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Fertilizer experiments on maincrop potatoes 1955-61

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In the first 10 years after the 1939-45 war, knowledge of the fertilizer requirements of maincrop potatoes was based almost entirely on pre-war experiments, but between 1956 and 1962 the results of many fresh manurial experiments were published. A summary of the responses to fertilizer in over 100 of these experiments was made by Boyd (1961*a*).

This paper describes the results of 124 experiments of uniform design testing the effect of standard levels of fertilizer for maincrop potatoes in the years 1955-61. The experiments were done in Wales and all Regions of England, except the South-Western Region, by the staff of the Regional Soil Chemistry Departments of the National Agricultural Advisory Service (N.A.A.S.). In most Regions, the experimental programme was completed in 1959, but, in two Regions, experiments of the same design were done in 1960 and 1961 also. The work had three main objects: (1) to determine the optimal combination of the three major nutrients, nitrogen (N), phosphorus (P) and potassium (K); (2) to compare fertilizer responses on different soil series; (3) to test the value of methods of soil analysis in predicting crop response to fertilizers. This paper deals mainly with the first two objects; a comparison of methods of soil analysis based mainly on the experiments described here was reported to Open Conferences of the Soil Chemists of the N.A.A.S., the proceedings of which are to be published by the Ministry of Agriculture.

The experiments were of the conventional $3 \times 3 \times 3$ design (single replicate) and tested all twenty-seven combinations of three levels of each nutrient, as shown in Table 1. Except in one Region, there was one additional plot per block without N and with intermediate levels of P and K, and in some Regions there was a second additional plot in each block testing the effect of magnesium supplied by 5 cwt. Epsom salts per acre in the presence of $N_1P_1K_1$.

Choice of experimental sites

In the past, the sites of experiments done on commercial farms have usually been determined

without much regard for the kind of soil, or only in relation to the nutrient status of the soils as determined by soil analysis. The present series of experiments appears to be unique, not only in being the largest ever undertaken on potatoes in this country, but also in being the first of its size on any crop in which the sites have been restricted to particular soil series or complexes. A description of the soils included in the investigation is given in the Appendix; the soils are listed in Table 2 together with the N.A.A.S. Region and the county in which the experiments were done and the number of experiments. There were three groups of sandy soils, the Holme Moor complex in Yorkshire, and the Newport and Bridgnorth series in the East and West Midlands (ref. nos. N/3, EM/7 and WM/8 in Table 2), and four sandy loams, the Croxdale complex (ref. no. N/2) of Durham, the Curtisden series in Kent and East Sussex (ref. no. SE/12), the Faversham Series of Kent (ref. no. SE/11) derived from Brickearth, and the lighter-textured Fen Silts (ref. no. E/10). Apart from the 'warp' soils of N.W. Cumberland, the other English soils were mostly silty loams, silty clay loams and clay loams; they include the rest of the Fen silts, other Fen soils, some with an admixture of degraded peat, from Kesteven (ref. no. EM/6), 'warp' soils adjoining the Rivers Humber and Trent (ref. nos. Y and L/4 and EM/5), and the Evesham series (ref. no. WM/9). The remaining English soil group, the 'warp' soils of N.W. Cumberland (ref. no. N/1), although pedologically distinct, resembled the Welsh soils (ref. nos. A/13, B/14, B/15 and C/16) in being from an area of high rainfall and live-stock

Table 1

	Nutrient level				
	0	1	2	3	
	cwt./acre				
N	—	0.4	0.8	1.2	As sulphate of ammonia
P ₂ O ₅	0.0	0.5	1.0	—	As superphosphate
K ₂ O	0.0	0.75	1.5	—	As muriate of potash

farming, and its fertilizer responses proved to be much more akin to those of Wales than to the soils of lowland England.

The experimental sites were selected by members of the Regional Soil Chemistry Departments, often with assistance from the local N.A.A.S. county staff. Because of the need to find a co-operative farmer and a uniform experimental site, it is never possible in experimental work of this kind to choose the sites at random, and it is difficult to ensure that they shall be representative. Whilst farming standards on the selected farms are likely to be better than average, the third objective mentioned above, comparison of different methods of soil analysis, requires sites of contrasted nutrient status, and so, on these farms, sites deficient in P or K or both nutrients are likely to have been preferred.

Because some degree of selection is inevitable, it is always advisable to check the degree and type of bias by survey methods. This should be easy where, as in the present experiments, the sites have been limited to particular kinds of soil. It is particularly desirable to be able to compare the nutrient status of the experimental sites with a random sample of fields under the same crop and on the same soil, because this offers the possibility of making some adjustment to the average fertilizer responses given by the experiments. The extent of bias can be indicated in a more general way by comparing management on the selected

fields or farms with that on a random sample of farms; fertilizer practice, for example, might be a useful indicator.

The only groups of experiments for which it has been possible so far to check the representativeness of the experimental sites directly against a random sample of potato-growing fields on the same soil series are those from the Blacktoft and Saltmarshe series in the East and West Ridings of Yorkshire, and the Newport and Bridgnorth series in East Shropshire.

Table 3 shows the percentage distribution in six categories of soil P and K values of samples from the experimental sites, twenty-five in Yorkshire and fifteen in East Shropshire, and from randomly selected potato fields sampled in the course of recent surveys of fertilizer practice. Except for K in East Shropshire, the proportion of experimental sites classed as 'low' or 'very low' exceeded that in the random sample, whilst there were fewer 'high' and 'very high' sites. If the percentage distribution of experimental sites had been that of the random sample, the mean responses to P and K on the Blacktoft and Saltmarshe series would have been less by 0.18 and 0.15 ton/acre respectively, and the mean response to P on the Newport and Bridgnorth series would have been less by 0.15 ton/acre.

If the degree of selection exercised for these groups of experiments is representative of the other groups, the above comparison gives some grounds

Table 2. *Grouping of experimental sites*

Region	Ref. no.	Name of soil group	Counties	Years	No. expts.
Northern	N/1	'Warp' soils (2nd Terrace Marine Alluvium)	Cumberland	1955-59	9
	N/2	Croxdale complex	Durham	1955-59	9
	N/3	Holme Moor complex	Yorkshire, North Riding	1958-59	5
Yorks. and Lanes.	YL/4	Blacktoft and Saltmarshe series (Alluvium, River Humber)	Yorkshire, East and West Ridings	1956-59	25
East Midlands	EM/5	'Warp' soils (Alluvium, River Trent)	Lincolnshire, Lindsey	1955-58	4
	EM/6	'Fen' soils	Lincolnshire, Kesteven and Lindsey	1957-59	3
	EM/7	Newport and Bridgnorth series	Nottinghamshire	1955-61	13
West Midlands	WM/8	Newport and Bridgnorth series	Shropshire, Cheshire, Worcestershire, Staffordshire	1955-60	11
	WM/9	Evesham series	Warwickshire	1957-59	5
Eastern	E/10	Fen silts	Lincolnshire, Holland, Cambridgeshire	1957-60	7
South-eastern (Wye)	SE/11	Faversham series	Kent	1955-59	6
	SE/12	Curtisden series	Kent, East Sussex	1955-58	8
Wales (Aberystwyth)	A/13	Penrhyn/Denbigh complex	Carmarthenshire, Cardiganshire	1957-59	7
	B/14	Penrhyn/Denbigh complex	Caernarvonshire, Denbighshire	1957-59	5
	B/15	Castleton series	Anglesey	1957-59	2
	C/16	Castleton series	Monmouthshire, Brecon	1957-59	5

for thinking that, where the average responses are based on a reasonable number of centres, the degree of bias, although not negligible, may be of secondary importance compared with the differences in fertilizer response between soil series. In general, the effect of the bias is likely to be in the direction of reducing the differences between soil series.

Experimental technique

The plots were marked out, the fertilizers weighed up and applied and the crop harvested by members of the N.A.A.S. Regional Soil Chemistry Departments. Apart from this, all cultivations were under the farmer's control and the sites were in other respects treated exactly as the rest of the field. At the outset it had been intended that the fertilizers should be applied by hand over the ridges immediately before the seed was planted, but in some Regions where machine-planting on the flat is widespread it was often necessary to broadcast the fertilizer before planting, or, in a few instances, immediately after planting. A comparison of responses on sites where the fertilizer was applied over the ridges with those where it was broadcast is given later in the paper.

The plots were usually, though not always, lifted by hand and consequently the plot-size was kept to a minimum, the mean harvested area per plot being $\frac{1}{194}$ th acre and the range $\frac{1}{140}$ th– $\frac{1}{240}$ th acre. Having regard to the small number of plants harvested (60–100 per plot), the accuracy attained, as judged by the standard errors, was satisfactory. The average standard error per plot, based on the conventional 15 degrees of freedom, was 1.07 tons/acre, about 12 % of the mean yield.

Soil classification and mean responses to fertilizers

Table 5 gives for each of the soil groups listed in Table 2, and described in more detail in the Appendix, the mean yield of potatoes (total tubers) in tons per acre and the mean responses to each level of nutrient, together with the linear \times linear interactions. To simplify discussion the soils have been arranged in order of texture.

A cursory glance at the results of Table 5 shows that there was considerable variation between

series in mean yield and fertilizer response. As the restriction of the experimental sites to particular soil series was an important feature of the experimental programme, it will be appropriate to consider first whether there is evidence for real variation in response between series, or whether the observed differences between the means of Table 5 could have arisen from seasonal differences, or, in view of the small number of sites in many of the series, purely from experimental error.

Taking all available soils in the years 1955–59, Table 4 gives an analysis of soil and year differences in the responses to each nutrient; the pooled experimental error is also shown. A substantial part of the variation in response to the lower rates

Table 3. Comparison of soil P and K status of experimental sites and of random samples of fields under potatoes

(Blacktoft and Saltmarsh series)				
Percentage of fields in each category				
Soil category	Soil P (citric acid)		Soil K (citric acid)	
	Expts.	Survey	Expts.	Survey
VL	—	1	4	—
L	24	8	16	5
M	12	11	24	20
MH	64	73	44	41
H	—	7	12	33
VH	—	—	—	1
No. of fields	25	96	25	96

(Newport and Bridgnorth series; East Shropshire)

Percentage of fields in each category				
Soil category	Soil P (Morgan's)		Soil K (Morgan's)	
	Expts.	Survey	Expts.	Survey
VL	7	3	—	3
L	20	5	53	44
M	13	8	—	33
MH	33	25	40	16
H	27	54	7	3
VH	—	5	—	—
No. of fields	15	63	15	63

Note. VL, very low; L, low; M, medium; MH, medium-high; H, high; VH, very high.

Table 4. Contribution of soils and seasons to variance per site of responses to N, P and K

Total yield ((tons/acre) ²)							
	D.F.	P ₁ –P ₀	K ₁ –K ₀	N ₂ –N ₁	P ₂ –P ₁	K ₂ –K ₁	N ₃ –N ₂
Seasons	4	1.35	4.26	1.57	0.60	0.36	0.71
Soils within seasons	57	1.11	2.40	0.67	0.40	0.48	0.43
Soils	19	1.86	5.69	0.77	0.49	0.70	0.50
Seasons within soils	42	0.80	1.09	0.72	0.38	0.37	0.43
Soil-season groups	61	1.13	2.52	0.73	0.42	0.47	0.45
Within groups	65	0.69	0.92	0.41	0.36	0.41	0.38
Pooled experimental error	1905	0.31	0.31	0.31	0.31	0.31	0.31

Table 5. *N.A.A.S. potato experiments 1955-61: mean yields, responses to fertilizer and linear \times linear interactions*
(tous total tubers per acre)

Soil group	Reference	No. of centres	Mean yield	Response to nitrogen			Response to phosphorus			Response to potassium			Interactions			Experimental error	
				N ₁ -N ₀ , N ₂ -N ₁ , N ₃ -N ₂			P ₁ -P ₀ , P ₂ -P ₁			K ₁ -K ₀ , K ₂ -K ₁			NP, NK, PK			Res. ^a	Interact.
				Total	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total		
Lowland England Loamy sands	N/3 EM/7 WM/8	5	9.73	2.07	0.76	0.21	3.04	1.26	0.35	1.62	1.01	0.50	1.51	0.18	-0.07	-0.20	0.29
		13	10.03	2.09	0.68	0.27	3.04	0.57	0.12	0.69	0.71	-0.10	0.61	-0.16	-0.36	-0.12	0.20
		11	11.32	—	0.65	0.11	—	0.54	0.13	0.67	0.92	0.32	1.24	-0.18	-0.14	0.23	0.15
		29	10.47	(2.08)	0.69	0.20	(3.97)	0.68	0.17	0.85	0.84	0.16	1.00	-0.12	-0.12	0.00	0.09
		Mean	10.47													0.11	0.11
Sandy loam Croxdale	N/2 SE/12 SE/11 E/10a	9	9.89	1.13	0.77	0.01	1.91	1.21	0.47	1.68	1.95	0.61	2.56	0.05	-0.14	0.26	0.23
		8	10.20	1.29	0.33	0.02	1.64	0.97	0.65	1.62	1.48	0.50	1.98	-0.14	-0.30	0.38	0.18
		6	14.86	1.03	0.06	-0.19	0.90	0.33	0.10	0.43	-0.01	-0.03	-0.04	0.14	-0.09	0.11	0.22
		4	16.64	3.45	0.87	0.18	4.50	0.64	-0.05	0.59	1.66	0.19	1.85	0.54	1.15	0.48	0.20
		Mean	13.18	1.68	0.36	-0.01	2.03	0.68	0.31	0.99	1.02	0.25	1.27	0.10	0.16	0.31	0.12
All sands and sandy loams Silty loam and silty clay loam	E/10b Y and L/4a Y and L/4b EM/5	56	11.25	(1.80)	0.60	0.10	(2.50)	0.77	0.26	1.03	1.08	0.26	1.34	-0.02	-0.03	0.14	0.07
		3	11.73	1.38	0.80	-0.13	2.05	1.39	0.76	2.15	0.10	-0.29	-0.19	0.50	0.38	-0.44	0.28
		7	10.08	0.96	0.18	-0.08	1.06	0.32	0.40	0.69	0.58	0.35	0.93	-0.05	0.33	0.46	0.15
		18	8.30	0.77	-0.13	-0.24	0.40	0.63	0.45	1.13	-0.05	-0.02	-0.10	-0.02	0.12	-0.15	0.19
		Mean	9.44	0.73	0.22	-0.08	0.26	0.88	1.14	2.02	-0.04	0.26	0.22	-0.52	0.42	-0.38	0.34
Silty Clay Loam and Clay Loam 'Fen' soils	EM/6 WM/9	32	9.15	0.86	0.07	-0.25	0.68	0.69	0.53	1.22	0.10	0.05	0.15	-0.04	0.23	0.02	0.06
		3	11.68	2.89	1.19	-1.07	3.01	1.73	0.83	2.56	-0.16	0.20	0.04	2.41	0.88	0.90	0.32
		5	7.73	—	-0.10	0.30	—	1.03	0.44	1.47	0.24	0.15	0.39	0.29	-0.16	0.30	0.26
		40	9.16	(1.03)	0.13	-0.24	(0.92)	0.81	0.54	1.35	0.10	0.07	0.17	0.18	0.23	0.12	0.04
		Mean	9.16													0.05	0.05
Wales and N.W. England Sandy Loams	Wales B/15 Wales C/16	2	5.41	0.10	0.05	-0.47	-0.32	1.90	0.39	2.29	0.41	0.71	1.12	0.07	-0.08	-0.19	0.39
		5	11.20	1.12	-0.23	-0.10	0.79	1.22	0.72	1.94	0.97	0.34	1.31	-0.28	-0.91	0.55	0.26
		7	9.55	0.83	-0.15	-0.21	0.47	1.41	0.63	2.04	0.81	0.45	1.26	-0.18	-0.67	0.34	0.22
		Mean	7.50													0.27	0.27
		Mean	7.53													0.27	0.27
Loam and Silt Loam Fenrlyn/Denbigh	Wales A/13 Wales B/14	7	7.50	1.07	0.34	-0.11	1.30	1.06	0.64	1.70	2.82	0.39	3.21	-0.04	-0.18	0.83	0.17
		5	7.58	0.05	-0.03	-0.21	-0.19	1.83	0.66	2.52	0.54	0.12	0.66	0.20	0.52	0.04	0.25
		12	7.53	0.65	0.19	-0.15	0.69	1.38	0.66	2.04	1.87	0.28	2.15	0.06	0.11	0.50	0.18
		Mean	7.53													0.15	0.15
		Mean	7.53													0.15	0.15
Organic Fine Sandy Silty Loams Cumberland 'Warp' soils	N/1	9	9.82	1.93	0.39	-0.32	2.00	2.13	0.95	3.08	3.03	0.66	3.69	0.74	-0.37	1.18	0.21
		28	8.77	1.10	0.16	-0.22	1.04	1.63	0.74	2.37	1.99	0.44	2.43	0.22	-0.24	0.67	0.11
		124	10.02	1.40	0.37	-0.08	1.69	0.98	0.46	1.44	0.97	0.24	1.21	0.10	0.00	0.25	0.032
		Mean	10.02													0.032	0.032
		Mean	10.02													0.032	0.032

^a Not applicable to response N₁-N₀.

of application of P and K could be attributed to soil series. At the higher rate of application the influence of soil was much less; for P, in particular, the influence of soil and season appeared small in relation to the variation within soil-year groups. By contrast with P and K, response to both levels of N was particularly influenced by season, with soil group of secondary though not negligible importance. A somewhat similar conclusion was reached by Boyd (1961*b*) from the results of seven groups of experiments in England, Wales and East Scotland; the requirements of the potato crops for P and K were clearly dependent upon type of soil, but nitrogen responses did not vary greatly between soils. However, in the present series of experiments, the response N_1-N_0 , determined from extra plots outside the factorial scheme, varied considerably between groups of experiments, responses ranging from 0.1 ton/acre in the seven experiments from the Bangor Sub-centre of Wales to 2.7 tons/acre for the Fen silts.

In general, the value of restricting the experimental sites to particular soil series seems to be confirmed, and this conclusion is reinforced by analysis of variance of the mean yields, not shown in Table 4; as Table 5 shows, the most fertile soils, the Faversham series and the Fen silts, had mean yields of the order of 15 tons/acre, whilst others yielded only half as much. Probably the true potential yields of the series would not differ so greatly if allowance could be made for differences in farm techniques.

Whilst the foregoing analysis indicates that classification of potato fields according to soil series gives some indication of their fertilizer responses, there are so many soil series in the country that it would be useful to know how far they can be grouped in relation to other characteristics such as those listed in the Appendix.

The grouping by texture which has been adopted for Table 5 achieves some success in distinguishing between the N and K responses of the different series, both tending to be greater on the lighter-textured soils. Thus most of the sands, sandy loams and very fine sandy loams gave good responses to K while the silty loams, silty clay loams and clay loams did not. Excluding the soils from Wales and Cumberland, the mean responses were as shown in

Table 6. The difference in response to K is associated with a somewhat lower K status of the lighter soils; mean available K (Morgan's reagent) was 69 p.p.m. for the sands and 130 p.p.m. for the silts and clays.

This conclusion is reinforced by a comparison of texture variations within the same or closely allied soil series. Thus for the 'warp' soils adjacent to the River Humber we can compare the Blacktoft and Saltmarshe series; the two series are of similar origin but the Blacktoft series has the higher clay fraction. Although the numbers of centres are very small, we can also compare the two classes of Fen silt soils listed in the Appendix, the 'light' silts being mainly very fine sandy loams, while the 'medium' silts were mainly silty loams (Table 7).

Within each soil group, there were larger responses to N and K, and somewhat smaller responses to P, on soils of lighter texture. Further examination of the P responses in Tables 6 and 7 indicated that soils of different texture, but the same soil P value, showed rather similar crop responses to P, the apparent effect of soil texture arising mainly from the fact that most of the heavier soil groups were relatively low in P. By contrast, there seems to be a fairly close relationship between soil texture and K response; although the mean soil K determinations by Morgan's reagent predicted fairly well the differences in mean K response between light and heavy soils, the association of K response and soil K determination for soils of the same texture was relatively poor.

The series not included in the above comparison between light and heavy soils, the Castleton series, the Penrhyn/Denbigh series and the Cumberland 'warp' soils, are from areas of high rainfall, the average being around 40 in. per annum. These soils

Table 6

	No. of centres	Mean responses to fertilizer (tons/acre)		
		N_3-N_1	P_2-P_0	K_2-K_0
Sands and sandy loams	56	0.70	1.03	1.34
Silty loams and clay loams	40	-0.11	1.35	0.17

Table 7

Soil	No. of centres	Mean yield	Mean response to fertilizer (tons/acre)			Mean P and K in soil	
			N_3-N_1	P_2-P_0	K_2-K_0	p.p.m. P (Olsen)	p.p.m. K (Morgan)
Saltmarshe	7	10.07	0.10	0.63	0.93	28	69
Blacktoft	18	8.30	-0.37	1.13	-0.10	21	105
'Light' silts	5	16.63	1.58	1.10	1.39	54	131
'Medium' silts	3	11.73	0.66	1.48	-0.20	31	224

are similar in showing very limited N responses and large or very large responses to P and K (Table 5). It is not of course possible to distinguish between the direct effect of high rainfall and its influence on soil factors such as lime status or on farming type.

The British Classification of soils, given in the third column of the Appendix, brings together series of very different fertilizer responses. Thus the 'brown earths of low base status' include the soils from Wales with low N and high P responses and the Newport and Bridgnorth series with high N and low P responses. Again, the classification into 'ground water gleys' brings together the 'warp' soils of the River Trent, responsive to P but relatively unresponsive to N and K; the Cumberland 'warp' soils, responsive to P and K but not to N; and the Fen silts, responsive to all three nutrients.

There is an indication that soil series with impeded drainage may be more responsive to P than more freely drained soils. In Table 8, the sixteen soil groups and their responses to P (P_2-P_0) have been re-grouped according to the average depth of freely drained soil (see Appendix). For all four groups in lowland England with free drainage to more than 18 in., the mean response to 1.0 cwt. P_2O_5 /acre was not more than 0.7 ton/acre, whereas of the five groups with poor natural drainage, none had a response below 1.5 tons/acre.

There is little information on the influence of soil acidity on P response, as only a very few acid soils were included. Compared with other soils of the same series, responses to P on the eight soils with pH < 5.5 were greater by 0.6 ton/acre.

An additional check on the effectiveness of the grouping into soil series can be made by comparing fertilizer responses of the same series in different parts of the country. From the present data we can compare the Newport and Bridgnorth series in the East and West Midland Regions and the Castleton series and Penrhyn/Denbigh complex in different parts of Wales. Table 9 shows that in the two groups of Newport and Bridgnorth series the N and P responses were closely similar. The response to the higher level of K was less for the East Midland sites.

The comparison of series within Wales is based only on very small numbers, but receives some support from later experiments in the period 1960-62. Comparing the Castleton series in North Wales (Anglesey) with those in South Wales and Monmouth shows good agreement except for the initial response to N_1 , which was negligible for the North Wales centres. For the Penrhyn/Denbigh complex in North and Central Wales, there was again a difference in response to the initial rate of N, which was very small for the North Wales

centres. There was also a big discrepancy in the K response, not explicable in terms of soil analysis. Similar differences in response to N occurred in experiments in the period 1960-62.

As soil series differ in their ability to provide plant nutrients, because of the parent materials from which they were derived or from long-continued use of fertilizers, it is possible that the information on fertilizer responses provided by soil series could be given equally well by soil analysis. This can be checked by the results of investigations undertaken by the N.A.A.S. Soil Chemists' Conference. Results given in Table 9 refer to almost the same soils as the rest of the paper; two groups, the Cumberland 'warp' soils and the Fen soils from the East Midland Region, were excluded because of their variable content of organic matter, whilst another group, consisting of sites on Magnesian Limestone in the East Midland Region, was included. The first two lines in the table show the variances per site of the responses to P and K before and after fitting a linear regression of crop

Table 8. *Relation between response to P and depth of freely drained soil*

	No. of soil groups	No. of sites	Response P_2-P_0 (tons/acre)
Lowland England			
Drainage free to below 18 in.	4	34	0.63
Drainage impeded at 12-18 in.	4	33	1.16
Drainage impeded at < 12 in.	5	29	1.77
Wales and N.W. England			
Drainage free to below 18 in.	2	19	2.04
Drainage impeded at < 12 in.	1	9	3.08

Table 9. *Variance of responses to P and K in relation to soil classification and determination of available P and K in soil*

	D.F.	Variance per site ((tons/acre) ²)	
		P response	K response
1. Total variance	113	1.041	2.015
2. Variance after fitting regression on soil P or K	112	0.661	1.464
3. Variance within soil groups	101	0.840	1.244
4. Variance within soil groups after fitting regression on soil P or K	100	0.584	1.096
5. Variance within soil groups after fitting separate regressions for each soil group	88	0.469	0.989

response on log (soil P or K). The rest of the table gives the variance within soil groups, line 3 showing the total variance, line 4 the variance remaining after fitting parallel regression lines and line 5 the variance after fitting separate regressions for each soil group. Both soil group and soil analysis reduced the variance per site of the P and K responses, soil group being much more effective for K and soil analysis much more effective for P; the two variates taken together were more effective than either alone. By fitting separate regressions within each soil group the variance could be reduced to less than half of its original value.

*Response curves and interactions
between nutrients*

The foregoing discussion has been based almost entirely on the mean responses to N, P and K. Table 5 is also of interest for the information it provides on the mean response curve for each nutrient and on the interactions between nutrients.

When the experiments were planned it was widely believed that the P requirement of potatoes was fairly small. In fact the highest rate (1.0 cwt. P_2O_5 /acre) proved to be below the optimum on many soils, particularly in the high-rainfall districts. In Table 5, additional responses to the higher rate were substantial except for the Newport and Bridgnorth series, the Faversham series and the lighter-textured Fen silts. The results for the East and West Midlands are in agreement with previous results of twenty-two experiments in the West Midlands, mostly on soils derived from Triassic drift, which gave a mean response to the same dressing of P of 0.42 ton per acre (Edwards, Watkin & Webber, 1956), much the same as the figure of 0.67 ton/acre in Table 5.

The levels of K were also rather low by modern standards of potato manuring and most of the lighter soils and soils in high-rainfall areas showed an additional response to the high rate of dressing. Except for some of the sandy soils, there was a consistent linear \times linear PK interaction; this was particularly evident for the soils in high-rainfall areas where the average response to 1.5 cwt. K_2O /acre was 1.7 tons without P, 2.5 tons at the P_1 level and 3.1 tons/acre at the P_2 level (Table 10). The response curve for K became steeper at the highest level of P. A very similar result was obtained in the earlier potato experiments in Wales (Boyd, 1961b).

For nitrogen, the three sandy soils at the head of Table 5 form the only group showing consistent positive response up to the N_3 level (1.2 cwt. N/acre). The other English lighter-textured soils mostly gave negligible responses for N_3-N_2 , while almost all the remaining groups had negative responses above 0.8 cwt. N/acre. In each of the

five groups from high-rainfall districts (Castleton series, Penrhyn/Denbigh complex and Cumberland 'warp' soils) high N reduced yield, the mean reduction being 0.22 ± 0.11 ton/acre; for the heavier soils, excluding those in high-rainfall districts, the mean reduction was 0.24 ± 0.04 ton/acre.

Taking all centres together, the linear \times linear NP and NK interactions were small, but the Fen silts (East Region) and Fen silty clays (East-Midland Region) showed large positive NP and NK interactions. Table 11 shows that for these soils there was a response up to the N_1 level at all combinations of P and K but beyond this level response began to decrease again when no PK was applied; with intermediate levels of PK, response reached a maximum around the N_2 level and then decreased again, whereas with P_2K_2 (and also P_1K_2 and P_2K_1) the maximum response was at or above the N_3 level. Much the same response curves were obtained for K at the corresponding levels of basal NP.

Results for a substantial number of soils showed some detrimental effect on yield of high levels of both N and K. For the three loamy sands and the Croxdale and Curtisden series the response N_3-N_2 was less at the highest level of K than at K_0 or K_1 , the mean response for plots with P being:

	Level of K			
	0	1	2	
	(tons/acre)			
Response N_3-N_2	+0.11	+0.25	-0.26	± 0.14

On these lighter-textured soils it is possible that this was caused by excessive concentrations of salts close to the tuber. In addition, it is probable that the magnitude and sign of the NK interaction is

Table 10. *Response to K in Wales and N.W. Cumberland*

Level of P	(tons per acre)		Total response to K
	K_1-K_0	K_2-K_1	
0	1.45	0.28	1.73
1	2.10	0.37	2.47
2	2.40	0.67	3.07
	± 0.17		

Table 11. *Fen soils. Nitrogen response curve for contrasted levels of PK*

Level of N	(mean yield, tons/acre)		
	Level of PK		
	00	11	22
0	(10.71)	(11.26)	—
1	13.27	13.76	12.99
2	12.98	15.32	15.54
3	11.69	14.12	15.69

related to the date at which the crop succumbs to blight; in blight years, the delay to maturity resulting from heavy dressings of these two fertilizers may be disadvantageous. This may explain why four of the five sets of soils in high-rainfall areas showed a negative NK interaction, and mean responses N_2-N_1 for the 28 soils decreased with increasing levels of K.

	Level of K (plots with adequate P only)			
	0	1	2	
	(tons/acre)			
Response N_2-N_1	0.95	0.60	0.05	± 0.34

In an earlier series of experiments in Wales (Boyd, 1961b) there was a large positive interaction of N and K.

Fertilizer placement and response

Originally it was intended that fertilizer should be applied 'over the ridges' before planting, the ridges then being split to cover both seed and fertilizer. In some areas (e.g. the silt and 'warp' soils, and in Wales and the north of England) the fertilizer was applied in this way on most or all of the experimental sites, but in others, particularly the West Midlands, much of the potato acreage is planted by machines without fertilizer attachments, the fertilizer being broadcast before planting. Altogether there were twenty-two centres where the fertilizer was broadcast 'on the flat' before planting and a further five where the fertilizer was broadcast after planting and the land subsequently ridged. This is scarcely sufficient to permit reliable comparison to be made between responses to fertilizer applied 'on the flat' and 'over the ridges'. Moreover, there is some indication that the centres differed in other respects than planting method, as the average yield of the 'ridge' and 'flat' sites differed by 2.5 tons/acre, the former being the larger.

From previous experimental results (Cooke, 1949) the sites with fertilizer 'over the ridges' would be expected to give greater responses at lower rates of application, but possibly smaller responses at higher rates when compared with sites where it was applied 'on the flat'. Considering first the responses to N on the two types of site, there was a larger

response (N_2-N_1) 'on the flat' (as might have been expected from the lower level of yield) but a very similar response (N_3-N_2) on both types of site. It does not look as though the observed falling off in N response at high levels of application is associated with method of fertilizer application. The results for K were more in conformity with expectation in that the average response on the sites where the fertilizer was broadcast 'on the flat' was more or less linear, whereas for the corresponding 'over the ridges' sites there was little response above the K_1 level (Table 12).

Fertilizer response and previous crop

With few exceptions, the cropping in previous years was recorded for each field in which an experiment was sited. Thus the average fertilizer responses obtained after a ploughed-up ley or permanent grass may be compared with those on sites where the potato crop was in a purely arable rotation, whilst the latter can be divided into sites where potatoes followed a root crop and those where the previous crop was a cereal. Clearly, comparisons of this kind do not have the same validity as a direct experimental comparison of the different rotations within a single field, because farms with different rotations are likely to differ in other important respects, for example, in the number of livestock carried. That farming system may be at least as important as the immediately previous crop is suggested by results of the two experiments at Rothamsted comparing the effects of ley and arable rotations, one of the experiments being sited on an old arable field and the other following a very old permanent pasture. For the first 10 years, the nitrogen responses of the testing crops (wheat, potatoes, barley) were influenced much more by the long-term history of the fields than by whether or not the test crops followed 3 years of ley or 3 years of arable cropping.

Whilst one must be cautious, therefore, in attributing any differences in fertilizer response solely to previous cropping, the results do indicate how far there may be consistent differences in response between farms of different types. Moreover, the gross effects of region and soil type can be partly eliminated by basing the comparison on differences within soil series.

Table 12. *Mean yield and responses in relation to method of fertilizer application*

How fertilizer applied:	Yield at N_1 level	Response (tons/acre)		Yield without K	Response	
		N_2-N_1	N_3-N_2		K_1-K_0	K_2-K_1
'On the flat'	9.67	0.66	0.28	9.48	0.34	0.46
'Over ridges'	11.31	0.21	0.30	10.82	0.59	0.06

Note. For N the figures are for plots receiving P_2K_2 ; for K they are for plots receiving P_2 averaged over the three rates of N.

Table 13 shows the mean response to N for crops following cereals, those following roots and those following leys and permanent grass. The response to N was greater at each level and on both kinds of soil after cereals than after the other crops. On the lighter soils there was a response to N after cereals up to the highest level tested (1.2 cwt. N/acre) but only up to 0.8 cwt./acre after roots or leys. On the heavier soils there was a response after cereals up to 0.8 cwt. N/acre; whereas after roots or leys there was little response above 0.4 cwt. N/acre and high rates of N depressed yields substantially. Satisfactory comparisons of N response after short and long leys and permanent grass cannot be made, as these differences are associated with soil series and climate; taking the average of all centres the mean responses were almost the same for short and long leys.

These results indicate that differences in N response associated with type of rotation are likely to be of major importance both on the same farm and between farms on the same soil series. A similar result was obtained from analysis of a large series of sugar beet experiments (Boyd, Garner & Haines, 1957) in which the nitrogen value of leys or permanent grass to the beet crop was estimated to be about 0.4 cwt. N/acre. From Table 13 the difference in optima appears to be of the same order.

There is little indication that growers are aware of the importance of previous cropping and rotation. Surveys of fertilizer practice and the survey of maincrop potatoes (Potato Marketing Board, 1958) show that, within a district or county, there is virtually no difference, either between or within farms, in the manuring of potatoes according to previous crop.

Comparison with previous experimental results

The average level of response in this series of experiments may be compared with responses to the same dressings from pre-war experiments summarized by Crowther & Yates (1941), and other experiments done between 1941 and 1956 and summarized by Boyd (1961*a*) (Table 14). Despite the major changes in farming and, in particular, in potato husbandry and fertilizer use, the average responses to N and P fertilizer were of much the same order as those of the earlier experiments. Responses to K were substantially less, partly, perhaps, because increased fertilizer use has built up K levels in the soil and, in part, because some rather unresponsive soil series were chosen for the latest experiments. There is also some reason to think that the seasons were rather unfavourable to K responses; there were two bad 'blight' years (1958 and 1960).

Optimal dressings

Responses to each nutrient at near-optimal combinations of the other two nutrients are given in Table 15 for three groups of soils—sands and sandy loam soils, heavier soils and soils from the high-rainfall areas of Wales and Cumberland.

For N, the average response curves for the three groups of soils were similar in that the average yield rose to a maximum at between 0.8 and 1.0 cwt. N/acre and then decreased again; the corresponding optima at current prices were about 0.8–0.9 cwt. N/acre for the first two groups and 0.7 cwt. N/acre for Wales and N.W. Cumberland. There were substantial year-to-year differences in

Table 13. N response and previous cropping

Previous crop	(tons/acre)											
	Lighter soils						Heavier soils					
	No. of sites	Mean yield	Level of N			No. of sites	Mean yield	Level of N			No. of sites	Mean yield
			1-0	2-1	3-2			1-0	2-1	3-2		
Cereal	21	9.25	1.98	0.46	0.18	17	8.41	2.06	0.20	-0.03		
Roots	6	13.36	1.34	0.29	-0.10	6	11.26	1.57	0.04	-0.54		
Leys	21	10.18	1.49	0.23	0.03	11	9.92	1.06	-0.24	-0.63		

Table 14. Comparison with previous potato experiments

	No. expts.	Mean response (tons/acre)		
		0.8 cwt. N	1.0 cwt. P ₂ O ₅	1.5 cwt. K ₂ O
N.A.A.S. Expts. 1955-61	124	1.77	1.44	1.21
Earlier series 1941-56	112	1.75	1.36	2.00
Crowther & Yates 1900-40	200	1.98	1.16	1.86

response and because of severe 'blight' attacks in 2 years and the exceptionally dry summer of 1959 the particular set of years in which the experiments were done may have been rather unfavourable to N responses. Previous series of experiments in the years 1949-56 discussed by Boyd (1961*a*) appeared to have optima in the range 1.0-1.2 cwt. N/acre; this is the average optimum for sites following a cereal in the present series.

Average P responses were large in Wales and N.W. Cumberland, where most of the soils were low in P, and on the heavier soils of lowland England for which almost all soils were classed as low or medium in P; average responses were much less on the English sands and sandy loams which had many soils with satisfactory levels of soil P. The optimum at current prices lies beyond the highest rate tested, probably 1.0-1.5 cwt. P_2O_5 /acre for the heavier soils and for those sandy soils low in P, and more than 1.5 cwt. P_2O_5 /acre for Wales and N.W. England; for sands and sandy loams with satisfactory P levels the optimum was 0.5-1.0 cwt. P_2O_5 /acre, falling to 0.0-0.5 cwt. P_2O_5 /acre on soils high in P.

The three groups of soils also had very different K responses. The first level of K (0.75 cwt. K_2O /acre) gave 0.9 ton/acre extra yield on the sandy soils and light Fen silts and 2.4 tons extra yield on the soils from Wales and N.W. England. The heavier soils showed only small responses; few gave any increase in yield for dressings greater than 1.0 cwt. K_2O /acre and responses to lower rates were often worth little more than the price of the fertilizer. For the soils in high-rainfall districts and for most sands and sandy loams in England the optimum at current prices was probably of the order of 2.0 cwt. K_2O /acre, compared with 0.0-1.0 cwt./acre for heavier soils.

SUMMARY

Results are given of 124 factorial experiments testing N, P and K fertilizers for maincrop potatoes; the experiments were done by N.A.A.S. Soil Chemists in the years 1955-61. The experimental sites were in sixteen groups, corresponding to particular soil series or complexes.

There were substantial differences in mean yield and in response to the lower levels of P and K between soil series; the influence of soil was less at higher rates of application. Alternative methods of soil classification which appeared to be associated with response were texture, experiments on the lighter-textured soils showing higher responses to K; and depth of freely drained soil, soils with impeded drainage being associated with larger P responses. Responses to P and K were particularly large on soils in Wales and N.W. Cumberland.

For N, differences in response between soils were less important than differences from season to season; crops on the lighter-textured soils were rather more responsive to N. N response also varied with previous cropping, being greater after a cereal crop; after roots or leys on the heavier soils, yields decreased sharply at high levels of N.

For most of the heavier-textured soils and for sands and sandy loams deficient in P, the average optimal dressing was probably 1.0-1.5 cwt. P_2O_5 /acre (above the highest rate tested), and possibly more than 1.5 cwt. for soils from Wales and Cumberland; for sands and sandy loams with medium levels of soil P the average optimum was 0.5-1.0 cwt. P_2O_5 /acre, but not more than 0.5 cwt. P_2O_5 /acre on soils high in P. The heavier soils generally showed only small responses to K, whereas soils from Wales and Cumberland and most sands and sandy loams had optima of the order of

Table 15. *Mean responses to each nutrient at near-optimal levels of the other nutrients*

Nutrient level (see below)	(tons/acre)		
	Lowland England		Wales and N.W. England
	Lighter soils	Heavier soils	
N_2-N_1	0.68	0.46	0.25
N_3-N_2	-0.02	-0.29	-0.32
P_1-P_0	0.77	0.99	1.90
P_2-P_1	0.53	0.54	1.05
K_1-K_0	0.94	0.31	2.40
K_2-K_1	0.57	0.08	0.67
Fertilizer rate (cwt. N, P_2O_5 and K_2O /acre)			
	Level 1	Level 2	Level 3
N	0.40	0.80	1.20
P_2O_5	0.50	1.00	—
K_2O	0.75	1.50	—

2.0 cwt. K₂O/acre. For N, the average optimum was only about 0.8 cwt. N/acre, rather less than previous estimates, possibly because of seasons particularly unfavourable to N responses.

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APPENDIX

Description of soils

Ref. nos.	Series name (if any)	British classification	Parent material	Surface soil	Subsoil	Drainage	Special features	Type of farming
N/1	'Warp' soils	Ground water gleys	2nd Terrace Marine alluvium	10 in. dark brown fine sandy silty loam, high in organic matter. Stoneless	Yellow brown fine sandy silty loam, stoneless, laminated	Freely drained to 10 in.	Weakly structure below surface. Productivity limited by lack of artificial drainage	Predominantly grassland with short arable breaks
N/2	Croxdale Complex	Surface water gleys	Carboniferous (Coal Measures) drift	8-12 in. dark grey brown sandy loam to loam, sub-angular to crumb structure. Rusty mottling at certain sites. Some angular and rounded stones	12 in. yellowish brown coarse sandy clay loam with grey and rusty mottling, prismatic structure, tenacious, many stones, over dark brown sandy clay loam with much grey and rusty mottling. Many stones	Freely drained to 8-12 in.	Relatively easy to cultivate. In wet seasons drainage is a limiting factor	Predominantly grassland (dairying) with arable breaks
N/3	Holme Moor Complex	Degraded podsollic soils with gleyed subsoils	Post-glacial sands of Jurassic and Triassic origin	10 in. dark dull grey loamy sand, weak granular structure, stoneless	5 in. dark dull grey loamy sand, tendency to single grain structure. This represents zone of leaching. 9 in. yellowish brown to greyish brown sand with humus and iron staining (B horizon) over brownish yellow sand with light grey and brown streaks, rusty mottles, essentially single grain structure. Clay bed at variable depth	Freely drained to horizon just above clay bed	Soils easy to cultivate. Although light in texture the underlying clay bed maintains a water table within the range of plant roots. Humic iron pans can affect drainage and rooting in places. Surface soil subject to blowing in spring. Organic matter distribution improved with cultivation	Arable with short leys

Y1/4	Blacktoft and Salt-marsh Series	Brown earths of high base status with gleying	Alluvium (artificial or natural warp)	12-15 in. warm brown to dark greyish brown loam to silty clay loam. Crumb or laminated structure well developed, calcareous, stoneless	Below 15 in. warm brown to pale brown clay loam to silty clay. Laminated except in heavier-textured soils which have well developed columnar structure. Calcareous, stoneless. Rusty and pale grey mottling sometimes present. In a few instances warp lies over original topsoil derived from lacustrine clay at 30 in. while in others peat is present at 36-60 in.	Freely drained to 15 in.	Cultivations usually deep. Tilth dependent on frost action. Dries out rapidly in spring, essential to plant potatoes as soon as ridges are drawn	Predominantly arable
EM/5	'Warp' soils	Ground water gleys (over peat)	Alluvium (artificial warp)	8 in. greyish brown silty loam to silty clay loam. Stoneless	8 in. grey brown, brown and yellowish brown silty loam to silty clay loam, slightly mottled, over variable depth of grey, brown to yellowish brown silty clay, mottled, laminated, over peat at 24-60 in.	Impeded below 8 in. Drained by pumping. Liable to flooding from tidal River Trent	A peat bog reclaimed by warping and pump drainage. Usually, fairly high organic matter prevents excessive 'capping', nevertheless timing of cultivations is critical	Arable
EM/6	Fen soils (degraded peats)	Ground water humose gleys	Degraded peats over alluvium	10 in. dark grey or grey brown peaty silty clay loam. Stoneless	8 in. dark grey, brown or mottled brown with yellowish brown silty clay over mottled grey-brown, brown and yellowish brown silty clay	Natural drainage impeded below 10 in. Drainage depends on pumping into artificial rivers	Incorporation of remaining peat with underlying silty clay has formed highly productive soils. Structure stabilized by organic matter. On some heavier soils cultivations can be difficult	Arable

Ref. nos.	Series name (if any)	British classification	Parent material	Surface soil	Subsoil	Drainage	Special features	Type of farming
EM/7, WM/8	Newport and Bridgnorth Series	Brown earths of low base status	Triassic sandstone drifts	10 in. brown or grey brown loamy sand. Pebbly in Bridgnorth Series	10-20 in. brown or reddish brown loamy sand over reddish sand (Newport) or red sandstone (Bridgnorth). Stony in Bridgnorth Series	Freely or excessively drained	Soils very sandy and low in organic matter. Liable to drought in summer. Very easy to cultivate at any time of year	Arable with short leys. Soils very suitable for irrigation
WM/9	Evesham Series	Calcareous soils with gleying	Lower Lias	10 in. dark grey brown calcareous clay loam to clay	20 in. olive brown calcareous clay often passing into grey clay with rusty mottles. Below 30 in. grey highly calcareous clay, occasional thin limestone bands	Freely drained to 10 in. Seasonally, percolation of water is slow	Difficult to cultivate when wet. Forms an excellent frost tilth	Predominantly grassland. Cereals are the main arable crop
E/10a	Light Silts	Ground water gleys	Marine alluvium	18-24 in. loamy very fine sand to very fine sandy loam	Considerable depth (often at least 42 in.) of very fine sandy loam, laminated, occasionally slight gleying with some grey mottling and iron streaking from 18 in.	Freely drained to 18-24 in.	Low in organic matter, weak structure, liable to surface capping, stoneless. Highly productive, easily cultivated	Arable
E/10b	Medium Silts	Ground water gleys	Marine alluvium	12-18 in. silty loam to silt loam	Variable depth (usually considerable) of silty clay loam to silty clay, laminated, slight to moderate gleying with grey mottling and grey and rusty streaking on occasions	Freely drained to 12-18 in.	Usually low in organic matter, fine angular structure, stoneless. Highly productive, easily cultivated	Arable
SE/11	Faversham Series	Brown earths of high base status	Brickearth	10-12 in. brown very fine sandy loam	Red brown very fine sandy loam becoming slightly heavier in texture with depth	Freely drained	Soils 'cap' on surface when exposed to heavy rain	Arable with short leys. Much intensive horticulture including fruit growing

SE/12	Curtisden Series	Brown earths of low base status with gleying	Hasting Beds (Tunbridge Wells and Ashdown Sands)	9 in. grey brown very fine sandy loam	11 in. yellowish brown very fine sandy loam with much fine rusty mottling and many small iron/manganese concretions. Below 20 in. yellowish brown very fine sandy loam with common medium to large rusty mottles. Becomes very compact with depth	Freely drained to 9 in.	Drainage is slow because of high fine sand and silt fractions and compaction at depth. Liable to 'cap' on surface. When cultivated under suitable conditions will produce a good tilth	Mainly grass-land (dairying) with arable breaks
A/13, B/14	Penrhyn/Denbigh Complex (including Corwen Series)	Brown earths of low base status	Ordovician or Silurian Shales or drift derived from them	8-14 in. brown to reddish brown loam to silt loam containing abundant shale fragments	6-8 in. yellowish brown loam to silt loam containing abundant shale fragments. The colour becomes paler with depth and passes into weathered shale material at 14-22 in. Permeability may be reduced by a compact layer	Freely drained to 24 in.	Easily cultivated soils, friable, strongly developed sub-angular and crumb structure	Mainly live-stock. Long leys with short arable breaks
B/15, C/16	Castleton Series	Brown earths of low base status	Old Red Sandstone drift	8-12 in. reddish brown sandy loam, occasional stones	Below 12 in. reddish brown sandy loam becoming more stony and compact with depth	Freely drained to 24 in.	Normally easily cultivated and because of the high fine sand and silt content these soils tend to 'cap' on the surface under prolonged arable cultivation	Generally as for Penrhyn/Denbigh Complex. Occasional longer arable breaks in South Wales
Ref. nos.	Series name (if any)	Mean pH	Mean organic matter (Finsley)	Mean p.p.m. P (Olsen)	Mean p.p.m. K (Morgan)	Mean rainfall (in.)		
N/1	'Warp' soils	5.6	5.3	19	77	Annual	Apr.-Sept.	
N/2	Croxdale complex	6.4	5.6	21	62	30-35	15-20	
N/3	Holme Moor complex	6.4	3.9	25	74	25-28	12-14	
YL/4	Blacktoft and Saltmarsh series	8.0	3.7	23	92	22-25	13-14	
EM/5	'Warp' soils	8.2	4.1	25	161	20-25	12-14	
EM/6	'Fen' soils	6.2	15.8	24	250	22-28	11-12	
EM/7, WM/8	Newport and Bridgnorth series	6.9	2.3	29	60	22-28	11-12	
WM/9	Evesham series	7.6	6.1	10	124	25-30	12-15	
E/10a	Light silts	7.5	2.8	54	131	22-25	12-13	
E/10b	Medium silts	7.1	4.2	31	224	20-22	11-12	
SE/11	Faversham series	7.4	2.5	40	78	20-22	11-12	
SE/12	Curtisden series	6.3	3.6	23	57	22-28	10-11	
A/13, B/14	Penrhyn/Denbigh complex	6.1	6.7	20	31	28-35	11-13	
B/15, C/16	Castleton series	6.2	4.0	25	68	30-60	15-20	