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Growth and yield of sugar beet on contrasting soils in relation to nitrogen supply

I. Soil nitrogen analyses and yield

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SUMMARY

Nine field experiments with sugar beet in 1968–70 tested eight amounts of nitrogen fertilizer (0–290 kg N/ha) on a shallow calcareous loam (Icknield Series), on a deep sandy loam (Newport Series) and on a heavy clay loam (Evesham Series). Top soils and sub-soils, sampled during autumn, winter and spring before the experiments, were analysed by several methods for available and potentially-available nitrogen. The largest increases in potentially-available mineral-nitrogen shown by incubation occurred in the calcareous loams every year in both top soil and sub-soil, and the sandy loam, particularly the sub-soil, generally produced least. Attempts to forecast the optimum nitrogen fertilizer dressing from the soil analyses were moderately successful, the best technique being anaerobic incubation of air-dry soil; the date of sampling had little effect. The optimum dressings were always between 0 and 125 kgN/ha, the calcareous loams generally needing least nitrogen fertilizer and the loamy sands most.

INTRODUCTION

Many field experiments throughout the sugar-beet producing regions of the world show that for maximum yield the optimum nitrogen dressing is far less than the amount the crop takes up (recently reviewed by Draycott, 1972). Not surprisingly, there is much controversy in Great Britain (and abroad) between sugar-beet growers, advisers and scientists on nitrogen requirements of this crop. Boyd *et al.* (1970), in their paper on manuring sugar beet, found 75–100 kg N/ha was the average optimum dressing for 7 years, and less was needed in the 3 drier years of the decade, and in most years (not all), site-to-site differences in response to amounts of fertilizer nitrogen applied at more than 113 kg/ha were no greater than could be expected from experimental error. There was some evidence of diminished response where sugar beet followed crops other than wheat or barley and a slightly enhanced response on Chalky Boulder clays. Holmes (1970) suggested that sand and oolitic limestone soils respond to above-average dressings of nitrogen fertilizer, but Boyd *et al.* found no evidence for increased response amongst sands. It was therefore decided to make a detailed analysis of the growth and chemical composition of crops on three contrasting soils to gain a fuller understanding of how sugar beet utilizes soil and fertilizer nitrogen.

Part I describes analyses of soil samples taken during autumn, winter and spring prior to sowing sugar beet to test methods of measuring potentially-available soil nitrogen which have shown promise for predicting fertilizer requirement (Last & Draycott, 1971). Methods investigated by us previously and now in more detail, included the incubation of fresh and air-dry soils, both aerobically and anaerobically, barium hydroxide extractable 'glucose', total nitrogen and organic carbon. The contribution made by the sub-soil has also been included, as work on the pattern of root growth of sugar beet (Draycott, Durrant & Messem, 1974) suggests this might be considerable for such a deep-rooted crop (Durrant *et al.* 1973).

EXPERIMENTAL PROCEDURE

Locations and soils

Nine experiments were made on commercial farms under the supervision of the British Sugar Corporation field staff, three in each of the years 1968–70. In each year, one experiment was made on each of three soil types: (*a*) the Icknield Series in the Felsted sugar factory area, near Royston,

Table 1. *Details of experimental fields, dates of fertilizer application and sowing, and varieties grown*

Year and factory area	National grid reference	Soil series	Organic carbon (%) Top soil	Organic carbon (%) Sub-soil	Total nitrogen (%) Top soil	Total nitrogen (%) Sub-soil	Previous crops	Date of fertilizer application	Date of sowing	Variety
1968										
Felsted	147/327.404	Icknield	2·4	0·9	0·26	0·09	Barley, wheat, sugar beet	5 March	22 March	Sharpe's Klein 'E'
Newark	43/666.768	Newport	1·4	0·6	0·09	0·04	Cereals, potatoes, ley	5 March	5 April	Sharpe's Mono
Nottingham	112/790.413	Evesham	2·1	1·2	0·21	0·11	Barley, barley, barley	1 March	29 March	Sharpe's Klein 'E'
1969										
Felsted	147/334·406	Icknield	2·1	0·7	0·24	0·08	Wheat, barley, barley	11 March	8 April	Bush Mono
Newark	43/665.767	Newport	1·1	0·4	0·09	0·03	Barley, barley, sugar beet	25 March	20 April	Sharpe's Mono
Nottingham	112/790.414	Evesham	2·0	1·0	0·22	0·10	Barley, barley, barley	10 April	21 April	Sharpe's Mono
1970										
Felsted	147/331.402	Icknield	2·1	0·7	0·22	0·06	Barley, beans, wheat	19 March	18 April	Monotri
Newark	43/675.755	Newport	0·9	0·5	0·08	0·04	Barley, barley, sugar beet	16 March	18 April	M. 32
Nottingham	112/769.392	Evesham	2·8	1·5	0·27	0·15	Barley, wheat, seeds	3 April	19 April	Sharpe's Mono

Herts, a shallow calcareous loam described in detail by Avery (1964); (*b*) the Newport Series in the Newark factory area, near Elkesley, Nottinghamshire, a deep sandy loam described by Mackney & Burnham (1966); (*c*) the Evesham Series in the Nottingham factory area, near Bottesford, Leicestershire, a clay loam described by Osmond *et al.* (1949). Some of the characteristics of these soils are shown in Table 1. Surveys have shown that about 25 % of the beet acreage in Britain is sandy loam, 10 % clay, whilst the chalk/limestone soils account for about 5 % of the total area of 196 000 ha.

Design and fertilizer treatments

The experiments were laid out in five randomized blocks and eight amounts of nitrogen tested, ranging from 0 to 290 kg N/ha in equal increments as 'Nitro-Chalk'. Plots of 0·0067 ha received a basal dressing of 63 kg P_2O_5/ha, 125 kg K_2O/ha and 376 kg NaCl/ha. All the fertilizers were spread by hand on the dates shown in Table 1. The roots were also harvested by hand from 0·0029 ha at the end of the season, weighed and analysed for sugar percentage, impurities and juice quality at the Central Laboratory of the British Sugar Corporation at Peterborough.

Soil sampling

Samples were taken from the experimental area of each field during autumn, winter and spring before the fertilizers were applied. The top soil samples comprised 60 cores taken with a cheese auger 0–23 cm and the sub-soils 20 cores taken with a screw auger, having removed all traces of the surface 23 cm with a spade. The depth to which the subsoil was sampled was 23–91 cm on the sandy loam, 23–76 cm on the clay loam and only 23–61 cm on the shallow calcareous loam where sampling at depth was immensely difficult. A thin limestone band occurred at 46 cm in 1968 and 1969 on the clay loam sites which required considerable pressure to pierce but subsequent sampling to a depth of 76 cm was possible at all three sites. The sampling of sandy loams (Newport Series) in the Newark factory area created few difficulties in comparison with the other two soil types.

Agronomic details

Table 1 also lists some of the more important agronomic factors at each trial site. To minimize the effects on germination and emergence, fertilizers for the beet crop should be applied at least 10 days before sowing and the experimental manures were, on average, applied 24 days before sowing but on the clay loams the interval narrowed to an average of 18 days, perhaps reflecting the slower drying of the soils during early spring.

The juxtaposition of fertilizer application and sowing dates is, to some extent, reflected in the average plant densities which ranged from 81000/ha at Newark to 69000/ha at Nottingham, and in 1969 at Nottingham where the two operations differed by only 11 days, the final population was only 64000/ha. A Sharpe's seed variety was used in the majority of trials but no strictures were applied to varieties because nitrogen fertilizer × variety interactions are small.

Pests and diseases were recorded on the trials by the British Sugar Corporation field staff, and damage attributable to pests was inconsequential. Routine virus yellows counts were made on the trials during August and were appreciable at Felsted on the calcareous loams in 1969 and 1970 where incidences reported were 13 and 10% respectively; on all other trials, less than 4% incidence was recorded.

No serious mineral deficiency arose in the crops, but at Felsted odd plants showed symptoms of Mn and Fe deficiency in all 3 years, although incidence was very low and no corrective measures were applied. The calcareous loams also 'capped' very readily in 2 years and emerging plants were retarded in early growth with serious loss of yield in 1970, and all three crops grown on this soil type made very slow progress during the seedling to 4-leaf stage growth.

Soil analysis

All fresh and air-dry soils were ground to less than 2 mm, incubated aerobically by the method described by Gasser (1961), and the increases in ammonium and nitrate-nitrogen measured. An anaerobic method for the determination of potentially-available nitrogen in soils, originally described by Waring & Bremner (1964) and investigated by us (Last & Draycott, 1971) was again tested on the air-dry soils. The glucose equivalent of the air-dry soils as a measure of available nitrogen was also tested, determined by the anthrone method (Jenkinson, 1968). The organic carbon and total nitrogen considered to be coarse measures of nitrogen requirement, were determined on air-dry soils by the methods of Tinsley and Kjeldahl respectively (Table 1).

Results for mineral-N values are expressed as mg/kg oven-dry soil. Nomenclature used throughout is as follows:

mineral-nitrogen (NH_4+NO_3) in fresh soil	Min-N_f
increase in mineral-nitrogen (NH_4+NO_3) in fresh soil incubated aerobically	ΔMin-N_f
increase in mineral-nitrogen (NH_4+NO_3) in rewetted air-dry soil incubated aerobically	ΔMin-N_{ad}
increase in mineral-nitrogen (NH_4) in air-dry soil incubated anaerobically	ΔMin-N_{aa}

RESULTS AND DISCUSSION

Soil analysis

Table 2 shows the amounts of mineral-nitrogen present in the fresh soils (i.e. before incubation) sampled during autumn, winter and spring. Most of the soils contained very little mineral-nitrogen in winter and spring and it is concluded that the residue of *fertilizer* nitrogen in top and sub-soil available for

Table 2. *Mineral nitrogen in fresh soil sampled in autumn, winter and spring from three fields in each year*, 1968–70

	Top soil				Sub-soil			
	Autumn	Winter (mg/kg)	Spring	Mean	Autumn	Winter (mg/kg)	Spring	Mean
Calcareous loam								
1968	18	16	61	32	20	14	23	19
1969	8	6	8	7	6	7	8	7
1970	19	9	9	12	18	12	10	13
Mean	15	10	26	17	15	11	14	13
Sandy loam								
1968	12	12	12	12	14	7	9	10
1969	7	3	4	4	4	2	3	3
1970	10	5	3	6	8	5	5	6
Mean	10	7	6	7	9	5	6	6
Clay loam								
1968	9	7	11	9	7	8	8	8
1969	2	2	5	3	3	1	3	2
1970	15	8	6	10	10	12	7	10
Mean	9	6	7	7	7	7	6	7

Table 3. *Mineral nitrogen produced during aerobic incubation of fresh* ($\Delta Min\text{-}N_f$) *and air-dry* ($\Delta Min\text{-}N_{ad}$) *soil, during anaerobic incubation of air-dry soil* ($\Delta Min\text{-}N_{aa}$) *and barium hydroxide glucose concentrations*

Means of three sampling dates (Autumn, Winter, Spring) in 1968–70

	Top soil				Sub-soil			
	ΔMin-N_f	ΔMin-N_{ad} (mg/kg)	ΔMin-N_{aa}	Glucose (mg/100 g)	ΔMin-N_f	ΔMin-N_{ad} (mg/kg)	ΔMin-N_{aa}	Glucose (mg/100 g)
Calcareous loam								
1968	28	36	68	24	13	24	19	8
1969	24	32	39	20	3	13	7	7
1970	18	36	36	19	7	17	3	5
Mean	23	35	48	21	8	18	10	7
Sandy loam								
1968	16	23	13	9	1	12	3	5
1969	13	17	6	9	2	6	1	3
1970	14	23	1	9	7	9	0	3
Mean	14	21	7	9	3	9	1	4
Clay loam								
1968	11	17	13	13	4	17	7	5
1969	15	21	24	14	4	10	6	6
1970	15	28	41	20	8	15	12	8
Mean	14	22	26	16	5	14	8	6

Table 4. *Correlation coefficients between soil factors*

	Concentration of organic carbon (%)	Concentration of nitrogen (%)	Glucose	ΔMin-N_f	ΔMin-N_{ad}	ΔMin-N_{aa}
			Top soils			
Concentration of organic carbon (%)	—	0·96**	0·85**	0·39	0·52	0·79*
Concentration of nitrogen (%)	—	—	0·91**	0·48	0·57	0·82**
Glucose	—	—	—	0·76*	0·83**	0·96**
			Sub-soils			
Concentration of organic carbon (%)	—	0·98**	0·68*	0·34	0·47	0·62
Concentration of nitrogen (%)	—	—	0·76*	0·38	0·47	0·67*
Glucose	—	—	—	0·50	0·68*	0·88**

* $P < 0{\cdot}05$; ** $P < 0{\cdot}01$.

the sugar-beet crop was negligibly small. An exception was the calcareous loam in 1968 which contained over 60 mg N/kg in the surface and 20 mg/kg in the subsoil in spring, or approximately 314 kg/ha in the top 60 cm of soil. The results suggest that this was partly residual fertilizer nitrogen and partly mineralized organic nitrogen.

Table 3 shows that the amounts of mineral-nitrogen produced during incubation were similar each year and, on average, incubation of fresh top soil increased the amount of mineral-nitrogen (ΔMin-N_f) in the calcareous loams by 24 mg/kg (approximately equivalent to 80 kg N/ha) compared with increases of only 14 mg/kg by the other two soil types. The sub-soils also reflected this pattern, with the calcareous loams increasing by 7 mg/kg and the sandy loams by only 3 mg/kg. Means of the autumn, winter and spring results are given because the time of sampling the soils had no effect on Δ-Min-N_f.

The interrelation between the soil values shown in Table 4 indicates that concentrations of organic carbon and nitrogen and barium hydroxide extractable glucose were all interrelated, highly significantly in the top soils but in the sub-soils the glucose was less closely related to the concentrations of organic carbon and nitrogen present.

Concentrations of organic carbon and nitrogen in top soils were not related to mineral-nitrogen produced by aerobic incubation but were significantly correlated with the amount of mineral-nitrogen produced by the anaerobic technique. Glucose, however, was very strongly related to all three mineral-nitrogen values, particularly to ΔMin-N_{aa}, $r = 0{\cdot}96$, and for ΔMin-N_{ad} a value of 0·83 was obtained, compared with 0·73 obtained by Last & Draycott (1971) and 0·78 by Jenkinson (1968). Subsoils showed the same trend in relationships but r values were generally lower.

ΔMin-N_f and ΔMin-N_{ad} for the soils were significantly interrelated, $r = 0{\cdot}82$, compared with the value of 0·61 reported by Last & Draycott (1971) in a previous investigation of soils which were much more variable in texture and type than the soils in this work.

Air-drying, as usual, caused more nitrogen to mineralize when subsequently incubated, and the amount produced increased on average by 50 % in top soils and by 180 % in the sub-soils. Incubation of air-dry soils, however, did not change the *relative* amounts produced in either top or sub-soils, compared with the results from fresh soils. The lowest values for ΔMin-N_{ad} were obtained from the top and sub-soils sampled in 1969 (after the rather wet summer of 1968). The calcareous loam top soils on average produced most nitrogen during anaerobic incubation (ΔMin-N_{aa}) and the sandy loams least; the sub-soils followed the same pattern. Anaerobic incubation produced the largest extremes between soil types and years. As with the air-dry aerobic incubations, soils in 1969 produced the lowest average increase.

The barium hydroxide-extractable glucose concentration was, on average over the 3 years, largest in the calcareous loam, ranging from 19 to 25 mg/100 g, whilst the sands contained on average only 9 mg/100 g in the top soil. The glucose concentration in the clay loams was intermediate in value, although in 1970 the value rose to 20 mg/100 g, probably attributable to the previous cropping, a ley which had received a dressing of 20 t/ha of farmyard manure. The effect of previous cropping was also apparent at Newark in 1968, where the remnants of a previous ley resulted in an above-average glucose level in the subsoil. Time of sampling did not affect the concentration of glucose in top or sub-soils, just as it did not affect the amounts of nitrogen produced by incubation.

Optimum nitrogen dressing, yield and nitrogen uptake

The effects of nitrogen fertilizer on the crop are summarized in Appendix Table 1; full details of the yields in these and similar experiments will be dealt with in a later paper. The optimum dressing for sugar yield in these nine experiments differed between fields but was never significantly greater than 125 kg N/ha. All the determinations of potentially available nitrogen were to some degree related to the optimum nitrogen dressing; there was no response to fertilizer when ΔMin-N_{ad} exceeded 28 mg/kg or when ΔMin-N_{aa} exceeded 36 mg/kg in the top soil. Responses to nitrogen fertilizer were also small when the sub-soils contained much potentially-available nitrogen.

The crop factor best related to the soil mineral-nitrogen data was the response in sugar yield (t/ha) to fertilizer. The differences between requirements of different fields were clearly demonstrated by values of ΔMin-N_{ad} and ΔMin-N_{aa}. Response to applied nitrogen was always greater than 1·4 t sugar/ha where the ammonium-nitrogen produced by anaerobic incubation did not exceed 13 mg/kg in the top soil; also sub-soils from responsive fields produced below-average amounts of ammonium-nitrogen. Response in sugar yield was also associated with low organic carbon and total nitrogen concentrations in both soil horizons (Table 1).

Barium hydroxide-extractable glucose was well correlated with yield response ($r = -0{\cdot}91$, $P < 0{\cdot}01$) and distinguished between responses from the clay and calcareous loams which the other soil factors were unable to do. The results for glucose indicated large (1·9 t sugar/ha) yield responses on the sands with glucose concentrations of less than 10 mg/100 g, decreasing to medium response (1·0 t sugar/ha) with glucose increasing to 14 mg/100 g and small or zero response where glucose increased to more than 19 mg/100 g.

A variate which might be expected to be related to the crop yield and/or nitrogen requirement is the amount of mineral nitrogen present in soils sampled freshly in spring (Table 2). This reflects the immediate nitrogen status of a soil at a time close to initial growth of the crop, probably when deficiency of any nutrient has a great effect on subsequent growth. Although the top-soil sample from the unresponsive experiment at Felsted in 1968 contained 61 mg mineral-nitrogen/kg (equivalent to 205 kg N/ha), there were no appreciable differences in magnitude between the other fields, Perhaps for this reason the factor was not indicative of potential yield, fertilizer requirement or response to fertilizer.

The total nitrogen uptakes (Appendix Table 1) were derived from the analyses of total nitrogen in dried plant material and the final dry-matter yields. Uptake from the unfertilized plots ranged from 172 to 73 kg/ha and was considerably lower than average at only 87 kg/ha from the sandy loams. ΔMin-N_{aa} and extractable glucose were good

Table 5. *Correlation coefficients between optimum nitrogen requirements, yields and nitrogen uptake and various soil measurements*

	Top soil				Top soil plus sub-soil	Top soil	
	ΔMin-N_f	ΔMin-N_{ad} (mg/kg)	ΔMin-N_{aa}	Glucose (mg/100 g)	ΔMin-N_{aa} (mg/kg)	Concentration of organic carbon (%)	Concentration of nitrogen (%)
Optimum N dressing	−0·50	−0·65*	−0·68*	−0·82**	−0·62	−0·70*	−0·76*
Maximum sugar yield	−0·45	−0·77*	−0·33	−0·42	−0·13	−0·07	−0·19
Maximum sugar yield response to N	−0·57	−0·70*	−0·80*	−0·91**	−0·77*	−0·86**	−0·93**
N uptake on unfertilized plots	+0·55	+0·42	+0·77*	+0·73*	+0·86**	+0·79*	0·72

* $P < 0{\cdot}05$; ** $P < 0{\cdot}01$.

indications of nitrogen uptake, as were organic carbon and total nitrogen in the top soils. The trial at Felsted 1970 was exceptional where a large nitrogen uptake was indicated by soil tests, but only 84 kg/ha was present in the crop at final harvest. This result is attributable to poor growth of the crop during the spring and a small number of plants per hectare. On average, unfertilized crops on the calcareous loam and clay loam soils contained the same amount of nitrogen (129 kg/ha), whilst the crops on the sandy loams took up 42 kg nitrogen/ha less.

Summated values of potentially-available nitrogen in top soil plus sub-soil were calculated, taking into account the sampling depth and Table 5 shows that these values were closely related to nitrogen uptake.

CONCLUSIONS

The analytical data show few differences attributable to the time of sampling. If such incubation techniques were used as a guide for the nitrogen manuring of sugar beet in Great Britain, the results of this investigation suggest the soil samples could be taken at any time during the autumn or winter, preferably after ploughing, which would give ample time for the analyses and subsequent recommendations to be made well ahead of sowing.

The mineral-nitrogen values obtained by incubating the fresh top soils were more variable than those obtained with air-dry soils; although their magnitudes differed, the range of values obtained was nearly identical. Anaerobic incubation of the soils was best able to identify the optimum nitrogen requirement of the crops, particularly those with very low requirements. This confirms our previous work (Last & Draycott, 1971).

Anaerobic incubation increased the amount of nitrogen mineralized, compared with the other methods, in both the calcareous and the clay loam top soils, but the sandy loam top soils and all their sub-soils gave smaller increases. Anaerobic incubation produced large mineral-nitrogen values for fertile soils and small values where yields were small. Anaerobic incubation of all sub-soils produced relatively small amounts of mineral-nitrogen, and would under-estimate the potential mineral-nitrogen in the lower horizons, compared with the values obtained by aerobic incubation of the same soils, indicating that, under ideal conditions of aeration and temperature, sub-soils may produce large amounts of mineral-nitrogen during the growing season (see Part II).

The increases in sugar yield from optimal nitrogen fertilizer and nitrogen uptake by the unfertilized crop were related significantly to organic carbon, total nitrogen and glucose concentrations in the soils, but extreme agronomic and climatic factors can affect the nitrogen uptake, as at Felsted in 1970 and Nottingham in 1968.

All soils within a particular series showed closely similar analytical values and the range for each Series could best be identified by ΔMin-N_{ad}, ΔMin-N_{aa} or glucose concentration in the top soil; all were related to crop performance, but the differing nitrogen requirements within a soil Series from year to year could be accounted for only by a combination of anaerobic incubation and a knowledge of recent previous cropping. In addition, the barium hydroxide-extractable glucose in the top soil indicates the different yield responses expected from beet crops grown on differing soil series.

Appendix Table 1. *Effect of nitrogen fertilizer on sugar yield and total nitrogen uptake at harvest*, 1968–70

	Sugar yield (t/ha)									Nitrogen uptake (kg/ha)		
Nitrogen dressing (kg/ha) ...	0	41	83	125	166	207	250	291	S.E.	0	125	250
Calcareous loam												
1968	6·49	7·01	6·73	6·59	6·60	6·94	6·70	6·69	±0·202	171	214	258
1969	5·96	6·40	5·63	5·38	4·74	5·39	5·67	4·91	±0·343	134	218	242
1970	3·55	4·15	3·93	4·02	3·84	4·01	3·52	3·62	±0·280	84	128	178
Mean	5·33	5·85	5·43	5·33	5·07	5·44	5·29	5·08	—	130	187	226
Sandy loam												
1968	5·93	6·59	7·98	7·80	7·96	8·52	7·72	7·98	±0·248	112	205	257
1969	5·96	7·09	7·76	8·15	7·88	8·53	8·29	8·22	±0·237	77	152	249
1970	4·69	5·59	5·97	5·92	6·75	5·81	5·90	6·16	±0·315	73	133	208
Mean	5·53	6·43	7·23	7·30	7·54	7·61	7·31	7·45	—	87	163	238
Clay loam												
1968	7·76	8·35	8·66	8·58	8·52	8·53	8·46	8·57	±0·236	131	173	240
1969	6·55	6·43	7·09	7·23	7·71	7·66	7·17	7·45	±0·271	96	143	179
1970	7·38	7·64	7·48	7·38	7·32	7·21	7·13	7·06	±0·139	159	243	274
Mean	7·23	7·47	7·75	7·75	7·85	7·80	7·59	7·69	—	129	186	231

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