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The pinto bean accounts for about 25 per cent or 227,000 metric tons (near 5 million cwt) of the total dry bean production in the United States. Colorado was the leader in 1974, producing 72,575 metic tons (1.6 million cwt). North Dakota ranked fourth behind Idaho and Nebraska. The 1974 production of pinto beans in North Dakota occupied about 40,470 ha (100,000 acres). Most of these acres were in the Red River Valley where annual rainfall is sufficient to produce an average yield near 1120 kg/ha (1,000 lbs/ac).

Expansion of irrigated acreage in the Northern Plains will make it possible to grow crops that are not traditional to this area. Many factors will combine to determine the relative suitability of new crops. Production response, prices, and available market are of immediate concern to the individual producer. For efficient use of irrigation water and other production inputs it is essential that crop responses to water management be determined and defined by quantitative relationships.

The study reported in this paper provides data for pinto beans in the following areas: (1) relationship of yield to water use, (2) average seasonal distribution of water use for sizing of system pumping rates, (3) crop curves for use in irrigation scheduling methods that rely on techniques for estimating water use, (4) plant water stress criteria for determining when to irrigate, and (5) root zone depth advance with time after crop emergence.

Methods

This study was conducted at the Carrington Irrigation Branch Station from 1972 thru the 1974 growing seasons. Pinto beans were grown as a test crop in an experiment which was designed to evaluate multiple field management concepts for center pivot sprinkler systems (9). Treatments included variation of center pivot system capacities and variation of water management levels. For the latter treatments, irrigations were begun at preselected levels of water depletion from the active root zone. The selected depletion limits for each treatment are given in Table 1.

Table 1. Irrigation Treatments

Treatment Code	Fields served by one center pivot system	Allowable root zone soil moisture depletion prior to initiation of irrigations (% of available water capacity)
Dryland	0	—
S1-1	1	50
S1-2	2	50*
S2-2	2	65
S1-3	3	50*
S2-3	3	65

*Changed to 30 percent for the 1973 and 1974 seasons.

Main plots were 6.9 m x 5.5 m (22.5 x 18 feet) and all treatments were replicated three times. A split plot randomized block design was obtained by splitting each main plot with three bean varieties. These were Idaho 111, Idaho 114 and Wyoming 166. The bean plots were rotated with oats and potatoes from season to season.

Irrigations were applied by plot irrigators (9) which were operated to simulate a 75.7 liter/second — 53.4 ha (1200 gpm — 132 acre) center pivot system. Gross application of water was limited to 2.5 cm (one inch) per 48 hour period. Total application per irrigation was limited to 5.1 cm (two inches). All irrigations were scheduled by a computerized water balance model (9). Soil type in

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the plot area was Heimdal loam. Available water holding capacity averaged 16.5 cm (6.5 inches) to a depth of 122 cm (4 feet). Field capacity was based upon observed *in situ* profile water content in the early growing season following periods of excessive rainfall. The lower limit of available moisture was observed during periods when plant growth rates had virtually ceased in the dryland plots.

Phosphorous and potassium levels tested high to very high according to NDSU soil test standards. Pre-season nitrogen averaged near 112 kg/ha (100 lbs/ac) in the top two feet of soil profile. Pre-season fertilizer applications averaged 56, 39, and 30 kg/ha (50, 35 and 27 lbs/ac), respectively, for N, P_2O_5, and K_2O in each production year. Seeding rate was 67 kg/ha (60 lbs/ac) and row spacing was 61 cm (24 inches).

Soil moisture content was measured by neutron method in each plot of replication two. Measurements were made weekly to a depth of 122 to 152 cm (4 to 5 feet). Plant water stress development was measured by pressure chamber (8) and diffusion porometer (4) techniques. Leaf xylem pressure measurements were taken daily (Monday thru Friday) for much of each growing season. Four to five leaf samples were taken from each sampled plot. Treatments studied were dryland, S1-3 (the wettest treatment) and S2-2 or S2-3 (intermediate moisture regimes).

The transpiration resistance data were taken periodically as an additional measurement with xylem pressure. The daily xylem pressure data were also observed together with prevailing ambient and wet bulb air temperature, wind velocity (at 2 meter height) and solar radiation intensity.

Crop cover and phenology development were observed visually and recorded at 7 day intervals by photographing the plot areas.

Results

Yield Response to Water Management and Water Use

Yearly yield and irrigation summaries are given in Table 2 for each treatment and variety. In 1972, the Idaho 114 and Wyoming 166 varieties outyielded the Idaho 111 variety by an average 293 kg/ha (262 lbs/ac). Average irrigated yield for the two superior varieties was 3124 kg/ha (2789 lbs/ac) versus 2190 kg/ha (1955 lbs/ac) for the dryland treatment. No significant yield difference was observed between the irrigated treatments thus suggesting that 65 per cent depletion of available root zone moisture prior to irrigation was not detrimental to yield potential in the 1972 season.

In 1973, a significant yield difference was not obtained between the tested varieties. Yield response to irrigation was greater than in 1972. The highest yield was produced by the wettest (S1-2) irrigation treatment. Average yield for the S1-2 treatment was 3774 kg/ha (3370 lbs/ac) which exceeded dryland by 2195 kg/ha (1960 lbs/ac).

In this production year the highest irrigated yields were obtained for the treatment allowing only a 30 per cent depletion of available root zone moisture prior to initiation of irrigations. Yield for the S2-3 treatment, allowing 65 per cent depletion, was significantly depressed by 519 lbs/ac relative to the S1-2 treatment. This variation in yield response to water management between 1972 and 1973 appears related to climatic differences between the two seasons. The 1973 season was distinctly warmer than 1972. This is illustrated in Figure 1 where average maximum daily ambient air temperatures are plotted by 15 day intervals in each season for the months of June, July and August. The data show that daily maximum air temperatures averaged below 26.7°C (80°F) for each 15 day interval except August 15-31 in 1972. By contrast maximum daily air temperatures averaged near 29.4°C (85°F) for three out of the six 15 day intervals in 1973. These warmer periods in the 1973 season probably caused periods of water stress in the drier S2-3 treatment. This likelihood will be further demonstrated in later discussion.

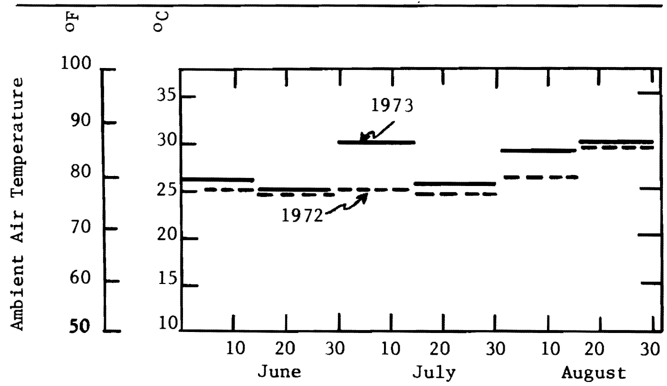

Figure 1. Maximum daily ambient temperatures as averaged by 15 day intervals in 1972 and 1973.

Yield data for the 1974 season was unfortunately confounded by high winds which destroyed the autonomy of most of the individual plots at the time of harvest. A partial yield sample was obtained for only the dryland and S1-1 treatment in replication two.

The yield data in Table 2 were averaged by treatment for the superior varieties in each season and then plotted in Figure 2 as a function of the respective estimated water use amounts. Water use, for each treatment, was estimated for the period from crop emergence to date of vine cutting or killing frost. This computation in each season was made with the Jensen et al. (3) water balance model and the observed crop curve for each specific season. This procedure was utilized in preference to the field measured values of water use which were estimated to exhibit the influence of drainage loss periods.

Table 2. Summary of yield and irrigation data

Treatment	Applied Irrigation Water		Estimated Crop Water Use*		Average yields by variety; kg/ha (lbs/ac) Idaho 111		Idaho 114		Wyoming 166		Mean	
1972												
	cm	in	cm	in.	lbs/ac	kg/ha	lbs/ac	kg/ha	lbs/ac	kg/ha	lbs/ac	kg/ha
Dryland	0.0	0.0	22.6	8.9	1598	1790	2062	2309	1848	2070	1836a	2056
S1-1	20.3	8.0	32.5	12.8	2688	3011	2931	3283	2582	2892	2734b	3062
S1-2	22.9	9.0	33.5	13.2	2501	2801	3031	3395	2809	3146	2780b	3114
S2-2	15.2	6.0	32.8	12.9	2689	3012	2997	3357	2968	3324	2885b	3231
S1-3	20.3	8.0	32.5	12.8	2172	2433	2553	2859	2688	3011	2471b	2768
S2-3	12.7	5.0	32.0	12.6	2676	2997	2573	2882	2758	3089	2669b	2989
				Mean	2388a	2675	2691b	3014	2609b	2922		
1973											Mean	
Dryland	0.0	0.0	21.1	8.3	1486	1664	1378	1543	1367	1531	1411a	1580
S1-1	20.3	8.0	35.3	13.9	3069	3437	2978	3335	2910	3259	2986bc	3344
S1-2	27.9	11.0	38.4	15.1	3274	3667	3262	3653	3574	4003	3370c	3774
S1-3	25.4	10.0	36.1	14.2	3336	3736	3114	3488	3149	3527	3199bc	3583
S2-3	10.2	4.0	32.5	12.8	2692	3015	2945	3298	2916	3266	2851b	3193
				Mean	2771a	3104	2736a	3064	2783a	3117		
1974												
Dryland	0.0	0.0	23.6	9.3	1123	1258	1259	1410	833	933		
S1-1	22.9	9.0	32.3	12.7	2525	2828	2655	2974	1940	2173		

Yields reported are from rep. 2 only. Bean swaths in all other plots were rolled by high winds thus confounding yield measurements.

*From crop emergence to harvest date or killing frost. Water use was estimated by using the observed crop coefficient curve for each season and the Jensen et al. (3) water balance model.

Yield response to estimated water use in Figure 2 is linear with a slope of 134.7 kg/ha-cm (305.5 lbs/ac-inch). The three years of data fit the same line, with an R^2 = .92. The highest yields and corresponding water use occurred in 1973, thus indicating yield for this season was boosted by warmer temperatures and more water use relative to either the 1972 or 1974 seasons.

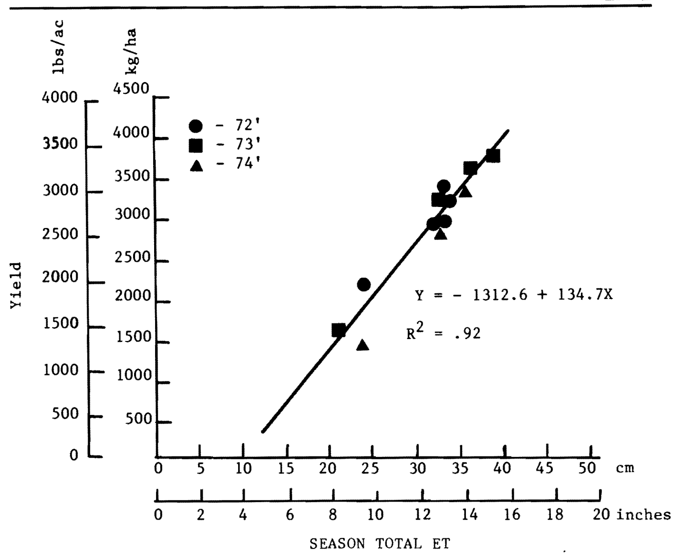

Figure 2. Pinto beans yield vs. seasonal crop water use, CIBS, 1972-74

The relationship of yield to water use in Fig. 2 is in agreement with concepts presented by Stewart and Hagen (11). They concluded, after an extensive literature review, that crop yields for normative irrigation regimes are usually linearly related to seasonal water use. A normative irrigation regime was defined as a water management scheme which provides for irrigation at reasonably regular intervals of moisture depletion. This was generally the case in this experiment.

For all plotted points in Figure 2 the average irrigated yield was 3236 kg/ha (2889 lbs/ac) vs. the average dryland of 1612 kg/ha (1439 lbs/ac). The yield difference (1624 kg/ha (1450 lbs/ac) when multiplied by the 1974 price level, near 44c/kg (20c/lb), makes this crop an attractive alternative for production in North Dakota. The yield slope of

134.7 kg/ha-cm (305.5 lbs/ac-inch) also demonstrates that this crop has a high response per unit of water use. With efficient scheduling of water application this crop should compete very well with others on the basis of value per unit of water application and/or energy requirement associated with the irrigation method.

Seasonal Distribution of Daily Water Use Rates

In each season soil moisture measurements were taken at approximate 7 day intervals. From these data, average evapotranspiration rates were computed for each time interval by balancing changes in soil moisture storage with accumulated irrigation and rainfall amounts. These data points were fitted with a fourth order polynomial curve as given in Figure 3. This curve varies from .18 cm per day (.07 inches per day) at crop emergence (near 6/3 in each year) to a maximum of .53 cm (.21 inches) per day at 50 to 60 days after emergence. The curve then declines to about .25 cm (.10 inches) per day by September 1. Over this time period total seasonal water use sums to 37.3 cm (14.7 inches). Standard error for this curve was .20 cm/day (.08 inches/day).

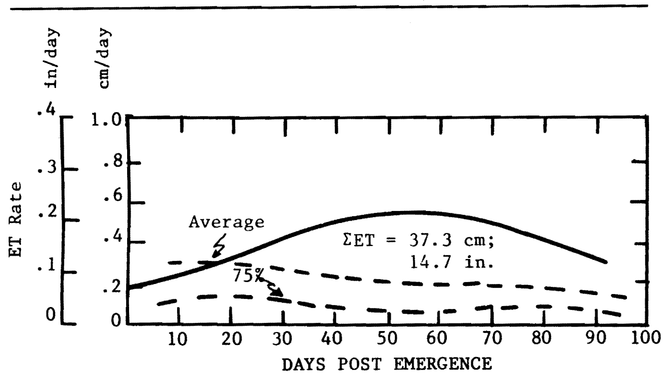

Figure 3. Average daily evapotranspiration (ET) rate for pinto beans. Broken curves indicate rainfall distributions at Carrington for average and 75 percent likelihoods, respectively

If a sprinkler system capacity is based upon the peak ET rate on this curve, the net pumping rate must equal or exceed an evaporation rate of .23 ha-cm/day (.21 ac-in/day). For a 53.4 ha (132 acre) center pivot system and an 80 per cent average application efficiency, this ET rate can be met by a 41.3 liter/sec (654 gpm) pumping rate. This pumping requirement also assumes that no rainfall is available to supply some of the crop water need. The climate, however, at Carrington averages 21.3 cm (8.4 inches) of rainfall in the period from June 1 through August 30. When the distribution of the average seasonal rainfall is added to Fig. 2 the pumping rate need only be equivalent to .114 ha-cm/day (.14 ac-in/day) during the peak use period. This converts to a pumping rate of 27.5 liter/sec (436 gpm) for 80 per cent application efficiency and 53.4 irrigated ha (132 ac). For the rainfall distribution which can be expected with 75 per cent certainty the irrigation pumping requirement must be increased to .196 ha-cm/day (.19 ac-in/day) or 37.2 liter/sec (590 gpm) for the same conditions as given above. These examples merely illustrate that pumping requirement will vary from year to year depending on actual rainfall amounts and distribution. Soil moisture storage capacity must also be considered to fully evaluate the relative adequacies of pumping rates that do not equal the expected peak crop water use rate.

Simulation studies by Stegman and Ness (10) indicated high performance levels can be obtained with pumping rates as low as 34.7 liter/sec (550 gpm) for 53.4 ha (132 acre) center pivot systems that are properly scheduled by water balance models. With less sophisticated scheduling methods higher pumping rates of 37.9 — 44.2 liters/sec (600-700 gpm) are needed to achieve acceptable productive performance on soil types similar to those in this experiment.

Crop Coefficient Curves For Water Balance Scheduling Methods

In each season, measured crop water use (ET) was compared with estimated potential evapotranspiration over each interval of soil moisture measurement. Potential evapotranspiration (ET_p) was computed by the Jensen-Haise (2) equation. This data set was expressed in ratio form (ET/ET_p) and plotted versus days post emergence. Each data point was plotted at the midpoint of the time interval between dates of moisture measurement. A fourth order polynomial was fitted to the three years of data and plotted as a smooth curve in Figure 4. The magnitude of standard error for this curve was 0.14.

The crop coefficient curve rises from ET/Et_p = .22 at emergence to 1.0 in 55-60 days after emergence. Crop height at the time of full cover averaged 53.3 cm (21 inches). In the 1972 and 1973 seasons the irrigated plots were cut for harvest at 95 days after initial emergence.

Variations in climate were observed to cause the actual crop curve for each season to shift horizontally from the average as plotted in Figure 4. In 1974, the time to complete ground cover was shortened by above average temperatures in late June and July. Maturity was, however, delayed by a cool August which averaged 3.7°C (6.6°F) below normal. The variation in time from emergence to complete ground cover ranged between 50 to 65 days in the three years.

As an alternative to the time parameter "days post emergence," the ET/ET_p data set was related to an accumulative variable defined as a growing degree unit (12). The growing degree units for each day were computed with the relationship:

$$GDU = \text{Base temperature} - T_{ave}$$

Where:

Base temperature = 10°C or 50°F

T_{ave} = Daily average ambient air temperature, computed as $(T_{max} + T_{min})/2$.

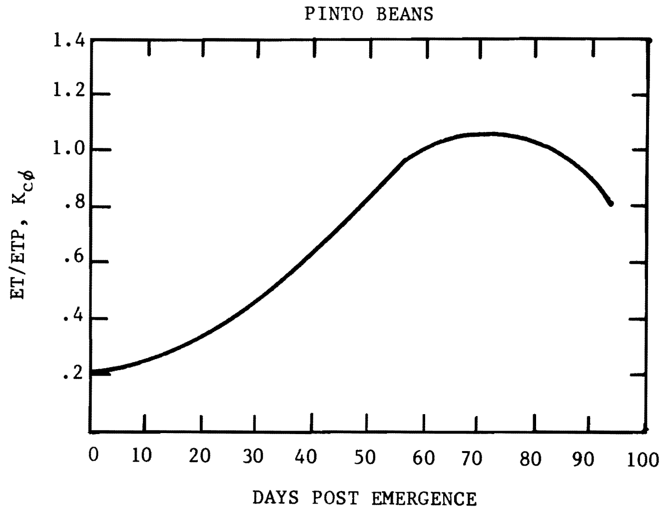

Figure 4. Crop coefficient curve vs. days post emergence for Jesen-Haise Method of estimating evapotranspiration.

The GDU parameter was summed in each season from date of planting to harvest and correlated with phenology data. A cross correlation between the GDU vs. phenology data and phenology vs. days post emergence data was used to produce the crop curve in Figure 5. The phenology relationship of crop growth to growing degree units was quite consistent for the three years with a variation of 531 to 564* (956 to 1016)** GDU's from planting to full ground cover. On the average, emergence occurred at 55 (100) GDU's after planting, first flowering at 372 (670) and full ground cover at 538 (970) units. The accumulation from planting to cutting of the vines ranged from 779 (1403) to 1021 (1840) for an average of 882 (1590) units. This spread at harvest was in part due to cutting at slightly different stages of maturity from season to season. The average value 882 (1590) should, however, be useful in determining the probabilities of adequate growing season length for pinto bean production in the north central area of North Dakota.

The curve in Figure 5 is related to a parameter which is more specific to the temperatures of a given season. Hence, seasonal variation of the curve should be reduced.

***GDU accumulation when temperatures in °C and base temperature taken as 10°C.**

****GDU accumulation when temperatures in °F and base temperature taken as 50°F.**

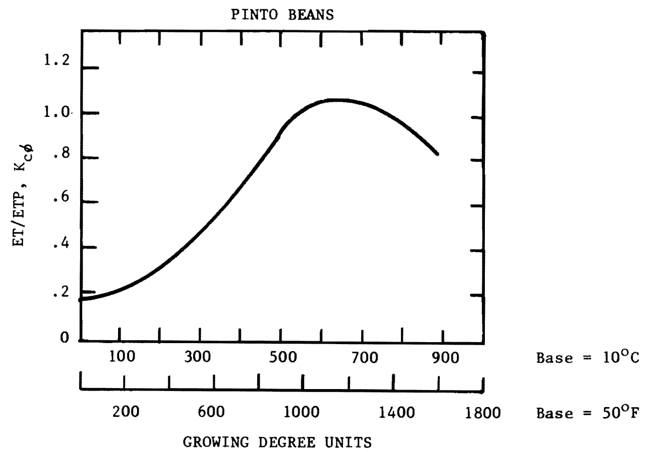

Figure 5. Crop coefficient curve vs. growing degree units for Jensen-Haise Method of estimating evapotranspiration.

Criteria For Determining When To Irrigate

Irrigations are often scheduled on the basis of an allowable soil moisture depletion criteria. Root zone moisture content is allowed to decrease to a selected limit before irrigation water is applied to eliminate the existing moisture deficit. Research evidence (1,6) indicates, however, that a given depletion limit may not prevent moisture stress at all levels of evaporative demand that can be expected from the climate in a given area. One approach to irrigation scheduling is to allow relatively small limits of depletion, thus maintaining a soil wetness that minimizes the likelihood of plant water stress. This method requires frequent irrigation and also makes it likely that drainage losses will increase. Water use efficiencies are generally lower for irigation regimes that maintain very high levels of moisture availability. This consequence probably accounts for the usual selection of a depletion limit which tends to allow some moisture stress.

To check the suitability of a particular depletion limit for average conditions, the xylem pressure data from all three seasons were correlated with available moisture level. For this comparison, root zone moisture content (AM) was expressed as the per cent available water remaining in the root zone. A curve of best fit for these data is presented in Figure 6. This curve represents the average xylem pressure which was observed over all data points at each level of available moisture. Average ambient air temperature for all data was 25.4°C (77.8°F).

Figure 6 shows that for average climatic conditions leaf xylem pressure increases very gradually as moisture depletion increases. At an AM of about 35 per cent the curve in Figure 6 begins to increase in curvature with ever increasing slope to complete depletion of available soil moisture. The scatter of data about this average curve was quite large with the coefficient of determination equal to 0.33.

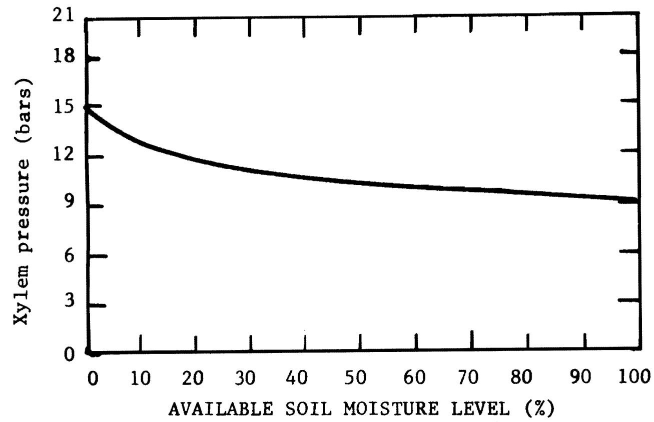

Figure 6. Average relationship for xylem pressure of pinto bean leaves with soil moisture level (CIBS, 1972-74, average curve for 1240 data points)

Significant additional correlations were obtained between leaf xylem pressure and ambient air temperature and solar radiation intensity. The best two parameter relationship was obtained between leaf xylem pressure and root zone moisture content (expressed as $(AM^{1/3})$ and ambient air temperature. This relationship is plotted as a family of curves in Figure 7. The coefficient of determination for this two parameter relationship was 0.65. Addition of other measured variables (solar radiation intensity, or wind velocity) did not materially improve this correlation.

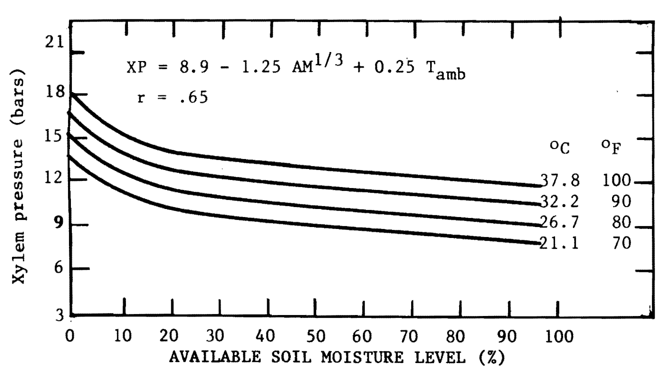

Figure 7. Correlation between xylem pressure of pinto bean leaves and soil moisture at four ambient air temperature levels CIBS, 1972-74

Use of the curves in Figures 6 and 7 as tools for determining when to initiate irrigations requires: (1) advance estimates of soil moisture deficit; (2) three to five day advance forecasts of expected maximum ambient air temperatures; and (3) selection of a critical stress or leaf xylem pressure limit.

Data from the literature (4) suggest that significant stomatal closure occurs in snap beans at 11 to 12 bars. Only a limited amount of transpiration resistance data were taken during this experiment, but data taken on 8/17/73 appear to corroberate this stress level as critical for pinto beans also. These data are plotted in Figure 8 where leaf transpiration resistance is seen to increase rapidly from an early morning non stress level to significant stress by late morning. Corresponding leaf xylem pressures at this late morning period varied from 11 to 11.6 bars.

If 11.5 bars is chosen as a critical stress level, Figure 6 indicates that moisture depletion can take place to about an AM of 35 per cent for average climatic conditions. Figure 7 further shows that the stress levels can be limited to less than 11 bars if root zone moisture levels are maintained above AM's of 31, 52, and 77 per cent when maximum ambient air temperatures are expected to reach 26.6, 29.4, and 32.2°C (80, 85 and 90°F), respectively.

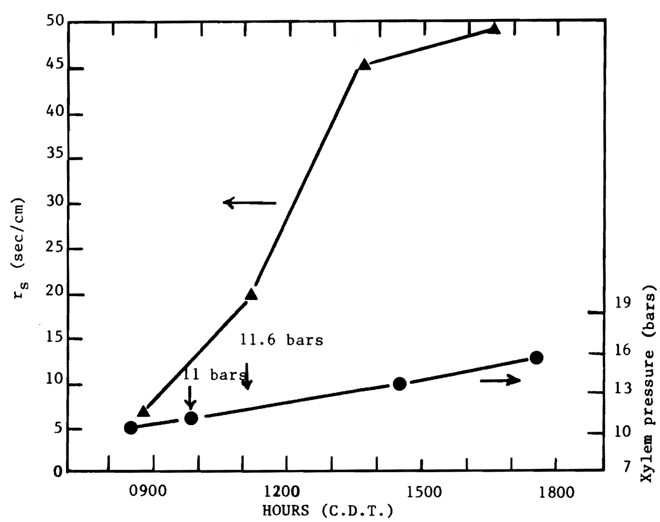

Figure 8. Trends of stomatel diffusion resistance (r_s) vs. leaf xylem pressure for pinto beans under clear sky and dryland conditions.

These data appear to help further explain the production results for the 1972 and 1973 seasons. For the cooler 1972 season (as shown earlier in Figure 1) a 65 per cent depletion limit was a safe limit because maximum ambient air temperatures generally averaged near 26.6°C (80°F). In 1973, when air temperatures averaged near 29.4°C (85°F) for considerable periods during the season, higher production should have been achieved with the wetter water management treatments, as was the case.

With water balance scheduling methods, the curves in Figure 7 offer a set of criteria for determining when to irrigate. In the early season the probabilities for cooler temperatures might be used to allow somewhat greater relative depletion than later in the season. Also needed are good advance forecasts of expected temperatures and a knowledge of the active root zone depth. This depth advance in the Heimdal loam soil was determined indirectly from an analysis of soil moisture withdrawal patterns. These data were fitted with a third order polynomial curve which is shown in

Figure 9. For irrigation management, this curve indicates root zone depth advances to near 91.4 to 106.7 cm (36 to 42 inches) by the time of full cover.

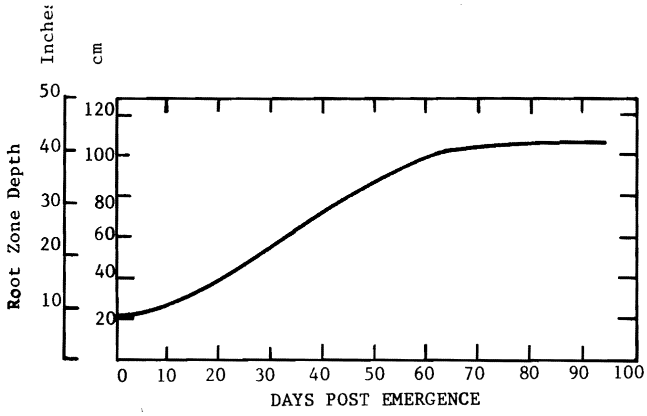

Figure 9. Average relationship of root zone depth with days after emergence for pinto beans (CIBS, 1972-74).

An additional factor which must be considered in short growing season areas is the potential effect of water management practice on delay in crop maturity. This effect was brought into sharp focus in the 1974 season when frost occurred on August 31. Yield losses were substantial in irrigated fields on the Carrington Station (7), whereas dryland areas in the corners of fields irrigated by a center pivot system did attain maturity. To reduce this hazard associated with the climate of North Dakota, it may be best in most years to terminate irrigations in early to mid August, particularly on medium to finer textured soils with high water holding capacity.

Summary

A three year study of irrigated pinto bean production was conducted on a Heimdal loam soil at the Carrington Irrigation Branch Station. Water management levels were applied as the principle experiment variable to obtain data on production response to water use. Plant stress development was additionally studied by measurement of leaf xylem pressure and transpiration resistance.

Yield increases relative to dryland averaged 1624 kg/ha (1450 lbs/ac) for Idaho 114 and Wyoming 166 varieties. Irrigated yield averaged 3235 kg/ha (2889 lbs/ac) and the yield slope per ha-cm of water use was 134.7 kg (305.5 lbs/ac-in).

Seasonal water use was estimated to average near 37.3 cm (14.7 inches) from crop emergence to date of vine cut. The corresponding peak use rate averaged .53 cm/day (.21 inches/day).

The plots were each season planted in the last week of May with crop emergence averaging near June 3. Vine cut subsequently occurred at about 95 days post emergence or at an average growing degree unit accumulation of 882* (1590)**.

Crop curves for water balance scheduling methods were developed as functions of either days post emergence or growing degree units. The latter parameter can be specifically calculated for each growing season thus tending to reduce variability in this curve from season to season. The period from emergence to full cover averaged 55 to 60 days or 538* (970)** growing degree units.

Leaf xylem pressure data were correlated with ambient air temperature and root zone soil moisture content. By addition of an allowable stress limit, criteria were developed to determine when irrigation should be initiated. These data should be particularly useful for pinto beans grown on soils similar to those of this experiment.

Water management was observed to affect the total time from planting to maturity. In short growing season areas, this factor must be considered in the scheduling of late season irrigations.

***Based on temperatures in °C**

****Based on temperatures in °F**

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