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Crop–Water Production Functions for Sweet Corn

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Abstract. **Sweet corn (*Zea mays* L.) was irrigated using randomized complete block and line source experimental designs in 1984 and 1985 on a mixed, mesic Cumulic Ultic Haploxeroll soil. Irrigations were scheduled when ≈50% of the available water was depleted in the root zone of the 100% treatment to refill the root zone to 0% to 100% of field capacity (five irrigation levels). Four yield parameters were measured for all plots: yield of all ears before husking, yield of good husked ears, kernel yield (fresh), and total dry matter production of plants and ears. Maximum relative total unhusked ear yield and near-maximum evapotranspiration (ET) were obtained at 85% of maximum water applied, indicating that high yields can be maintained with deficit irrigation. Without irrigation, only 44% of maximum yield was obtained. Maximum water use efficiency (WUE), defined as the total unhusked ear yield in $kg \cdot ha^{-1} \cdot mm^{-1}$ET, occurred between 407 and 418 mm of ET. The maximum WUE corresponded to ≈313 mm water applied (WA); maximum yield, however, occurred within the range of 449 to 518 mm WA. Irrigation treatments to achieve maximum WUE were predicted to result in a 10% yield reduction.**

Crop–water production functions are useful for irrigation scheduling, estimation of water requirements for maximum yield, determination of maximum water use efficiency, allocation of water on a farm and regional level, and as an aid to economic analyses (Stewart et al., 1975 and 1977).

The objectives of this study were to: 1) develop production functions for several yield components of sweet corn in response to water applied (WA) and evapotranspiration (ET); and 2) determine water use efficiency (WUE), the ratio of product produced per unit of ET. Although the results relate specifically to western Oregon climate and soil conditions, wider application and use is possible, especially in areas of irrigated agriculture with a dry, warm summer and wet, mild winter.

Materials and Methods

Cultural practices. Experiments were conducted in 1984 and repeated in 1985 on a Cumulic Ultic Haploxeroll, mixed mesic (Chehalis silty clay loam) soil at the Oregon State Univ. Vegetable Research Farm. Planting dates of 'Jubilee' sweet corn were 31 May 1984 and 30 May 1985, respectively. Harvest dates at processing maturity (at ≈72% kernel moisture) were 10 Sept. 1984 and 5 Sept. 1985. Fertilizer was applied at the rate of 250, 74, and 46 $kg \cdot ha^{-1}$ for N, P, and K, respectively. Plants were thinned to a uniform population of 61,415 plants/ha.

Yield components measured were total number of ears, unhusked fresh weight yield, yield of good husked fresh ears, fresh kernel yield, and total fresh and dry matter production of plants and ears. Good husked fresh ears were defined as those acceptable for commercial processing. These yield parameters were also expressed on a relative (percent of maximum) basis.

Experimental design. A line source (LS) and a randomized complete block (RCB) design, each with four replications, were used each year. The water application rates used for each experiment are shown in Table 1. All treatments were irrigated simultaneously.

Gradients for the LS experiment were formed by appropriate spacing of the plots perpendicular to the irrigation line. Access tubes for soil water measurements and catch cans for measurement of applied water were placed in the center row of three row plots. These three rows were used for ear yield measurements, while only the center row was used for plant plus ear yield measurements (total dry matter production). Cuenca and Stewart (unpublished data) and Hanks et al. (1976 and 1980) describe the line source experimental design and statistical aspects in more detail.

Table 1. Irrigation treatment levels and total water applied (WA) for the line source and randomized complete block experiments.

Line source		Randomized complete block	
Treatment[z] (%)	Water applied (mm)	Treatment[z] (%)	Water applied (mm)
	1984[y]		
100	428	100	492
73	345	70	382
40	246	50	311
8	148	24	214
0	125	0	125
	1985[x]		
100	604	100	599
77	487	77	484
57	385	57	386
26	228	26	230
0	99	0	99

[z] Percentage of the maximum irrigation water only.
[y] Includes 125 mm of precipitation from planting to harvest.
[x] Includes 99 mm of precipitation from planting to harvest.

In the RCB experiment, irrigation treatments were established on separate seven-row, 6 × 6 m plots. Each plot had four sprinklers located in the corners. Water quantities were regulated by controlling the time the plot sprinklers were open. Measurements of water applied and soil water were made in the center row. Ear yields were taken from the middle three rows, while only the center row was used for measurement of total dry matter production. Plots in the RCB were separated by 15 m of border to separate water applications. Further details on the experimental methods are reported by Braunworth and Mack (1987), while statistical details of the design are described by Little and Hills (1978).

Irrigation procedures. Irrigations commenced when about 50% of the available water in the root zone was depleted in the 100% treatment level. Irrigations were intended to refill the root zone of the 100% treatment level plots to field capacity in both years.

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However, water applied averaged 70% and 91% of the amount required to refill the root zone to field capacity for the LS and RCB experiments, respectively, in 1984. Thus, the intended 100% level was a slight irrigation deficit treatment.

Water application levels (WA) are detailed in Table 1. Since WA for these treatments, other than the 100%, never refilled the root zone to field capacity, they were defined as deficit irrigation treatments.

In 1985, 49% and 57% of the available water was depleted from the 100% treatment level plots for the LS and RCB experiments, respectively, before irrigations. The irrigations replaced an average of 92% and 90% of the depleted water in the root zone for the LS and RCB experiments, respectively, a slight irrigation deficit.

Timing of the first irrigation used the Food and Agriculture Organization of the United Nations modified Penman equation to estimate 50% depletion of the root-zone water. Root zones of 0 to 450 and 0 to 240 mm in 1984 and 1985, respectively, were selected to permit the first irrigation to occur at a reasonable time, because early season measurements of ET by any method are usually not accurate. In 1984, after the first irrigation, the root zone used for scheduling was 0 to 750 mm. In 1985, the second and third irrigations were based on a 0 to 450-mm root zone, while, in later irrigations, a 0- to 750-mm root zone was used.

A neutron meter (model 503DR Hydroprobe Moisture Depth Gauge, Campbell Pacific Nuclear Corp., Pancheco, Calif.) was used to measure soil water content, permitting computation of soil water depletion between irrigations in the root zone and beyond to a depth of 2250 mm. These measurements were used for determination of 50% depletion of available water in the root zone for scheduling irrigations after the first one. The neutron meter was calibrated for the 0- to 150-mm soil horizon and for greater depths separately. Measurement depth intervals were 0 to 150 mm, and then every 300 mm, to a depth of 2250 mm. Soil water measurements were made on all plots every 2 to 4 days, which included a measurement just before each irrigation.

ET was estimated from calculations using a modification of a water balance procedure (Cuenca and Stewart, unpublished data). The modifications were measurement of soil water depletion between irrigations two to three times rather than once, and soil water measurements of the surface (0- to 150-mm) layer of the soil. Also, ET maximum was obtained from the 100% irrigation treatment level plots.

Results and Discussion

Crop–water production functions. Crop–water production functions were developed for 1984 and 1985 from combined data from the LS and RCB experiments. These describe, on a relative basis, the responses of total unhusked yield, good husked yield, kernel yield, and total dry matter to relative WA. A relative basis is used to allow comparison of these production functions to other functions developed in other years or climates. Functions of these yield parameters on a relative basis (0% to 100%) in response to relative WA are shown in Figs. 1 and 2 for 1984 and 1985, respectively. Similar responses were found for all four yield components to relative WA, with the R^2 values ranging from 0.58 to 0.92.

The relative crop–water production functions of total unhusked yield and good husked yield vs. WA for 1984, shown in Fig. 1, indicate maximum yields at 93% and 86% of the maximum water applied (505 mm), respectively. Thus, water applied within a range of 434 to 470 mm produced maximum yields. In 1985, maximum yields were obtained at 76% and 75% of the maximum water applied (653 mm); i.e., 493 mm. Measurements of soil water content indicated that little deep percolation occurred with the maximum irrigation quantities, indicating that deficit irrigations can achieve near-maximum yields with substantial water savings. The optimal level for irrigation depends, of course, on the price of water and of sweet corn.

The response of the relative good husked yield to ET is shown in Fig. 3 for 1984 and 1985, separately for each experiment. The relative yield parameters vs. relative ET production functions for 1984 and 1985 were convex, quadratic for the RCB experimental design, but linear for the LS design. The response of four yield parameters to relative ET were similar (data not shown). The functions are similar between years, but the 1985 functions have less unexplained variability, as evidenced by greater R^2 values. The maximum yields in 1985 were obtained at 91% and 100% of the maximum ET for the RCB and LS experiments, respectively. In 1984, the relative ET for the minimum yields was about 65%, while, in 1985, ≈45% relative ET resulted in the minimum yields. Yield measured at the lowest relative ET levels in 1984 was 62%, greater than the 45% levels in 1985. This difference accounted for some of the variation in the functions between years.

Yaron (1971) suggested that offset values of yield vs. ET relationships will change according to field and weather conditions, but that the slope will remain constant. In the present study, differences in the intercept in the 2 years appear to be due to variation in the values of ET and yield, resulting from differences in distribution of rainfall. The greater relative ET and yield for the non-irrigated plots in 1984 was due to a better rainfall distribution during June. In 1985, 82% of the seasonal rainfall occurred in the first week of June. This caused depletion of available water in the soil to occur earlier in the season, allowing crop stress to develop sooner.

Table 2 shows a summary of key weather factors for 1984 and 1985 with long-term averages from the Hyslop Field Laboratory (Redmond, 1985), ≈4.5 km from the experiment site. Precipitation was above-average in June of both years. July 1985 had a 3.5C warmer maximum temperature than average, while July 1984 was only 0.2C above average. Correspondingly, the pan evaporation was greater in July 1985 than in July 1984. Overall, with the exception of the high precipitation in June, the conditions of both years resulted in a higher demand for water than average conditions. Therefore, in years with a lesser water demand, slight reductions in the maximum ET and depth of water to be applied could be expected.

The quadratic, convex relative yield vs. relative ET relationships were found for the RCB experiment, but these relationships were linear for the LS experiment. In contrast to these quadratic functions, Barrett and Skogerboe (1978) and Stewart and Hagan (1973) stated that most yield vs. ET crop–water production functions are linear, similar to the results here reported for the LS experiment. However, Stewart and Hagan (1969a, 1969b) reported quadratic, convex functions of yield vs. ET for wheat and alfalfa, and Grimes et al. (1969) and Howell et al. (1984) for cotton. In some cases, a range of ET points tends to cluster about a given maximum yield, as shown for grain corn (Hanks, 1983). It is not physically reasonable to expect ET and yield to increase linearly without bound. In support of the quadratic function from the RCB experiment, Vaux et al. (1981) indicated that, theoretically, the yield vs. ET production relationships should have a section of the curve where additional ET does not result in further yield increases. Downey

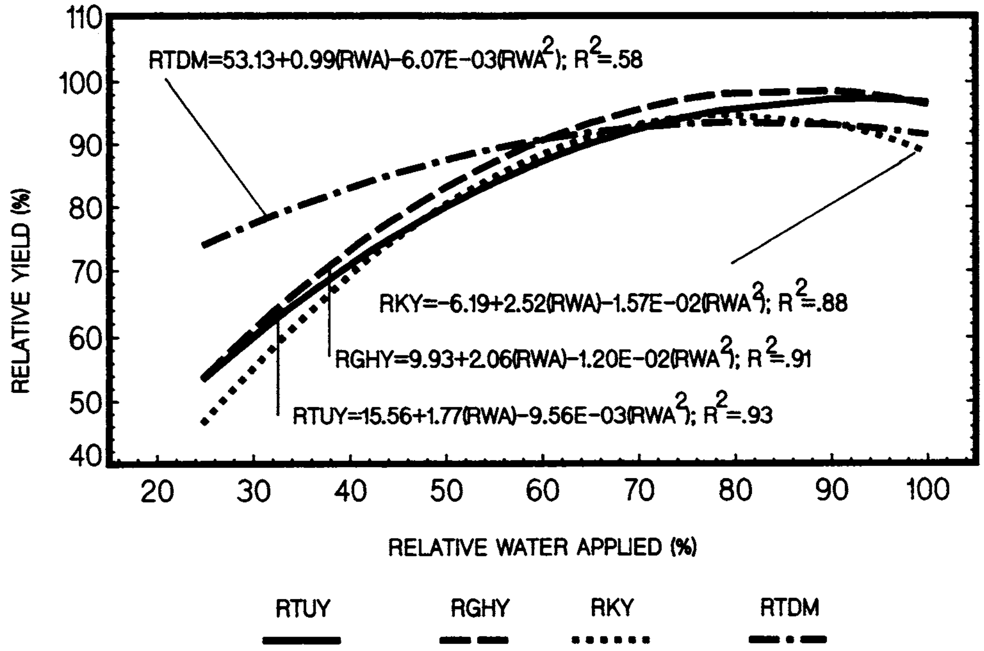

Fig. 1. Relative total unhusked yield (RTUY), good husked yield (RGHY), kernel yield (RKY), and total dry matter (RTDM) as a function of relative water applied (RWA) for the randomized complete block and line source experiments combined in 1984.

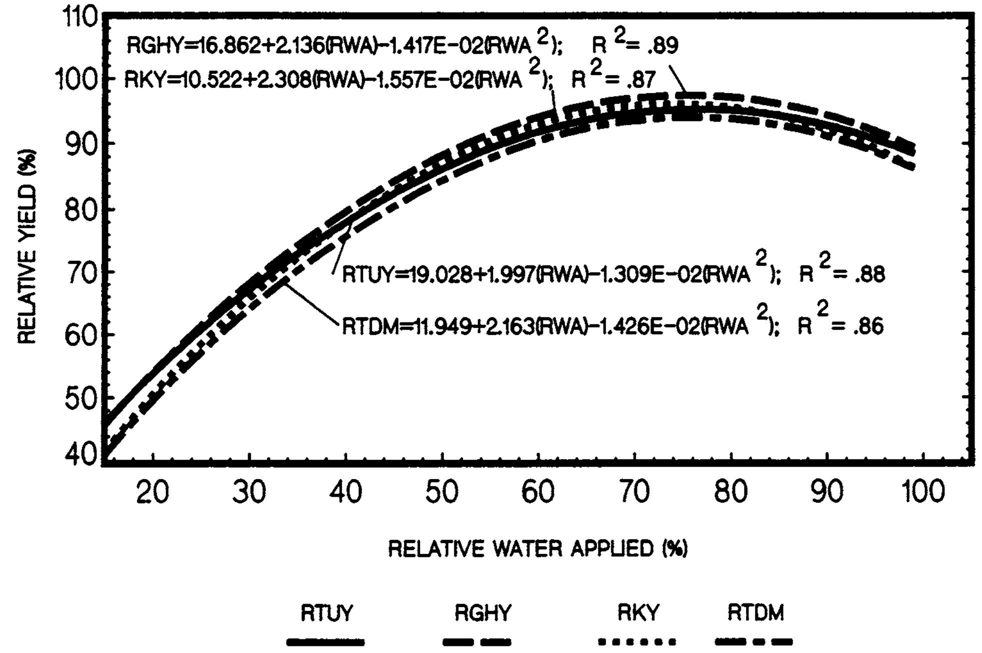

Fig. 2. Relative total unhusked yield (RTUY), good husked yield (RGHY), kernel yield (RKY), and total dry matter (RTDM) as a function of relative water applied (RWA) for the randomized complete block and line source experiments combined in 1985.

(1972) indicated the difficulty of deriving a single unique function of yield related to ET, and pointed out that timing of ET deficits can influence yield to a greater degree than seasonal ET.

To summarize the 2 years with two experiments per year, the relative crop–water production functions of the total unhusked yield vs. WA or ET are presented in Fig. 4 and, in units of t·ha^{-1} and mm of WA or ET, in Fig. 5. The functions from both years and both experimental designs were similar enough to allow combining the data for the general relationships expected in the Willamette Valley and similar areas that can be used for water resource planning and crop production guidelines. Maximum relative yield ($\approx 30\ \text{t·ha}^{-1}$) occurred at 85% of the maximum water applied, or 484 mm of water applied. This level of water applied corresponds to 100% of the relative ET. In the case of no irrigation, 15% relative WA resulted in 41% relative ET with 44% relative total unhusked yield. These results agree with those of Petersen et al. (1985), who reported maximum sweet corn yields with 435 mm ET and also with Evans et al. (1960), who reported maximum yield of sweet corn at about 435 mm ET, also with a convex function.

Water use efficiency. Water use efficiency (WUE) (Hillel and

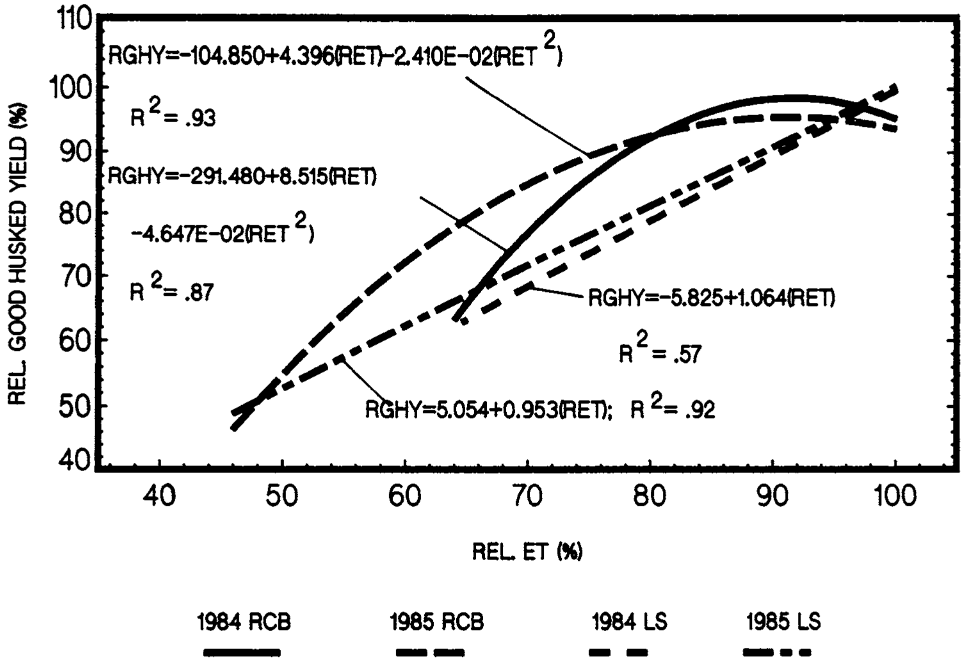

Fig. 3. Relative good husked yield (RGHY) as a function of relative ET (RET) for the randomized complete block (RCB) and line source (LS) experiments, 1984 and 1985.

Table 2. Monthly summary of weather factors for 1984 and 1985 and 30-year averages.

Period	Temperature Maximum (C)	Temperature Minimum (C)	Pan evaporation (mm/month)	Precipitation (mm/month)	Solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$)
1984 June	20.9	8.1	24	106	22.9
1985 June	24.1	8.6	172	82	25.8
30-year average	22.6	9.1	144	31	20.8
1984 July	27.3	10.6	214	4	28.8
1985 July	30.6	11.3	249	14	26.8
30-year average	27.1	10.3	197	8	22.9
1984 August	27.4	9.6	191	0	22.9
1985 August	27.2	10.0	190	3	21.4
30-year average	26.9	10.4	177	21	19.0

Guron, 1973) is defined as the quotient of dry matter yield divided by ET and, in this study, as kilograms of total fresh unhusked ear yield per hectare per millimeter of ET. The regressions of WUE with ET as the independent variable from the experiment in 1984 and 1985 resulted in significant relationships.

The regression of WUE with ET for the 1984 RCB experiment is shown in Fig. 6. The low WUE at the lower ET levels is due to the fact that ET of the non-irrigated plots is relatively high compared to the maximum ET, while the yield was very low. WUE increases to a maximum of 68.0 $kg \cdot ha^{-1} \cdot mm^{-1}$ at 418 mm of ET, then decreases. Lower WUE at the higher ET levels occurred because the yield increases at a decreasing rate with additional ET.

The WUE vs. ET relationship for the 1985 RCB experiment (Fig. 6) is convex and quadratic, as in 1984. In 1985, the maximum WUE occurred at 407 mm of ET, corresponding with a maximum WUE of 64.4 $kg \cdot ha^{-1} \cdot mm^{-1}$. Since the variability between years is ≈5%, maximum WUE values averaging 66.2 $kg \cdot ha^{-1} \cdot mm^{-1}$ can be expected for sweet corn on a silty clay loam soil in the Willamette Valley in western Oregon.

These WUE curves indicate the importance of deciding whether maximum yield or maximum WUE is the primary production goal. The following equations from the RCB experiments show that maximum yields and maximum WUE do not occur at the same WA.

$$1984\text{: TUY} = 4.126 + 0.119\ (\text{WA}) - 1.326\text{E-}04\ (\text{WA}^2) \quad r^2 = 0.94 \qquad [1]$$

$$1985\text{: TUY} = 7.024 + 8.817\text{E-}02\ (\text{WA}) - 8.509\text{E-}05\ (\text{WA}^2) \quad r^2 = 0.85 \qquad [2]$$

where: TUY = total unhusked yield ($kg \cdot ha^{-1}$) and WA = mm water applied (irrigation + precipitation).

The solution of Eq. [1] and [2] for the WA that resulted in maximum total unhusked yield was 449 and 518 mm for 1984 and 1985 RCB experiments, respectively. From the equations shown in Fig. 6, the total unhusked yield level where maximum WUE occurs can be computed. When these yield levels were substituted into Eq. [1] and [2], the quantities of WA required for maximum WUE were found to be 315 and 311 mm for the 1984 and 1985 RCB experiments, respectively. These water

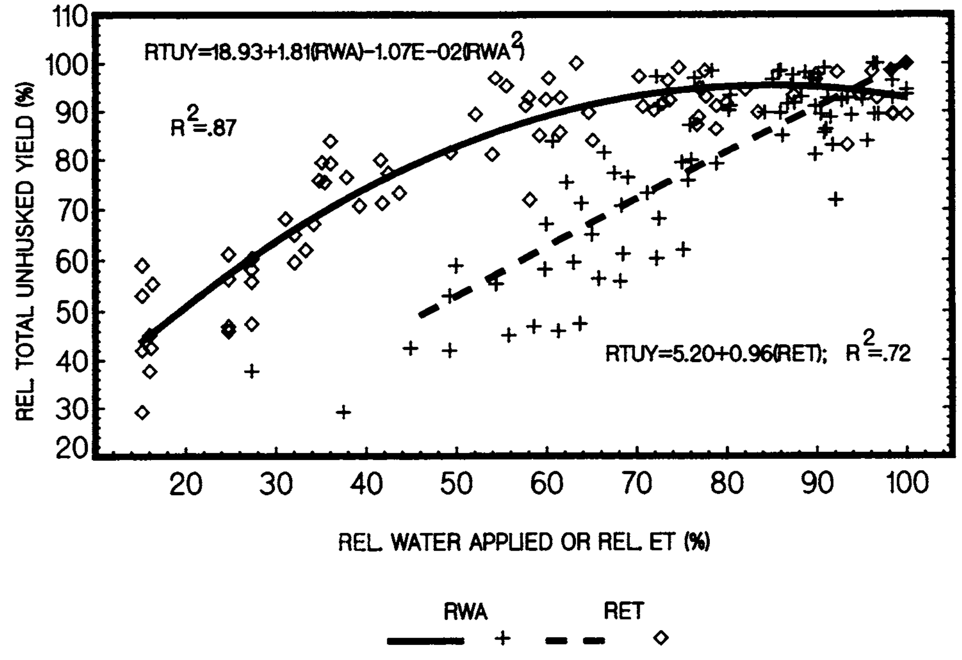

Fig. 4. Relative total unhusked yield (RTUY) as a function of relative water applied (RWA) and relative ET (RET) for the 1984 and 1985 randomized complete block and line source experiments combined.

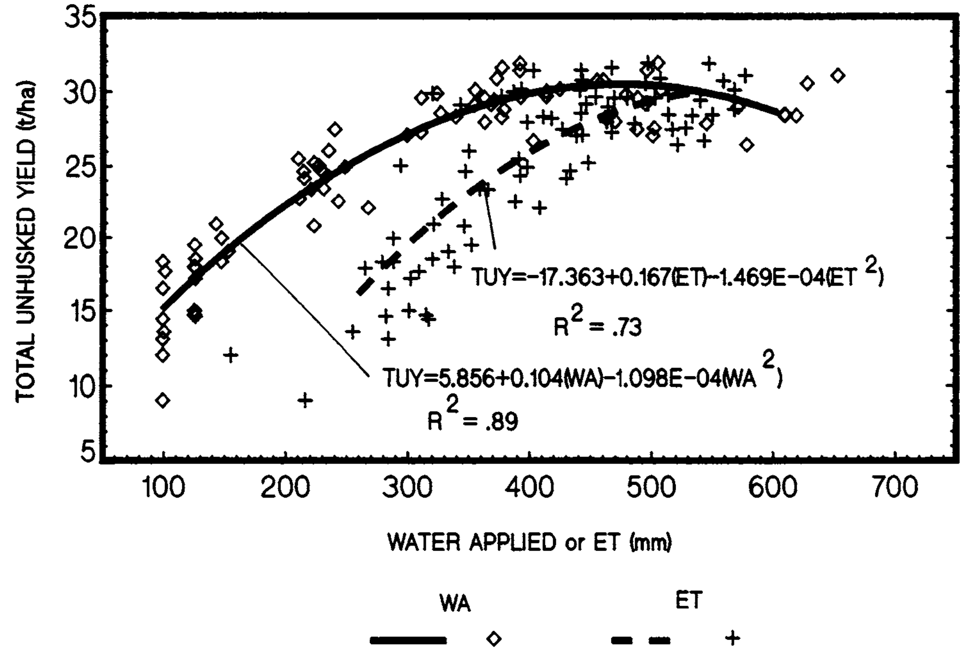

Fig. 5. Total unhusked yield (TUY) as a function of water applied (WA) and ET for the 1984 and 1985 randomized complete block and line source experiments combined.

application levels would result in an 8% and 12% yield reduction in 1984 and 1985, respectively. On the average for both years, the maximum yield occurs at 484 mm WA while maximum WUE occurs at 313 mm WA, only 65% of the amount needed for maximum yield. Irrigating to achieve maximum WUE would result in a calculated average yield reduction of 10%.

Vaux et al. (1981) showed a function of WUE similar to those presented in Fig. 6 and pointed out that maximum WUE and maximum yield do not occur at the same level of water supply. Viets (1966) also noted that WUE can decrease from a maximum if ET increases with less relative effect on yield, which was found in this study. Hillel and Guron (1973) measured increases in WUE with increases in water applications.

In summary, Stewart and Musick (1982) discussed the problems and opportunities associated with WUE and yield maximization. They asked questions related to the allocation of water as follows: "Is a fixed amount of irrigation water utilized more efficiently by the full irrigation of a small area that would oth-

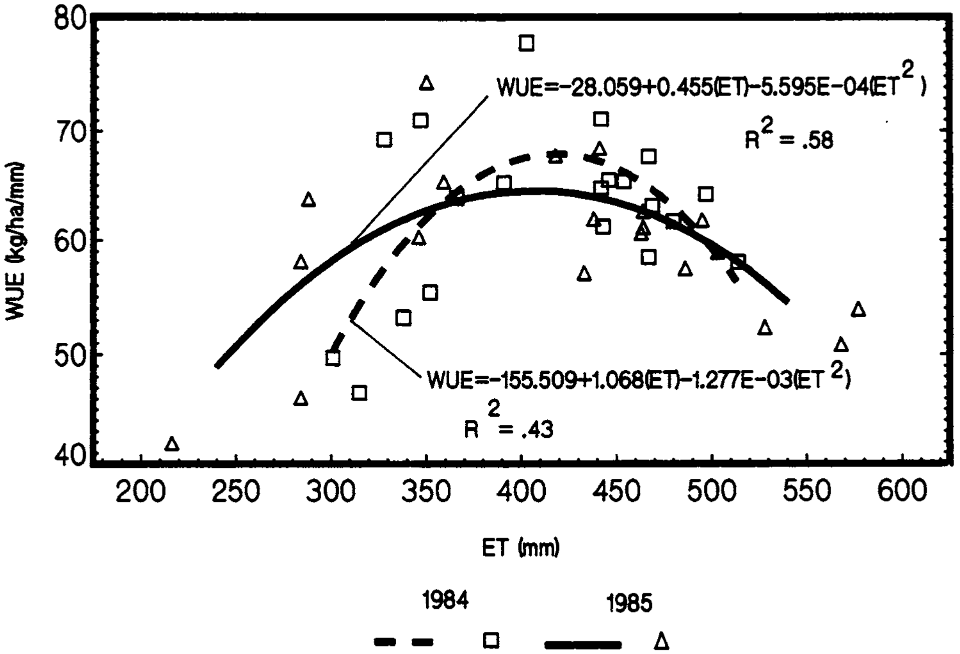

Fig. 6. Water use efficiency (WUE) based on total unhusked yield (TUY) as a function of ET for the randomized complete block experiment, 1984 and 1985.

erwise be in dryland production? Also: Should limited irrigation be practiced on some crops to permit full irrigation on other crops?"

From the results of this study it is clear that the prices of water and sweet corn are important factors for determination of how much water to apply to sweet corn. Growers are presently most likely to make maximum yields their goal since water is usually available and not expensive. This condition may not always exist. If water use becomes regulated, or is limited on a specific farm, these data could provide a basis for planning the allocation of water to sweet corn.

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