	—	10·9	10·8	6·1	15·0	—	—
				Coarse Gafsa phosphate						
1954	P 640	—	—	—	29·1	10·6	—	—	58	2
1955	P 644	—	—	—	29·5	10·3	—	—	43	4
1956	P 648	—	—	—	28·6	11·6	—	—	88	16
				Fine Gafsa phosphate						
1954	P 641	—	—	—	29·0	12·2	—	—	99	98
1955	P 645	—	—	—	29·0	11·9	—	—	98	96
1956	P 649	—	—	—	28·6	12·7	—	—	99	98

made by ammoniating a mixture of triple superphosphate, potassium chloride and ammonium sulphate. In each year the 'coarse' and 'fine' samples of Gafsa phosphate were prepared from a single batch of imported rock. In 1954 and 1955 the 'coarse' material was ground to the fineness customary for rock phosphate intended for superphosphate-making (about half passing the 100-mesh B.S. sieve); in 1956 nearly 90 % of the material used passed this sieve). The 'fine' rock phosphate was prepared by further grinding and in each year practically all passed the 300-mesh B.S. sieve.

STATEMENT OF RESULTS

Results of individual experiments are given in full by Cooke & Widdowson (1958). The results of all similar experiments have been grouped together and are discussed here. Where more than a very few experiments of either type were carried out on any one crop the centres have been grouped by the pH (in water) of soil samples taken before the fertilizers were applied. The following division is used throughout this paper: 'acid' soils: pH 6·5 and below; 'neutral' soils: pH 6·6 and over.

(i) *Groups of experiments*

The differences between average crop yields given by the phosphates tested in each group of experiments were examined by calculating a standard error derived from the interaction between treatments and experimental centres. To facilitate comparisons between superphosphate (tested at 0·3 and 0·6 cwt. P_2O_5/acre) and the other phosphates (tested at 0·45 cwt. P_2O_5/acre) the yield given by 0·45 cwt. P_2O_5/acre was calculated from the response curve established by 0·0, 0·3 and 0·6 cwt. P_2O_5/acre applied as superphosphate in each group of experiments. Tables 2 and 3 list mean yields for groups of experiments together with standard errors which apply *only* to the yields given by phosphate fertilizers and *not* to comparisons between yields given by phosphates with yields obtained without phosphate. Corresponding standard errors for the average P_2O_5 contents of crops were not calculated since samples of crops were not analysed for all experiments in each group.

For some crops the percentage of phosphorus in the produce increases rapidly with increasing amounts of added phosphate, and phosphorus uptakes show relatively larger differences between amounts of added phosphate than do the actual yields. The phosphorus contents of crops may therefore provide extra information on the amounts supplied by the fertilizers tested; since phosphorus may be taken up too late in the season to produce proportionate increases in yields, comparisons made on this basis must be treated with caution. Earlier experiments (Cooke, 1956) showed that the phosphorus contents of potatoes do not provide any information on the value of phosphate fertilizers which cannot be obtained from the yield data; potatoes grown in these experiments were therefore not analysed. For other crops samples of the produce from most (but not all) of the experiments were analysed and used to calculate the average phosphorus uptakes by crops given in Tables 2 and 3. Values given in parentheses in these tables for the amounts of phosphorus taken up from 0·45 cwt. P_2O_5/acre applied as superphosphate are simple averages of values given by 0·3 and 0·6 cwt. P_2O_5/acre.

(ii) *Superphosphate equivalents*

The efficiencies of the tested phosphate fertilizers in terms of the standard material (superphosphate) were calculated for all sizeable groups of experiments. The superphosphate response curves were plotted and the dressings of P_2O_5 applied (as superphosphate) which would have been required to give yields, or phosphorus contents, equal to those given by the other tested phosphates were read off. These 'superphosphate equivalent dressings' were expressed as percentages of the amounts of P_2O_5 applied by the materials under test. 'Percentage superphosphate equivalents' calculated in this way are stated in Table 4 for the phosphates tested as alternatives to superphosphate. It should be emphasized that the method is approximate and the information derived from small groups of experiments is necessarily ill-defined. (The procedure is not appropriate where the phosphates under test give very different yields from superphosphate or where the superphosphate response curve is flat.)

(iii) *Individual experiments*

Direct and rigid comparisons between yields or phosphorus contents given by superphosphate and values given by the other phosphates tested could not be made, since superphosphate was tested at 0·3 and 0·6 cwt. P_2O_5/acre and the other materials at 0·45 cwt. P_2O_5/acre. Although the superphosphate response curves in groups of experiments were regularly shaped (Tables 2 and 3), in individual experiments the curves were often quite irregular; therefore the yields given by 0·45 cwt. P_2O_5 applied as superphosphate could not be calculated using the usual procedure (given by Crowther & Yates (1941)). The results of individual experiments were, however, examined by calculating yields, and phosphorus contents for 0·45 cwt. P_2O_5/acre applied as superphosphate by taking the mean of values given by 0·3 and 0·6 cwt. P_2O_5/acre. (This procedure tends to undervalue superphosphate in experiments where the response curve given by this fertilizer has a normal shape.) Differences between calculated yields for 0·45 cwt. P_2O_5/acre as superphosphate, and those given by 0·45 cwt. P_2O_5 applied by other phosphates, and by no phosphate, were examined by using the appropriate standard error in each experiment. This procedure is only approximate, but it serves to indicate the nature and magnitude of differences between superphosphate and the other phosphate fertilizers.

The examination of the effects of superphosphate, summarized for each group of experiments in Table 5, shows that superphosphate (at 0·45 cwt. P_2O_5/acre) gave increases which were approximately significant ($P = 0·05$ or greater) at about two-thirds of the individual centres, and that there were no significant depressions in yield due to superphosphate. Comparisons of superphosphate with the other phosphate fertilizers (summarized in Tables 6, 7 and 9) show that significant differences between yields, or phosphorus contents, were much less frequent; the results were therefore examined further by listing the numbers of positive and negative effects which exceed the standard error of the comparison made. Comments made here are restricted to differences which exceed the standard error (corresponding to approximately $P = 0·3$).

RESULTS OF THE FIELD EXPERIMENTS

The results of each series of experiments which are summarized in Tables 2, 3 and 4 are discussed for each crop separately. Comment on differences between mean yields given by the phosphate fertilizers tested, which are summarized in Tables 2 and 3, is restricted to effects which were significant. 'Superphosphate equivalents' listed in Table 4 are used as the basis of more general statements on the effectiveness of the other fertilizers relative to superphosphate. Finally, the magnitude and nature of differences between yields and phosphorus contents in individual experiments are discussed for each fertilizer separately. The results of a few single experiments on other crops are not given here; in some of these yields were abnormally low and in others phosphate fertilizers had no significant effects on yields.

Type I experiments

Mean yields and mean phosphorus contents of the crops grown in Type I experiments are given in Table 2 after grouping the centres by soil reaction. 'Percentage superphosphate equivalents' calculated from these data are stated in Table 4. Dicalcium phosphate was fully equivalent to superphosphate for potatoes on both acid and neutral soils; nitrophosphate was inferior to superphosphate on average of both groups of experiments. On acid soils the ammoniated fertilizers tested were equivalent to superphosphate, but they were slightly inferior to super on average of the group of neutral soils. In the swede experiments none of the other phosphates tested was as efficient as superphosphate, this was true on the basis of both yields and phosphorus contents of the crops. In a small group of experiments on barley grown on neutral soils dicalcium phosphate and the ammoniated fertilizers were roughly equivalent to superphosphate, nitrophosphate was inferior. The significance of these comparisons for yields may be tested by using the standard errors listed in Table 2.

Barley

There were no significant differences between mean yields given by the phosphate fertilizers tested in the barley experiments.

Potatoes

In the potato experiments nitrophosphate gave significantly lower mean yields than superphosphate on average of both the groups of acid and neutral soils. Yields given by dicalcium phosphate and by the ammoniated fertilizers were not significantly different from those given by superphosphate.

Swedes

For swedes grown on the group of acid soils, all the other phosphates tested gave significantly lower yields than superphosphate. On average of the small group of three experiments on neutral soils there were no significant differences between yields of swedes given by the phosphates tested.

Kale

On average of two experiments on kale grown on acid soils, dicalcium phosphate, nitrophosphate, and ammoniated fertilizers were at least as effective as equivalent superphosphate.

Type II experiments

Mean yields and phosphorus contents of the crops grown in Type II experiments are stated in Table 3 after grouping the experiments by soil reaction. 'Superphosphate equivalents' calculated from these data are given in Table 4. In the experiments on grass dicalcium phosphate was practically equivalent to superphosphate on the basis of both yields and phosphorus contents of crops grown on acid soils; on the basis of yields it was inferior to superphosphate in the smaller group of experiments on neutral soils, but was roughly equivalent to superphosphate on the basis of P_2O_5 contents. Gafsa rock phosphates were of small value to grass grown on acid soils, being equivalent to only about one-quarter as much phosphorus supplied as superphosphate; they were of no value at all on average of the experiments on neutral soils. For swedes grown on acid soils dicalcium phosphate was equivalent to superphosphate on the basis of both yields and phosphorus contents of the crops; Gafsa phosphates were equivalent to about three-quarters as much phosphorus applied as superphosphate on the basis of yields, but they were nearly as effective as superphosphate on the basis of the amounts of phosphorus in the crops. On average of three swede experiments on neutral soils the three phosphates tested were only half as effective as superphosphate on the basis of crop yields; on the basis of phosphorus contents dicalcium phosphate was equivalent to superphosphate, but Gafsa rock phosphates were much inferior. For kale grown on acid soils dicalcium phosphate and Gafsa phosphates were only a little more than half as efficient as superphosphate. The significance of these general statements is examined below by using the standard errors listed in Table 3 for mean yields of groups of experiments.

Grass

There were no significant differences between average yields of grass given by superphosphate and by dicalcium phosphate on either acid or neutral soils. On average of the experiments on acid soils both coarse and fine Gafsa rock phosphate gave significantly lower yields of grass than superphosphate. In the small group of grassland experiments on neutral soils fine Gafsa phosphate was significantly inferior to superphosphate, coarse Gafsa phosphate also gave lower yields and the difference was nearly significant.

Kale

For kale grown on acid soils all three phosphates gave lower mean yields than equivalent superphosphate, but none of the differences were significant.

Swedes

On average of the large group of swede experiments on acid soils dicalcium phosphate was as effective as superphosphate, both rock phosphates gave lower mean yields than superphosphate at equivalent rate and for the coarsely ground material the difference was significant. On average of three experiments on neutral soils there were no significant differences between mean yields of swedes given by the different forms of phosphate tested.

In all the groups of Type II experiments the coarse and fine batches of Gafsa rock phosphate gave very similar average yields and there were no significant differences between the two forms.

Results at individual centres

The results of individual experiments have been examined in the way described above. Yields and

Table 2. *Mean yields and phosphorus contents of crops grown in Type I experiments testing dicalcium phosphate, nitrophosphate and ammoniated fertilizer*

Soil group	No. of exps.	Without phosphate	Superphosphate			Dicalcium phosphate	Nitro-phosphate	Ammoniated fertilizer	Standard error* of yields given by phosphates
P_2O_5 applied (cwt./acre) ...	...	0·00	0·30	0·45†	0·60	0·45	0·45	0·45	
Potatoes (total tubers, tons/acre)									
Acid soils	11	7·03	8·60	9·12	9·52	9·18	8·62	9·25	±0·139
Neutral soils	8	9·86	11·56	11·93	12·14	12·01	11·12	11·65	±0·210
All soils	19	8·22	9·84	10·30	10·62	10·37	9·67	10·26	—
Swedes (roots, tons/acre)									
Acid soils	10	9·36	13·96	14·95	15·52	13·99	13·34	13·97	±0·327
Neutral soils	3	10·25	18·25	18·75	18·89	17·67	18·34	18·66	±0·550
All soils	13	9·56	14·95	15·85	16·30	14·84	14·50	15·05	—
Barley (grain at 85% D.M., cwt./acre)									
Acid soil	1	41·2	42·2	42·5	42·7	42·4	41·3	42·4	—
Neutral soils	3	16·7	20·7	22·4	23·9	21·8	20·0	22·4	±1·02
All soils	4	22·8	26·1	27·4	28·6	26·9	25·3	27·4	—
Kale (total crop, tons/acre)									
Acid soils	2	7·54	7·36	(8·08)†	8·81	8·46	8·49	8·60	—
Amounts of phosphorus in crops (cwt. P_2O_5/acre)									
Swedes									
Acid soils	8	0·113	0·162	(0·170)	0·178	0·164	0·150	0·162	—
Neutral soils	3	0·094	0·164	(0·177)	0·190	0·158	0·177	0·178	—
All soils	11	0·108	0·163	(0·172)	0·182	0·162	0·157	0·166	—
Barley									
Acid soil	1	0·335	0·352	(0·354)	0·355	0·348	0·343	0·356	—
Neutral soils	3	0·113	0·142	(0·154)	0·165	0·150	0·134	0·148	—
All soils	4	0·168	0·195	(0·204)	0·213	0·200	0·186	0·200	—

* Standard errors apply only to yields given by phosphate fertilizers and *not* to yields obtained without phosphate.

† Yields given by superphosphate supplying 0·45 cwt. P_2O_5/acre are calculated from the average response curve equation except where they are given in parentheses, these latter values are simple averages of values given by superphosphate supplying 0·3 and 0·6 cwt. P_2O_5/acre.

Table 3. *Mean yields of crops grown in Type II experiments testing dicalcium phosphate and Gafsa rock phosphate*

Soil group	No. of exps.	Without phosphate	Superphosphate			Dicalcium phosphate	Coarse Gafsa	Fine Gafsa	Standard error* of yields given by phosphate
P_2O_5 applied (cwt./acre)	... ...	0·00	0·30	0·45†	0·60	0·45	0·45	0·45	
			Grass (dry hay, cwt./acre)						
Acid soils	18	42·0	45·7	46·9	47·8	46·4	43·4	43·7	±0·55
Neutral soils	6	36·4	39·4	39·9	40·1	39·2	37·0	36·5	±1·14
All soils	24	40·6	44·1	45·1	45·8	44·6	41·8	41·9	—
			Swedes (roots, tons/acre)						
Acid soils	16	9·79	14·04	14·97	15·52	14·99	14·28	14·49	±0·240
Neutral soils	3	15·38	17·11	17·32	17·40	16·85	16·80	16·76	±0·462
All soils	19	10·67	14·52	15·34	15·82	15·28	14·67	14·85	—
			Kale (total crop, tons/acre)						
Acid soils	6	13·93	15·75	16·11	16·31	15·69	15·54	15·58	±0·386
Neutral soil	1	22·97	24·17	25·28	26·33	25·05	24·13	24·25	—
All soils	7	15·22	16·95	17·42	17·74	17·03	16·77	16·82	—
			Amounts of phosphorus in crops (cwt. P_2O_5/acre)						
Grass									
Acid soils	18	0·177	0·219	(0·233)†	0·247	0·229	0·194	0·201	—
Neutral soils	6	0·144	0·171	(0·185)†	0·199	0·182	0·146	0·146	—
All soils	24	0·168	0·207	(0·221)†	0·235	0·217	0·182	0·187	—
Swedes									
Acid soils	15	0·088	0·129	(0·143)†	0·158	0·142	0·141	0·142	—
Neutral soils	3	0·145	0·182	(0·187)†	0·194	0·188	0·166	0·175	—
All soils	18	0·098	0·137	(0·150)†	0·164	0·150	0·145	0·147	—
Kale									
Acid soils	5	0·217	0·256	(0·276)†	0·297	0·270	0·258	0·255	—
Neutral soil	1	0·329	0·347	(0·408)†	0·469	0·381	0·378	0·360	—
All soils	6	0·236	0·271	(0·298)†	0·326	0·288	0·278	0·272	—

* Standard errors apply only to yields given by phosphate fertilizers and *not* to yields obtained without phosphate.

† Yields given by superphosphate supplying 0·45 cwt. P_2O_5/acre are calculated from the average response curve equation except where they are given in parentheses, these latter values are simple averages of values given by 0·3 and 0·6 cwt. P_2O_5/acre applied as superphosphate.

Table 4. *Percentage superphosphate equivalents of dicalcium phosphate, nitrophosphate, ammoniated compound fertilizer and Gafsa rock phosphate derived from mean yields and phosphorus contents of crops*

	From yields		From phosphorus in crops	
	Acid soils	Neutral soils	Acid soils	Neutral soils
Type I experiments				
Potatoes				
No. of experiments ...	11	8	—	—
Dicalcium phosphate	104	111	—	—
Nitrophosphate	68	41	—	—
Ammoniated fertilizer	109	72	—	—
Swedes				
No. of experiments ...	10	3	8	3
Dicalcium phosphate	67	52	73	57
Nitrophosphate	53	69	40	93
Ammoniated fertilizer	67	89	67	97
Barley				
No. of experiments ...	—	3	—	3
Dicalcium phosphate	—	88	—	89
Nitrophosphate	—	53	—	47
Ammoniated fertilizer	—	100	—	83
Type II experiments				
Grass				
No. of experiments ...	18	6	18	6
Dicalcium phosphate	84	57	87	92
Coarse Gafsa phosphate	20	5	23	4
Fine Gafsa phosphate	27	0	36	4
Swedes				
No. of experiments ...	16	3	15	3
Dicalcium phosphate	100	48	93	100
Coarse Gafsa phosphate	72	44	91	22
Fine Gafsa phosphate	79	42	93	40
Kale				
No. of experiments ...	6	—	5	—
Dicalcium phosphate	61	—	80	—
Coarse Gafsa phosphate	54	—	67	—
Fine Gafsa phosphate	55	—	59	—

phosphorus contents given by 0·45 cwt. P_2O_5 as superphosphate (calculated as the average of values given by 0·3 and 0·6 cwt. P_2O_5/acre) have been compared with yields and phosphorus contents obtained without phosphate fertilizer, and those given by the other phosphates tested at 0·45 cwt. P_2O_5/acre. The numbers of positive and negative effects exceeding the standard error appropriate to the comparison, and the numbers of effects which were approximately significant (at the $P = 0{\cdot}05$ level) are set out in Tables 5, 6, 7, 9 and 10. The results of this examination are discussed in this section for each material separately.

Comment is only made on the results of individual experiments where difference between yields or phosphorus contents are greater than the appropriate standard errors for the comparisons made, or where they are significant. Thus the statement 'superphosphate gave higher yields than dicalcium phosphate at twelve centres' implies that at each of these centres the difference between yields given by the two fertilizers was greater than the standard error calculated for this comparison.

Superphosphate

The numbers of responses to superphosphate are examined in Table 5. There were responses to this standard material in thirty-two of the thirty-six Type I experiments and at more than two-thirds of all the centres the effect was significant. There was no instance where superphosphate depressed yields. In the Type II experiments there were responses to superphosphate in thirty-nine of the total of forty-nine centres and at thirty of these the effects were significant. There was one centre on grassland where superphosphate depressed yields, but the effect was not significant. No analyses for phosphorus contents were carried out on potatoes, for the other crops grown in the Type I experiments phosphorus contents of the crops grown at most centres were determined, but many of the analyses were carried out on samples after bulking replicates which precluded statistical analysis of the data. Standard errors of phosphorus contents are available for so few Type I experiments that no examination of the data from individual centres is presented here. The data were more complete in the Type II series, of the total of thirty-six experiments for which standard errors are available, superphosphate increased phosphorus contents at thirty-three centres and the increases were significant at twenty-eight.

Dicalcium phosphate

The numbers of positive and negative differences of the comparison of dicalcium phosphate with superphosphate at individual centres are listed in Table 6. Dicalcium phosphate was tested in both Type I and II experiments. Of the total of sixty-one experiments on acid soils superphosphate gave higher yields than dicalcium phosphate at only twelve centres and dicalcium phosphate was superior to superphosphate at seven centres; four of the twelve experiments where superphosphate was superior to dicalcium phosphate were Type I experiments on swedes where, for the group as a whole, dicalcium phosphate was significantly inferior to superphosphate (Table 2). Dicalcium phosphate gave significantly lower yields than superphosphate in one experiment each on grass, swedes and potatoes (this number may arise by chance at the $P = 0{\cdot}05$ level of probability). In one experiment on swedes superphosphate was significantly inferior to dicalcium phosphate.

There were twenty-four experiments on all crops grown on neutral soils, the number of centres where superphosphate was superior to dicalcium phosphate was about equal to the number where dicalcium phosphate was superior (Table 6); there were no significant differences between superphosphate and dicalcium phosphate. Similar conclusions are derived from the examination made in Table 6 of the phosphorus contents of the crops of thirty-six Type II experiments.

On the basis of both yields and of phosphorus contents, and for experiments on both acid and neutral soils, dicalcium phosphate behaved in much the same way as superphosphate except in the Type I experiments on swedes where water-soluble phosphate had some advantage.

Nitrophosphate

The comparisons made at individual centres between yields given by superphosphate with those given by nitrophosphate are summarized in Table 7.

Table 5. *Numbers of positive and negative effects of superphosphate which exceed the standard error of the comparison and the numbers of approximately significant effects*

(Yields of crops grown with 0·45 cwt. P_2O_5/acre as superphosphate *minus* yields of crops grown without phosphate.)

	Total no. of exps.	No. of effects greater than standard error		No. of significant effects ($P = 0{\cdot}05$)	
		Positive	Negative	Positive	Negative
	Type I experiments				
Potatoes					
Acid soils	11	10	0	8	0
Neutral soils	8	7	0	6	0
Swedes					
Acid soils	10	9	0	7	0
Neutral soils	3	3	0	3	0
Barley					
Acid soil	1	1	0	0	0
Neutral soils	3	2	0	2	0
All crops					
Acid soils	22	20	0	15	0
Neutral soils	14	12	0	11	0
	Type II experiments				
Grass					
Acid soils	18	13	1	9	0
Neutral soils	6	4	0	1	0
Swedes					
Acid soils	16	15	0	15	0
Neutral soils	3	2	0	2	0
Kale					
Acid soils	5	4	0	2	0
Neutral soil	1	1	0	1	0
All crops					
Acid soils	39	32	1	26	0
Neutral soils	10	7	0	4	0

Table 6. *Comparisons of dicalcium phosphate and superphosphate at individual centres*

(Yields and phosphorus contents of crops grown with superphosphate *minus* yields and phosphorus contents given by dicalcium phosphate at an equivalent rate of dressing.)

	Total no. of exps.	No. of effects greater than standard error		No. of significant effects ($P = 0{\cdot}05$)	
		Positive	Negative	Positive	Negative
	Yields in Type I experiments				
Potatoes					
Acid soils	11	1	3	1	0
Neutral soils	8	1	2	0	0
Swedes					
Acid soils	10	4	1	1	0
Neutral soils	3	2	1	0	0
Barley					
Acid soil	1	0	0	0	0
Neutral soils	3	0	0	0	0
	Yields in Type II experiments				
Grass					
Acid soils	18	4	0	1	0
Neutral soils	6	2	2	0	0
Swedes					
Acid soils	16	1	3	0	1
Neutral soils	3	1	0	0	0
Kale					
Acid soils	5	2	0	0	0
Neutral soil	1	0	0	0	0
	Phosphorus contents in Type II experiments				
Grass					
Acid soils	14	2	1	1	0
Neutral soils	5	1	1	0	0
Swedes					
Acid soils	11	2	3	0	1
Neutral soils	2	0	0	0	0
Kale					
Acid soils	4	2	2	0	0

For all crops grown on acid soils, superphosphate gave higher yields than nitrophosphate at eleven out of twenty-two centres and at no centre was nitrophosphate superior to superphosphate. Out of fourteen experiments on neutral soil superphosphate was superior to nitrophosphate at nine centres and there was no instance where nitrophosphate was better than superphosphate. In three experiments on acid soils and in four experiments on neutral soils superphosphate gave significantly better yields than nitrophosphate. Superphosphate was consistently superior at individual centres to nitrophosphate for all three crops grown. This confirms the conclusions already derived from Tables 2 and 4 which show that nitrophosphate gave average yields of potatoes, swedes and barley which were not greater than those given by two-thirds as much phosphorus supplied as superphosphate.

Ammoniated fertilizer

Comparisons of crop yields given by ammoniated fertilizer with yields given by superphosphate are summarized in Table 7. For potatoes superphosphate was superior to ammoniated fertilizer at three centres on neutral soils, but at three centres on acid soils and one on neutral soil ammoniated fertilizer was superior to superphosphate. In five of the ten swede experiments on acid soils superphosphate gave higher yields than ammoniated fertilizer. In the four experiments on barley the two sources of phosphate gave very similar yields. The only significant differences between yields given by superphosphate and by ammoniated fertilizer were in one potato experiment on neutral soil where superphosphate gave significantly more crop than ammoniated fertilizer and in another experiment in the same group where ammoniated fertilizer was significantly superior. Phosphate in the ammoniated fertilizers tested appeared to be, for practical purposes, as effective as superphosphate except in the swede experiments which suggested that water-soluble phosphate was generally superior to insoluble phosphates.

In 1954 the experiments tested a batch of powdered ammoniated superphosphate having about 70% of its total phosphorus present in a water-soluble form. In 1955 and 1956 a complete NPK fertilizer (based on triple superphosphate) which had been ammoniated and then granulated was used, slightly more than half of its total phosphorus was water-soluble. No direct comparisons can be made between these two materials but superphosphate was not consistently superior, or inferior, to the ammoniated material tested in the individual experiments in any one year. Yields given by superphosphate and by ammoniated fertilizer are compared in Table 8 by stating averages for all the swede and potato experiments in each year. The groups of experiments were small and any differences which may exist between the ammoniated superphosphate used in 1954 and the product tested in the two later years are complicated by differences between the sites used and between the three growing seasons. The available evidence suggests, however, that the phosphate in the two kinds of ammoniated products behaved similarly.

Gafsa rock phosphate

Comparisons between Gafsa phosphate and superphosphate at individual centres are summarized in Table 9. Both the coarse and fine grindings of Gafsa phosphate were consistently inferior to superphosphate in the grass experiments. At more than half of the centres superphosphate gave higher yields than Gafsa. Superphosphate gave significantly higher yields than coarse Gafsa in eight experiments and was significantly superior

Table 7. *Comparisons of nitrophosphate and ammoniated fertilizers with superphosphate at individual centres*

(Yields of crops grown with superphosphate *minus* yields given by nitrophosphate (or by ammoniated fertilizer) at equivalent rates of dressing.)

	Total no. of exps.	No. of effects greater than standard error: Positive	Negative	No. of significant effects ($P = 0{\cdot}05$): Positive	Negative
	For nitrophosphate				
Potatoes					
Acid soils	11	4	0	1	0
Neutral soils	8	5	0	3	0
Swedes					
Acid soils	10	6	0	2	0
Neutral soils	3	2	0	0	0
Barley					
Acid soil	1	1	0	0	0
Neutral soils	3	2	0	1	0
	For ammoniated fertilizers				
Potatoes					
Acid soils	11	0	3	0	0
Neutral soils	8	3	1	1	1
Swedes					
Acid soils	10	5	0	0	0
Neutral soils	3	0	0	0	0
Barley					
Acid soil	1	0	0	0	0
Neutral soils	3	0	0	0	0

Table 8. *Mean yields of potatoes and swedes (in tons of roots/acre) grown in Type I experiments, averaging all experiments in each year*

	P_2O_5 applied (cwt./acre)	1954	1955	1956
Potatoes				
No. of experiments	—	7	7	5
Without phosphate	0·00	10·87	7·33	5·76
With superphosphate	0·30	12·90	8·57	7·34
	0·60	13·76	9·24	8·16
With ammoniated fertilizer	0·45	13·07	9·05	8·03
Swedes				
No. of experiments	—	5	5	3
Without phosphate	0·00	7·75	13·81	5·61
With superphosphate	0·30	15·85	16·76	10·33
	0·60	18·20	16·82	12·22
With ammoniated fertilizer	0·45	16·49	16·48	10·48

Table 9. *Comparisons of coarse and fine Gafsa rock phosphate with superphosphate at individual centres*

(Yields and phosphorus contents of crops grown with superphosphate *minus* yields and phosphorus contents of crops grown with rock phosphate at equivalent rates of dressing.)

	Total no. of exps.	No. of effects greater than standard error: Coarse Gafsa, Positive	Coarse Gafsa, Negative	Fine Gafsa, Positive	Fine Gafsa, Negative	No. of approximately significant effects ($P = 0{\cdot}05$): Coarse Gafsa, Positive	Coarse Gafsa, Negative	Fine Gafsa, Positive	Fine Gafsa, Negative
				For crop yields					
Grass									
Acid soils	18	11	1	11	1	6	0	6	0
Neutral soils	6	3	1	4	0	2	0	1	0
Swedes									
Acid soils	16	5	1	5	2	4	1	1	1
Neutral soils	3	1	0	1	1	0	0	1	0
Kale									
Acid soils	5	2	1	3	0	1	0	0	0
Neutral soil	1	1	0	1	0	0	0	0	0
				For phosphorus contents					
Grass									
Acid soils	14	11	0	9	1	8	0	7	0
Neutral soils	5	4	0	5	0	4	0	4	0
Swedes									
Acid soils	11	1	3	3	4	1	1	0	1
Neutral soils	2	1	1	0	0	0	0	0	0
Kale									
Acid soils	4	2	0	3	0	1	0	1	0

to fine Gafsa in seven experiments. There were no grassland experiments where Gafsa phosphate was significantly superior to superphosphate.

Superphosphate gave higher yields than both coarse and fine grindings of Gafsa phosphate in about one-third of all the experiments on swedes. Superphosphate gave significantly greater yields of swedes than coarse Gafsa phosphate in four experiments on acid soils, but it was significantly superior to fine Gafsa in only one experiment in this group and also in one experiment on neutral soil.

In the kale experiments superphosphate gave higher yields than coarse and fine Gafsa phosphate at a few of the individual centres; superphosphate was significantly superior (to coarse Gafsa) in one experiment.

Comparisons made on the basis of the phosphorus contents of the crops (and listed in Table 9) confirm those made on the basis of yields which are discussed above. In the grass experiments superphosphate gave significantly more phosphorus in the crops than Gafsa in more than half of the individual centres. Gafsa phosphate was not significantly superior to superphosphate at any centre. There were very few significant differences between phosphorus uptakes from superphosphate and from Gafsa phosphate in the swede and kale experiments.

This examination of the effects of Gafsa phosphate at individual centres confirms the general conclusions derived from the average yields given in Table 3. Gafsa phosphate is of very little value for crops of hay or silage taken within a few months of applying this fertilizer to grassland, but it is quite a useful fertilizer for swedes and kale grown on acid soils.

Coarse versus fine grinding of Gafsa phosphate

Average yields and phosphorus contents of crops given in Table 3 do not show any worthwhile improvement in the efficiency of Gafsa phosphate from grinding this fertilizer more finely than is customary. Comparisons at individual centres, between yields and phosphorus contents of crops given by coarse and fine grindings, are summarized in Table 10. There were marked differences between yields given by fine and coarse Gafsa at only a few centres. The finely ground Gafsa gave significantly higher yields than the coarse material in five of the thirty-nine experiments on acid soils (three of these were on swedes and there was one centre each on grass and kale). Coarse Gafsa was not significantly better than the fine material in any of the experiments.

Fine Gafsa gave crops containing more phosphorus than was obtained from coarse Gafsa in nine of the thirty-six experiments where samples were analysed. The fine rock phosphate gave significantly more phosphorus in the crops than the coarse material in two experiments on swedes and one experiment on grass. The coarse phosphate was significantly superior to the fine material in one swede experiment.

Residual effects of the fertilizers tested

A few of the Type I experiments on arable crops, and some of the Type II grassland centres, were continued for a second year to measure the residual effects of the phosphates tested in the first year. No further dressings of phosphate were given but basal dressings of nitrogen and potassium fertilizers were given in accordance with local practice.

Experiments on arable crops

In three Type I experiments carried out in successive years on neutral soils in one parish of Oxfordshire, potatoes grown in the first years were followed by cereals; mean yields are given in Table 11. The average response to superphosphate by first-year potatoes was not large, dicalcium phosphate gave the same average yield as superphosphate, nitrophosphate and ammoniated fertilizers were slightly inferior. In the individual potato experiments the only significant effects were one response to superphosphate and a greater yield from superphosphate than from nitrophosphate in the same experiment. For second-year cereals there was a small average response to superphosphate and little difference between average yields given by the fertilizers tested. Barley grown in one experiment gave a significant response to superphosphate, but there were no significant differences between yields given by superphosphate and by the other phosphates tested. At the other two centres wheat was grown, superphosphate applied the year before had no significant effects on yields and there were no significant differences

Table 10. *Comparisons of finely ground with coarsely ground Gafsa rock phosphate at individual centres*

(Yields and phosphorus contents of crops grown with finely ground Gafsa phosphate *minus* yields and phosphorus contents of crops given by coarsely ground Gafsa phosphate.)

	Total no. of exps.	No. of effects greater than standard error: Positive	No. of effects greater than standard error: Negative	No. of significant effects ($P = 0.05$): Positive	No. of significant effects ($P = 0.05$): Negative
	For crop yields				
Grass					
Acid soils	18	1	4	1	0
Neutral soils	6	1	1	0	0
Swedes					
Acid soils	16	5	2	3	0
Neutral soils	3	1	0	0	0
Kale					
Acid soils	5	1	1	1	0
Neutral soil	1	0	0	0	0
	For phosphorus contents				
Grass					
Acid soils	14	3	0	1	0
Neutral soils	5	1	0	0	0
Swedes					
Acid soils	11	4	1	1	1
Neutral soils	2	1	0	1	0
Kale					
Acid soils	4	0	0	0	0

Table 11. *Mean yields of first-year potatoes and of second-year cereals in three experiments and of second-year cereals in five experiments*

	P_2O_5 applied in first year (cwt./acre)	Three experiments at Barford St John, Oxon: First-year potatoes (tons/acre of tubers)	Three experiments at Barford St John, Oxon: Second-year cereals (cwt./acre of grain)	Yields of cereals grown in second year of five exps. (cwt./acre of grain)
Without phosphate	0·00	9·3	27·4	27·9
Superphosphate	0·30	9·8	27·8	28·7
	0·60	9·8	28·3	28·6
Dicalcium phosphate	0·45	9·8	28·0	28·2
Nitrophosphate	0·45	9·6	28·9	29·2
Ammoniated fertilizer	0·45	9·4	28·9	29·3

between superphosphate and the other materials tested.

Altogether five Type I experiments were continued in cereals for a second year; mean yields are stated in Table 11 (this group includes the three experiments carried out in Oxfordshire which are discussed above). Phosphates applied in the first year had only a small effect on the average yield of the second-year cereal crops. Barley was grown at two centres and at both superphosphate increased the yield significantly, but there were no significant differences between yields given by superphosphate and by the other phosphates tested. There were no significant effects in any of the other three experiments where the second-year crop was wheat.

The effects of phosphate fertilizers on yield of both first- and second-year crops in these arable-land experiments were so small that they do not provide critical comparisons between the various materials tested. Superphosphate and the other phosphates tested appeared to have similar residual effects.

Experiments on grassland

Seven experiments on grass grown on acid soils and four centres on neutral soils were continued for a second year in the 1955–57 period. Mean yields of hay and phosphorus contents are given for each group of soils in Table 12.

The yields measured in the first years illustrate the effects discussed above for the main series of Type II experiments; dicalcium phosphate was satisfactory for grass both on acid and on neutral soils while Gafsa phosphate was of little use. Yields in the second years in experiments on acid soils show that Gafsa phosphates were much more effective than in the first year; both grindings of rock phosphate gave mean yields similar to those given by dicalcium phosphate and by superphosphate. On average of the small group of experiments on neutral soils second-year yields were low and the only marked response was to the high rate of superphosphate, dicalcium phosphate and Gafsa phosphates had only small effects on yields. The phosphorus contents of the herbage listed in Table 12 confirm these conclusions; on acid soils second-year phosphorus uptakes from dicalcium phosphate and from Gafsa phosphate were equal to those from superphosphate. In the experiments on both acid and neutral soils superphosphate gave an irregularly shaped response curve in the second year, the second increment of superphosphate giving much larger increases in yields and phosphorus contents than the first increment.

Comparisons of superphosphate with the other materials tested have been made for the individual centres but the data are not tabulated in detail here. On the seven centres on acid soils superphosphate increased yields significantly in the first year in three experiments, but there was a significant increase at only one centre in the second year. Superphosphate was significantly superior to dicalcium phosphate in one experiment and to Gafsa phosphate in two experiments in the first year, but the only significant difference in the second-year yields of grass was at one centre where coarse Gafsa phosphate out-yielded superphosphate. In the first year there was a general tendency for superphosphate to give markedly better yields than Gafsa phosphate, but in the second year there was a tendency at some of the centres for dicalcium phosphate, and (to a lesser extent) Gafsa phosphate, to give higher yields than superphosphate. In the four experiments on neutral soils superphosphate gave significant responses at one centre in both the first and second years. Superphosphate was significantly superior to Gafsa phosphate in two of the experiments in the first year, but there were no significant differences between materials at any of the centres in the second year. An examination of the phosphorus contents of the crops showed similar effects.

Table 12. *Mean yields and phosphorus contents of hay from eleven experiments on grass which were continued for a second year*

	P_2O_5 applied in first year (cwt./acre)	Yields of dry hay (cwt./acre): Acid soils, First year	Acid soils, Second year	Neutral soils, First year	Neutral soils, Second year	Amounts of P_2O_5 in the hay (cwt./acre): Acid soils, First year	Acid soils, Second year	Neutral soils, First year	Neutral soils, Second year
No. of experiments ...	—	7		4		7		4	
Without phosphate	0·00	40·4	39·8	41·1	20·0	0·167	0·179	0·171	0·087
With superphosphate	0·30	42·6	39·6	45·1	20·4	0·214	0·186	0·205	0·091
	0·60	44·9	42·4	45·8	23·1	0·242	0·210	0·237	0·104
With dicalcium phosphate	0·45	43·9	41·8	44·5	20·9	0·220	0·198	0·217	0·095
With Gafsa phosphate									
Coarse	0·45	40·2	41·8	41·2	20·5	0·180	0·199	0·176	0·088
Fine	0·45	42·0	41·4	41·6	20·6	0·192	0·197	0·178	0·091

As there were so few experiments on grassland the following conclusions on the residual values of the phosphates tested must be regarded as tentative. Dicalcium phosphate was roughly equivalent to superphosphate on the basis of both immediate and residual effects. Gafsa rock phosphate was of little value for grass when applied in the spring before cutting in the same summer, but in the following year on acid soils it had residual effects similar to those given by superphosphate. There was no indication that Gafsa phosphate is of much value to grass grown on neutral soils even in the second year. The residual effects of finely ground Gafsa phosphate were not markedly greater than the residual effects of the coarsely ground material.

DISCUSSION

Superphosphate increased crop yields significantly in about two-thirds of the experiments. Significant differences between yields given by superphosphate and by dicalcium phosphate or ammoniated fertilizer were rare, but superphosphate gave significantly better yields than nitrophosphate or Gafsa rock phosphate in many experiments. It is difficult to distinguish between fertilizers which behave similarly under most conditions (like dicalcium phosphate and superphosphate) even when a considerable number of experiments of modern design have been carried out. Where the fertilizers tested were clearly inferior to superphosphate under some or all of the conditions used, the volume of the work described here was sufficient to provide approximate valuations of the novel materials relative to superphosphate.

Dicalcium phosphate

Dicalcium phosphate dihydrate in powder form was roughly equivalent to superphosphate for potatoes (both on acid and on neutral soils). On average of the Type I experiments on swedes dicalcium phosphate was significantly inferior to superphosphate on both acid and neutral soils, but in the Type II swede experiments on acid soils dicalcium phosphate was equal to superphosphate. Many of the Type I experiments were laid down in the drier areas of north-east England and south-east Scotland, while the Type II experiments were mostly in wet areas of Western England and Wales. It is likely that superphosphate was more effective than dicalcium phosphate because the water-soluble phosphorus which it contained gave the crops a good start under dry conditions after sowing.

Nitrophosphate

The nitrophosphate used was made on pilot-plant scale by the process used to make the product tested in earlier work (Cooke, 1956) which was roughly equivalent to superphosphate for both potatoes and swedes. In the work reported here nitrophosphate was consistently inferior to superphosphate for barley, potatoes and swedes. No explanation can be given for the success of this kind of nitrophosphate in 1951–53 in comparison with the poor results obtained in 1954–56. The batches used in 1951–53 were made separately before each year's work, that used in 1954–56 was made in 1953 and stored until required. The water- and citric-acid-solubilities of the phosphorus of the materials used in the earlier and the later work were not materially different. Table 1 gives solubilities of samples of nitrophosphate drawn from the bulk stock before each year's work, there is no suggestion that slow changes in the nitrophosphate took place on storage which lead to decreased solubility of the phosphorus. It is possible that the material used in 1954–56 contained a larger proportion of its phosphorus in apatite-type combination, it is also possible that the granules of the products used in the later years did not break down so quickly in the soil to release phosphate ions.

Ammoniated fertilizer

On average of the three years' work (and of the two different products tested) the phosphorus in ammoniated fertilizers was as effective as superphosphate for barley and potatoes, but in swede experiments on acid soils the products were only two-thirds as effective as superphosphate. A lightly ammoniated powdered superphosphate was tested in 1954, a more heavily ammoniated granulated NPK mixture based on triple superphosphate was used in 1955 and 1956. The product tested in 1954 had 70% of its total phosphorus in water-soluble form, 95% being soluble in citric acid solution. The NPK compound tested in 1955 and 1956 had a water-solubility of 56% and a citric-acid-solubility of 99%. A tentative conclusion from this work is that a properly manufactured fertilizer, based on ammoniated superphosphate or triple super, may be regarded as equivalent to superphosphate for many practical purposes, provided that at least half of the total phosphorus present is soluble in water and that practically all is soluble in citric acid.

Granulated and powdered fertilizers containing dicalcium phosphate

The value of dicalcium phosphate in granulated fertilizers produced by ammoniation of superphosphate and by nitrophosphate processes has been the subject of much American work. A typical investigation reported by Cook, Lawton, Robertson & Hansen (1956) showed that when powdered fertilizers were well mixed with soil the proportion of the phosphorus in the fertilizer which was water-soluble had little effect on the percentage which was adsorbed by the plants, citrate-soluble phosphorus gave as good yields as water-soluble phosphorus. When *granulated* fertilizer was mixed with the soil the proportion of the total phosphorus which was water-soluble affected both the percentage of phosphorus taken up from the fertilizer by the crop and also the yields. The workers concluded that for maximum efficiency at least half of the phosphorus in a granulated fertilizer should be soluble in water. Where the fertilizers were placed in bands both the amount of phosphorus taken up by crops and the yields depended on the proportion of phosphorus which was water-soluble; to grow full crops fertilizers applied in bands had to have at least 40% of their phosphorus in a water-soluble form. All fertilizers containing little or no water-soluble phosphorus should be mixed with the soil rather than placed in bands and they should be in powdered form rather than granulated.

Most field experiments testing dicalcium phosphate (including those described here) have employed the dihydrate in powder form, but it is likely that dicalcium phosphate in granulated materials is generally present as the anhydrous salt. Terman, Bouldin & Lehr (1958) showed that dicalcium phosphate dihydrate was appreciably more available than the anhydrous salt on acid, and also on neutral and calcareous soils. The fertilizer value of dicalcium phosphate may be complicated by the physical and chemical form in which this substance is present. The physical properties of granules and the natures of the other salts present may affect both the rate at which water reaches dicalcium phosphate and the rate at which phosphate ions diffuse into the soil solution. In other work Cooke, Mattingly & Widdowson (1958) showed that powdered nitrophosphates acted much more quickly than the granulated products from which they were made.

The scope of the experiments reported here is not sufficient to provide a definite valuation of ammoniated products under British conditions, but it appears to be possible to ammoniate superphosphate or triple superphosphate and obtain products which, for some arable crops, are not markedly inferior to superphosphate. If fertilizers based on ammoniated superphosphate are made on a large scale in this country it will be necessary to carry out extensive series of field experiments on the products sold to farmers to characterize the materials that are consistently satisfactory. If ammoniated phosphates replace superphosphate in granulated compound fertilizers it will be necessary to determine the minimum percentage of water-soluble phosphorus to be retained in the products if they are not to lose those advantages of superphosphate which are due to its quick action. It may also be necessary to investigate the effect of particular granulation techniques on the agricultural values of the fertilizers made. Comparisons of placing and broadcasting of ammoniated products may also be needed to determine the best ways of applying new kinds of fertilizers.

Gafsa rock phosphate

In giving practical advice on the use of Gafsa phosphate the low unit price of rock phosphate relative to superphosphate should be taken into account. Both coarse and finely ground Gafsa phosphates gave yields of swedes and kale similar to those given by two-thirds as much phosphorus applied as superphosphate. Since the cost of phosphorus in Gafsa phosphate is not more than half the cost of phosphorus in superphosphate, Gafsa may be used with advantage for swedes and kale grown on acid soils.

For grassland both grindings of Gafsa phosphate were of very little value in the year of application. Before it can be effective, rock phosphate must be washed by rain through the mat of herbage to the soil surface so that it may react with the soil. Average dates for applying the fertilizers and cutting the grass were the end of March and end of June, respectively, and it is not surprising that the rock phosphates were not as effective as superphosphate. The few experiments which were continued to measure residual effects showed that on acid soils Gafsa phosphate was as effective as superphosphate in the second year. Only four experiments on neutral soils were continued for a second year and in these Gafsa phosphate had very little immediate or residual value. Rock phosphates should not be condemned as grassland fertilizers from these experiments, since under the conditions of the work the Gafsa phosphate did not have sufficient time to react with the soil. In future investigations the fertilizers should be applied in autumn or early winter so that the dressings may be washed down to the soil surface well before growth starts in spring. Gafsa rock phosphate may prove to be quite a suitable fertilizer for grassland on acid soils in wet areas if it is assessed over a run of seasons following application.

The two grindings of Gafsa phosphate gave very similar yields on average of all experiments on each crop. On the basis of these experiments as a whole there is no justification for the extra cost of grinding rock phosphate intended for direct application more finely than is customary. In a few experiments, however, there were significant gains from fine grinding. Further comparisons of normally ground (100-mesh) rock phosphate with finer (300-mesh) material are needed to determine whether there are conditions of soil, climate, and cropping where the finer phosphate is superior.

Armiger & Fried (1958) investigated the effect of particle size on the fertilizer value of a number of rock phosphates mined from North Africa and North America. In general, fine grinding was not as important as the nature and origin of the phosphates tested in determining their agricultural value. Rocks ground so that all passed a 325-mesh sieve were rather more effective than much coarser materials, but batches ground so that all passed the 100-mesh sieve were only a little less efficient than finer batches which passed the 325-mesh sieve. The slight superiority of fine rock phosphate in this American work is in agreement with the results of some of the experiments reported here.

Residual effects

A few experiments on arable crops were continued to measure residual values and the second-year effects were so small that it was not possible to distinguish differences (if any exist) between the residual effects of superphosphate and the other fertilizers tested. It is doubtful whether it is worth attempting to make such comparisons of residual values in experiments on arable crops where small dressings are given in the first year, since ploughing and cultivating inevitably mix soil and fertilizer and dilute the effects of the phosphates tested. The experiments on grassland which were continued to measure residual effects have already been discussed; on acid soils the second-year effects of dicalcium phosphate and Gafsa phosphate were indistinguishable from those of superphosphate. In the first year of these grass experiments the response curve for superphosphate was normally shaped; in the second year there was a good average response to the double dressing of superphosphate, but the single dressing had little effect on yields; this suggests that a high proportion of the low dressing of superphosphate had been 'fixed'.

The 1954–57 series of co-operative experiments confirm earlier work on alternatives to superphosphate. Although phosphate fertilizers which are only partially soluble, or are quite insoluble, in water may be as satisfactory as superphosphate for certain crops and on certain classes of soil, no water-insoluble phosphate has been consistently superior to superphosphate. On acutely phosphate-deficient soils, or in dry and cold weather, the stimulus to early rapid growth which is provided by water-soluble phosphate may often result in higher yields being obtained from superphosphate than from insoluble phosphates. The use of other fertilizers providing some or all of their phosphorus in non-water-soluble forms can only be justified where the materials can be offered to the farmer more cheaply (per unit of plant nutrient) than fertilizers based on superphosphate or ammonium phosphates.

SUMMARY

The results of about ninety field experiments carried out over three years to test dicalcium phosphate, nitrophosphate, ammoniated fertilizer and Gafsa rock phosphate are summarized and discussed. Soils with pH values of 6·5 and below are listed as 'acid', those with higher pH values as 'neutral'. All comparisons were made in terms of fertilizers supplying the same total amounts of phosphorus.

Dicalcium phosphate dihydrate gave approximately the same yields as superphosphate for potatoes (both on acid and on neutral soils) and for grass, kale and barley. In one group of swede experiments mostly carried out in the north-east of the country dicalcium phosphate was inferior to superphosphate, but it was equal to superphosphate in another group of swede experiments, most of which were on acid soils in wetter areas.

A nitrophosphate made in England on pilot-plant scale was consistently inferior to superphosphate for barley, potatoes and swedes.

A lightly ammoniated powdered superphosphate was tested in the first year, a more heavily ammoniated granulated NPK mixture based on triple superphosphate was tested in the two later years. The phosphorus in the two ammoniated fertilizers behaved similarly and was as effective as phosphorus in superphosphate for barley and potatoes; for swedes grown on acid soils the ammoniated products were only two-thirds as efficient as superphosphate.

Gafsa rock phosphate used on acid soils gave yields of swedes and kale similar to those given by two-thirds as much phosphorus applied as superphosphate. Rock phosphate had little effect on the yield of grass cut three months after the fertilizer was applied even on acid soils; superphosphate applied at the same time increased yields. A few grass experiments on acid soils were continued to measure residual effects; in the second year after application Gafsa phosphate was as effective as superphosphate. Gafsa was of very little immediate or residual value for grass grown on neutral soils. Rock phosphates are cheap fertilizers and are suitable for certain crops grown on acid soils in wet areas, they may also be suitable for grassland in these areas if their effects are assessed over a run of seasons following the application. Gafsa phosphate ground to pass a 300-mesh sieve gave average yields of swedes, kale and grass similar to those given by coarser materials of which 50–80 % passed the 100-mesh sieve. For the experiments as a whole there was no general justification for grinding rock phosphate more finely than is customary; in a few individual experiments however there were significant gains from fine grinding.

This investigation, which was carried out under the auspices of the Fertiliser Conference of the Agricultural Research Council, was made possible by the enthusiastic co-operation of local workers, most of whom are listed at the beginning of this paper. Grateful acknowledgement is made to those officers and to: J. H. A. Dunwoody for statistical analyses of the data from the field experiments, R. G. Warren for analyses of the experimental fertilizers, and to A. Penny for assistance in the co-ordination of the experiments.

Sincere acknowledgement is made also to those firms which supplied some of the special fertilizers tested: Imperial Chemical Industries Ltd, Hy. Richardsons and Co. (York) Ltd, and Scottish Agricultural Industries Ltd.

REFERENCES

ANGUS, J. (1953). *Proc. Fertil. Soc.* no. 23.

ARMIGER, W. H. & FRIED, M. (1958). *J. Agric. Fd Chem.* **6**, 539.

COOK, R. L., LAWTON, K., ROBERTSON, L. S. & HANSEN, C. M. (1956). *Proc. nat. Comm. Fertil. Appl.* **32**, 49.

COOKE, G. W. (1956). *J. Agric. Sci.* **48**, 74.

COOKE, G. W., MATTINGLY, G. E. G. & WIDDOWSON, F. V. (1958). *J. Agric. Sci.* **50**, 253.

COOKE, G. W. & WIDDOWSON, F. V. (1958). Report on field experiments on phosphate fertilizers carried out in 1954 to 1957. *Report presented to the National Agricultural Advisory Service, Conference of Soil Chemists*, no. SC/C/261.

CROWTHER, E. M. & YATES, F. (1941). *Emp. J. Exp. Agric.* **9**, 77.

D'LENY, W. (1953). *Proc. Fertil. Soc.* no. 24.

TERMAN, G. L., BOULDIN, D. R. & LEHR, J. R. (1958). *Proc. Soil Sci. Soc. Amer.* **22**, 25.

(*Received* 20 *October* 1958)