Irrigated Sugarbeet Root Yield Response in the Texas High Plains

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ABSTRACT
Traditionally, sugarbeets (Beta vulgaris L.) were irrigated at high levels in the Texas High Plains. As underground water supplies diminished, coupled with increasing energy costs; most producers have shifted to limited irrigation of sugarbeets. A production function was developed relating irrigation levels, nitrogen rates, and rainfall to root yields for the Texas High Plains. Based on eight years of yield data from Bushland, Texas, on Pullman clay loam soil (fine, mixed thermic Torrertic Paleustoll) in level borders, the function explained 87 percent of the yield variation. Marginal analysis indicated producers should be applying 94 cm of irrigation water to maximize profits given the 1986 price relationships. The economically rational stage of production (Stage II) was calculated to be 69 to 97 cm of total irrigation water applied given 136 kg (300 pounds) of total nitrogen available. However, producers surveyed only applied an average of 67 cm of irrigation water which results in sub-optimal profits. Sensitivity analysis of optimal irrigation and nitrogen levels indicated changes in irrigation costs, sugarbeet prices, and nitrogen prices changed the optimal levels relatively little.

Additional Key Words: Beta vulgaris L., production function, irrigation, nitrogen, economics

Sugarbeets (Beta vulgaris L.) in Texas are grown solely in the High Plains. In 1985, four counties (Castro, Deaf Smith, 

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hectares (ha) of sugarbeets harvested in Texas (Texas Agricultural Statistics Service, 1958-1985). Harvested hectares increased from the 800 ha level in 1958-1963 to 15,000 ha in 1985. Sugarbeet root yields averaged 43 Mg ha\(^{-1}\) from 1958-1985 and ranged from a low of 29.4 Mg ha\(^{-1}\) in 1975 to a high of 51.1 Mg ha\(^{-1}\) in 1981.

The growing season for sugarbeets in the Texas High Plains extends from April through October which includes the six months with the highest potential evapotranspiration (ET). The semi-arid climate, with an annual rainfall of only 46 cm coupled with high summer temperatures and winds, necessitates irrigation for consistent production. Eighty-three percent of the annual rainfall occurs during the six-month growing season. However, rain frequently occurs in high intensity storms. Sugarbeets are usually grown on graded furrows where the high soil moisture levels after irrigating can increase storm runoff. As a result, seasonal irrigation requirements are higher than may be expected. Emergence irrigation is also a common practice, helping to insure a stand. The sugarbeet leaves usually cover the soil effectively before ET reaches its peak in July, of slightly over 0.76 cm per day (Schneider and Mathers, 1969).

Sugarbeets have traditionally received full irrigation to produce near maximum yields. Fully irrigating beets was promoted when underground water supplies were abundant, coupled with relatively low energy costs for pumping. However, as water supplies diminished and energy costs for pumping increased over the past decade, producers have tended to reduce water applications. Research has focused on reducing late season irrigations in an effort to reduce irrigation costs while leaving yields and percent sugar largely unaffected. Hobbs et al. (1963) compared sugarbeets against seven other crops (alfalfa, barley, sweet corn, sweet clover, peas, potatoes, and soft wheat) and found beets superior in withstanding moisture stress. In southern Idaho, withholding late season irrigation (after August 1) reduced root yield slightly on a shallow soil, but not on a deep soil (Carter et al. 1980a). Erie and French (1968) in the Salt River Valley of Arizona working with spring harvested sugarbeets determined that yield was not reduced until the soil reaches the permanent wilting moisture percentage. Late water stress decreased root yield, but increased percent sucrose enough that sugar yield was unchanged. Therefore, irrigation can be discontinued three to four weeks before harvest even when ET is very high during this period. Similar results in Idaho were found by Carter et al. (1980b). Winter (1980) in the Texas High Plains reported that sugarbeets are well suited to production with limited irrigation. Yields are directly proportional to total water use with a yield response of 0.32 Mg cm\(^{-1}\) of water applied during the summer (Winter, 1988). Thus, while sugarbeets exhibit drought tolerance, they are also highly responsive to irrigation up to the amount needed to totally satisfy ET.
Brewbaker (1934) found the quality of beets as indicated by percent sucrose and coefficient of apparent purity was not affected by irrigation in northern Colorado. Parashar and Dastane (1973) in India also found that irrigation level did not affect the percent sucrose. However, Barbieri (1982) found in research done in Italy, that irrigation increased mean root weight and size of roots but decreased the percentage sucrose. However, high amounts of irrigation can sometimes increase the percent sucrose. This is usually associated with leaching of nitrogen from permeable soils (Haddock and Kelly 1948; Archibald and Haddock 1952; Haddock 1959). Irrigation effects on root quality are frequently difficult to separate from nitrogen effects. While water stress sometimes increases sucrose percentage on a fresh weight basis and quality appears to be improved, this is primarily a dehydration effect (Carter, 1980b; Eric and French, 1968). In fact, impurities in the root may increase during stress. Winter (1989) found that water stress during the growing season decreased Na but increased K and amino-N in the root at harvest. As a result, sugar loss to molasses increased in water-stressed beets. This was true even in the years when more nitrogen was applied to the sugarbeets that received more water.

Nicholson et al. (1974), in Colorado, developed a multivariate production function which predicted sugarbeet root yields as related to available nitrogen, consumptive use of water, and percent stand. The function only explained 52 percent of the yield variation (R² = 0.52). None of the regression coefficients were significantly different from zero. A single variate function (Hoyt, 1984) predicted sugarbeet sucrose in pounds per acre (Y = -3440.24 + 1047.79W - 23.41W²), where W was applied irrigation water plus rainfall for the growing season. While this relationship explained 92 percent of the variation in sucrose yields, it was based on only one year of data as was generally the case in Hexem and Heady (1978). Solomon et al. (1985) reviewed other sugarbeet functional forms relating evapotranspiration to yields.

Limitations of these yield relationships point to the need for an improved sugarbeet production function to assess causal factors of yield response in the Texas High Plains. The objective of this research was to develop a production function useful to producers relating irrigation levels, nitrogen rates, and rainfall to root yields.

**MATERIALS AND METHODS**

The sugarbeet research was conducted at Bushland, Texas, on Pullman clay loam soil (fine, mixed Thermic Torrertic Paleustoll). This soil has a moderately permeable surface horizon about 25 cm thick. The subsoil, extending to 53 cm, is a very slowly permeable clay. Due to the very low permeability of this soil, loss of water or nitrate-nitrogen to deep percolation would have
been negligible during these studies (Winter, 1981).

The cultivars Mono-Hy D2, (1976-79), and Mono-Hy TX9, (1982-87), were seeded on 76-cm beds in late March or early April. Over the years of research, seeding rates were held constant at 16 to 19 seeds m\(^{-1}\) and the resulting stands were thinned to 20 cm between plants resulting in 64,500 plants ha\(^{-1}\). Irrigation plots each year included eight 76-cm rows in width and were varied over the years from 11.7 to 27.4 m in length. The plots were relatively disease free compared to typical producer fields. Two or more of the center rows from each plot were harvested for yield in November. Sugarbeets were produced each year in level borders to improve the accuracy of measuring irrigation water applied to the plots and rainfall received on the plots. The amount of water applied was measured with an in-line flow meter. All treatments were uniformly watered for emergence in the spring. In most years, seasonal irrigations of three different levels were applied during the period of about June 10th to September 10th.

Total available nitrate nitrogen in the root zone was measured from 0 - 1.8 m each year prior to planting. In some years, varying rates of fertilizer nitrogen were applied based on expected root yield which depended mainly on irrigation. Other inputs except irrigation and nitrogen, were the same for all irrigation treatments.

Sugarbeet root yields were determined for eight years (1976, 1977, 1978, 1979, 1982, 1984, 1986, and 1987). During this period, 2 to 6 replications of each treatment were evaluated, giving a total of 246 observations. Available nitrogen (residual + applied) ranged from 18.2 kg to 226.1 kg with total irrigations (preplant + seasonal) ranging from 8 cm to 77 cm. Yields ranged from 30.5 to 100.4 Mg ha\(^{-1}\).

Yields obtained in research may exceed producer yields for a number of reasons: lack of timeliness of disease and insect control, soil variability, stand variability, weeds, harvest losses, severe weather incidents, and other factors such as lower water use efficiency in graded furrows as compared to level borders. Three estimates of the difference between producer yields and those obtained in the research were evaluated by selecting the method which minimized the average of the sum of deviations between predicted yields using Equation 1 (research results), and the five-year average yield of the producers surveyed. The predicted yields, using Equation 1, were based on the producers' irrigation levels and nitrogen rates. However, 40-year normal monthly rainfall for Amarillo, Texas was used for the rainfall variables.

The first method simply multiplied the predicted yields from Equation 1, using producer levels of irrigation and nitrogen, by 70 percent; the percentage research yields varied from the 1976-85 county average yields (Texas Agricultural Statistics Service, 1976-
1985). These adjusted yields were then compared to reported yields and the sum of the deviations was averaged across producers resulting in an average reduction of 20.6 Mg ha⁻¹ from predicted yields. The next two methods result in subtracting a constant amount from the predicted yields of Equation 1, rather than a percentage amount. The second method used 70 percent of the predicted yield of Equation 1, but was based on the average surveyed producer irrigation level of 67 cm irrigation water and 136 kg nitrogen. Compared to reported yields, the average of the sum of deviations was a 22.4 Mg reduction from predicted yields. The final method also reduced the predicted yield of Equation 1 by 30 percent, but was evaluated at the maximum yield level (end of Stage II) of 97 cm irrigation water and 136 kg nitrogen. This resulted in an average of the sum of deviations of a 24.7 Mg reduction from the predicted yields. Thus, the first of the three estimating methods, a 30 percent reduction from predictions of Equation 1, minimized the sum of the deviations between predicted and reported yields.

RESULTS AND DISCUSSION

From the above research data, a useful production function predicting root yields was developed. A multivariate regression analysis using the Reg Procedures (SAS), resulted in the following predictive equation:

\[
Y = 15.407697 + 0.011403 \text{TI} - 0.000083 \text{TP} + 0.315169 \text{TN} - 0.001218 \text{TN}^2 + 0.000883 \text{TITN} + 0.002475 \text{MP} - 1.010128 \text{SEP} + 0.397414 \text{OCT} - 0.046391 \text{OCT}^3
\]

\[
R^2 = 0.868, F = 171.727, df = 245
\]

Brackets include the corresponding standard error of the estimate of each regression coefficient. The corresponding t-values are given in parentheses. All regression coefficients were significant at the 1 percent level.

Variables included in the equation are:

\[
Y = \text{yield of sugarbeets in Mg of roots per hectare},
\]

\[
\text{TI} = \text{total irrigation (cm) applied, including preplant or emergence}
\]

\[
\text{TN} = \text{total nitrogen (residual + applied) in kg},
\]

\[
\text{TITN} = \text{cross product of total irrigation x total nitrogen},
\]

\[
\text{MJ} = \text{May, June rainfall in cm},
\]

\[
\text{SEP} = \text{September rainfall in cm},\text{ and}
\]

\[
\text{OCT} = \text{October rainfall in cm}.
\]

The negative signs of the exogenous variable SEP and OCT³ reflect harvesting losses due to untimely rainfall. While a more desirable functional form would have included a rainfall-irrigation interaction term, the nature of the research (being on level
borders) prevented statistical significance. Sugar content was not significantly different across nitrogen rates and irrigation levels over the range of the research data. Therefore, the analysis only deals with impacts on root yields and assumes no impact on sugar quality.

Producer yields and research yield adjustment

Ten sugarbeet producers were selected from a list of producers, two from each of five counties in the Texas High Plains. Nine of the ten producers were using furrow irrigation practices and were the basis for evaluating current production practices. They were requested to provide machinery operations, number and amount of irrigations, chemicals used, custom services hired, and root yields. Five-year average root yields of surveyed producers ranged from 40.3 to 76 Mg ha\(^{-1}\), with an average yield of 52.2 Mg ha\(^{-1}\). Since producer yields vary from research yields, a 30 percent reduction from research yields was determined to best reflect producer field conditions, Equation 2.

\[ Y = [15.407697 + 0.011403 \text{ TP} + 0.315169 \text{ TN} - 0.001218 \text{ TN}^2 + 0.000853 \text{ TTN} + 0.002475 \text{ MJ} - 1.010128 \text{ SEP} + 0.397414 \text{ OCT} - 0.046391 \text{ ocp} \times 0.70 \]

Stages of production and range of economically rational irrigated production

Given the above production response function (Equation 2), the stages of production, and the range over which economically rational production would occur, can be defined. Irrigation levels outside this rational production region are considered irrational given the assumption of maximizing net returns. Figure 1 shows the yield response function related to varying irrigation amounts based on 136 kg of total nitrogen (to provide adequate fertility levels for maximum yields). A 40-year average monthly rainfall period was used to depict a long term weather history using data from Amarillo, Texas (1947-1986), the nearest NOAA reporting station; where: May = 7.01 cm, June = 8.29 cm, September = 4.80 cm, and October = 3.84 cm, (NOAA).

Thus, Equation 2 can be reduced to a more simple equation by entering the precipitation amounts (given above) as follows:

\[ Y = 9.645607 + 0.007982 \text{ TP} + 0.000058 \text{ TP}^2 + 0.220618 \text{ TN} - 0.000853 \text{ TN}^2 + 0.000618 \text{ TTN} \]

Stage I, in Figure 1, represents the region where adding additional units of input (irrigation water) increases the productivity of all other inputs. Yields increase at an increasing rate. The boundary of Stage I and Stage II represents the greatest efficiency in the use of variable inputs, i.e. average physical product (APP) of irrigation water is maximum at this point. However, net returns are not necessarily maximized at this point and often can be increased with additional units of the input, moving into Stage II. In Stage II, each additional unit of input increases yield (total physical product, TPP), but yield per unit of water (APP) decreases. Thus, yield increases at a decreasing rate until TPP reaches a maximum, boundary of Stage II and Stage III. Stage III is the region where additional
water causes production to decline. Thus, Stage II is the economically rational production region given the assumption of maximizing net returns with respect to the variable input.

Figure 1. Sugarbeet production function with 136 kg/ha of total nitrogen.
The beginning of Stage II is defined where APP is maximum and equal to marginal physical product (MPP), Figure 1. Average physical product is the average amount of yield or TPP produced per unit of irrigation water at each input level:

\[
\text{APP} = \frac{\text{TPP}}{\text{Input level}} = \frac{\text{Yield}}{\text{irrigation level}}
\]

Whereas MPP is the additional yield produced by using an additional unit of irrigation water:

\[
\text{MPP} = \frac{\Delta \text{TPP}}{\Delta \text{input level}} = \frac{\Delta \text{Yield}}{\Delta \text{irrigation level}}
\]

Where \(\Delta\) means the incremental change of the item.

Thus, we can solve for maximum APP where \(\text{MPP} = \text{APP}\) by taking the first derivative of APP with respect to TI and setting it equal to zero as follows:

\[
0.007982 \text{TI} - 0.000058 \text{TI}^2 + 0.000618 \text{TNAPP}\frac{\text{TI}}{\text{TI}} = 0
\]

\[
\text{APP} = 0.007982 \text{TI} - 0.000058 \text{TI}^2 + 0.000618 \text{TN}
\]

\[\frac{\text{dAPP}}{\text{dT}} = 0.007982 - 0.000116 \text{TI} = 0\]

Thus, the beginning of Stage II is at 69 cm irrigation water.

Maximum yield

After determining the beginning of Stage II (above) at 69 cm, the end of Stage II or the maximum yield (TPP) can be determined by setting the first derivative of Equation 3, equal to zero and solving for TI. However, in this functional form, total nitrogen (TN) is an implicit variable. In the following example, TN was assumed to be 136 kg.

\[
\frac{\text{dy}}{\text{dT}} = -0.000174 \text{TI}^2 + 0.015964 \text{TI} + 0.000618 \text{TN}
\]

\[
\frac{\text{dy}}{\text{dT}} = -0.000174 \text{TI}^2 + 0.015964 \text{TI} + 0.000618(136) = 0
\]

Using the quadratic equation, yield is maximum when TI equals 97 cm (disregard negative result).

\[
\text{TI} = \frac{-b \pm \sqrt{(b^2 - 4ac)}}{2a} \quad \text{where: } Y = ax^2 + bx + c = 0
\]

\[
\text{TI} = \frac{-0.015964 \pm \sqrt{(0.015964)^2 - 4(-0.000174)(0.084154)}}{2(-0.000174)}
\]

\[
\text{TI} = 97 \text{ cm}
\]

Thus, the economically rational irrigation production region (Stage II) is defined as being between 69 and 97 cm given 136 kg of total nitrogen, Figure 1. The end of Stage II varies with the level of nitrogen. For example, using 100 kg TN, yield is maximum at 95 cm irrigation water compared to 105 cm using 400 kg TN.
Figure 2. Sugarbeet production functions at various levels of total nitrogen.

Figure 2 indicates a family of alternative production functions using 50, 100, 150, and 200 kg TN. As TN increases, yields generally increase at a decreasing rate for each production relationship. However, a high level of 250 kg TN reduces yields at all levels of irrigation below those of 150 and 200 kg TN (not shown).

**Optimal irrigation level**

While the above mathematical analyses determined the
price received by producers given 14 percent sugar, and the cost of applying irrigation water \((P_1)\) was $1.58/cm; includes $0.18/cm cost of irrigation labor (Texas Agricultural Extension Service, 1987). Solving for the maximum profit level of irrigation at a nitrogen rate of 136 kg results in:

\[
\frac{dy}{dT_i} = -0.000174T_i^2 + 0.015964T_i + 0.000618TN = \frac{P_1}{P_{SB}}
\]

\[
= -0.000174T_i^2 + 0.015964T_i + 0.000618(136) = \frac{1.58}{34.25}
\]

Multiplying both sides of the equation by 34.25 results in:

\[
= -0.005973T_i^2 + 0.546768T_i + 2.88229 = 1.58
\]

and subtracting 1.58 from both sides of the equation results in:

\[
= -0.005973T_i^2 + 0.546768T_i + -1.30229 = 0
\]

Using the quadratic equation to solve for the maximum profit level of irrigation (disregard negative result) indicates:

\[
T_i = \frac{-0.546768 \pm \sqrt{(0.546768)^2 - 4(-0.005973)(-1.30229)}}{2(-0.005973)}
\]

\[
T_i = 94 \text{ cm}
\]

Thus, the irrigation level which maximized profit given the 1986 irrigation water cost-sugarbeet price relationship was 94 cm.

**Maximum levels of nitrogen**

It is also of interest to evaluate the amount of TN needed which produces the maximum root yield given the most profitable level of irrigation as determined above. Setting the first derivative with respect to TN equal to zero and using the implicit irrigation water value of 94 cm (maximum profit level of irrigation), the amount of nitrogen needed to produce maximum yields was 163 kg.

\[
\frac{dy}{dT_N} = -0.001706TN + 0.220618 + 0.000618TI
\]

\[
= -0.001706TN + 0.220618 + 0.000618(94) = 0
\]

\[
= -0.001706TN + 0.278612 = 0
\]

\[
TN = \frac{-0.278612}{-0.001706} = 163 \text{ kg}
\]

This is also the end of Stage II with respect to nitrogen at the 94-cm irrigation level. This only solves for the maximum root yield without respect to potential impacts on root quality or profits. However, producers on slowly permeable soils similar to the Pullman series will typically apply nitrogen at rates lower than the maximum amount of TN needed due to the possibility of high nitrogen levels reducing sugar content. A general field practice to safeguard against this possibility is apply supplemental nitrogen

\[
\frac{dy}{dT_i} = \frac{P_1}{P_{SB}} \quad \text{and} \quad \frac{dy}{dT_N} = \frac{P_N}{P_{SB}}
\]

resulting in 88.3 cm of water and 151 kg of nitrogen.

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2 This method of first approximation can be solved exactly by the simultaneous solution of

\[
\frac{dy}{dT_i} = \frac{P_1}{P_{SB}} \quad \text{and} \quad \frac{dy}{dT_N} = \frac{P_N}{P_{SB}}
\]

resulting in 88.3 cm of water and 151 kg of nitrogen.
until TN equals 8 kg ha⁻¹ of nitrogen per expected Mg of beets, rather than applying supplemental nitrogen equal to the maximum TN level, to maximize root yields, (Printz, personal communication).

**Optimal nitrogen rate**

This analysis is somewhat limited since the research was not designed to evaluate interactions between nitrogen rates and the percent sucrose from sugar beets. Research suggests that high rates of nitrogen decrease percent sugar. The research was primarily designed to evaluate yield response to water rather than for this interaction, since the sugar beets were adequately fertilized. Thus, the analysis only deals with impacts on root yields and assumes no impact on sugar quality. To determine the optimal nitrogen rate to maximize profits with all other inputs held constant, the first derivative of the production function with respect to TN is set equal to the ratio of the cost of the last unit of nitrogen and the product price. Again, product price of $34.25/Mg (Pₛₚₜ) was used and the cost of applying nitrogen (Pₙ) was $0.24 kg⁻¹. Solving for the maximum profit rate of TN at the maximum profit level of irrigation, 94 cm, results in:

\[ \frac{dy}{dTN} = -0.001706TN + 0.220618 + 0.000618TI = \frac{Pₙ}{Pₛₚₜ} \]

\[ = -0.001706TN + 0.220618 + 0.000618(94) = \frac{0.24}{34.25} \]

Multiplying both sides of the equation by 34.25 results in:

\[ = -0.058416TN + 9.54247 = 0.24 \]

and subtracting 0.24 from both sides of the equation results in:

\[ = -0.58416TN + 9.30018 = 0 \]

\[ TN = \frac{-9.30018}{-0.58416} \]

\[ TN = 159 kg \]

Thus, the nitrogen rate which maximized profits given the 1986 nitrogen-sugar beet price relationship was 159 kg.

**Sensitivity of profit-maximizing input levels**

Historically producers irrigated sugar beets at high levels; when water supplies were abundant and when irrigation energy costs were low. However, as underground water supplies diminished, coupled with the sharply rising energy costs of the past decade, producers have recently tended to limit irrigation amounts. The 1987 survey of producers indicated two-thirds were irrigating at levels too low to be in Stage II, the stage of economically rational production. The level of irrigation applied by a producer is sensitive to input costs, sugar beet prices, and seasonal water availability. The following analysis evaluated the sensitivity of maximum-profit irrigation levels with respect to sugar beet prices and variations in pumping costs and nitrogen prices.

Varying the price of sugar beets from $22/Mg to $44/Mg resulted in a narrow range of profit-maximizing irrigation level of
only 1.3 cm (95.2 to 93.9), at an irrigation cost of $1/cm. At $6/cm, the range of optimal irrigation levels was only 10.5 cm (88.1 to 77.6). As the cost of irrigation water increased from $1/cm to $6/cm with the price of sugarbeets held constant at $34.25/Mg (1986 price), the profit-maximizing irrigation level decreased only 9.5 cm, from 94.9 to 85.4 cm. Hoyt (1984) also found that profit-maximizing water quantities were not significantly affected by varying crop prices at low and medium water costs in Colorado.

The profit-maximizing irrigation level was also relatively insensitive to varying rates of TN. The optimal irrigation level only changed by 7.3 cm (90.6 to 97.9) when nitrogen was varied from 50 to 250 kg. Also, ranging the price of nitrogen from $0.10 to $0.40/kg only changed the profit-maximizing amount of TN by 5 kg.

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