THE FERTILIZER REQUIREMENTS OF SUGAR BEET

By D. A. BOYD, H. V. GARNER and W. B. HAINES

Rothamsted Experimental Station, Harpenden

(With Two Text-figures)

1. INTRODUCTION

Unlike some continental countries, which have series of simple manurial trials on the main farm crops covering hundreds, and in some cases thousands, of trials, this country can boast very few major series of trials on any one crop. Whilst sufficient trials have been carried out in Great Britain to indicate broadly the fertilizer requirements of each of the more common crops, our knowledge of the extent to which these requirements differ according to district and soil type depends as much on informed observation as on experimental results. Thus, Crowther & Yates (1941) in summarizing the results of all available experiments on the main arable crops carried out in the United Kingdom between 1900 and 1940 were unable to do more than subdivide the experimental sites into three broad regional groups.

Much the greater part of the experiments carried out both in this country and on the continent have been simple trials testing only two levels (usually presence and absence) of a fertilizer nutrient or of combinations of nutrients. Trials with three or more rates of one of the major nutrients, usually with a basal dressing of the other two, are fairly common on the continent but less common here. Neither of these types of trial can give more than an approximate answer to the question of what is the optimal (most profitable) combination of nutrients to apply to a crop; this information can only be obtained from more complex experiments in which at least three levels of the three major nutrients are tested alone and in combination. Sugar beet and potatoes are the only crops on which substantial numbers of trials of this kind have been undertaken, those on sugar beet, with which this paper is concerned, forming the largest body of manurial experiments of uniform design undertaken on any crop in this country.

The experiments were carried out for the Sugar Beet Research and Education Committee by the Chemistry and Field Experiments Departments of Rothamsted Experimental Station, the Agriculturalists attached to the sugar-beet factories and the County Agricultural Organizers. 360 experiments were carried out in the years 1933–49. Full reports on the results were submitted annually to the parent committees, and numerous articles by the late Dr E. M. Crowther and others gave farmers the main lessons learnt from the series; however, no detailed account of the results has previously been published. The experiments were undertaken primarily to test the ability of different methods of soil analysis to predict the fertilizer responses of sugar beet, and this aspect of the data will be discussed fully in a later paper. The present paper sets out to use the experimental results as a guide to what are the optimal dressings of fertilizer for sugar beet.

2. DESCRIPTION OF EXPERIMENTS

Apart from a preliminary year in which nitrogen, phosphate and potash were tested at two levels only, the experiments fall into two main series. Series I consists of 156 experiments carried out in the years 1934–39; these were of the standard $3 \times 3 \times 3$ design in three blocks of nine plots each. The treatments tested were:

Nitrogen (N): 0, 0·4 and 0·8 cwt. N per acre as sulphate of ammonia.

Phosphate (P): 0, 0·5 and 1·0 cwt. P_2O_5 per acre as superphosphate.

Potash (K): 0, 0·6 and 1·2 cwt. K_2O per acre as muriate of potash.

Series II ran from 1940 to 1949 in which period there were 204 experiments testing N, P, K and salt (S). The intermediate levels of the three major nutrients given above were omitted from this series, and salt was also at two levels only (none and 5 cwt. per acre). The design was a standard 2^4 in four blocks of eight plots each, the interaction NPKS being confounded. From 1944 onwards a further factor, Borax, at levels of 0 and 20 lb. per acre, was added to the second series, the arrangement of the experiment in four blocks of eight plots remaining unchanged with the interactions PKB, NSB and NPKS confounded.

The geometric mean of the standard errors per plot over all the experiments was under 10% of the mean yield of total sugar; this indicates that the experiments were carried out with reasonable care and accuracy. In only three of the experiments was the standard error per plot greater than 20% of the mean yield; all three were exceptionally phosphate deficient and two of the sites were acid. The number of occasions on which an experiment had to be abandoned due to crop failure, etc., was very small indeed.

The weight of dirty roots, and, in most cases, of tops, was obtained in the field, whilst samples handled by the factories provided the dirt tare and sugar percentage from which the results could be calculated in terms of total sugar. Soil samples taken from the experimental sites provide soil phosphate and potash values by five different methods, together with estimates of pH, free $CaCO_3$, air-dry moisture, loss on ignition, saturation capacity, organic carbon and nitrogen. A full mechanical analysis was carried out for each centre in the years 1936–46. Notes on the growing crop, weather conditions during growth and on previous cropping and manuring are also available.

Experiments were carried out in each of the eighteen factory areas, of which seventeen are in England and one (Cupar) in Scotland; the location of the English factories is shown in Fig. 1. From 1940 onwards experiments were also carried out in the southern counties of England, referred to subsequently as the 'Southern' Area. In addition, Mr H. W. Gardner, until lately of the Hertfordshire Institute of Agriculture, Oaklands, St Albans, carried out experiments in Hertfordshire; this group

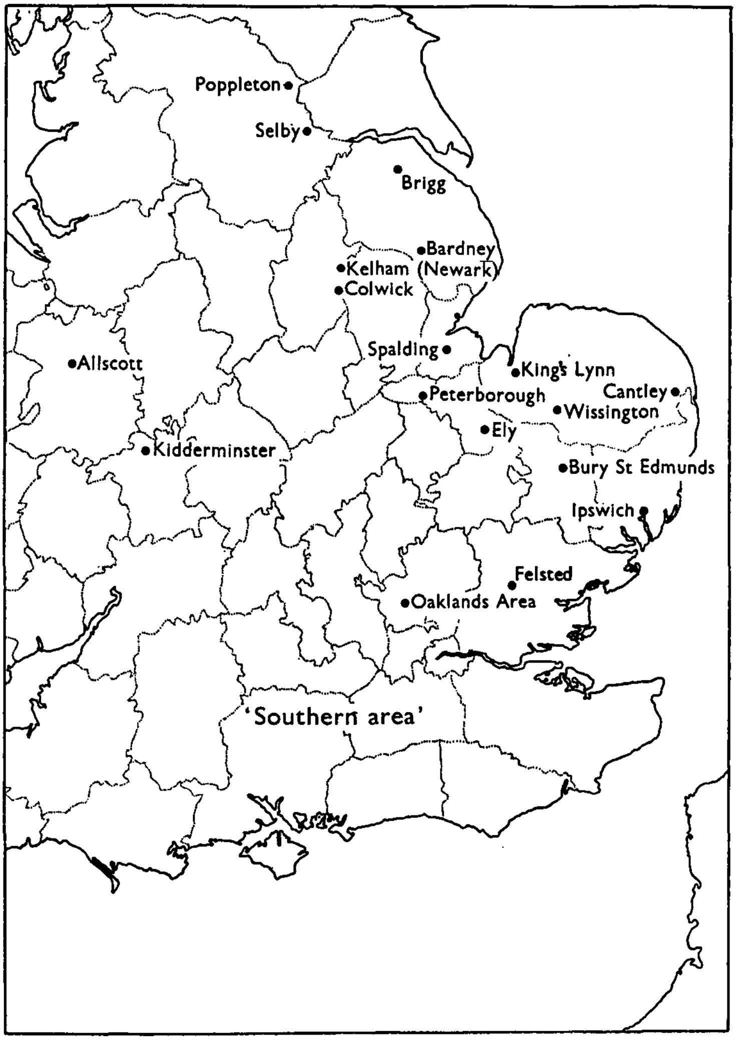

Fig. 1. Location of sugar-beet factories.

of experiments is referred to as the 'Oaklands' Area. In each factory area there was normally one experiment annually, but in the earlier years some factory areas were represented by two or even three centres.

3. VALUE OF EXPERIMENTS AS A GUIDE TO MANURING

(1) *Choice of site.* In attempting to use the experimental results as a guide to how sugar beet should be manured to-day, we must bear in mind that they were not carried out solely for this purpose, but to investigate the relationship between soil analysis and crop response, and this has to a considerable extent influenced the choice of sites. The responsibility for first choice of the experimental sites rested with the fieldmen of the factory area concerned. As might be expected, the fieldmen at first tended to choose better-than-average sites, for the keen farmer with land in good heart is usually more willing to provide facilities for this type of work than his less progressive neighbour. This may well have been mainly responsible for the small responses to fertilizers obtained in a preliminary year's experiments in 1933 and in 1934. There is evidence that subsequently the fieldmen in most factory areas were more careful to choose responsive sites; indeed twenty-eight, or about 10% of the sites, were recorded as having received no manure for many years, or as being on farms recently taken over after a period of poor management. In the 1930's such a fraction would not be unduly high for farms as a whole, though even at that time it might be rather high for sugar-beet-growing farms; to-day there can be very few such fields coming into sugar beet. A certain amount of selection was also exercised by the Chemistry Department, Rothamsted, since after the first few years the fieldmen were asked to provide several sites from which one was chosen at Rothamsted after comparison of the soil samples. The aim of this selection was to widen the range of soil P and soil K status under experiment. In the main the selection operated in the direction of lower status and higher responses, but it may also have tended to reduce differences between factory areas, since in an area with soils mainly low in potash the tendency would be to select any high-potash site offered and vice-versa.

Choice of site was also affected from year to year by the decisions of a conference held early each year to discuss the results of the previous season's experiments; one effect of these discussions was that in 1939, following a dry season in which beet suffered seriously from drought, a much higher proportion of the sites than usual were located on heavy loams or clays; a similar excess of heavy soils occurred again in 1948, also following a very dry season.

The distribution of centres within each factory area varied considerably. Some factories, such as Colwick, which had centres in each of five counties, spread their net widely, whilst others concentrated their sites on one or two small districts. Thus, for Felsted, most of the centres lie within a five-mile radius of the factory, and all are on soils derived from a single geological formation, the Chalky Boulder Clay.

It is clear from the foregoing that even at the time the experiments were carried out, the experimental sites were not a random sample of sugar-beet-growing farms, and that, in particular, they probably contained too high a proportion of P- and K-deficient fields. In work of this kind some unconscious selection of sites is inevitable; wherever such data are to be used to advise farmers on manuring, the experimental work should be accompanied by a survey of the nutrient status of the soils on a random sample of fields under the crop in question. In this way the experimenter can ensure that the centres chosen are representative of the soils or district, and it will be then clear to him what weight should be attached to any experiments carried out on specially deficient sites.

(2) *Changes in husbandry and environmental conditions.* In deciding how far the experiments can be considered to be representative of present-day conditions on beet-growing farms, we must also take account of the substantial changes in farming practice in general, and beet growing in particular, which have been taking place since the series were begun in 1934. Of particular importance in relation to these experiments is the four-fold increase in consumption of each fertilizer nutrient in the past twenty years. Phosphate consumption rose to particularly high levels around 1950, and there is no doubt that the phosphate status of soils has materially improved during this period, so much so that experimenters now find it extremely difficult to obtain P-deficient sites for trials on arable crops. In spite of this, the mean values of available P for the experimental sites show no consistent trend over the years, suggesting that there may have been increasing selection of sites in the later years which compensated for the influence of the general improvement. The mean annual values for available K show a decline which is formally significant but which is very largely due to high values in the first two years and very low values in the last two years.

Fig. 2 includes other factors for which quantitative data are available; sowing date and plant population were recorded for practically every experiment, and their annual mean values are presented. The data for winter and summer rainfall are the mean rainfalls per month for the five months November–March and for the five months May–September; the rainfalls used were an average over the following six stations: York, Cranwell (Lincs), Birmingham, Sprowston (Norfolk), Cambridge and Rothamsted (Herts). Estimates of percentage loss of crop due to virus yellows infection (Hull, 1953) have also been included.

The annual means of the main effects of N, P and K are also shown in Fig. 2. Apart from the main effect of N, none of the main effects and interactions show a significant linear trend. The decline in the response to N, however, has been one of the more remarkable features of the experimental results. In the period 1934–41 the annual mean response to nitrogen was substantial in each season and the average response was 5·4 cwt. sugar per acre. In the rest of the period there were several years with mean responses under 2 cwt. sugar per acre (1943, 1944, 1948, 1949) and the average 1942–9 was only 2·8 cwt. sugar per acre. Had no other information been available it might well have been wondered whether such a reduction in response was likely to be permanent.

A similar trend is also evident for some of the uncontrolled factors included in Fig. 2. For example, there has been a definite change in practice in respect of date of sowing during the period under review. In the first five years, the mean sowing dates were all about the beginning of May, quite independently of winter rainfall which was very low in 1933 and 1934. Thereafter the mean date was advanced fairly steadily to reach mid-April for the mean of the last five years in spite of the inclusion of that quite exceptional season, 1947. A similar steady trend over the years is shown by the mean plant populations, which were well over 25,000 plants per acre in the pre-war years but fell to little over 20,000 plants from 1945 to 1948. Both these trends appear to be still in progress.

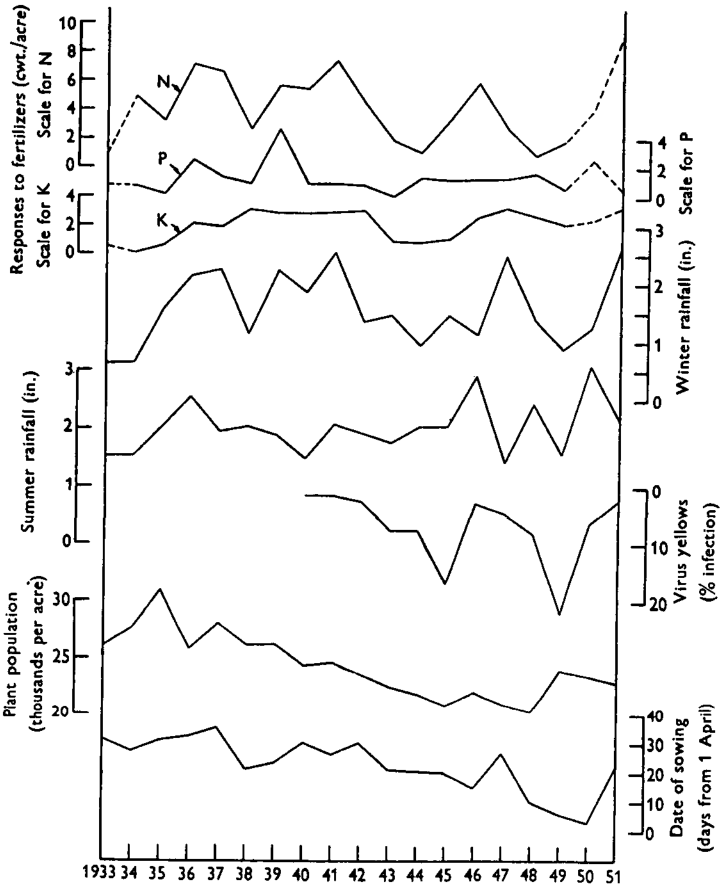

Fig. 2. Annual means of responses to fertilizers and of uncontrolled factors.

To obtain further information on how far the trend in the nitrogen responses was merely due to the chance occurrence of a run of seasons favouring low responses, data for three additional years have been included. For 1933 we have the results of a preliminary year of experiments with N, P and K at two levels only, which led up to Series I in 1934, whilst for 1950 and 1951 there is a series of $3 \times 3 \times 3$ experiments organized by Dr N. H. Pizer, Soil Chemist for the Eastern Province of the N.A.A.S.; we are indebted to him for permission to use the mean responses for these two years. The response curves given by Series I have been used to adjust them to the levels of dressing used in the Factory Sugar Beet Series. It happens that both years were seasons with good nitrogen responses, 1951 being a year of exceptional responses both on sugar beet and other crops, whereas in 1933 the average response to nitrogen was very small indeed. These additional values make it probable that the falling-off in nitrogen response in the period of 1934–49 can be fully explained by the large year-to-year variations in response; the linear term for slow changes for the period 1933–51 is very small.

For the period 1933–51 there is a marked association between winter rainfall and nitrogen response ($r = +0{\cdot}71$), which alone accounts for about half the variance of the responses. One inch above (or below) the mean rainfall per month in this period was sufficient to increase (or decrease) the nitrogen response by $2{\cdot}54 \pm 0{\cdot}48$ cwt. sugar per acre. A similar correlation of winter rainfall with response was found by Fisher (1924) for Broadbalk (wheat), Rothamsted, and attributed by him to the effect of rainfall in leaching out nitrates from the soil; this seems the simplest explanation to offer for these results on sugar beet also.

There is some association between the mean annual responses to nitrogen and sowing date ($r = +0{\cdot}33$), but sowing date is also associated with the amount of winter rainfall ($r = +0{\cdot}34$) and, after taking out the rainfall effect, sowing date appears of minor importance. There is also a small positive correlation of nitrogen response with summer rainfall ($r = +0{\cdot}25$) and the three factors together account for 63 % of the total variance of the annual mean responses to N.

Information on virus yellows infestation is available only for the latter part of the experimental period, but is interesting in showing a close relationship with both winter rainfall and nitrogen response. Experiments described by Hull & Watson (1947) have shown that one of the effects of virus yellows infection is to reduce fertilizer responses, and, because of this, the incidence of virus yellows had been widely assumed to be the main factor responsible for the sub-normal nitrogen responses in 1943 and 1944 and 1947–9. For the twelve years for which records are available the negative correlation of percentage loss due to virus yellows with nitrogen response is of much the same magnitude as the positive correlation of winter rainfall and nitrogen response. The four seasons with the largest nitrogen responses certainly had the least virus damage, whilst 1949 had high infection and low response. On the other hand, 1945 had high infection but a normal response. Indeed, it could be argued that winter rainfall might have affected responses not so much by virtue of its direct effect on soil conditions as by its influence on the numbers of the aphid vectors surviving the winter, were it not that wet winters might have been expected to assist the survival of the aphids rather than the reverse.

Whatever the ultimate cause of the variation in responses, it is a point of some importance that the winter rainfall is known before the crop is sown, whereas the level of virus is not. Before basing practical recommendations on such a result, however, confirmation from an independent series of experiments would be valuable.

Year-to-year variation in response (total sugar) was considerably smaller for phosphate and potash than it was for nitrogen. The mean annual effect of phosphate showed no perceptible trend and no correlation with rainfall and sowing date. The inclusion of the values for 1934, 1950 and 1951 accentuates the trend in the effect of potash on total sugar yield, and this approaches significance for the period 1934–51. The potash responses, like those due to nitrogen, were closely associated ($r = +0{\cdot}66$) with winter rainfall, which accounted for about half the variance of the responses. Consequently there is also a positive correlation between the seasonal means of the main effects of N and K, although, as will be shown later, there is a strong negative correlation between their means for factory areas.

4. EFFECTS OF FERTILIZERS IN THE ABSENCE OF SALT

(1) *Mean response over all sites.* Table 1 gives the general average of the mean yields and of the main effects and interactions of nitrogen (0·8 cwt. N per acre), phosphate (1·0 cwt. P_2O_5 per acre) and potash (1·2 cwt. K_2O per acre) for all 328 centres on mineral soils 1934–49 in the absence of salt. The estimates of error are derived from the Factory Areas × Seasons interaction; for reasons described later it seems probable that this will tend to give an overestimate of the true error. The experimental errors, due to plot variability, etc., formed rather more than half of the total variance of the interactions, about one-third for the main effects of P and K, and one-eighth for the main effect of N. (Throughout the paper the capital letters N, P and K will be used both in referring to the main effects of the nutrients and to the nutrients themselves.) The mean response to

nitrogen, averaged over all other treatments, was just under 10% of the mean yield; the mean responses to phosphate and potash were smaller, being respectively 4 and 5% of the mean yield. All the interactions are positive, NK being the largest. The second-order interaction NPK was not calculated for the 3 × 3 × 3 experiments carried out up to 1939, and in all subsequent calculations its value has been assumed to be zero for those years, giving an average value for 1934–49 of 0·08 cwt. per acre. For the years 1940–9 salt was included as an additional factor, and in obtaining the estimate of NPK shown in Table 1 the four-factor interaction NPKS has been assumed to be zero.

19% of the mean yield. It should be particularly noted that the two-factor interactions do not enter into this expression.

(2) *Effect of uncontrolled factors.* The 328 experiments on which Table 1 is based form the whole of the available data for mineral soils in the years 1934–49. On a substantial number of the sites, however, there were special conditions of manuring, cultivation or previous cropping, and these sites have been separated from the remainder; the average of the main effects and interactions for these sites are given in Table 2.

In considering the influence of the different factors shown in Table 2 it must be borne in mind not only

Table 1. *Main effects and interactions over* 328 *centres on mineral soils* 1934–49 (*cwt. sugar per acre*). (*Plots without salt*)

N	3·73 ± 0·24	NP	0·26 ± 0·11	NPK	0·14* ± 0·09
P	1·55 ± 0·15	NK	0·77 ± 0·12		
K	2·13 ± 0·15	PK	0·17 ± 0·12	Mean yield	39·51

* 1940–9 only; for 1934–9 values assumed to be zero (see text).

Table 2. *Influence of various uncontrolled factors on fertilizer responses*

	No. of centres	Main effects and interactions (cwt. sugar per acre)						
		N	P	K	NP	NK	PK	NPK
Farmyard manure to beet	36	2·48	0·98	1·60	0·85	0·32	−0·50	0·11
After old grass*	16	−1·13	1·94	2·32	−0·50	0·80	−0·89	−0·38
Deep-ploughed†	14	7·02	3·19	2·18	−0·28	1·06	0·61	0·16
Fields recently taken over‡	19	2·61	4·30	1·14	0·08	0·69	0·68	0·07
Acid sites (pH below 5·8)	10	2·20	5·04	4·04	0·78	2·15	1·31	0·43
Centres not included above	219§	4·21	1·07	2·20	0·30	0·74	0·30	0·08

Notes:

* Old grass or long ley ploughed up within 5 years of beet crop.
† Including only those sites where raw subsoil had been brought to the surface.
‡ This group included fields stated to have been recently taken over in a poor or derelict condition and fields on which no manures had been applied for at least 3 years.
§ Fourteen centres on which two or more of the factors occurred have been excluded from this table.

Using the above interactions, the effects of each nutrient alone and in combination with the other two are shown below for comparison with the mean responses given in Table 1:

	Response (cwt. sugar per acre)	
	Alone	In presence of other nutrients
Nitrogen	2·78	4·84
Phosphate	1·20	2·06
Potash	1·27	3·15

The effect of each nutrient was substantially increased when it was used in the presence of the other two nutrients; the effects of nitrogen and phosphate were almost doubled and that of potash more than doubled.

The combined effect of the three nutrients at the above rates is given by the sum of the three main effects plus the three-factor interaction NPK: $3·73 + 1·55 + 2·13 + 0·08 = 7·49$ cwt. sugar per acre or

that the averages are based on only small numbers, but that any of the factors considered may be associated with other factors on which we have no information, but which may themselves substantially influence the response to fertilizers. Thus the availability of farmyard manure is associated with differences in farming type, which is reflected in differences in cropping and manurial practice, and consequently in soil nutrient status. The interpretation of this kind of data is, in fact, subject to much the same uncertainties as arise when we attempt to estimate 'effects' from survey data. Whilst a very full description of the experimental site, with previous cropping and manuring and other relevant information, was available for almost all centres, we cannot be certain that all sites in the above categories have been recorded as such, although it seems unlikely that substantial numbers have been overlooked. It would have been valuable if in later years there had been an equally careful record of the incidence of virus yellows, but observations of this kind on the growing crop and at harvest were not recorded systematically.

There was a small number of acid sites, most of which gave remarkably high responses to phosphate and potash. Compared with the mean of the 219 centres not specially differentiated, the average of the main effects and interactions, other than N, are very high for these sites.

In general, fields which had been dunged in preparation for the beet crop were avoided, but this was not always possible, especially in some districts where it is normal practice to dung for beet. Smaller responses were usually obtained on the dunged sites, but the average reductions in response shown in Table 2 are not in agreement with those of Crowther & Yates (1941), who found that farmyard manure has only a small effect on the response to nitrogenous fertilizers, whilst substantially reducing the response to phosphate and potash.

Sites which had been under a long ley or old grass within 5 years of the experimental beet crop formed a group sharply distinguished from the remaining sites, almost all showing a negative response to N, in spite of the fact that, in most cases, the beet crop was at several years remove from the original ploughing-up. It has long been recognized that the chief component of the 'stored-up fertility' of much of the grassland ploughed up during the last war was in fact its reserves of nitrogen and organic matter. It is no doubt for the same reason that in an experiment on Highfield, Rothamsted, following old grassland ploughed in 1948–9, markedly lower nitrogen responses of wheat and potatoes are still being obtained compared with those from a parallel experiment (on another part of the same farm) sited on old arable land. Three of the sixteen experiments deserve special mention, since they not only give the largest negative responses to nitrogen but negative responses to phosphate also. Two of these were in fields which had been heavily stocked and manured on a Farm Institute, and the third was one of the well-known fattening pastures near Market Harborough. Clearly these sites, and perhaps others, were by no means typical of the old grassland being ploughed at that time. Certainly only one of the seventeen sites showed a substantial positive response to phosphate in the presence of N and K, and this was on a site shown by soil analysis to be extremely deficient, and in an area noted for phosphate deficiency.

Depth of ploughing was not recorded for all sites, but when a field had been deep-ploughed this was usually noted; in particular, the field notes frequently recorded that a site had been deep-ploughed for the first time and where unweathered subsoil had been observed on or near the surface. Table 2 shows that such sites gave substantially greater nitrogen and phosphate responses than sites not newly deep-ploughed. Whilst there is experimental evidence of the high phosphate requirements of some deep-ploughed sites, there have been very few tests of the value of nitrogen in these conditions. Certainly subsoil is usually markedly deficient in organic matter, and it may not be entirely out of place to note that nitrogen-hunger is much the most serious nutrient deficiency of crops grown on the opencast coal and ironstone sites.

The remaining group of experiments in Table 2 consists of those noted as being on farms recently taken over after allegedly poor farming together with nine fields specifically noted as having received no farmyard manure or fertilizer for at least 3 years preceding the beet crop. The phosphate response was markedly higher on these sites, whilst there was some reduction in the response to nitrogen and potash.

(3) *Differences between factory areas*. After removing the sites specially differentiated in Table 2, and adjusting for seasonal variation, differences between factory areas for the remaining 219 centres are on the whole fairly small (Table 3). Tested against the error obtained from variations within factory areas, only potash shows significant differences between factory areas. The selection of sites was by no means a random one, however, and must have much exaggerated the variation within factory areas. Indeed, for nitrogen and for phosphate in the presence of other fertilizers, the variation between factory areas would be judged significantly subnormal.

The main effect of P is small in all factory areas, and if, as is commonly done, the value of this nutrient were judged solely by the magnitude of its main effect it would be dismissed as unnecessary for sugar beet except under the special circumstances indicated by Table 2. Since, however, all three fertilizer nutrients are normally applied to sugar beet, it is more relevant to farm practice to consider the effect of omitting phosphate from a complete fertilizer (Table 4). For this purpose the appropriate expression in terms of main effect and interactions is P + NP + PK + NPK, or in terms of treatments NPK − NK. Since the experimental errors form only a small part of the variation from centre to centre within factory areas, the loss of accuracy by comparing treatments involving only pairs of plots instead of using all plots as with the main effects is also fairly small.

For phosphate the only noteworthy feature is the contrast between the northern and western areas and the remainder. In the north and west the phosphate responses were either so small as to be uneconomic (Brigg, Colwick, Newark, Selby) or sufficient to justify only a small dressing of fertilizer (Allscott and Kidderminster, Bardney, Poppleton); of the East Anglia and Fenland Areas, King's Lynn and Wissington and the Fenland centres had average responses of over 2 cwt. sugar per acre, with Bury, Cantley and Ipswich having average responses of 1·5–2·0 cwt. sugar per acre. In the absence of potash there were substantial responses to phosphate by the Chalky Boulder Clay centres of Felsted, Ipswich and Bury. The Oaklands area failed to give an economic return from phosphate.

For potash, differences between centres were highly significant whether we consider the main effect or the response to potash with other fertilizer. Excluding the one centre (Chalky Boulder Clay soils) where, on the average, no response to potash was obtained, all areas show a substantial return from potash manuring, ranging from 2·0–2·5 cwt. sugar per acre for Bardney, Brigg (in absence of phosphate), King's Lynn and Newark (in absence of phosphate) to over 5 cwt. sugar per acre for Colwick, Ipswich (excluding Chalky Boulder Clay soils) and Oaklands. The negative or zero potash responses for the Chalky Boulder Clay soils of the Felsted, Ipswich and Bury factory areas were very consistent from centre to centre; for other clay loams and heavy loams included in the series normal potash responses were obtained.

For nitrogen differences in response between factory areas were relatively small. The responses in the presence of K were particularly uniform, due to the negative correlation of N and NK.

The effects of fertilizers on thirty-two fen peat soils are also summarized in Tables 3 and 4. The main effect of nitrogen was small and positive, but there was a consistently negative NK interaction, and the combined response to all three nutrients was less than the response to P and K alone. In the absence of nitrogen there were substantial responses to phosphate and potash, both being greater than the mean value for all mineral soils.

The main effects and interactions for yield of tops in tons per acre are given for all sites in the Appendix. The only effect of any importance is that of nitrogen for which the mean response over all other treatments was 2·72 tons per acre (2·98 tons in presence of P and K). There are no large differences between factory areas and no obvious association between responses of tops and of sugar for different areas.

Table 3. *Main effects and interactions by factory areas**

Factory area	No. of centres	Cwt. sugar per acre N	P	K	NP	NK	PK	NPK
Mineral soils:								
Allscott and Kidderminster	17	5·00	0·98	3·78	0·44	0·24	0·29	−0·06
Bardney	12	4·90	0·19	1·92	1·05	0·03	0·42	0·02
Brigg	16	5·38	0·70	1·19	0·39	0·76	−0·56	0·20
Bury†	14	4·89	1·39	2·30	0·31	1·51	0·26	−0·11
Cantley	14	2·67	1·85	2·78	0·16	1·55	0·01	−0·34
Colwick	11	2·49	1·81	5·18	−0·04	1·55	−0·26	−0·16
Felsted†	16	6·16	1·28	1·12	0·94	−0·53	−0·72	−0·28
Ipswich†	9	3·87	0·61	3·56	0·24	0·93	0·92	0·22
King's Lynn	10	3·15	1·65	0·67	−0·25	0·98	0·66	−0·02
Newark	13	4·32	0·84	1·95	−0·74	0·25	−0·56	0·24
Oaklands	13	2·46	0·16	3·62	0·36	1·25	0·18	0·18
Poppleton	14	4·74	0·69	2·15	0·11	0·86	0·51	0·39
Selby	16	4·10	0·59	1·72	−0·66	0·83	0·73	0·11
Spalding, Ely, Peterborough	12	3·34	0·70	1·45	0·45	0·90	1·18	0·03
Wissington	20	5·00	1·94	1·74	0·59	0·78	0·75	0·27
All mineral soils	219	4·22	1·07	2·20	0·30	0·73	0·30	0·08
Fen peat soils	32	0·42	2·08	2·71	0·02	−0·47	0·79	−0·15

* Including only those sites not differentiated in Table 2. Separate values are not shown for Cupar (seven sites) and Southern area (five sites).

† Those sites in the Bury and Ipswich areas which were on Chalky Boulder Clay have been included with Felsted.

5. THE EFFECT OF SALT

Series II consisted of 190 experiments on mineral soils and 18 on fen soils testing 5 cwt. salt per acre as well as the response to N, P and K fertilizers; the fertilizer responses discussed in the previous section referred only to half of each experiment, i.e. the sixteen plots without salt, but the information obtained on the effects of salt are of great interest. The mean responses to potash and salt on mineral soils are given in Table 5. The experiments have demonstrated clearly the value of salt for sugar beet, 5 cwt. of salt having given very nearly its weight in sugar in the absence of potash. Potash and salt are closely related in their effects; this is shown by the large negative interaction between them and by the fact that the soil analysis for K predicts the salt response to much the same extent as the potash response. It appears that in the physiology of the plant the two elements concerned are to a large extent interchangeable. The idea which was once current, that salt releases potash from the soil to become available to the plant, received no support from analysis of crop samples from the experiments. Nitrogen fertilizers by increasing the general level of yield necessarily increase the amount of potash absorbed by the total crop, but salt increases the size of the crop without increasing its potash content. Indeed on the average of five seasons the crops grown with salt actually removed from the land slightly less potash than those without salt. Few, if any, farmers who use salt omit potash from their fertilizer for do more than repay its cost. On the other hand, salt gives an economic return whether or not potash is applied, the mean response of 2·5 cwt. sugar per acre in the presence of N and K being worth about £2 per acre net. A point of interest is that in addition to being considerably larger than the effect of potash, the effect of salt is also less variable from season to season.

Although potash can be replaced either partially or wholly by sodium in the form of chloride or nitrate, it must be remembered that sugar beet tops contain very large quantities of potash. If the tops are removed for feeding there is a substantial drain on the available potash in the soil, especially if the urine from the animals is lost. There may, therefore, be a case for including potash in sugar beet fertilizers, even if salt is applied, in the interest of the succeeding crops.

Table 4. *Fertilizer responses by factory areas**

		Cwt. sugar per acre			
			Reduction in response due to omission of		
Factory area	No. of centres	Combined response to all three nutrients	N	P	K
Mineral soils:					
Allscott and Kidderminster	17	9·70	5·62	1·65	4·25
Bardney	12	7·03	6·00	1·68	2·39
Brigg	16	7·47	6·73	0·73	1·59
Bury†	14	8·47	6·60	1·85	3·96
Cantley	14	6·96	4·04	1·68	4·00
Colwick	11	9·32	3·84	1·35	6·31
Felsted†	16	8·28	6·29‡	1·22‡	−0·41
Ipswich†	9	8·26	5·26	1·99	5·63
King's Lynn	10	5·45	3·86	2·04	2·29
Newark	13	7·35	4·07§	−0·22	1·88§
Oaklands	13	6·42	4·25	0·88	5·23
Poppleton	14	7·97	6·10	1·70	3·91
Selby	16	6·52	4·38	0·77	3·39
Spalding, Ely, Peterborough	12	5·52	4·72	2·36	3·56
Wissington	20	8·95	6·64	3·55	3·54
All mineral soils	219	7·57	5·33	1·75	3·31
Fen peat soils	32	5·06	−0·18	2·74‖	2·88‖

* Including only those sites not differentiated in Table 2. Separate values are not shown for Cupar (seven sites) and Southern area (five sites).

† Those sites in the Bury and Ipswich areas which were on Chalky Boulder Clay have been included with Felsted.

‡ Without K, response to N 7·91, to P 3·22 cwt. sugar per acre.

§ Without P, response to N 5·07, to K 2·52 cwt. sugar per acre.

‖ Without N, response to P 3·00, to K 4·32 cwt. sugar per acre.

beet, especially on land low in potash, but even in the presence of both N and P the extra response from potash where salt is applied is scarcely sufficient to

Table 5. *Mean responses to potash and salt on mineral soils*

	Cwt. per acre		
	1·2 cwt. K_2O	5 cwt. salt	1·2 cwt. K_2O + 5 cwt. salt
No N or P	1·18	2·55	2·69
N only	2·62	4·75	5·13
P only	1·56	2·50	2·29
N and P together	3·47	5·01	5·90
	2·21 ± 0·20	3·70 ± 0·26	4·00 ± 0·27

Since they are based on not more than ten experiments, much reliance cannot be placed on the means for the different factory areas. They suggest that in some areas potash may give a substantial response whether or not salt is applied; these areas include Allscott, Bardney, Newark, Colwick, King's Lynn, Cantley, the Southern area and Cupar. The position is complicated by substantial negative PS and PKS interactions in some areas. On eighteen fen soils the response to salt was very much less than on the mineral soils, potash giving a slightly larger response than salt on these soils.

6. THE VALUE OF SOIL ANALYSIS IN PREDICTING CROP RESPONSES

Since the primary purpose of the experiments was to investigate the relationship between soil analysis and crop response, it would be inappropriate to omit some mention of the results obtained. The following section examines the ability of the citric acid method, one of five different methods tested, to predict crop responses. A paper dealing with the detailed results of the mechanical and chemical analyses of the experimental soils is in preparation. In Table 6, data from 312 centres on mineral soils (omitting the Scottish centre, Cupar) have been divided into four groups according to the estimate of available phosphate and potash (mg. citric sol. P_2O_5 or K_2O per 100 g.) given by soil analysis, and each of these soil analysis groups has been subdivided according to the phosphate or potash response. To obtain a more accurate estimate of the responses at each centre the table is based on the main effect of phosphate (i.e. the response averaged over all other treatment combinations) and the response to potash in the presence of nitrogen (i.e. averages of plots with and without phosphate).

For both nutrients there is a clear association between soil analysis and crop response. Mean responses are under 1 cwt. sugar per acre for sites high in P and K, but exceed 3 cwt. sugar per acre for sites low in P and 4 cwt. sugar per acre for sites low in K. It is sometimes supposed that the difference between the responses of sites low in P or K, and the responses of sites where P or K is satisfactory, gives a direct measure of the value of soil analysis. A moment's thought will show that this is not so, except in the rare case where no fertilizer would normally be applied to the crop in the absence of a recommendation by soil analysis.

A more realistic assessment of the financial return from soil analysis may be made by comparing the returns from applying the optimal dressing appropriate to each soil group with the returns from applying the optimum dressing appropriate to all sites. This approach gives values of 5·9*s.* per acre for phosphate analysis and 8·7*s.* per acre for potash analysis. The distribution of the sites, given in the right hand side of Table 6, shows that there is in fact a substantial percentage of the sites which give little or no response, although classified as relatively low in P or K, whilst some of the sites high in P and K have nevertheless given a marked response. At high levels of soil phosphate and potash the recommendations not to use fertilizer on the unresponsive sites results in substantial savings in fertilizer, but these are offset by the large losses resulting from the failure to apply a dressing on the small number of very responsive sites. Thus about 20 % (17 out of 83) of the sites with responses greater than 2·5 cwt. sugar per acre are high in citric soluble phosphate. Similarly, over 10 % (20 out of 151) of the sites giving low or negative responses have less than 16 mg. citric soluble P_2O_5.

The prediction is not materially improved if allowance is made for soil texture. Contrary to what might be expected, phosphate responses were little greater on the heavier than on the lighter soils, whilst, if the Chalky Boulder Clay soils are excluded, potash responses were similar on light and heavy soils.

There were significant differences in phosphate status between factory areas, but these were not at all closely related to the phosphate responses; soil potash values did not differ significantly between factory areas and these also showed no clear relationship with the potash responses.

For phosphate the present test was a favourable one in so far as the optimum dressing appropriate to

Table 6. *Soil analysis and crop responses* (*cwt. sugar per acre*)

(1) Soil analysis groupings (mg. citric sol. P_2O_5 or K_2O per 100 g.)	(2) No. of sites	(3) Mean response	(4) Optimum dressing (cwt. P_2O_5 or K_2O per acre)	(5) Percentage of total number of sites having responses: Neg.	0·0–1·2	1·3–2·5	2·6–5·0	5·1 and over
Phosphate								
0 –16	57	3·20	0·92	3·5	2·9	4·2	4·2	3·5
16·1–24	69	2·04	0·56	6·1	2·6	5·5	5·7	2·3
24·1–48	131	1·11	0·08	12·8	10·0	10·6	6·7	1·9
Over 48	55	0·53	—	6·7	3·8	4·8	1·6	0·6
All	312	1·59	0·37	29·1	19·3	25·1	18·2	8·3
Potash								
0 – 6	81	4·20	2·50	3·2	3·5		9·6	9·6
6·1– 8	91	3·85	2·34	3·8	7·7		8·7	9·0
8·1–12	81	2·19	1·49	4·5	9·6		7·7	4·1
Over 12	59	0·82	—	7·7	7·4		1·3	2·6
All	312	2·83	1·90	19·2	28·2		27·3	25·3

the general mean was fairly small. For potash, however, the mean response over all sites was high enough for the optimum dressing to be at least 1·5 cwt. K_2O per acre; whatever the degree of deficiency, the effect of higher dressings than this is likely to be relatively small. For sugar beet, therefore, the value of soil analysis for potash largely depends upon its ability to single out those sites upon which manuring can safely be omitted, and the same must apply equally to other heavily manured crops such as potatoes. It is only for crops which normally receive little or no fertilizer that the diagnosis of deficiency becomes really valuable.

7. OPTIMUM DRESSINGS

The information given in §4, on the responses of sugar beet to the three standard fertilizer nutrients refers only to an arbitrary level of each nutrient. To give an opinion on the amounts of fertilizer which farmers can profitably apply, we need to know what responses would have been obtained had greater or smaller dressings been applied, or if the ratio of N:P:K had been different.

In making an accurate assessment of the optimal combination of the three nutrients the experimental data must fulfil two main requirements: the treatments must be at three or more levels and the optimal quantities must fall within the range of levels tested. The first of these requirements is met for only 6 of the 16 years covered by the Factory Sugar Beet Series, since only Series I, which ran from 1934 to 1939, provides information on the effects of different levels of fertilizer nutrients (see §2 above). The general means of each of the twenty-seven treatment combinations, corrected for block effects, are presented in Table 7 for 131 experiments on mineral soils; results for the centres on Chalky Boulder Clay have been excluded from this table. The table exhibits the same general features as have been noted in §4 for the two series of experiments taken together, namely the substantial effects of nitrogen and potash, especially when both these nutrients are applied. Comparison of the effects of these fertilizers at the middle and higher levels shows that although the main effect of each nutrient falls off at the higher rate of dressing, the interaction NK increases, its mean value at the intermediate level being + 0·36 cwt. and at the higher level + 1·03 cwt. sugar per acre. Fortunately the average values of the main effects and interactions at the higher level of Series I are fairly similar to those for the two periods combined, so that it would not be unreasonable to assume that the response curves are also similar.

The second requirement is not met for either of the two important nutrients, N and K. The values given in Table 7 have been used to calculate the net returns for each treatment combination, given in £ per acre in Table 8. The substantial additional net return at the higher level of N and K indicates that the optimal dressings must be above the highest level tested in the experiments. It can be regarded as reasonably certain that the optimal dressing of N and K in the absence of salt is at least 1·0 cwt. N and 1·5 cwt. K_2O per acre, although it is probable that the theoretical optima are greater, perhaps reaching 1·2 cwt. N and 2·0 cwt. K_2O per acre. The extra profit to be derived from these higher dressings must, however, be small compared with their extra cost.

The response to phosphate in Tables 7 and 8 was small, and would scarcely pay for the cost of application. Somewhat greater NP and PK interactions for the period 1934–49 than for 1934–9, together with the need for rapid establishment in spring, suggest that there may in fact be some case for applying a small

Table 7. *Treatment means, corrected for block effects, for 131 experiments on mineral soils (Series I) (cwt. sugar per acre)*

	P_0				P_1				P_2			
	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean	K_0	K_1	K_2	Mean
n_0	31·91	33·17	33·35	32·81	32·50	33·97	34·13	33·53	33·48	33·89	34·60	33·99
n_1	34·11	36·30	36·67	35·69	36·06	37·57	37·72	37·12	36·69	37·61	38·89	37·73
n_2	35·52	37·37	39·06	37·32	36·23	38·32	39·77	38·11	36·93	38·59	40·19	38·57
Mean	33·85	35·62	36·36	35·27	34·93	36·62	37·20	36·25	35·70	36·70	37·89	36·76

Standard error of an individual value, ±0·26; of a mean of three treatments, ±0·15.

Table 8. *Net returns from fertilizers* 1934–49 (131 *experiments on mineral soils*). *£ per acre*

	P_0			P_1			P_2		
	K_0	K_1	K_2	K_0	K_1	K_2	K_0	K_1	K_2
N_0	—	1·2	0·4	−0·5	1·0	0·2	−0·4	−0·7	−0·5
N_1	2·4	5·1	4·7	4·2	5·8	5·0	3·8	4·3	5·5
N_2	3·3	5·5	7·4	3·0	5·6	7·1	2·7	4·5	6·3

quantity of phosphate for sugar beet, say up to 0·5 cwt. P_2O_5 per acre. At the same time we must bear in mind that even this small quantity may well be an overestimate of the present-day requirement of phosphate for sugar beet, since no allowance has been made for some selection of the experimental sites in the direction of phosphate-deficiency, or for the considerable rise in phosphate consumption both during and since the period covered by the experiments. It is certain that profit from the use of phosphate fertilizer is likely to be very small compared with that from nitrogen and potash or salt.

In applying the above general recommendations to individual circumstances, it should be noted that where the tops are fed to stock there will be some incentive to use a somewhat higher rate of nitrogen, since the response of tops falls off much more slowly at high levels of nitrogen than that of sugar. More nitrogen will also be necessary on deep-ploughed sites where raw subsoil has been brought to the surface. On the other hand, although many workers have for convenience assumed an exponential form of the response curve, there is good evidence that excess nitrogen can be harmful, especially on fields which are naturally, or due to recent management, rich in organic matter. Thus in § 4 above it was shown that it would be wise to reduce substantially the amount of nitrogen applied to fields recently under a grazed ley or permanent grass; some reduction should also be made on dunged fields unless the manure is poor or strawy. There may also be some reason to vary the nitrogen dressing according to the previous winter's rainfall, if the results of § 3 are confirmed. There appear to be no reasons to make differential recommendations on nitrogen according to factory area, and, if we exclude Felsted and the Chalky Boulder Clay soils of neighbouring areas, the same is true for potash. For phosphate, there is some evidence of higher requirements for some of the factory areas in East Anglia and around the Wash, whilst, except in acid soils, responses are likely to be very small in the East and West Midlands and in Yorkshire.

On the fen peat soils there is little need for nitrogen and large dressings of this nutrient may well depress yield; worn-out peats, however, will have nitrogen requirements closer to those of ordinary mineral soils. Optimal dressings are probably up to the higher level of phosphate tested in the experiments (1·0 cwt. P_2O_5 per acre) and well above the highest level of potash tested.

SUMMARY

The paper describes the results of over 300 factorial experiments carried out in each factory area in the years 1934–49 for the Sugar Beet Research and Education Committee of the Ministry of Agriculture as a result of co-operation between Rothamsted workers and the agriculturists and fieldmen attached to the beet factories. All the experiments tested the effects of levels of nitrogen, phosphate and potash, and rather more than half tested the effect of salt also.

Except on fen soils, nitrogen gave substantial responses in all factory areas, especially in the presence of high levels of potash or salt. Large variations in response from season to season were closely associated with the rainfall of the preceding winter months, responses being greater after wet winters than dry ones.

In spite of some selection of sites in favour of greater responses, the average net returns from phosphate were relatively small.

The effect of potash was closely linked with the amount of nitrogen applied; in the presence of nitrogen, dressings well above the level of 1·2 cwt. K_2O per acre tested in the experiments are likely to give a useful net return. Soils derived from the Chalky Boulder Clay seem to be exceptional in showing no response. Apart from this, there were only small variations in responses to nitrogen and potash between factory areas. The application of 5 cwt. salt gave substantial responses in almost all parts of the country, whether or not potash was also applied; on the other hand, responses to potash were usually small when salt was also applied.

Whilst there was a general relationship between soil analysis for phosphate and potash (citric acid method) and crop response, adjustments to the optimal dressings according to soil analysis were not of sufficient reliability to be of much practical value.

REFERENCES

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

FISHER, R. A. (1924). *Proc. Roy. Soc.* B, **213**, 89.

HULL, R. (1953). *Plant Path.* **2**, 39.

HULL, R. & WATSON, MARION (1947). *J. Agric. Sci.* **37**, 301.

(*Received* 10 *August* 1956)

APPENDIX

Table A. *Main effects and interactions by factory areas* (1934–49)

Factory area	No. of centres	N	P	K	NP	NK	PK	NPK
		Sugar (cwt. per acre)						
Mineral soils:								
Allscott	19	2·87	3·11	3·34	0·18	0·98	0·31	0·03
Bardney	21	4·13	1·88	2·12	0·41	0·20	0·46	0·25
Brigg	21	4·72	1·61	1·58	0·49	0·85	−0·31	0·08
Bury	20	4·19	1·50	1·82	0·46	0·86	0·10	−0·22
Cantley	20	2·84	2·34	3·13	0·02	1·16	0·64	−0·28
Colwick	16	1·68	1·19	4·12	0·17	1·18	−0·36	−0·33
Cupar	16	1·90	0·50	1·41	0·45	0·88	0·51	0·51
Felsted	17	6·00	1·47	0·18	0·74	−0·21	−1·07	−0·16
Ipswich	20	4·29	1·30	2·64	0·73	0·40	−0·08	−0·06
Kidderminster	15	4·97	1·07	3·23	0·09	0·37	0·26	0·25
King's Lynn	19	4·83	1·70	1·47	0·32	0·82	0·67	0·11
Newark	16	5·19	1·18	1·31	−0·71	0·08	−1·01	0·29
Oaklands	14	2·00	0·24	3·64	0·55	1·40	−0·34	0·17
Poppleton	17	4·09	0·91	1·63	−0·06	0·98	0·21	0·43
Selby	18	3·99	0·66	1·56	−0·73	0·96	0·74	0·02
Spalding	12	2·00	1·28	1·30	0·45	0·66	0·57	−0·19
Southern area	10	0·66	3·00	2·04	1·08	1·36	1·61	0·67
Ely and Peterborough	13	2·44	2·39	2·13	0·24	1·29	−0·11	−0·05
Wissington	24	4·82	1·90	1·78	0·32	0·89	0·63	0·22
All mineral soils	328	3·73	1·55	2·13	0·26	0·77	0·17	0·08
Fen peat soils:								
Ely	13	1·15	1·76	3·35	0·22	−0·20	1·13	−0·05
Peterborough	16	0·00	2·24	2·39	0·14	−0·69	0·46	−0·23
Wissington	3	−0·53	2·60	1·67	−1·43	−0·43	1·67	−0·13
All fen peat soils	32	0·42	2·08	2·71	0·02	−0·47	0·79	−0·15
		Tops (tons per acre)						
Mineral soils:								
Allscott	17	2·35	0·85	0·07	0·08	0·65	0·05	−0·21
Bardney	21	2·89	0·23	0·14	0·04	−0·03	0·34	0·02
Brigg	21	2·87	0·25	0·40	0·11	0·25	0·03	−0·03
Bury	17	2·74	0·14	0·16	−0·07	0·28	0·13	−0·05
Cantley	18	3·14	0·61	0·16	0·43	−0·13	0·16	0·01
Colwick	14	2·53	0·01	1·04	−0·27	−0·13	0·40	−0·22
Cupar	16	3·56	−0·19	0·81	0·10	0·30	0·22	0·08
Felsted	16	2·28	0·21	−0·10	−0·04	−0·10	0·13	0·04
Ipswich	10	2·52	0·11	0·41	0·08	0·04	−0·02	0·10
Kidderminster	14	2·79	0·35	0·16	0·28	0·28	0·02	0·14
King's Lynn	19	1·91	0·16	−0·08	0·18	−0·10	0·03	0·00
Newark	16	3·40	0·23	0·52	0·11	0·40	−0·11	0·09
Oaklands	13	2·69	−0·17	0·07	0·40	0·38	−0·20	−0·08
Poppleton	16	3·14	0·12	0·72	−0·02	0·54	0·46	0·06
Selby	17	3·00	0·05	0·68	0·08	0·51	−0·05	−0·06
Spalding	12	1·67	0·43	0·26	0·39	0·04	−0·19	0·01
Southern area	8	2·60	0·31	0·23	0·49	−0·04	−0·09	−0·21
Peterborough	8	2·31	0·48	0·21	0·04	−0·07	0·22	−0·20
Wissington	13	2·75	0·78	0·21	0·05	0·14	−0·12	−0·15
All mineral soils	286	2·72	0·25	0·32	0·12	0·18	0·09	−0·04
Fen peat soils:								
Ely	12	0·86	0·86	0·14	0·39	−0·03	0·46	−0·02
Peterborough	13	1·61	0·55	0·47	−0·03	0·00	0·23	0·05
Wissington	2	2·01	3·32	0·38	−0·88	−1·91	−0·85	−0·08
All fen peat soils	27	1·30	0·89	0·32	0·10	−0·16	0·26	0·01