Draycott, A. P. and Webb, D. J. 1971. Effects of nitrogen fertilizer, plant population and irrigation on sugar beet: I. Yields. *The Journal of Agricultural Science.* 76 (2), pp. 261-267.

J. agric. Sci., Camb. (1971), **76**, 261–267
With 1 *text-figure*
Printed in Great Britain

Effects of nitrogen fertilizer, plant population and irrigation on sugar beet

I. Yields

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(*Revised MS. received* 22 *September* 1970)

SUMMARY

Five experiments (1965–9) on calcareous sandy loam tested all combinations of four amounts of nitrogen (0–1·8 cwt/acre N) and four plant populations (8000–54 000 plants/acre) given to sugar beet grown with and without irrigation. On average, nitrogen and plant population influenced yields greatly but irrigation relatively little. In all years between 0·6 and 1·2 cwt/acre N and between 17 000 and 32 000 plants/acre gave largest sugar yield. Giving more nitrogen or increasing the plant population neither increased nor decreased sugar yield much in any year. Irrigation was beneficial in only two out of five years.

Sugar yield was linearly related to root dry-matter yield. Although total dry matter was greatest when the largest plant population was given the largest dressing of nitrogen and irrigation, the proportion of dry matter in the roots was decreased by all three factors.

INTRODUCTION

Until recently all sugar-beet crops in England were sown thickly enough to allow singling by hand to a uniform plant population, optimally about 30 000 plants/acre. With the introduction and rapid acceptance by sugar-beet growers of monogerm seed, together with pelleting of the seed, the crop can be sown to a final stand. Such crops often have many more, and sometimes fewer than 30 000 plants/acre, so it is important to know the effects of plant population on yield and on fertilizer and water requirements of the crop.

Many experiments with sugar beet have been described testing nitrogen fertilizer (Boyd *et al.* 1970; Draycott, 1969), plant population (Garner & Sanders, 1939; Goodman, 1966) and irrigation (Penman, 1952; Price & Harvey, 1961), but few have investigated how these three practices interact. Harris (1970) found a negative interaction between plant population and nitrogen, also an unexpected negative interaction between plant population and irrigation. Penman (1952, 1962*a*, *b*) reported small effects of irrigation on response to nitrogen—on average, there was a small negative interaction.

EXPERIMENTAL

Five experiments, 1965–9, at Broom's Barn Experimental Station near Bury St Edmunds, Suffolk, tested 0, 0·6, 1·2 and 1·8 cwt/acre N as 'Nitro-Chalk' and 7800, 15 700, 31 400 and 52 300 plants/acre all with and without irrigation. Nitrogen, plant population and irrigation were in factorial combination and there were two replicates. Irrigation was applied to sub-blocks and the nitrogen and plant population treatments randomized in each sub-block. In 1965 the smallest plant population was omitted; plots testing an additional 0·5 cwt/acre P_2O_5 and 0·5 cwt/acre K_2O were included with 15 700 and 52 300 plants/acre, both given 1·8 cwt/acre N.

The nitrogen fertilizer was broadcast by hand during seed-bed preparation, as was a basal dressing of phosphate and potash (0·5 cwt/acre each of P_2O_5 and K_2O in 1965 and 1·0 cwt/acre of each subsequently). Every year the crop also received an adequate dressing of sodium either as agricultural salt or kainit. The experiments were made on soils formed from calcareous drift deposits and classified as Ashley, Stretham, or a local variant of the Ashley series.

The three smallest populations were obtained by sowing the sugar beet (variety Sharpe's Klein E) in 20 in rows and hoeing to give in-row spacings of 40, 20 and 10 in (7800, 15 700 and 31 400 plants/acre respectively). To achieve a plant population of 52 300 plants/acre, the seed was sown in 10 in rows and hoed to give an in-row spacing of 10 in. Every sixth row was omitted, leaving a space of

20 in to allow tractor-mounted implements to cultivate the crop. The plant populations quoted are theoretical and in practice differed slightly each year; the populations based on counts of roots at harvest are given in the results section below.

Oscillating spray lines supplied the irrigation and each of the irrigated sub-blocks was surrounded by a discard area at least 20 ft wide. Water was given as necessary to prevent the calculated soil moisture deficit from increasing to more than 1·5 in. Enough was usually given to bring the deficit to about 0·5 in, but this depended on the weather. The soil moisture deficits were calculated by the method of Penman (1948) and a detailed account of the soil moisture in the experiments is given in part III. The total amount of irrigation given in each experiment was: 1965, 2·50 in; 1966, 2·57 in; 1967, 5·50 in; 1968, 1·28 in and 1969, 3·40 in.

The crop was harvested by hand and an area of 0·0046 acre taken from the central six rows of each plot where the crop was grown in 20 in rows. The total plot area was 0·0115 acre. Where the crop was in 10 in rows two groups of five rows were taken from each plot; the four outer rows were weighed and analysed separately from the inner six but, unless otherwise stated, the yields and analyses described below are the averages of all the ten rows. The tops (leaf plus crown) were weighed and subsampled in the field. Roots were counted into sacks and washed, weighed and analysed for sugar content (percentage fresh weight) and purity of juice. Dry-matter determinations were made on the tops and roots.

RESULTS AND DISCUSSION

Main effects of nitrogen, plant population and irrigation

Table 1 shows the main effect (1965–9) of each of the three factors by averaging over all levels of the other two factors. Nitrogen increased root yield greatly, especially the first 0·6 cwt/acre, and the increase from the second and third 0·6 cwt was much less. It also increased tops yield and each 0·6 cwt/acre increased it by a similar amount. Nitrogen decreased sugar content but the first 0·6 cwt/acre had less effect than the larger dressings. Sugar yield (the product of root yield and sugar content) was increased greatly (11 cwt/acre) by the first 0·6 cwt/acre, slightly (1·8 cwt/acre) by a further 0·6 cwt/acre and decreased slightly but not significantly by more nitrogen. Juice purity was decreased by nitrogen, especially by more than 0·6 cwt/acre. All these effects of nitrogen fertilizer on sugar-beet yields and quality agree with results of many experiments made on commercial farms in England (Draycott, 1969; Boyd *et al.* 1970).

Table 1 also shows the mean effect of plant populations on the crop. Increasing the plant population to 32 300 plants/acre increased root

Table 1. *Main effect of nitrogen, plant population and irrigation each averaged over all levels of the other two factors on fresh yields, sugar content and juice purity. Means of five experiments*, 1965–9

	Root yield (ton/acre)	Tops yield (ton/acre)	Sugar content (%)	Sugar yield (cwt/acre)	Juice purity (%)
Nitrogen (cwt/acre), 5 years					
0	14·95	7·06	17·2	51·0	94·94
0·6–0	+3·25	+3·04	−0·1	+10·8	−0·17
1·2–0·6	+1·0	+2·92	−0·5	+1·8	−0·79
1·8–1·2	+0·37	+2·39	−0·4	−0·7	−0·61
S.E.	±0·179	±0·204	±0·05	±0·65	±0·106
Plant population (plants/acre), 4 years					
8800	15·6	9·35	15·9	49·0	93·43
16900– 8800	+3·22	+1·42	+0·8	+13·0	+0·62
32300–16900	+0·64	+0·95	+0·3	+3·5	+0·50
54000–32300	−0·28	+0·37	0·0	−1·0	+0·36
S.E.	±0·179	±0·204	±0·05	±0·65	±0·106
Irrigation, 5 years					
Without	17·67	10·52*	16·8	59·1	94·15
With	+0·62	+0·93*	−0·1	+1·5	+0·22
S.E.	±0·454	±0·438*	±0·09	±1·14	±0·112

* Four years only

S.E.'s calculated from the experiments × treatments interaction.

yield, sugar content and sugar yield. Further increase in plant population did not increase sugar content further and slightly decreased root and sugar yields. Increasing plant population throughout the range tested, increased yield of tops and juice purity. These results also confirm those of other plant-population studies with the sugar-beet crop (reviewed by Harvey, 1958).

Compared with nitrogen and plant population, irrigation had little effect on average (Table 1). It increased yields and juice purity and decreased sugar content.

Table 2 shows the main effect of the three factors on sugar yield in each year. Response to nitrogen was similar in four out of five years; increasing amounts of nitrogen increased yield to a maximum, obtained with between 0·6 and 1·2 cwt/acre. Effects of plant population were also very similar from year to year and the smallest population for maximum yield was between 16900 and 32300 plants/acre every year. As expected, response to irrigation differed greatly from year to year. Sugar yield was increased significantly in only two years (1967 and 1969), when potential transpiration was considerably in excess of rainfall (Appendix, Table 1). Response to irrigation in relation to soil moisture is discussed by Draycott & Durrant (1971*b*).

The inner three rows of each group of five of the largest plant population were harvested and analysed separately from the outer rows in some of the experiments. Yields from the inner rows (63000 plants/acre) were similar to those from the outer rows (42000 plants/acre). The root yields were 17·4 and 17·3 tons/acre and sugar yields 60·3 and 60·7 cwt/acre from inner and outer rows respectively. Yield of tops was greater from the inner (13·9 tons/acre) than from the outer rows (11·9 tons/acre). From the discussion of main effects of plant population above, these yields are as expected.

First-order interactions

Table 3 shows the mean effect of sugar yield of nitrogen and plant population, nitrogen and irrigation, and plant population and irrigation, each averaged over all levels of the third factor.

The effect of nitrogen on the sugar yield was very similar indeed when the crop was grown with 8800, 16900 and 32300 plants/acre—1·20 cwt/acre nitrogen gave maximal yield. However, when the population was increased to 54000 plants/acre, 0·60 cwt/acre nitrogen was sufficient for maximal sugar yield. The smaller sugar yield from large nitrogen dressings given to the large plant population reflected smaller root yield, not smaller sugar content (see dry-matter yields below).

With 0·6 cwt/acre nitrogen, irrigation had little effect on response to N, but with 1·2 and 1·8 cwt N/acre, nitrogen and irrigation interacted and as the nitrogen dressing increased, the response to irrigation increased. The increased response was from increased yield of roots, not increased sugar content. Plant population and irrigation did not interact and irrigation increased the sugar yields from all the plant populations by a similar amount.

Few experiments in England have investigated these three interactions in the sugar-beet crop. Harris (1970) tested nitrogen (94 and 188 kg/ha) on several plant populations (32000–140000 plants/ha) and noticed that the leaves of dense stands of plants seemed nitrogen-deficient compared with those of wide-spaced plants. However, as in our experiments, only the 32000 plants/ha responded to the extra nitrogen, but the negative interaction

Table 2. *Main effect on sugar yield (cwt/acre) in each year of nitrogen, plant population and irrigation, each averaged over all levels of the other two factors*

	1965	1966	1967	1968	1969
Nitrogen (cwt/acre)					
0	51·1	54·0	59·2	51·7	38·8
0·6–0	+8·6	+16·7	+6·2	+10·9	+11·7
1·2–0·6	−1·3	+2·0	+0·9	+2·2	+5·1
1·8–1·2	+4·7	−2·4	−0·7	−4·6	−0·4
S.E.	±1·56	±1·09	±0·82	±0·88	±1·09
Plant population (plants/acre)					
8800	—	54·6	52·3	48·1	41·1
16900–8800	—	+13·8	+13·4	+14·9	+9·7
32300–16900	—	+4·6	+5·2	+1·4	+2·9
54000–32300	—	−1·4	−3·1	−0·5	+0·9
S.E.		±1·09	±0·82	±0·88	±1·09
Irrigation					
Without	57·9	67·0	61·1	60·4	48·9
With	+0·8	−0·2	+6·1	−1·2	+2·2

Table 3. *Effect of nitrogen and plant population, nitrogen and irrigation, and plant population and irrigation each averaged over all levels of the third factor; means of experiments* 1966–9

Sugar yield (cwt/acre)

Nitrogen (cwt/acre)	Plant population (plants/acre)				Irrigation		Plant population (plants/acre)	Irrigation	
	8800	16900	32300	54000	Without	With		Without	With
0	41·8	52·6	54·7	54·7	51·4	50·5	8800	47·8	50·3
0·6	50·6	62·8	67·2	68·6	62·0	62·6	16900	61·0	63·0
1·2	52·1	66·9	71·7	68·7	63·2	66·5	32300	65·0	65·9
1·8	51·6	65·6	68·2	66·0	60·8	64·8	54000	63·7	65·3
S.E.	±1·30				Vertical and interaction ±0·92		—	±0·92	
					Horizontal ±1·39		—	±1·39	

Table 4. *Effect of nitrogen, plant population and irrigation on sugar yield* (*cwt/acre*). *Mean* 1966–9

Nitrogen (cwt/acre)	Without irrigation					With irrigation				
	8800	16900	32300	54000	Mean	8800	16900	32300	54000	Mean
0	42·6	54·0	54·9	54·1	51·40	41·1	51·1	54·5	55·3	50·50
0·6	50·2	62·8	67·4	67·7	62·03	50·9	62·9	67·1	69·5	62·60
1·2	49·5	64·3	71·0	68·0	63·20	54·7	69·5	72·4	69·4	66·50
1·8	48·7	62·8	66·8	65·1	60·85	54·4	68·4	69·7	66·9	64·85
Mean	47·75	60·98	65·03	63·73	—	50·28	62·98	65·93	65·28	—
S.E.	Within table ±1·294, means ±0·647									

was not significant. Different results have been obtained in the United States of America. Haddock & Kelley (1948) found a positive interaction between nitrogen (0–140 lb/acre) and plant population but their range of populations (19000–33000 plants/acre) was smaller than ours. Also, Herron, Grimes & Finker (1964) grew a range of populations (18000–36000 plants/acre) and found no interaction with nitrogen (0–120 lb/acre).

The effect of irrigation on response to nitrogen has been studied in England by Garner (1950), Penman (1952, 1962*a*,*b*), Price & Harvey (1961, 1962) and Harris (1970). They mostly report very small effects of irrigation on response to nitrogen. Contrary to our results, Penman suggests a negative interaction between irrigation and nitrogen though he tested a relatively narrow range of nitrogen (0·4–0·8 cwt/acre initially and 0·6–1·2 cwt/acre in later experiments) and it was only with the large nitrogen dressings that we found a positive interaction.

Harris (1970) reported the only thorough investigation of the interaction between plant population and irrigation in England. He found the small plant populations responded more than large populations and suggested that the reason for this largely unexpected result was that the large populations had a deeper root system—hence a larger reservoir of available soil moisture than the shallow rooted, wide-spaced plants. In our experiments there was no interaction. The effect of plant population on moisture use and root depth is dealt with separately (Draycott & Durrant, 1971*b*).

The effect of additional phosphate and potash was tested on two plant populations, with and without irrigation in 1965. The individual effects were not significant but there were indications that the sugar beet responded to the additional phosphate and potash, but the response was not affected by irrigation.

Second-order interaction

Table 4 shows the effect of nitrogen, plant population and irrigation on sugar yield. Irrigating the smallest plant population gave no increase in yield without nitrogen and only a small increase with 0·6 cwt/acre. However, as the nitrogen was increased, the response to irrigation also increased.

Different results were obtained with the largest population. Irrigation increased yield equally with all amounts of nitrogen. The intermediate populations showed a gradation of this interaction.

Thus, these results offer an explanation for the difference in the first-order interactions described above by us (no interaction between plant population and irrigation when averaged over nitrogen applications) and by Harris (1970), who found a negative interaction between plant population and irrigation. In Harris's experiments sugar beet needed little nitrogen fertilizer, consequently his results agree with ours when sugar beet at Broom's Barn is given 1·2 or 1·8 cwt/acre nitrogen.

Root dry matter and sugar yield

There was a significant linear relationship between sugar yield and root dry-matter yield for all the thirty-two treatment combinations for each of the four years 1966-9. The slope (+0·75) is equal to the average sugar content percentage of root dry matter (75 %).

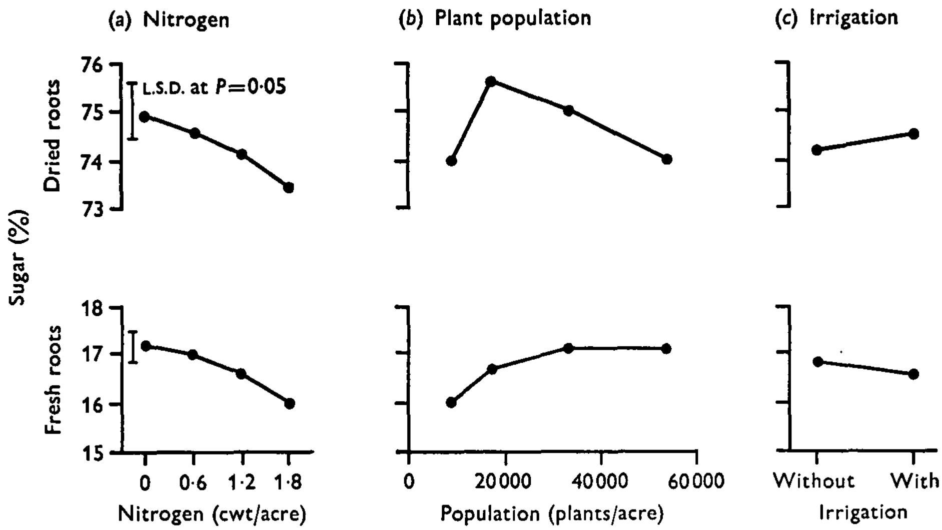

Fig. 1. Main effect of nitrogen fertilizer, plant population and irrigation on percentage sugar in fresh and dried roots. Mean of three experiments, 1967–9. (*a*) Nitrogen; (*b*) plant population; (*c*) irrigation. I, L.S.D. at $P = 0·05$.

Table 5(*a*). *Effect of nitrogen, plant population and irrigation on total dry-matter yield (ton/acre). Mean* 1966–9

Nitrogen (cwt/acre)	Without irrigation					With irrigation				
	8800	16900	32300	54000	Mean	8800	16900	32300	54000	Mean
0	3·74	4·50	5·12	4·70	4·52	3·62	4·29	4·79	4·93	4·41
0·6	4·53	5·63	5·99	6·13	5·57	4·67	5·38	6·08	6·31	5·61
1·2	4·70	6·11	6·73	6·49	6·01	5·12	6·46	6·97	6·89	6·36
1·8	4·95	6·08	6·54	6·55	6·03	5·35	6·74	7·03	7·10	6·56
Mean	4·48	5·58	6·10	5·97	—	4·69	5·72	6·22	6·31	—

Table 5(*b*). *Effect of nitrogen, plant population and irrigation on the dry matter in the roots expressed as a percentage of the total dry matter in the crop; means of four experiments* 1966–9

Nitrogen (cwt/acre)	Without irrigation					With irrigation				
	8800	16900	32300	54000	Mean	8800	16900	32300	54000	Mean
0	74·87	76·94	76·12	76·91	76·21	74·38	75·64	75·57	75·10	75·17
0·6	72·46	73·31	74·04	73·25	73·27	71·09	74·77	73·23	72·98	73·02
1·2	68·88	69·80	69·65	68·22	69·14	70·85	71·90	68·51	66·58	69·46
1·8	67·98	68·42	67·39	66·34	67·53	67·57	67·95	66·11	63·06	66·17
Mean	71·05	72·12	71·80	71·18	71·54	70·97	72·57	70·86	69·43	70·96

Thus increases in root dry-matter yield are generally accompanied by increases in sugar yield. It would be incorrect to infer that sugar content as a percentage of dry matter is a constant and that differences in sugar as percentage of fresh matter simply reflect changes in the amount of water in the roots. In fact, nitrogen, spacing and irrigation all had large consistent effects of the amount of sugar in the dry matter, as shown in Fig. 1.

Nitrogen fertilizer caused parallel decreases in the sugar content of both fresh and dry root matter (Fig. 1*a*). Increases in plant population (Fig. 1*b*) initially increased the sugar content as percentage dry matter and then decreased it (although the effects were somewhat variable from year to year), in contrast to the regular increases in the fresh matter. As expected, irrigation decreased the sugar content as percentage of fresh matter but, surprisingly, increased the sugar content as percentage of dry matter (Fig. 1*c*).

Distribution of dry matter

Effects of nitrogen, plant population and irrigation on total dry-matter yield (Table 5*a*) contrast with those on sugar yield. Most dry matter was produced with the largest amount of nitrogen given to the largest population with irrigation (7·10 tons/acre).

Table 5*b* shows the proportion of dry matter in the roots compared with the total production of dry matter. The means show that both nitrogen and irrigation decreased the proportion of dry matter in the roots. Increasing plant population increased the proportion to a maximum with 16900 plants/acre and further increases in plant population then decreased it.

Large dressings of nitrogen, together with large plant populations and irrigation, gave the smallest proportion of dry matter in the roots. As sugar yield was linearly related to root dry-matter yield, the decreases in sugar yield when the large plant populations were irrigated and given nitrogen were largely because of unfavourable distribution of dry matter in the plants. Presumably when sugar-beet plants are grown close together, the competition for light stimulates leaf growth at the expense of root. It is improbable that water or nitrogen were limiting the sugar yield of the large plant populations in the experiments (see Draycott & Durrant, 1971*a*, *b*).

We thank J. H. A. Dunwoody for the statistical analyses and H. Klemp and A. B. Messem for assisting in the field and laboratory.

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APPENDIX. Table 1

Rainfall and irrigation

	1965	1966	1967	1968	1969
			Rainfall (in)		
Apr.	2·24	1·65	2·36	1·87	1·42
May	1·77	1·48	2·42	1·17	2·97
June	2·56	2·27	1·34	2·62	1·72
July	2·79	2·96	2·33	2·73	2·66
Aug.	2·78	2·51	1·33	4·33	2·37
Sept.	3·40	0·77	1·81	5·96	0·06
Oct.	0·73	2·25	4·20	1·75	0·17
			Irrigation (in)		
June	—	—	—	—	0·25
July	0·75	0·50	3·25	1·28	2·50
Aug.	1·75	2·03	1·25	—	0·65
Sept.	—	—	1·00	—	—

Calculated potential transpiration (100 % *leaf cover*) (in)

	1965	1966	1967	1968	1969
Apr.	2·15	1·80	1·95	3·17	2·24
May	3·21	3·53	3·20	3·04	2·86
June	3·78	3·89	4·04	3·56	3·50
July	3·16	3·23	4·32	3·06	3·45
Aug.	3·25	3·31	3·48	2·28	2·67
Sept.	1·90	2·24	1·76	1·76	1·75
Oct.	1·32	1·14	1·77	1·39	0·99

Potential soil-moisture deficit on last day of each month (in)

	8800 plants/acre			54000 plants/acre		
	1967	1968	1969	1967	1968	1969
Apr.	0·46	1·07	0·81	0·46	1·07	0·81
May	0·92	1·20	0·70	0·96	1·47	0·70
June	1·92	0·82	1·62	3·21	2·23	2·53
July	4·00	1·05	3·20	5·29	2·46	4·11
Aug.	5·92	0·72	3·02	7·21	0·72	3·93
Sept.	5·70	0	4·64	6·99	0	5·55
Oct.	2·92	0·25	5·53	4·21	0·25	6·34
			Maximum soil-moisture deficit (in)			
	6·32	1·83	4·88	7·61	3·24	5·79
	13 Sept.	8 July	6 Oct.	13 Sept.	8 July	6 Oct.