DRAINAGE REQUIREMENT FOR SUGARBEETS GROWN ON SANDY SOIL

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Field-plot and lysimeter studies were conducted to determine the optimum water table depth for sugarbeets (*Beta vulgaris* L.) grown in irrigated sandy soils of the northern Great Plains. Field plots were located over a declining water table for 3 yr. The water table depths (expressed as time-weighted averages between 15 May and 30 Sept.) were 147, 203 and 229 cm. Four constant water table depths of 46, 101, 155 and 210 cm were maintained in the lysimeters for 1 yr. Sprinklers irrigated the field plots at levels of 0.5, 1.0 and 1.5, and the lysimeters at levels of 0.3, 0.8 and 1.3 times the calculated plant-water requirement. A nonirrigated treatment (precipitation only) was also included in the field-plot study. Highest yields of fresh sugarbeet roots, root dry matter, and sucrose were produced with the shallowest water table in the field plots, regardless of irrigation level. Sugarbeet yields were greater in the lysimeters with water tables 101 cm below the soil surface than in the lysimeters with either deeper or shallower water tables.

INTRODUCTION

Maximum plant growth requires ideal soil-water-air conditions. A soil-water-air environment favorable to plant growth may exist naturally or be provided by appropriate irrigation and drainage. Different plants respond differently to specific soil-water-air environments, and therefore, have different drainage requirements. The term "drainage requirement" has been defined as the minimum water table depth that must be maintained to best satisfy such plant needs as aeration, rooting volume, nutrition, and soil temperature (Doering et al. 1977). However, drainage designs must also consider effects of ambient conditions such as trafficability, soil salinity, irrigation management, water resource conservation, and environmental quality.

Natural variability of agricultural soils, climatic conditions, and the relative scarcity of precise drainage requirement information caused Ochs et al. (1980), Hiler (1969), and van Schilfgaarde (1963) to conclude that drainage engineers cannot design a single drainage system to optimize agronomic returns. Large areas of coarse- and moderately coarse-textured soils are proposed for irrigation in North Dakota with drain designs based on the specifications that the water table depth will always be deeper than 122 cm below the soil surface at all field locations. These lands in North Dakota are located in a subhumid climatic zone (see Thornthwaite 1941) and are naturally subject to high water table conditions; therefore, drainage and irrigation must develop simultaneously. These sandy soils in this area have an available water-holding capacity of about 9.4 cm in the top 122 cm of the profile according to Rivers and Shipp (1972). Thus, droughty conditions can develop in the spring, making crop establishment difficult. These soils are also subject to wind erosion when the surface is dry and not protected by either vegetation or residue.

Controlled water table depths have been utilized in Michigan, Minnesota, Indiana, Ohio, and South Carolina to provide subirrigation for crops by Criddle and Kalisvaart (1967), and Doty and Parsons (1979). A shallow, nonsaline water table in sandy soils can be particularly beneficial by providing some of the crop-water needs and by adding flexibility to irrigation schedules. The presence of a shallow water table in the spring would improve the soil-water conditions in the seedbed, enhance germination and seedling emergence, and decrease wind erosion potential.

The key element of the managed shallow water table concept is the crop drainage requirement. (In this paper, the crop drainage requirement is the minimum water table depth at which maximum sugarbeet growth occurs.) Hooghoudt (1952) showed lower yields of sugarbeets on water table depths both above and below 120 cm. Williamson and Kriz (1970) quote van Hoorn's data showing that yields of several crops increased as water table depth increased to near 150 cm; however, they had no deeper water table data. Recently, Benz et al. (1978), Follett et al. (1974), and Reichman et al. (1977) showed that high yields of high quality sugarbeets can be grown in sandy soils with average water table depths as shallow as 130 cm. However, the water tables in those field studies were not shallow enough to limit growth; thus, the data did not define the drainage requirement. Williamson and Kriz (1970) concluded that it was difficult to transfer drainage requirement results from one location to another because of soil differences, watering procedures, and climatic conditions. For example, Williamson and van Schilfgaarde (1965) obtained maximum corn yields in North Carolina when the water table was from 76 to 86 cm below the surface in a sandy loam soil, and Doering et al. (1977) found a 100-cm depth to be optimum for corn grown on sandy soils in North Dakota.

The objective of this study was to evaluate the drainage requirement for sugarbeets grown in sandy soils of North Dakota under several irrigation levels by growing sugarbeets in the field and in lysimeters with sufficiently deep and shallow water tables so as to reduce crop production.

MATERIALS AND METHODS

The effects of water table depths and irrigation regimes on sugarbeets grown on sandy soils in North Dakota were studied. Data were collected for 3 yr from field plots described by Reichman et al. (1977) and for 1 yr from field-installed lysimeters described by Reichman et al. (1979).

The location chosen had soils of the Hecla-Arveson-Fossum association, representative of many soils in eastern North Dakota where sugarbeets may be grown. Textures range from sandy loams to loamy sands. Hecla is an Aquic Haploboroll, Arveson is a Typic Calciaquoll, and Fossum is a Typic Haplaquoll, see U.S. Department of Agriculture (1981). Surface undulations were only about 20 cm

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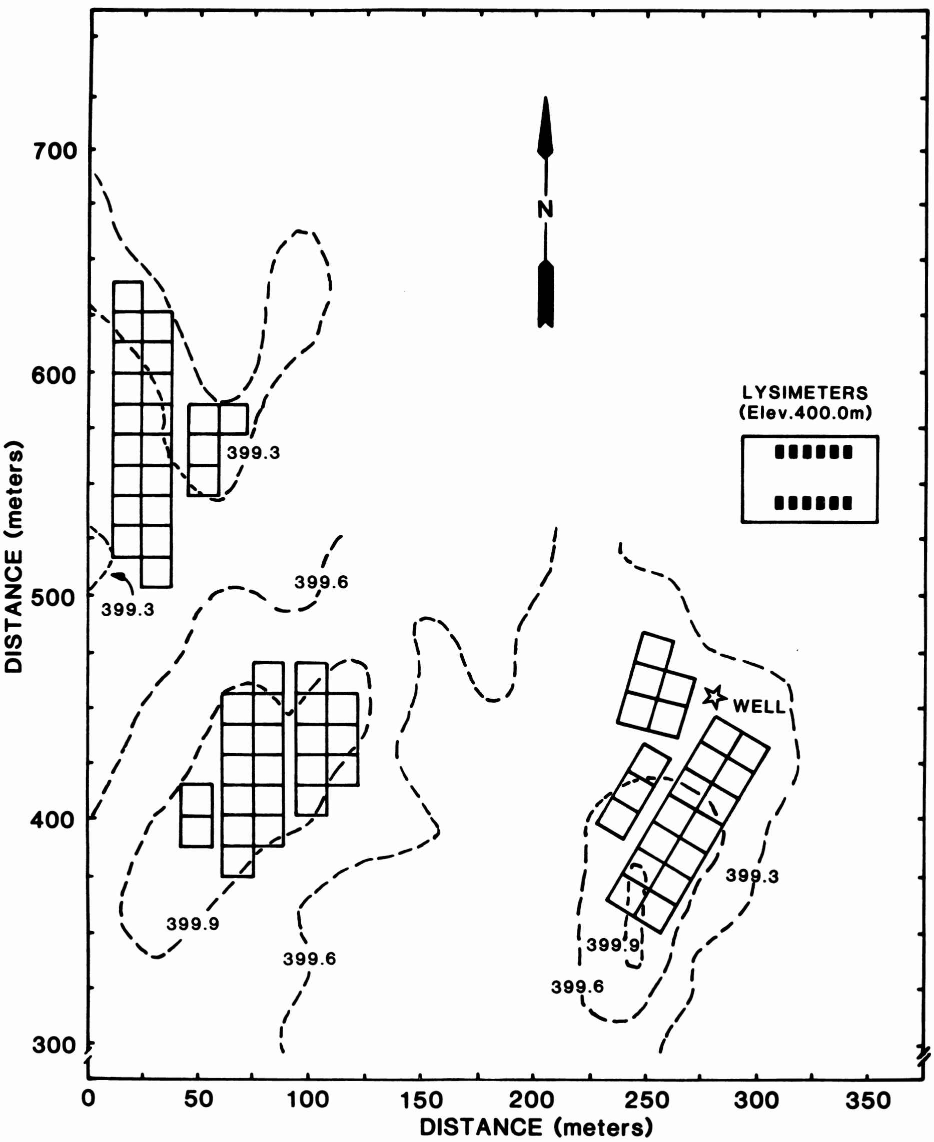

Figure 1. Plan view with elevation contours (meters above msl) of field plots, lysimeter area, and irrigation-drainage well.

over 100-m distances. Unpublished data from a corn uniformity study gave appropriate evidence of similar soil productivity on the plot areas.

Field Plots

The first 3 years data came from sugarbeets planted in 47-m² field plots. Three groups of plots were located so that the water table (as affected by the surface elevation and water table drawdown around the drainage well) for each block was at a different depth (Figs. 1, 2). The water tables declined as the growing season progressed because of the semiarid climate and regional drainage (Fig. 3). A time-weighted average water table depth was determined by planimetering each year's hydrograph. Three-year averages of the time-weighted (May-September) water table depths were 147, 203, and 229 cm in the three blocks.

These main blocks were divided into three replication units, each replication having a randomized factorial arrangement of irrigation and fertility plots. The statistical analyses were designed by H. Del Var Peterson (pers. commun.). This design gave valid tests for differences among means of irrigation and water table treatments but could not test for differences in replication means.

Three irrigation treatments and one nonirrigated treatment were applied to each of the three water table zones. These irrigation treatments were based on the potential evapotranspiration (ET_p) for a well-watered crop of alfalfa, the accepted crop reference (see Pair 1975), that was calculated for the period since the last irrigation. The amount of water applied was calculated using the following equation:

$$IW = C(ET_p \times K_c) - P_e + D \qquad (1)$$

where IW is the amount of water applied (cm); C is 0.5, 1.0, or 1.5 to establish three irrigation treatments; ET_p is expressed as the equivalent depth of water (cm) calculated by the Jensen-Haise method for the previous week (see Burman et al. 1980, Follett et al. 1973, Pair 1975); K_c is a crop coefficient (ranging from 0.2 to 1.0) that adjusted the ET_p for stage of crop growth, and referenced to a well-watered crop of alfalfa (Burman et al. 1980; Pair 1975); P_e is the effective precipitation measured during the previous week (cm); and D is the calculated water deficit (cm). The three levels of irrigation (one for each C value) were applied each week unless the calculated IW was less than 0.76 cm, then no irrigation was applied and the IW value became the

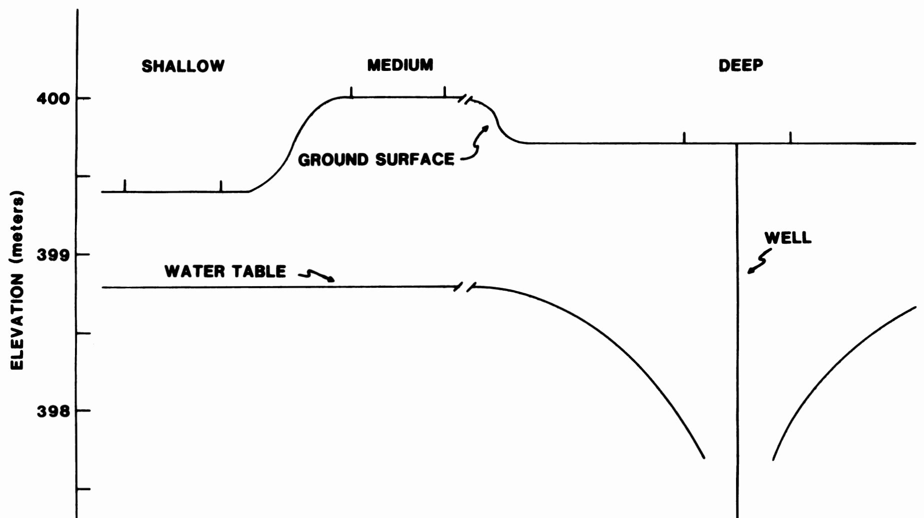

Figure 2. Graphic diagram of relative elevation of soil surfaces, water table and irrigation-drainage well used to establish water table depth differences.

water deficit (D) for the following week. Precipitation events less than 0.25 cm per day were considered ineffective and were disregarded. When weekly precipitation events were in excess of $(ET_p \times K_c) + D$, IW became negative and no irrigation was applied. This excess was assumed to drain past the root zone, i.e. a negative D was not carried forward. Thus, four irrigation treatments were used; each receiving different amounts of water (Table I).

A well (Figs. 1, 2) supplied good-quality irrigation water which was applied to the irrigated plots by a plot sprinkler (Bond et al. 1970). All plots including a nonirrigated set received precipitation.

In the first year, ammonium nitrate (33-0-0) at a rate of 112 kg N/ha, concentrated superphosphate (0-46-0) at a rate of 56 kg P/ha, and potassium sulfate (0-0-50) at a rate of 111 kg K/ha were broadcast, and zinc sulfate (36% Zn) was banded 5 cm to the side and 5 cm below the seed row at a rate of 5.6 kg Zn/ha. In the second and third years, ammonium nitrate was broadcast 1 wk after planting to provide 112 kg of N/ha (NH_4-N plus NO_3-N in the 0- to 91-cm depth); zinc sulfate and concentrated superphosphate were banded 5 cm to the side and 5 cm below the seed rows at rates of 4.4 kg Zn/ha and 33 kg P/ha, respectively.

Lysimeters

Twelve nonweighing lysimeters were constructed, each with a surface area of 11.9 m² (2.4 m by 4.9 m), and soil profiles were reconstructed by using material from the three soil horizons of the experimental field as described by Reichman et al. (1979). The top of each rigid lysimeter wall was positioned about 20 cm below the ground surface so that conventional farm machinery could be used for planting and cultivating. Four constant water table depths (46, 101, 155, and 210 cm) were maintained throughout the cropping season in the lysimeters by automatically adding or removing measured amounts of water at the bottom.

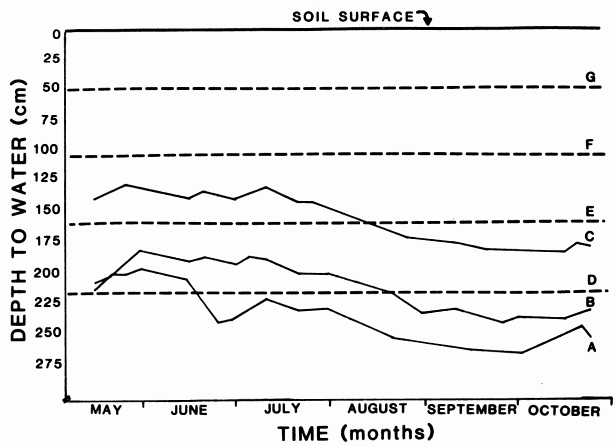

Figure 3 Hydrograph of water table depth during cropping seasons. Curves A, B and C indicate field conditions while curves D, E, F and G indicate lysimeter conditions.

Three irrigation treatments determined by using the values of 0.3, 0.8, and 1.3, respectively, for C in Eq. 1 were applied in a factorial arrangement with the water table treatments. The amount of water needed for each irrigation level was calculated by using Eq. 1 for the appropriate days, then water was applied each Monday and Friday as required for each treatment. Irrigation was started immediately after seeding because the weather was very dry. The total water (precipitation and irrigation) applied to each of the irrigation treatments is shown in Table I.

Ammonium nitrate was broadcast 1 wk after planting to provide a total of 168 kg of N/ha (NH_4-N plus NO_3-N in the 0- to 61-cm depth), and superphosphate and zinc sulfate were banded 5 cm to the side and 5 cm below the seed row at rates of 33 kg P/ha and 2.2 kg Zn/ha, respectively. Potassium sulfate had previously been broadcast at a rate of 111 kg K/ha.

Crop Yield Evaluation

Sugarbeets (cultivar Holly HH 10) were planted in rows spaced 61 cm apart in both field plots and lysimeters. Planting dates were 20 May, 4 May and 25 Apr., the first, second and third years in the field plots and 30 Apr. in the lysimeters. The corresponding harvest dates were 18, 16, 15 Oct. and 28 Sept. Treatments were repeated on the same field plots each of the 3 yr.

Yields were measured on 18.3 m of row in the field plots and on each of the four 4.88-m rows of the lysimeters. Yields from the lysimeter rows were not significantly different, so averages were used. Yields are reported in terms of fresh field material as well as total dry matter harvested, and sucrose yields are reported as the product of fresh root yield and sugar percentage. Treatment effects were tested using currently accepted statistical methods of Snedecor (1956).

TABLE I. IRRIGATION WATER AND PRECIPITATION RECEIVED BY FIELD PLOTS AND LYSIMETERS

Irrigation level	May			June			July			August			September			Irrigation total			Irrigation + rainfall		
	Year			Year			Year			Year			Year			Year			Year		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Field plot experiment. Irrigation applied (mm)																					
Rainfall only‡	39	110	33	94	34	68	128	140	39	64	36	37	35	11	105				360	331	282
0.5	0	0	0	0	14	0	13	11	60	49	39	39	11	8	10	73	72	109	433	403	391
1.0	0	0	0	0	29	0	63	18	143	112	125	110	22	17	21	197	189	274	557	520	556
1.5	0	0	0	0	141	0	74	43	226	200	209	176	66	25	39	340	318	441	700	649	723
Lysimeter experiment. Irrigation applied (mm)																					
Rainfall only	4			46			15			15			21						101		
0.3	33			46			33			46			9			167			268		
0.8	114			133			114			132			41			534			635		
1.3	191			216			191			216			78			892			993		

†The same irrigations were applied to all water table depth treatments.
‡All irrigation levels received precipitation.

The yields were correlated with water table depths for each irrigation level. Each data set was fitted to a four-constant equation (Johnson 1952) to determine the apparent maximum yield. Water table depths corresponding to maximum yields were plotted against corresponding irrigation levels to evaluate the complementary effect of the two sources of water.

RESULTS AND DISCUSSION

Field Experiment

Three-year-average fresh root yields are presented in Fig. 4. Largest yields of fresh roots were obtained with the shallowest water table depth. This shows that the plants were able to obtain the water they needed from the shallow (147 cm) declining water table. Also, water applied by irrigation did not increase yields with the shallowest water table.

Irrigation did increase root yields significantly at the deeper water table depths, but did not produce yields as large as the yields with the shallow water table. However, irrigation was unable to compensate fully for the differences in availability of water between the deep and shallow water tables. Yields of total dry matter and sucrose increased similarly to the root yields.

The field-plot data showed significant negative relationships with the water table depth, indicating that the highest sugarbeet production would be obtained with a water table depth near, or shallower than, 147 cm in these sandy soils. Since the yields were increased by irrigation in conjunction with the 203- and 229-cm water tables, but were not when the water table was at 147 cm, the need for irrigation is apparent only when water tables are deeper than 147 cm. Water tables near the 147-cm depth apparently supply nearly all of the water required by the sugarbeet.

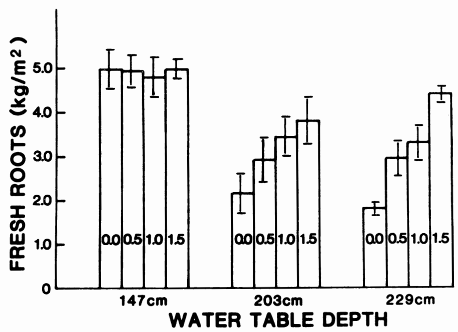

Figure 4. Effect of irrigation treatments (0.0, 0.5, 1.0 and 1.5 times the calculated amount of water required) on sugarbeet root yields with three water table depths in field plots.

Therefore, the deeper water table levels represented excessive drainage for these soils. Since the shallowest field water table did not suppress yields the data indicate that the water tables in the field experiments were too deep to define the drainage requirement (see definition in introduction). Hence the lysimeter experiment with shallower water tables was required.

Lysimeters Experiment

Fresh root, dry root material, and sucrose yields are presented as functions of relative irrigation level and constant water table depth in Fig. 5. The plotted data are the means of four replicates and the smooth curves represent functional relationships as expressed by Eq. 2 which was fitted to the data using the method of Johnson (1952). Thus,

$$Y = 10^{a-bx} - 10^{c-dx} \qquad (2)$$

where Y is the yield; x is the water table depth; a, b, c, and d are coefficients such that (10^{a-bx}) dominates the relationship for deep water table depths and (-10^{c-dx}) dominates the relationship for shallow water table depths (Table II). The lysimeter data were used to determine the values of coefficients for Eq. 2. Curves plotted from these equations showed distinct maximum yields (Table III) that were comparable to the highest field plot yields (Fig. 4).

All yields were significantly reduced by the 46-cm water table treatment as compared with deeper water tables at all irrigation levels (Table IV). Yields were unaffected by irrigation level at this water table depth, therefore the yield decrease is the result of the shallow water table and limited aeration. Yields from the lysimeters with 155- and 220-cm water table depths and the 0.3 and 0.8 irrigation treatments were also significantly lower than yields from the lysimeters with a water table at 101 cm. Thus, maximum yields were associated with water tables near 100 cm for the limited irrigation treatments (Fig. 5). Yields were depressed over the 101-cm water table with the 1.3 irrigation level but not with the lower irrigation levels. An apparent maximum yield did occur at a deeper water table depth.

The maximum yield levels were comparable for all irrigation levels, but were obtained at different water table depths for each irrigation level. Thus, the irrigation level interacts with the water table depth. The net effect of the interaction of irrigation and water table depth is that the irrigation level associated with maximum yield increased as the water table depth increased (Fig. 6). The coordinates plotted in Fig. 6 are the irrigation level and the water table depth corresponding to the maximum yield defined by Eq. 2 in Fig. 5. Comparable maximum yields are thus represented by any point on the curves in Fig. 6. Thus the irrigation requirement is substantially lower when the water table

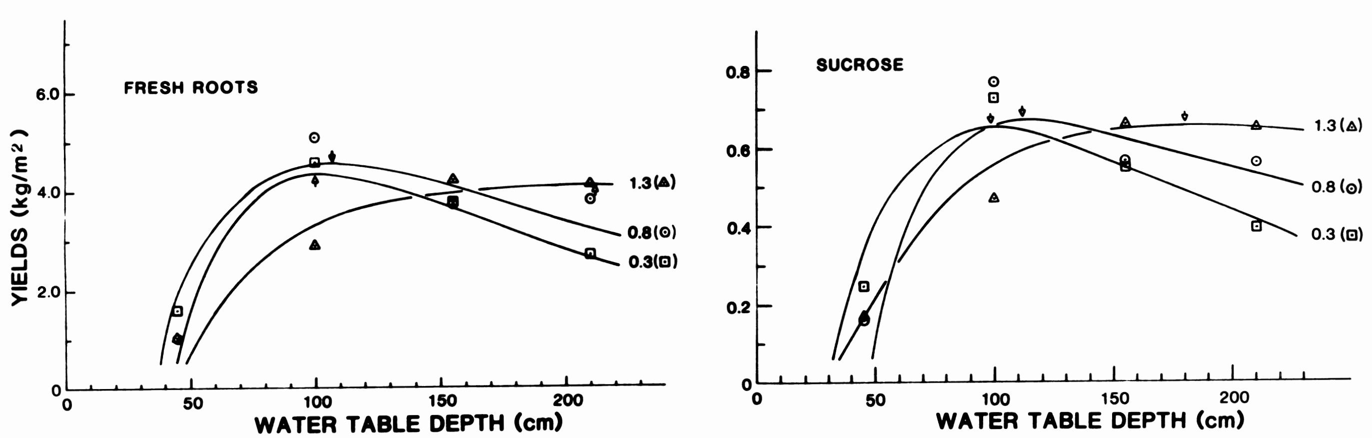

Figure 5. Effect of irrigation treatments (0.3, 0.8 and 1.3 times the calculated amount of water required) on root and sucrose yields with four water table depths in the lysimeters. The water table depths for the maxima of the fitted curves are indicated by arrow heads.

TABLE II. COEFFICIENTS OF THE YIELD VS. WATER TABLE DEPTH CURVES

Parameter	Irrigation	*a*	*b*	*c*	*d*
Fresh roots	0.3	1.983	-2.653×10^{-3}	2.578	-16.32×10^{-3}
	0.8	1.944	-2.011×10^{-3}	2.339	-13.44×10^{-3}
	1.3	1.650	-0.148×10^{-3}	2.130	-11.28×10^{-3}
Dry roots	0.3	2.481	-3.097×10^{-3}	2.715	-10.33×10^{-3}
	0.8	2.246	-1.815×10^{-3}	3.207	-20.97×10^{-3}
	1.3	2.149	-0.630×10^{-3}	2.304	-7.13×10^{-3}
Sucrose	0.3	2.171	-2.626×10^{-3}	2.470	-12.59×10^{-3}
	0.8	1.999	-1.293×10^{-3}	2.845	-19.29×10^{-3}
	1.3	1.955	-0.586×10^{-3}	2.208	-8.44×10^{-3}

TABLE III. MAXIMUM YIELDS OF SUGARBEETS AS ESTIMATED FROM FOUR-CONSTANT EQUATIONS FITTED TO LYSIMETER DATA

	Irrigation level		
	0.3	0.8	1.3
Fresh sugarbeet roots (kg/m^2)	4.34	4.56	4.10
Oven-dry sugarbeet roots (kg/m^2)	1.00	1.03	0.98
Gross sucrose (kg/m^2)	0.647	0.667	0.658

TABLE IV. STATISTICAL SIGNIFICANCE OF TREATMENT EFFECTS ON FRESH SUGARBEET ROOTS, DRY ROOT MATTER AND SUCROSE YIELDS IN LYSIMETERS

		F-values and significance symbols		
Source of variance	df	Fresh roots	Dry roots	Sucrose
Water table depth (WT)	3			
WI_{45} vs. others	1	468.00****	278.00****	349.00****
WT_{100} vs. WT_{155} & WT_{210}	1	11.14***	7.19**	15.97****
WT_{155} vs. WT_{210}	1	5.12*	0.24NS	4.52NS
Error *a*	12			
Irrigation rates (IR)	2			
$IR_{0.3}$ vs. others	1	0.50NS	0.10NS	0.97NS
$IR_{0.8}$ vs. $IR_{1.3}$	1	3.38*	0.52NS	0.78NS
IR × *WT*	6	9.64****	6.55****	9.45****
Error *b*	24			

Significance level of *F*-value: **** = 0.5%; *** = 1.0%; ** = 2.5%; * = 5.0%; NS > 5.0%.

depth is near 100 cm. So, providing a water table depth of about 100 cm by shallow drainage reduces the need for irrigation, and conversely, deep drainage wastes both irrigation water and the energy consumed while irrigating.

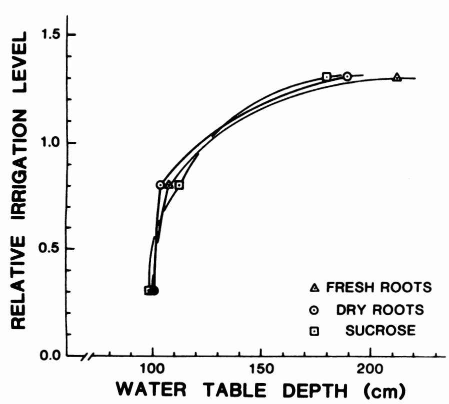

Figure 6. Combinations of irrigation level and water table depth that produced maximum yields of sugarbeet roots and sucrose.

Since the maxima for the root dry matter and sucrose yields occurred for a water table depth of about 100 cm for both the 0.3 and 0.8 irrigation levels (Fig. 5), the drainage requirement for sugarbeets grown on sandy soils in North Dakota is about 100 cm. Also, the irrigation requirement apparently was very low when the water table was near to 100 cm (Fig. 6).

SUMMARY OF RESULTS

In field plots on sandy soil with a declining water table:

(1) The greatest sugarbeet root and sucrose yields were obtained in association with the shallowest water table (3-yr average depth of 147 cm).

(2) Sprinkler irrigation, ranging from none to enough water to provide 1.5 times the calculated water need, produced no significant effect on yield over the shallowest water table.

(3) Even with irrigation which provided 1.5 times the calculated water need, yields from deeper water table treatments (3-yr average depths of 203 and 229 cm) never exceeded yields from the shallowest water table.

(4) Yield response to irrigation was significant with water tables deeper than 147 cm.

In lysimeters with automatically controlled static water tables at depths of 46, 101, 155, and 210 cm:

(1) Sugarbeet root and sucrose yields associated with the 46-cm water table were significantly suppressed for all irrigation levels compared to the deeper water tables.

(2) Sprinkler irrigation, which provided from 0.3 to 1.3 times the calculated water need, produced no effect on yield over the 46-cm water table, so the shallow water table caused the low yields.

(3) When the water table was at the 101-cm depth, yields were highest and were not affected by irrigation at the 0.3 and 0.8 irrigation levels but were significantly less for the 1.3 irrigation level, showing that over-irrigation did occur.

(4) Based on correlations of yield vs. water table depth for each irrigated level, the drainage requirement was shown to be about 100 cm for sugarbeets.

(5) The irrigation requirement increased significantly when the water table depth increased beyond 100 cm.

These results show that a shallow, nonsaline water table is a valuable agricultural resource that should not be removed by drainage. Also these results show that drains designed to maintain the water table at about 100 cm below the surface of these sandy soils are compatable with maximum yields, will reduce the irrigation and energy requirements, and will make irrigation schedules more flexible.

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