Effects of Water-Table Depth and Irrigation on Sugarbeet Yield and Quality[1]

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In North Dakota, irrigation is being developed[3] on large areas of coarse- and moderately coarse-textured soils underlain by shallow, nonsaline water tables (8)[4]. Thus, drainage is a part of initial irrigation development. Also, extensive areas of similar soils overlaying nonsaline aquifers are being privately developed for irrigation. High value crops such as sugarbeets (*Beta vulgaris* L.) are expected to be grown. Sugarbeets respond well to irrigation because they continue to grow in August and September when rainfall in North Dakota is very limited.

Irrigation should provide the correct amount of water to the root zone at the proper time for crop needs. Agricultural drainage should insure that the water table does not invade the root zone. Proper root environment and optimum crop yield depends upon adequate aeration of the root zone (7, 17), but under certain conditions, shallow water tables can effectively provide water for crop use. (9).

The effective root zone of sandy soils in irrigable areas of North Dakota may be only 24 to 36 inches deep (9) with an available water capacity between 2 and 3 inches (14). An evapotranspiration rate for sugarbeets as high as 0.3 inch/day has been reported (16). During the 2 years of this study, 20 days had potential evapotranspiration (ET_p) rates greater than 0.25 inches/day with 0.28 and 0.27 inches/day being the highest rates in 1971 and 1972, respectively. The low water-holding capacity and high evapotranspiration rate may require irrigating as frequently as every 4 to 6 days (9). For example, if 1.5 inches is considered the maximum allowable soil-water deficit, irrigation every 7 days from August 1 to August 27,

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[3]U.S. Department of the Interior, Bureau of Reclamation, 1965. Definite Plan Report on Garrison Diversion Unit (Initial Stage — 250,000 acres). Garrison Division, North Dakota — South Dakota, Missouri River Basin Project, Appendix A. — Land Classification. 324 p.

[4]Numbers in parentheses refer to literature cited.

1971 was inadequate because weekly evapotranspiration (ET) exceeded 1.5 inches during this period. The periods in 1972 with ET greater than 1.5 inches extended from July 3 to July 16 and from August 8 to August 20. However, with irrigations at 7-day intervals, corn yields were produced that were essentially as good as yields where a shallow water table apparently supplied adequate water (9). Immediately following irrigation, the surface 6 inches of soil will be wetter than field capacity; so, the available water will be more than the amount expressed by the difference between the field capacity and wilting point.

In irrigated areas with high water tables, subsurface drains are usually installed as deep as physically and economically feasible to minimize (1) the drain length per acre and (2) the possibility that the water table will invade the root zone and reduce crop growth. With sandy soils, deep drainage can cause drouthiness which decreases yields and also can increase the wind erosion hazard. Available information is inadequate for designing optimum drainage and irrigation systems on sandy soils to both maximize agricultural output and minimize environmental hazards. The objective of this field study was to evaluate, under a declining water-table, the effects of various irrigation amounts and degrees of drainage on yield, sucrose content, and quality of sugarbeets grown on sandy soils.

Methods and Materials

This research was conducted in 1971 and 1972 on soils of the Hecla-Arvason-Fossum associated with surface soil textures ranging from sandy loam to loamy sand. Hecla is a *udic haploboroll,* Arveson is a *typic calciaquoll,* and Fossum is a *typic haplaquoll* (18).

Four irrigation levels were included. The plots were irrigated weekly during the 65 (July 13 to Sept. 16) and 80 (June 28 to Sept. 12) days that irrigation was required (Figure 1). These short seasons account for lower seasonal ET values than are frequently reported. Precipitation between seeding and the first irrigation amounted to 9.31 inches and 6.95 inches for 1971 and 1972, respectively. Calculated ET between June 21 and October 18, 1971 was 17.2 inches and between May 15 and October 11, 1972 was 18.5 inches.

The irrigation water (IW) applied was calculated by the following formula:

$$IW = C(K_c \cdot ET_p) - P + D \qquad [1]$$

where C designated the irrigation level with values of 0.5, 1.0 or 1.5; ET_p was the evapotranspiration calculated according to the Jensen-Haise formula (10, 12) with adjustment (K_c) for stage of plant development; P was the measured precipitation (with events less than 0.10 inches ignored); and D was the water deficit carried over from the previous week. The fourth irrigation level was no irrigation. IW amounts less than 0.3 inch were not applied and became the deficit for the following week. Precipitation exceeding $[C(K_c \cdot ET_p) + D]$, i.e., causing IW to be negative, was assumed to drain through the root zone and have no effect on the next week's water deficit (19). Therefore, the amounts of water applied were equivalent to 0, 0.5, 1.0, and 1.5 times the calculated ET of sugarbeets. Since the local ground water was nonsaline, a shallow well was used for irrigation water. Each irrigation was applied by a rotating boom plot irrigator that applied water with very low impact energy at the rate of 1 in/hr (2). The irrigation treatments are illustrated in Figure 1 by showing the accumulation of water added by irrigation and rain throughout the irrigated season.

Each irrigation treatment was applied to three water-table zones. At sugarbeet thinning time in 1971 and 1972, the shallow, medium, and deep water tables were about 43 and 34, 69 and 64, and 83 and 79 inches below the soil surface, respectively. All water tables declined at approximately 0.25 inch/day each year.

In 1971, ammonium nitrate (33-0-0) was broadcast at 100 lb N/A. The top 3 feet contained an average of 104 lb N/A, resulting in 204 lb N/A. Concentrated superphosphate (0-46-0) and potassium sulfate (0-0-50) were applied uniformly over the experimental area at 50 lb P/A and 100 lb K/A, respectively. Surface applied fertilizers were disced into the soil. Zinc sulfate (36% Zn) was banded 2 inches to the side and 2 inches below the sugarbeet seed at a rate of 5 lb Zn/A.

Before planting in 1972, residual N from the 1971 treatment was estimated from soil samples collected to a 3-ft depth from each plot. The NO_3-N and the NH_4-N were extracted with 2 *N* KCL and determined by automated procedures for the Brucine (13) and the Berthelot reaction (1), respectively. Sufficient ammonium nitrate was then broadcast one week after planting to provide a total of 100 lb soil-plus-fertilizer N/A. At seeding time, concentrated superphosphate and zinc sulfate were banded 2 inches to the side and 2 inches below the sugarbeet seed at 29 lb P/A and 1.8 lb Zn/A, respectively.

Sugarbeets (*Beta vulgaris* L.), cultivar Holly HH 10[5] were planted in rows 2 feet apart on May 20, 1971 and May 4, 1972; were thinned on July 5 and June 1; and were harvested on October 18 and October 16, respectively. After thinning, populations were 29,000 and 30,000 plants/acre in 1971 and 1972, respectively. Sugarbeets were grown on the same plots both years.

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[5]Trade and company names are given for the reader's benefit and do not imply endorsement or preferential treatment of any product by USDA.

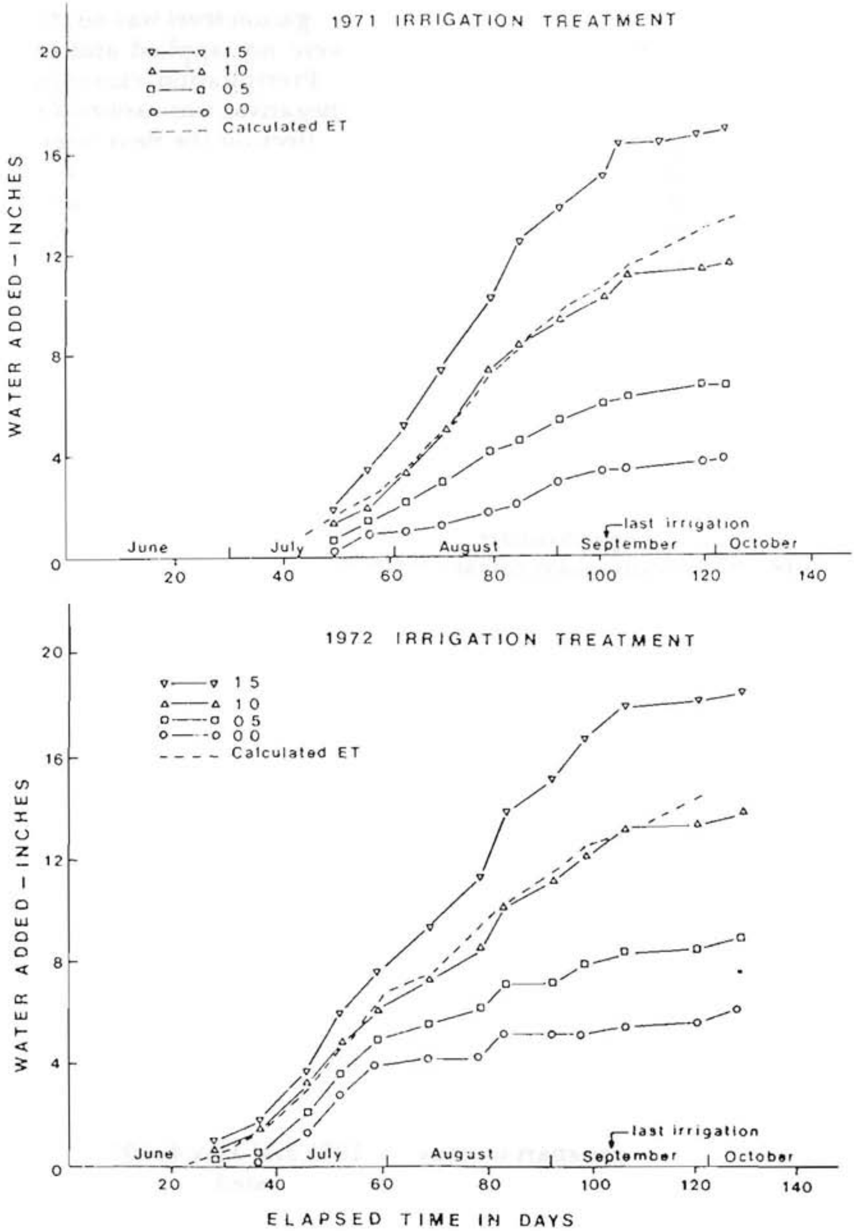

Figure 1.—Cumulative water added (irrigation and precipitation) during the 1971 and 1972 irrigation seasons for the 0.0, 0.5, 1.0 and 1.5 irrigation levels. Accumulated ET as calculated by the modified Jensen-Haise equation is also shown. Elapsed time is measured from June 1.

The plots were replicated four times in a factorial design with water tables confounded with field location. Thus, 48 plots, each consisting of 8 rows 45 feet long, were established.

Root yields were obtained from 28 feet of row in each plot. Fresh root weights were determined after washing to remove soil. Representative fresh root samples and brei samples were collected.

Factory tare, sucrose, and chemical determinations were provided by the American Crystal Sugar Company. Brei samples were extracted with an aqueous solution of lead subacetate, and sucrose, Na, K, and α amino-N concentrations were determined in the extract. Sucrose was determined polariscopically, Na and K by flame photometry, and amino-N by the Stanek-Pavlas method (3).

In interpreting these data, modifications of the equation for impurity value (4, 5, 6) and equations for the known sucrose loss (KSL), extractable sucrose (S_e), and sucrose recovery percentage (S_r) were used, all as suggested by the American Crystal Sugar Company. The impurity equation was modified by the sugar company to give the best empirical measure of the impurities of their molasses. Dividing the impurity value by the sucrose concentration gives an impurity index (I). Thus, the impurity index used in this paper was calculated by:

$$I = \frac{3.5\ \text{Na} + 2.5\ \text{K} + 9.5\ \alpha\ \text{amino-N}}{S_{\%}} \qquad [2]$$

where Na, K and α amino-N are the concentrations of the respective ions (in ppm) and $S_{\%}$ is the sucrose concentration (in percent) in the extract. Also, empirically:

$$\text{Gross Sucrose } (S_g) = \frac{\text{Root yield} \bullet S_{\%}}{100} \qquad [3]$$

gives gross sucrose in tons/acre from root yields in tons/acre; and

$$\text{KSL} = S_g\,(0.0001\ \text{I})1.5 \qquad [4]$$

gives KSL in tons/acre, where (0.0001 I) converts the impurity index to a decimal and 1.5 is the empirical constant relating sucrose to impurities in the molasses. Thus,

$$S_e = S_g - (\text{KSL}), \text{ and} \qquad [5]$$
$$S_r = 100\,(S_e/S_g). \qquad [6]$$

Extractable sucrose (S_r) is calculated in tons/acre and the sucrose recovery is expressed as a percentage.

Results and Discussion

All data were reduced to means of the four replications (Figures 2, 3, and 4). Analyses of variance (15) defined the significant differences shown in Table 1. The depth to water table af-

Table 1.—Significance of treatment effects on sugarbeet characteristics for the years 1971 and 1972.[1]

Source	Fresh root weights T/A	Sucrose concentration	Impurity index	Known sucrose loss T/A	Extractable sucrose T/A
Water-table depth (WT)	**	**	ns	**	**
Irrigation (IW)	**	ns	**	ns	**
WT x IW	**	*	ns	ns	**
Years (Y)	ns	**	**	**	**
WT x Y	ns	*	ns	ns	ns
IW x Y	ns	ns	ns	ns	ns
IW x WT x Y	ns	ns	ns	*	ns

[1]Confidence levels: ** ≥ 99%; * ≥ 95%; ns = not significant, according to the standard F test (15).

fected all measurements except impurity index. Irrigation rates affected the root weight, impurity index, and extractable sucrose. Significant differences in values were found between yearly data for all parameters except root weight. Where treatments caused different trends between different sets of conditions, interactions were significant. These interactions will be discussed further in the specific sections for each parameter.

The fresh root weight of these sugarbeets was statistically the same for both years (Figure 2). Therefore, the responses shown are discussed as means of the 2 years. As the mean fresh root weight for the shallow zone was about eight tons greater than for either of the other zones (mean weights were within two tons of each other), the water-table effect was significant. Apparently, the shallow water table was more favorable for sugarbeet growth than any of the other water tables.

Increasing rates of irrigation increased fresh root weights at both the medium and deep water table zones, but not at the shallow zone (Figure 2). This different response produced the significant WT X IW interaction. Apparently, the shallow water table pro-

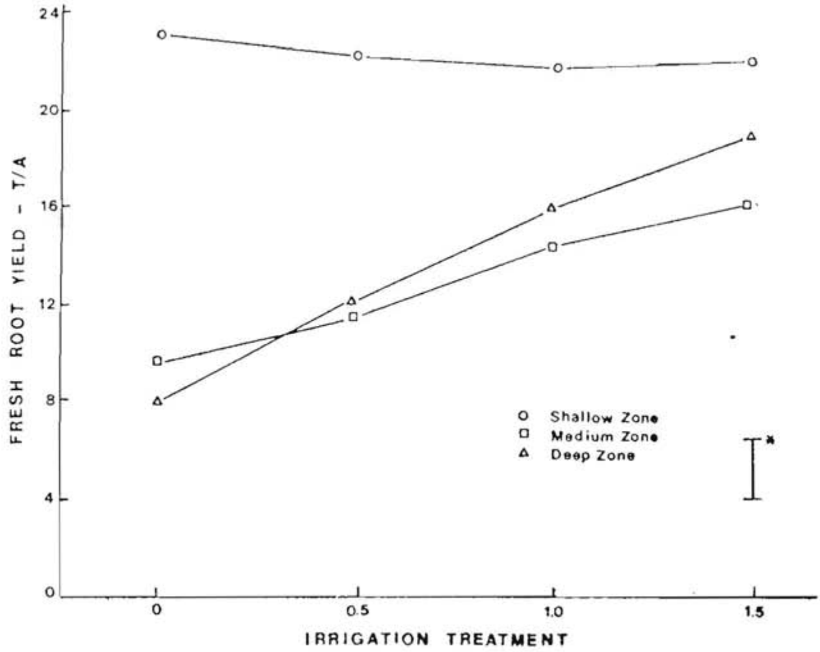

Figure 2.—The effects of water-table depth and irrigation treatment on 2-year means of fresh root yield. Means separated by more than the bar length are significantly different at the 95% confidence level.

vided adequate water for growth, and irrigation produced no increase in this zone. The difference between yields at the nonirrigated and the 1.5 times the calculated ET irrigation treatment was significant for both the medium and deep water-table zones. Thus, increasing irrigation rates on the medium and deep zones produced progressively increasing yields, but maximum yields were not attained. Theoretically, the maximum yield would be produced with irrigation at 1.0 times the calculated ET. However, data for this location show that sugarbeets will use more water and produce more yield as irrigation increases beyond the 1.0 ET level. Idso (11) also observed a similar phenomenon and suggested that "irrigation beyond the point where maximum transpiration is continuously maintained still results in considerable increases in net photosynthesis." The increases with 1.5 ET irrigation indicate either that weekly irrigations may not maintain optimum water availability within the root zone, or that the Jensen-Haise equation for calculating evapotranspiration underestimates water needed by sugarbeets. For the medium water-table depth, the difference in fresh root yields between the minimum to maximum irrigation rates was significant but yield differences between successive irrigation rates were not significant.

Fresh root yields were consistently higher in 1972 than in 1971 for the shallow water table, but were similar both years at the medium and deep zones. However, these different responses to water table in different years were not significant. Sucrose concentrations were significantly higher in 1972 than in 1971 (Figure 3). Water-table depth significantly affected sucrose concentration, but irrigation rates did not. The sucrose concentration was considerably lower for the medium zone than at the shallow or deep zones. The WT x Y interaction was significant because the increase in sucrose concentration over the deep water table (vs the other water tables) was greater in 1972 than in 1971. The interaction, WT x IW, was significant because of erratic responses in 1972 compared to no response in 1971.

Impurity index (equation [2]) was significantly larger in 1971 than in 1972 (Figure 4). A low impurity index is desirable, because improved sucrose storage is associated with a low impurity index. An impurity index value less than 400 is highly desirable because it indicates 94% sucrose recoverability. At 650, sucrose recoverability is only about 90%. The range of impurity index is greater and more consistent with treatment than the sucrose concentration. Significantly, declining impurity index values were associated with increasing irrigation rates while the sucrose concentration was associated with water-table level. Thus, high irrigation rates are recommended for sugarbeets.

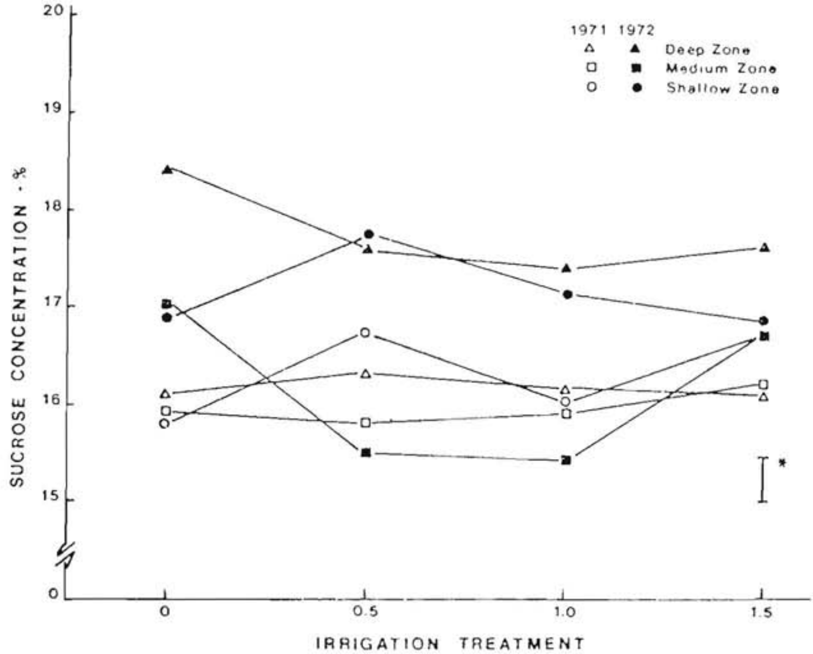

Figure 3.—The effects of water-table depth and irrigation treatment on the sucrose concentration. Means separated by more than the bar length are significantly different at the 95% confidence level.

Some sucrose relationships for this North Dakota study are shown in Table 2. The known sucrose loss (KSL) is used to estimate the amount of sucrose that will be refined from the sugarbeets. The KSL (equation [4]) was significantly affected by the water-table depth (Table 1). This difference was caused by significantly higher KSL values in 1971 at the nonirrigated, shallow-water-table site (Table 2). In 1971, significant differences in KSL measured at the deep water table were not correlated with irrigation treatment and therefore could not be attributed to irrigation treatment (Table 2). No significant differences in KSL were measrued in 1972, thereby causing a significant difference between years (Table 1). The I x WT x Y interaction (Table 1) was significant because the 1971 KSL for both the nonirrigated, shallow-water-table sites and the well-irrigated, deep-water-table sites were higher than the mean for the year (Table 2). In 1972, KSL tended to decrease as depth to the water table increased.

Extractable sucrose (S_e) was significantly greater in 1972 than in 1971 (Table 2). Irrigation treatment effects on S_e were very similar to those for fresh root yield. Duncan's new multiple range tests

Table 2.—Effect of water-table depth* and irrigation treatment† on sugarbeet quality factors.

Irrigation treatment	1971 Water-table depth			1972 Water-table depth		
	Shallow	Medium	Deep	Shallow	Medium	Deep
			Known Sugar Loss, (KSL) T./A			
1.5	0.22 a,A‡	0.18 a,A	0.22 a,AB	0.22 a,A	0.15 a,A	0.15 a,A
1.0	0.28 a,AB	0.16 a,A	0.25 a,B	0.19 a,A	0.14 a,A	0.15 a,A
0.5	0.27 a,AB	0.19 a,A	0.14 a,A	0.21 a,A	0.14 a,A	0.12 a,A
0.0	0.34 a,B	0.15 b,A	0.15 b,AB	0.19 a,A	0.13 a,A	0.11 a,A
			Extractable Sucrose, T/A			
1.5	3.12 a,A	2.42 b,A	2.93 ab,A	3.82 a,A	2.53 b,A	3.08 ab,A
1.0	2.99 a,A	2.12 b,A	2.43 ab,B	3.76 a,A	2.08 b,AB	2.55 b,AB
0.5	3.20 a,A	1.58 b,B	1.67 b,C	3.96 a,A	1.76 b,B	2.13 b,B
0.0	3.30 a,A	1.37 b,B	1.13 b,D	3.70 a,A	1.54 b,B	1.32 b,C
			Sucrose Recovery, %			
1.5	93.4	93.1	93.0	94.6	94.4	95.4
1.0	91.4	93.0	90.7	95.2	93.7	94.4
0.5	92.2	89.3	92.3	95.0	92.6	94.7
0.0	90.1	90.1	88.3	95.1	92.2	91.3

*The shallow, medium and deep water tables were 43 and 34, 69 and 64, and 83 and 79 inch below soil surface at sugarbeet thinning time in 1971 and 1972, respectively. All declined at about 0.25 inch per day during growing season.
†Irrigation treatment of 0.0, 0.5, 1.0 and 1.5 times the amount of water required by the crop, based on ET as calculated by the Jensen-Haise method.
‡Within-year means of rows and columns followed by different lower and upper case letters, respectively, are significantly different at the 95% level of probability, according to Duncan's new multiple range test (15).

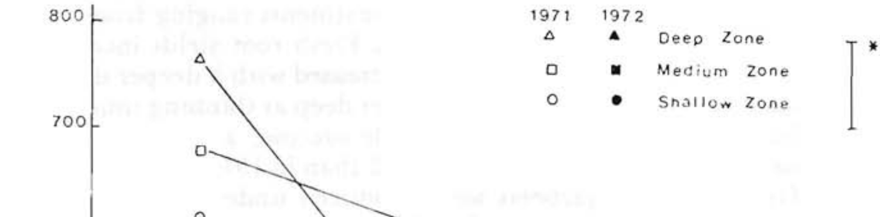

Figure 4.—The effects of water-table depth and irrigation treatment on the impurity index. Means separated by more than the bar length are significantly different at the 95% confidence level.

showed that the calculated extractable sucrose was significantly greater for the shallow water table than for the deeper water tables, and greater for the well irrigated plots than for the nonirrigated plots. Also, for the two deeper water tables, extractable sucrose was significantly greater for the 1.5 ET irrigation than for the other three irrigation treatments. The different effects of water-table depth and irrigation on extractable sucrose account for the significant WT x IW interaction. Extractable sucrose increased as applied water increased.

Sucrose recovery (S_r) relates to the refining efficiency and affects the crop value. Measured efficiencies ranged from 89.3 to 95.4%. According to sugar industry representatives, approximately 95% is the practical upper limit of sucrose recovery.

Summary and Conclusions

Sugarbeet fresh root yields, which were 20 to 24 T/A with a shallow water table declining from about 3 feet deep at thinning time, were not affected by irrigation treatments ranging from zero to 1.5 times the calculated crop need. Fresh root yields increased from 8 to 20 T/A as irrigation rates increased with a deeper declining water table that was more than 5 feet deep at thinning time.

Sucrose concentration, extractable sucrose, and, apparently, sucrose recovery were all greater in 1972 than in 1971.

High quality sugarbeets were produced under all treatments with impurity indexes ranging from 307 to 764. Impurity index was reduced and quality was increased by increasing irrigation and decreasing depth to water table.

The yield of extractable sucrose was higher in 1972 (3.81 vs 2.12 T/A as calculated using the impurity index) for the shallow water table than for the deeper water tables. Irrigation treatments did not affect extractable sucrose yields with the shallow water-table condition. For deeper water tables, however, extractable sucrose yield significantly increased as irrigation increased.

Maximum yields of high quality sugarbeets were obtained with a managed shallow water table and regardless of irrigation. Thus, the value of a shallow water table is clearly shown.

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