1983

Soybean Root Growth and Water Uptake

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SOYBEAN ROOT GROWTH AND WATER UPTAKE

by

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A thesis submitted
in partial fulfillment of the requirements for the
degree of Master of Science,
Major in Agronomy

South Dakota State University
November 1983

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser Date

(Head, Plant Science Department Date

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. R. A. Kohl, Associate Professor of Plant Science, for advice, guidance and assistance given while serving as my major adivsor thoroughout my graduate program. Appreciation is also extended to the other members of my graduate committee; Dr. M. L. Horton, Department Chairman, Associate Professors W. F. Lytle and Paul D. Evenson, Dr. John L. Wiersma and Dr. W. Hein.

I am grateful to the United States Agency for International Development for financing my graduate work in the U.S.A. through the Sri Lanka government. Special recognition is due to the former Director of Agriculture, (Government Department of Agriculture, Sri Lanka) Dr. C. R. Panabokke who stimulated my interest in this subject and made all the arrangements for my training in the U.S.A.

Special appreciation is also expressed to my wife and children for their patience and sacrifice, so that I could complete this thesis.

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INTRODUCTION

Rainfall is usually marginal for optimum crop production in the North Central Great Plains. As a result many farmers in this region are installing irrigation systems to supplement rainfall. The most common system installed is the center pivot. However, while this system has a low labor requirement it is costly. Economic reports from South Dakota State University indicate marginal to negative comparisions of irrigated crop production to dryland production.

Sprinkler irrigation systems such as side roll, tow lines, hand move, side move with trail lines etc. and surface irrigation depend on root zone soil water storage to extend intervals between irrigations to gain advantages of reduced costs in system design and labor requirements, lower soil evaporation and reduce weed germination. Large root zone water storage is also needed when center pivot systems are towed between two fields with growing crops.

The most significant parameters about which information is lacking in making design and associated management decisions concerning the above irrigation options are root zone depth in specific South Dakota soils and root activity in the lower part of the root zone. Questions arise such as: How rapidly and to what depth do roots penetrate in different South Dakota soils? Does root growth cease with flowering? What root density is required in a soil horizon to be significant in water uptake? It was with these questions in mind that a study was initiated into the root length density and water uptake pattern of soybeans in three South Dakota soils.

LITERATURE REVIEW

Rooting Depth

The expansion of the root system into deep, moist soil is essentially the most important means of supplying water to the plant, when the supply in the upper layers of the profile is insufficient. Reicosky (1979) reported water uptake from the subsoil to 150 cm in depth, by soybean when the water availability was limited in the upper layers. The vertical exploitation by soybean roots down to 180 cm in a deep loess soil, without a water table or soil physical barriers, was reported by Sivakumar (1977). Jung (1980) reported that the maximum rooting depth of soybean was 240 cm in a dry year and 180 cm in a wet year for the same loess soil in Iowa. Mitchell (1971) found soybean roots down to 183 cm in a Nicollett clay loam soil. Though there is information on root penetration little is known about root activity in the lower layers.

Rooting and Age

Mitchell (1971) describes the root development in soybeans in 3 phases. Phase I, covered the period from emergence to 31 days. During this period there was a gradual penetration of the tap root and rapid formation of secondary laterals in the first 10 cm of the soil profile. At 31 days 93% of the total root weight was in the 0 to 15 cm zone and the lateral extension was commonly found between 20 to 25 cm from the plant. Vertical elongation was 46 to 60 cm. Phase II, described the period from 67 to 80 days after planting. This was the root filling period for the 0 to 23 cm section of the profile and the beginning of deeper, vertical penetration by the lateral roots. Root weights in the 7 to 15 cm layer nearly tripled during this period and that in the 15 to 23 cm doubled. Vertical penetration was from 46 to 76 cm. Phase III, covered the period from 80 to 102 days after planting. During this period tap root growth slowed, and the major lateral roots elongated downward reaching depths ranging from 122 to 183 cm.

Root distribution has been believed to decrease monotonously in length as the soil depth increases. However, this pattern may be modified by the soil water status thoroughout the profile. Reicosky et al (1972) reported that the root density profile of soybeans showed marked differences as the soil water was depleted. They found an increase in root density between 50 to 70 cm on the 59th day after planting, forming a rooting bulge, when the water availability was limited in the upper layers. The data of Sivakumar (1977) showed a similar bulge, appearing 57 days after planting. When the drought continued this bulge shifted downward to between 75 and 150 cm. This shifting might be correlated with the shifting of the location of maximum water uptake (Burch et. al 1978). Information available in the literature regarding root growth and water uptake from the lower layers is limited, especially when there is continuous drought after flowering.

Water Uptake:

The flow of water into roots is largely passive; the driving force being the water potential gradient across the root-soil interface (Gardner 1960, Philip 1957). The passive uptake theory (Hornet 1948, Philip 1957, Gardner 1963) requires (a) that the water potential in the xylem of the plant be highest at the root tips and decrease in the direction of stem, and (b) that the plant water potential (ψ_p) be less than soil matric potential (ψ_m) for water uptake to occur. Kohl (1976) showed that root water uptake from a soil layer is a function of (a) the difference between the ψ_p and ψ_m of a given layer and (b) the root density of that layer. Gardner (1964) reported that the water uptake pattern was more closely related to the root distribution and somewhat less to soil properties. Theoretically, the root density distribution should correlate with the uptake patterns, but the results of some laboratory experiments suggest a weak dependence when water is readily available (Reicosky 1972). Some attempts to relate root density to soil hydraulic parameters and water uptake have been made, but theoretical predictions often do not agree with experimental results (Gardner 1964, Molze 1971 and Nimah and Hanks 1973).

Root Growth and Soil Water:

Newman (1966) showed that the rate of root dry weight accumulation was a direct function of the water potential of the soil in which they grew. His data suggests that the plant resistance to water movement is high. Lawlor (1973) also came to the same conclusion that root growth responded to the water potential of the medium around the roots and the major resistance to water flow was in the plant. Gardner et. al (1964) and Cole et. al (1974) showed that the wet weight of roots was affected much more than root lengths as the soil water content decreased. Taylor and Ratliff (1969) found that peanut root volume or root weights progressively decreased with a decrease in soil water potential between -0.19 and -12 bars but the elongation rates were not affected in this range. Thus, it appears that root length is not affected much by a decrease in soil water content in a profile layer. However, as the water content in a profile layer is decreased the root length in the layer below it would increase resulting in a greater root length per unit area. Therefore under limited water supplies in the upper layers one would expect to find greater root length per unit area. Camillo (1983) showed that the matric potential profile eventually acquired a mirrored shape of the relative root density profile, and the water potential at any depth was inversely proportional to the corresponding root density raised to a power that depends on soil texture.

Root Growth and Other Factors

The production of new roots and decomposition of old roots occur continuously and simultaneously during the whole growing period in soybeans (Sanders and Brown 1979). Borst et. al (1931) reported that the root weight declined after seed development began. Root density has been reported to decrease with increasing soil depth (Raper and Barber (1970) and Mitchell and Russell 1971).

Parameters of Root Growth

Root weight, root surface area and root number and/or length are most commonly used to define root distributions in the field. The interpretation of root weight data depends upon the assumption that the root mass is directly related to root activity. This assumption is not always valid, for two reasons. First, roots grown in soil can never be quantitatively recovered fully. Second, one could question whether the thicker and stubbier roots produced under less favorable environments are equally as active as the thin roots produced under favorable environments. A root's mass is likely to increase as the square of the diameter, yet it contacts little more soil than a thin root of equal length. It is doubtful if root mass can accurately represent a root system's ability to withdraw water from soil horizons occupied by a few thin roots.

Some researchers have used root surface area to represent root distribution, assuming that there is a direct correlation between root surface in contact with soil and root activity. Thus, per unit mass, young thin roots will have more surface than thick older roots. One could also ask whether the older, suberized roots are equally as active as younger roots. However, little is known about the relative activities of old, thick roots and young, thin roots. Though there are several approaches for the estimation of relative root surface, Pearson (1974) emphasized that a good, practical method for root surface estimation is badly needed.

Root number and/or length can also be used to characterize root distribution in the soil profile. Taylor et. al (1970) showed that the root count (the number of roots crossing a horizontal transect on the glass face of a rhizotron tank), and the length of root per cm^3 of soil at the same depth were highly correlated, and suggested that the most convenient of the two measurements could be used. Thus the root count on the broken faces of a soil core, from a particular depth, represent the root distribution for that depth.

Quantitative Aspects of Water Uptake and Root Length Density

Reicosky et. al (1972) noticed a maximum sink (sink reflects the rate of water extraction by roots) at 52 days at the depth of 50 to 70 cm. As time passed there was a progressive shift downward of this maximum sink. The increase in the sink term with time was related to an increase in plant demand for water. Uptake was as high as 0.67 cm^3/cm of root/day for roots where water was readily available. Variation in uptake in the zone of maximum sink activity appears to be related to plant requirement for water and to root density in that zone. Provided that water is available, increasing water need by plants can be met by an increase in root density and/or by an increase in the rate of uptake per unit length of root. At 73 days, 23% of the roots were located between 60 to 80 cm and absorbed 94% of the water. This showed that a small portion of the root system was responsible for a major portion of water uptake.

Bennett et. al (1979) showed that about 10% of the sorghum root system in contact with available water supplied adequate water to produce 65% of the yield compared to the control.

Allmaras et. al (1975) noticed that the zone of water depletion by soybeans moved downward from the 0 to 70 cm region at 65 days from planting to the 30 to 120 cm region at 85 days. The total depletion during this period was reported as 52 mm of water.

It appears, with limited water supplies in the upper layers, the contribution from the lower layers is important.

Soil Water and Transpiration

Jones et. al. (1982) reported that with non-limiting soil moisture, the transpiration flux increased from morning to mid-day while leaf resistance decreased. During the afternoon hours leaf resistance increased leading to a decrease in transpiration flux. The result indicated the dependence of leaf resistance on transpiration rate.

Zur and Jones (1982) in the above experiment but with limiting soil moisture, reported that the transpiration flux decreased with a decrease in soil water content. The stomatal diffusive resistance also increased with a decrease in soil water content. The total resistance to water flow from the soil through the plant increased with a decrease in transpiration.

MATERIAL AND METHODS

The experiments were conducted during the summers of 1982 and 1983 under field conditions at the Agronomy Farm at Brookings, S.D., the James Valley Irrigation Research Farm near Redfield, S.D., and on a private farm west of Gettysburg, S.D. Soil descriptions are given in a separate section, "properties of soils" under results and discussion.

A. Field Experiment

During both years the experimental plots measured 60 m by 36.6 m. Soybeans were drilled in 0.91 m rows, early in June at a population of 400,000 plants/ha. A single sprinkler line with sprinklers at every 6.1 m was placed through the center of the plot. This arrangement produces a linear irrigation gradient on either side of the line source, and has been used to investigate crop response to a continuous irrigation variable (Hanks et. al 1976). The plot layout and the locations of the line source, sprinkler heads, neutron access tubes and rain gauges are shown in figure 1. Root sampling and soil water monitoring were done at three locations; near the line source to represent fully irrigated conditions, beyond the reach of the sprinklers to represent the dryland situation and half-way in between to represent a partially irrigated condition. Two six meter lengths of the plot area across the line source were reserved for root sampling and soil water monitoring. A 12 meter area between the sampling areas was reserved for yield measurements.

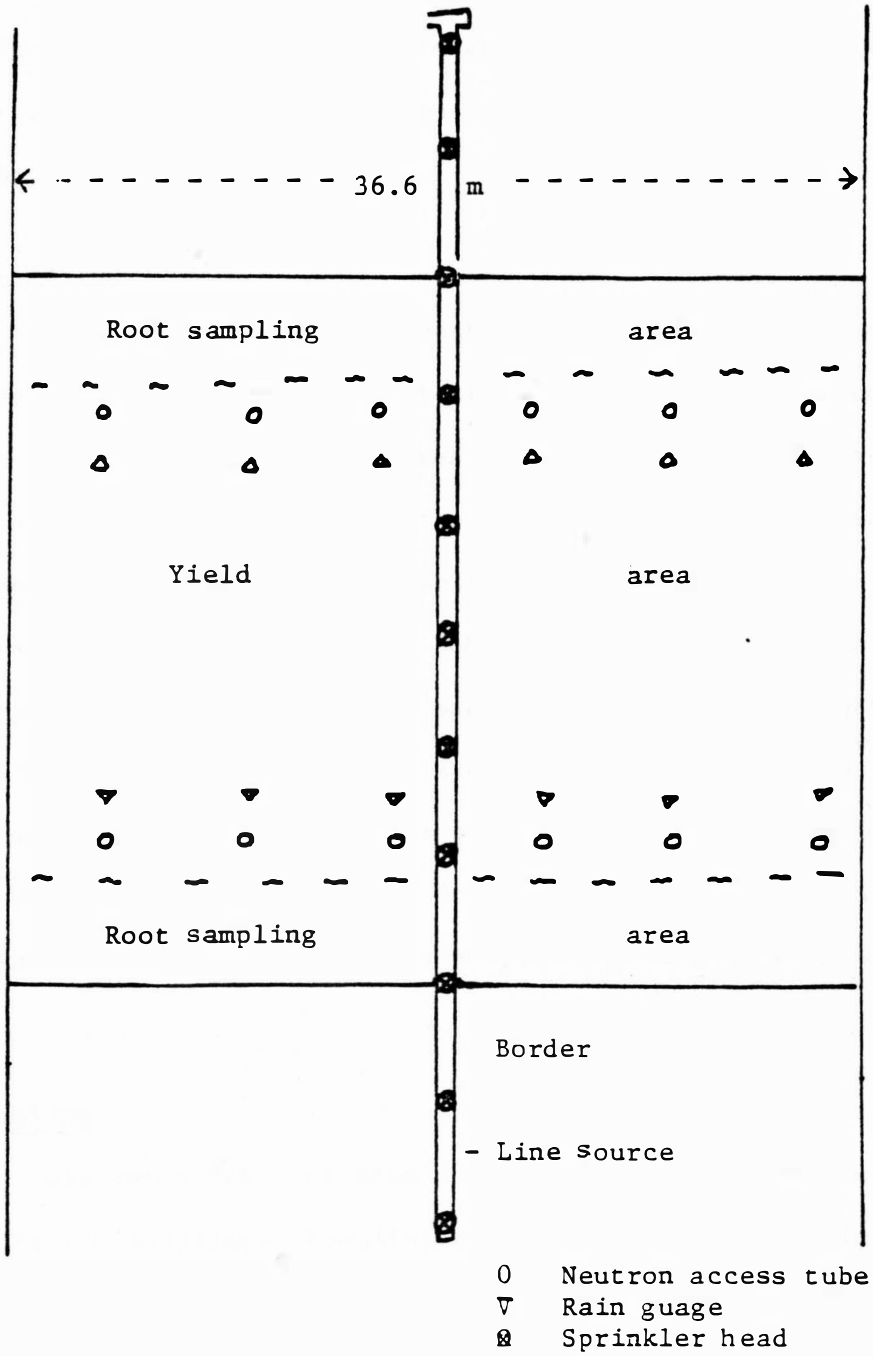

Figure 1. Field plot layout

Neutron access tubes were installed to a depth of 1.5 m. The tubes were installed close to the plant rows to facilitate cultivation. The neutron counts from 4 locations were averaged for a single treatment. The rain gauges were positioned at a height of 1 m near each tube.

Root Estimation

Of the methods used in quantitative studies on root growth described by Bohm (1979) volumetric root length (cm of root/cm^3 of soil) determination using soil cores appears to be very suitable for field experiments. However, the relatively small diameter of the cores can be a disadvantage in sampling soil layers with low root densities (Kirby and Rackham 1977). Bohm (1979) reported that at least five samples would be required in such situations for statistical analysis. The quantitative root estimation in the present investigation was carried out using volumetric root length (cm of root/cm^3 of soil) determination method described by Bohm (1979). In the present investigation 8-10 samples were taken per treatment at each sampling time.

Root Sampling

Soil cores for root sampling were taken from the area designated for sampling. Sampling was done three times during the growing season, except at Gettysburg in 1982, where the sampling was done only twice. The crop was 30-50 days old during the first root sampling and this represents the early season root growth. The crop was 80 to 90 days old during the second sampling (midseason root growth). During the third sampling, the crop reached its' physiological maturity (110-120 days).

Soil cores for root counts were taken with a Giddings probe mounted on a tractor. The soil tube had an inside diameter of 4.1 cm and could extract a one meter soil core. The cores were taken at a distance of 8 to 12 cm away from the base of the plant and between rows. Root sampling was extended to a minimum of 20 cm below the layer in which the last root was observed.

The core was first divided into 10 cm samples, 0-10, 10-20, 20-30 . . .etc. The 10 cm samples were then divided into equal halves. Each half was then broken into two and the number of roots on the broken faces was counted. The mean root count from the two breaks represent the count for the 10 cm sample. The linear equation (r=0.88) given below, developed by Kohl* for volumetric root length determination was used to change the counts into root density.

$$Y = 0.061 + 0.124X$$

Y = Root density (cm/cm^3 of soil)

X = Root count.

For counts less than 5, the following equation was used.

$$Y = 0.1X$$

The root density curves were first drawn for the 10 cm depth increments. From this the density for 15 cm depth increments was read and the 15 cm depth increment root density curves were drawn to match the volumetric soil water content curves.

*Dr. R. A. Kohl. unpublished data.

Soil Water Content

Volumetric soil water content was measured using the neutron probe. The water content was measured for every 15 cm depth increment, except for the top 15 cm. The gravimetric method was used to determine the mass water content of the top 15 cm profile layer for the Vienna and Lowry soils. This was changed to volumetric water content by multiplying by the bulk density. The neutron counts from the probe were changed into volumetric water content by using equations developed from calibration curves. The counts were taken every 8-10 days. These data were used to draw the soil water content curves.

Rainout Shelter

To represent the dryland situation in case of excessive rain, beans were planted under a rainout shelter in Vienna loam at Brookings.

B. Laboratory Experiments

Bulk density and water retention determinations were made on field collected cores.

Bulk Density

Bulk density of the profile down to 150 cm was determined. Soil cores were taken using the machine and tube as for root sampling. These cores were carefully divided into 10 cm lengths and dried. Three samples from each depth were averaged for bulk density values.

Porosity

Total porosity (E) was calculated by using the following equation.

$$E = 1 - \frac{\rho_b}{\rho_p}$$

ρ_b = Bulk density

ρ_p = Particle density

The particle density of the 3 soils ranged from 2.65 to 2.69 g/cm^3 throughout the profile (Sources: Same sources as given in tables 1, 2 & 3). The mean particle density (2.67 g/cm^3) was used in the above equation for the determination of total porosity. Aeration porosity (Ea) as calculated by using the following equation.

$$E_a = E - \theta_v$$

θ_v = Volumetric water content

Soil Water Retention

The pressure plate apparatus was used to determine soil water retention at various pressures ranging from -0.1 bar to -15 bars. A low pressure apparatus was used from -0.1 to -1 bar and a high pressure system was used from -3 bars to -15 bars. From the resulting data volumetric water content versus soil water potential curves were drawn. Soil water potential profiles (Ψ_m) were drawn by using these curves in conjuntion with the soil water content profiles.

Note on Terminology Used

Soil layer: The profile was divided into uniform layers of 15 cm depths each. Soil water content, bulk density and root length density data are reported for these layers.

Total root length = average root length density x rooting depth.

Irrigated treatment (T_1): Received irrigation to maintain optimum growth.

Dryland Condition (T_2): Received no irrigation water to supplement rainfall.

RESULTS AND DISCUSSION

The results and discussion of the data from the experiments on soybean rooting, conducted in Vienna silt loam, Great Bend silt loam and Lowry silt loam soils, respectively at Brookings, Redfield and Gettysburg, South Dakota are presented in four major parts; (A) soil physical characteristics (B) root growth (C) water uptake and (D) relationshp between water uptake and yield.

A. Soil Physical Characteristics

The soil physical characteristics such as bulk density, total porosity, soil water content and particle size distribution for the three soils are presented in tables 1, 2 and 3. Vienna loam is a fine-loamy, mixed Udic Haploboroll, developed in glacial till. The texture of the subsoil grades from loam to clay loam and contains occasional sand lenses. The soil is considered well drained but sump pumps are a necessity for buildings with basements in this soil because of moderately frequent perched water table conditions. Great Bend silt loam is a Udic Haploboroll of fine - silty mixed texture, developed in mixed silt and clay lacustrine material. The relative openness of this soil would argue against rooting depths being limited by soil aeration even with optimum water being supplied. Lowry silt loam is a coarse -silty mixed, typic Haplustoll, developed in loess.

The bulk density of the profile layers (each 15 cm in thickness) increased with depth in Vienna loam, from 1.25 to 1.78 g/cm^3. The bulk densities of Great Bend silt loam and Lowry silt loam

Table 1: Some soil physical characteristics of Vienna silt loam at Brookings (Agronomy Farm) South Dakota

Soil Depth (cm)	Bulk Density g/cm^3	Total Porosity (% vol)	Water Content Maximum	Water Content Minimum	Particle Size Distribution Sand	Particle Size Distribution Silt	Particle Size Distribution Clay*
			θ_v%		%		
0-15	1.24	53.7	29.4	12.1	42.9	34.4	22.7
15-30	1.33	50.2	26.5	11.7	40.9	37.9	21.2
30-45	1.39	47.9	26.4	11.0	42.9	32.3	24.8
45-60	1.45	45.7	27.1	12.5	38.4	33.3	28.3
60-75	1.54	42.3	27.8	12.5	38.4	33.3	28.3
75-90	1.63	39.0	28.5	15.5	38.4	33.3	28.3
90-105	1.74	34.8	29.1	15.7	38.4	33.3	28.3
105-120	1.74	34.8	29.1	18.9	38.4	33.3	28.3
120-135	1.78	33.3	29.5	20.8	39.9	33.8	26.3

*Source: Soil survey, Brookings County S.D. Series 1955, No. 3.

Table 2: Some soil physical characteristics of Great Bend silt loam at Redfield (James River Research Center). South Dakota

Soil Depth (cm)	Bulk Density g/cm^3	Total Porosity (% vol)	Water Content Maximum	Water Content Minimum	Particle Size Distribution Sand	Particle Size Distribution Silt	Particle Size Distribution Clay*
			- - - θ_v% - - -		- - - - - - % - - - - - - - -		
1-15	1.21	54.7	30.8	12.3	6.8	70.2	23.0
15-30	1.24	53.7	29.3	10.4	6.8	70.2	23.0
30-45	1.26	52.8	28.5	8.4	3.4	73.6	22.1
45-60	1.28	52.1	28.2	9.3	5.7	76.7	17.6
60-75	1.28	52.1	28.4	10.8	5.7	76.7	17.6
75-90	1.27	52.4	29.5	10.2	5.7	76.7	17.6
90-105	1.28	52.1	30.6	10.4	4.1	83.2	12.7
105-120	1.27	52.4	31.0	14.0	4.1	83.2	12.7
120-135	1.28	52.1	32.7	17.8	4.1	83.2	12.7

*Source: Genesis of the Soils of Lake Dakota Plain in Spink County S.D. Technical Bulletin 37.

Table 3: Some soil physical characteristics of Lowry silt loam at Gettysburg (Private farm), South Dakota.

Soil Depth (cm)	Bulk Density g/cm^3	Total Porosity (% vol)	Water Content Maximum	Water Content Minimum	Particle Size Distribution Sand	Silt	Clay*
			- - - θ_v% - - -		- - - - - - % - - - - - - - -		
1-15	1.32	50.6	24.8	10.2	12.3	70.2	17.5
15-30	1.29	51.7	22.8	11.1	12.0	67.	21.
30-45	1.24	53.6	21.5	10.3	14.0	69.	17.
45-60	1.26	52.8	20.2	9.3			
60-75	1.32	50.6	19.9	9.2			
75-90	1.29	51.7	19.8	9.7			
90-105	1.30	51.3	19.9	11.0			
105-120	1.33	50.2	20.1	12.4			
120-135	1.32	50.6	19.8	14.4			

*Source: Soil Survey of Walworth County, S.D. (1981)
Soil Survey of Sully County S.D. (1975)

profiles did not change significantly with depth and averaged 1.26 and 1.30 g/cm^3 respectively.

The total porosity (E) markedly decreased with depth from 54% to 33% in Vienna. This contrasts with almost constant porosities with depth in Great Bend and Lowry silt loam. The mean sand, silt and clay contents in Vienna are 39.9%, 33.8% and 26.3%. The mean sand, silt and clay in Great Bend soil and Lowry soil are 5.6, 77.1 and 15.2% and 12.8, 68.7 and 18.5% respectively. Unlike the other two soil types, the particle size distribution for Lowry is reported only for the top 36 cm. Vienna has the highest percentage of sand and clay, and the least amount of silt; about one-half that of the other two soil types.

Soil water contents (θ_v), reported here are measured values using the neutron probe during the growing season. The mean maximum water content is 0.28, 0.30 and 0.21 cm^3 of water/cm^3 of soil in Vienna, Great Bend and Lowry respectively. The mean minimum values are 0.13, 0.12 and 0.11 cm^3 of water/cm^3 of soil. However, in computing the mean minimum value in Vienna, the values from the lower layers (90 to 135 cm) were not used for conputation. The mean available water contents in the soil types are 0.15, 0.18 and 0.10 cm^3 of water/cm^3 of soil respectively.

B. Root Growth

1. Rooting depth

The root penetration depths in the three soil types, for two growing seasons are shown in figure 2. During the early stages of growth, the penetration depths in Vienna loam were 75 and 45 cm for 1982 and 1983 respectively. The roots penetrated down to 120 cm by midseason and there was no further penetration up to maturity in 1982. During the 1983 growing season early season penetration was 45 cm, 75 cm by midseason and 105 cm at maturity. The maximum penetration depth was 120 cm in 1982. Thus it appears, that the maximum rooting depth of soybean in this soil is 120 cm.

High bulk density (Philips 1962, Taylor and Gardner 1963, and Tacket 1964) and reduced soil aeration (Voorhees 1975) have been generally suggested as causes for limiting root penetration. Limiting bulk density values have varied from 1.3 g/cm^3 (Philips 1962) to 1.9 g/cm^3 (Tacket 1964). Because various factors, such as soil texture, soil water content, macro-pore sturcture, clay type, cementation, etc. in addition to bulk density affects a soil's mechanical impedence to root penetration, it is difficult to define a limiting bulk density. The density of the profile layer in which the penetration stopped in Vienna is 1.78 g/cm^3. This is a large value and indicates that bulk density could be a limiting factor in root penetration in this soil. However, other factors could also be significant.

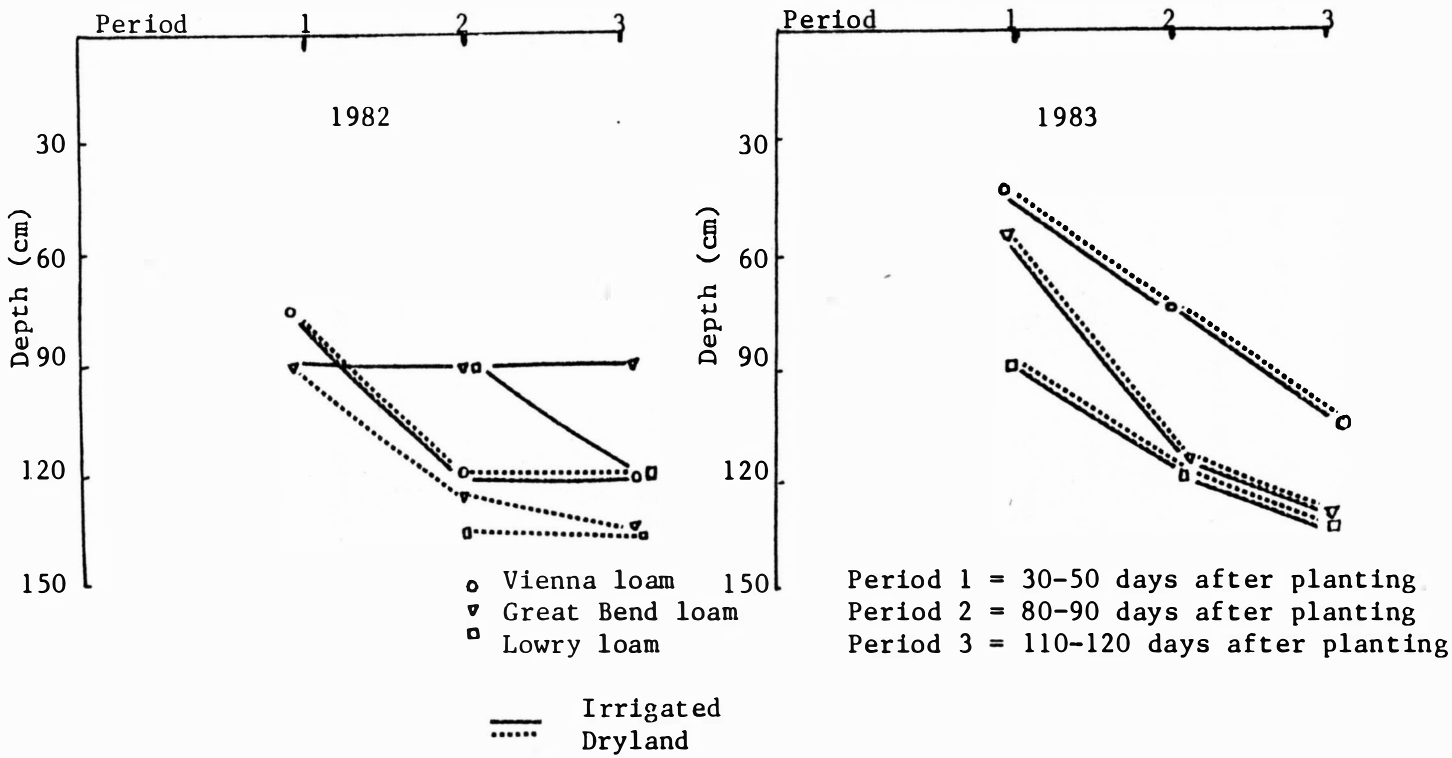

Figure 2. Rooting depth (cm) in the three soil types for three periods during the growing season in 1982 and 1983.

When the aeration porosity in a sandy soil decreased by 71% (0.31 to 0.09) the elongation rate decreased by 72% (Voorhees 1975). A perched water table persisting into early August in Vienna loam during the 1983 growing season might have reduced the aeration porosity to be as low as 0.07 as shallow as 90 cm. The penetration depth of 75 cm at midseason in 1983, compared to 120 cm in 1982, may be due to reduced aeration levels below 75 cm. The aeration porosity in Vienna loam was less than 0.09 at the depth at which penetration stopped during both years (Table 4). It appears that reduced aeration could have retarded root penetration below 120 cm in Vienna loam.

The penetration depth during the early growth period in Great Bend was 90 cm in 1982 and 75 cm in 1983. Penetration progressed further downward to the 120 cm depth by midseason under dryland conditions in both years. However, penetration stopped at the 90 cm depth in the irrigated treatment in 1982. The maximum penetration depth for the other treatments was 135 cm at maturity for both years.

The early season rooting depth in Lowry was 105 cm in 1983. By midseason dryland roots extended down to 135 in 1982 and 120 cm in 1983. No further penetration occurred in 1982 after midseason, but there was a 15 cm extension in 1983. Thus, the maximum rooting depth in this soil during both years was 135 cm.

It appears that the rooting behavior in Great Bend and Lowry is very similar. This is expected, as the bulk densities and the textures of the profiles are very similar.

Table 4: Aeration porosity in Vienna loam on four specific dates

Depth (cm)	1982 July 23	1982 August 20	1983 July 22	1983 August 20
15-30	0.30	0.38	0.25	0.37
30-45	0.20	0.37	0.24	0.36
45-60	0.21	0.36	0.21	0.32
60-75	0.19	0.27	0.15	0.26
75-90	0.14	0.21	0.11	0.20
90-105	0.10	0.14	0.07	0.10
105-120	0.09	0.13	0.06	0.09
120-135	0.07	0.10	0.04	0.06

According to Taylor and Gardner (1963), Tacket (1964) and Voorhees (1975) matric potential, bulk density and aeration respectively are not the limiting factors in the above soils for penetration below 135 cm depth.

The rooting depth of 4½ month age class soybean varieties was 180 cm (Mitchell 1971 and Jung 1980). The varieties used in the present investigation belong to the 4 month age class. Thus, the shallower rooting observed in the present investigation might be partially due to age class difference.

Jung (1980) reported rooting to 240 cm, in a dry year compared to 180 cm in a wet year. Rainfall during the 1982 growing season was much less than that received in 1983 (Figures 3, 4 and 5), at all locations. Similarity of rooting depths during both years in the present investigation suggest that even the dryness of 1982 was inadequate to cause further root penetration. Some other factor or factors than those discussed above must be preventing root penetration below 135 cm.

2. Vertical Extension Rate

The vertical root extension rate early in the season was 2.7 to 2.9 cm/day in 1982 and 1.1 to 1.7 cm/day in 1983. The relative dryness in 1982 might have accelerated the extension rate to reach more available soil water. By midseason the extension rate dropped to 0.6 to 0.8 cm/day. The extension rate approaching maturity ranged

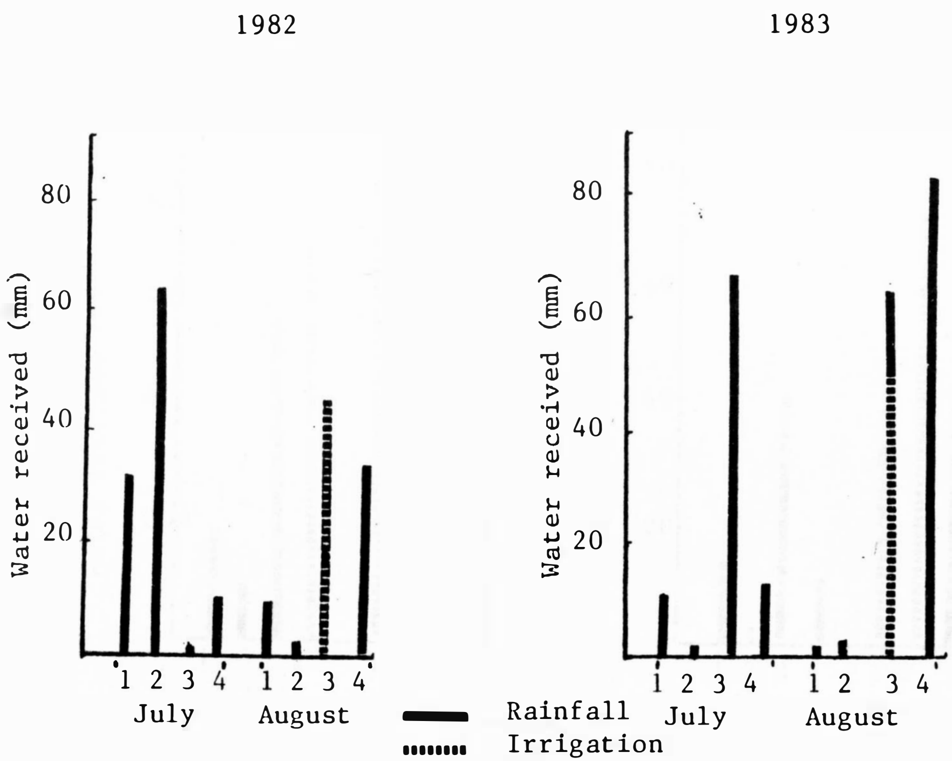

Figure 3. Water received (mm/week) in Vienna loam during the months of July and August in 1982 and 1983

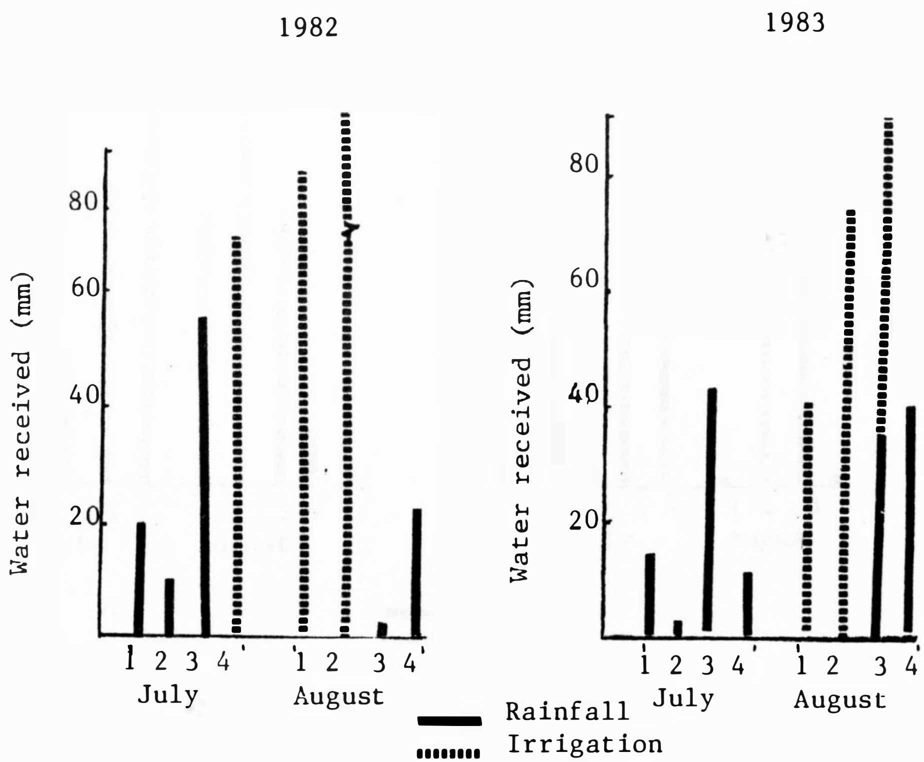

Figure 4. Water received (mm/week) in Great Bend silt loam during the months of July and August in 1982 and 1983.

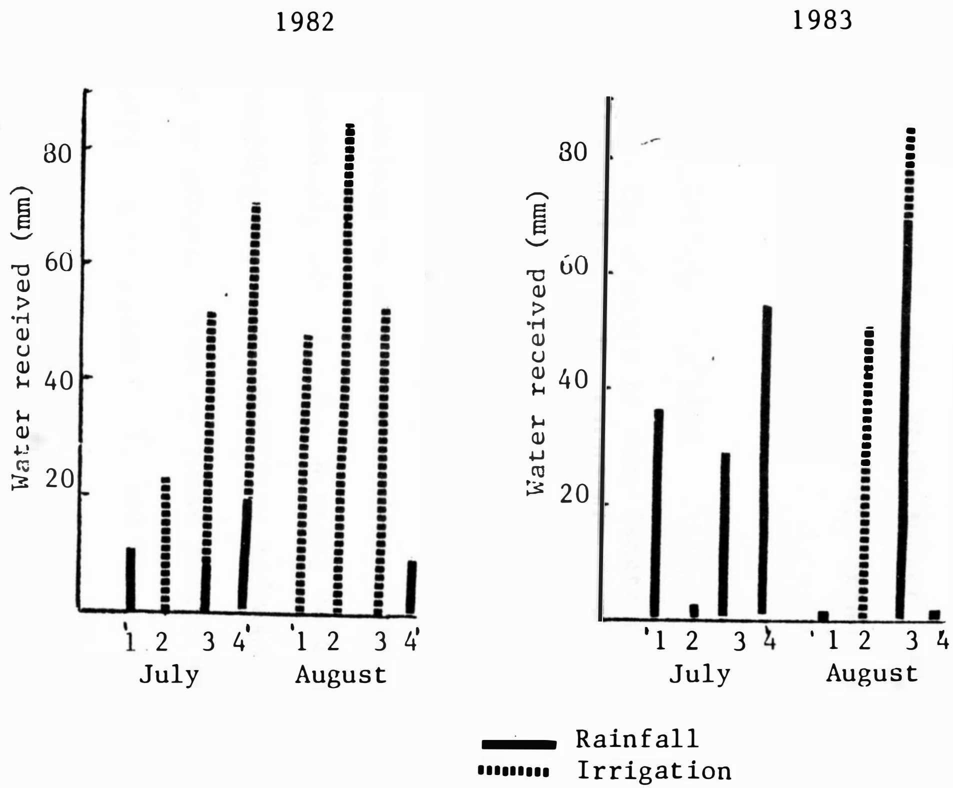

Figure 5. Water received (mm/week) in Lowry silt loam during the months of July and August in 1982 and 1983

from 0.0 to 0.8 cm/day. During the 1982 growing season (relatively dry year) the roots reached the maximum penetration depth by mid-season, thus the extension rate during maturation was zero. However, during the 1983 growing season vertical penetration progressed to maturity, so the extensin rate was greater than zero (0.5 to 0.8 cm/day). The maximum extension rate was observed early in the season and then the extension rate decreased with plant age. The extension rates observed in this study support the work of Allmaras et. al (1975). They reported that the extension rate through midseason was 1.7 cm/day.

3. Root Density Profiles

The changes in root length density (cm root/cm^3 of soil) in the soil profile as a function of depth and time are shown in figures 6, 7 and 8. The root density ranges from a high of 1.68 cm of root/cm^3 of soil in the top 15 cm to 0.01 cm of root/cm^3 of soil at the maximum rooting depth. However rooting density did not decrease monotonously with depth. Rooting bulges were observed in the profile, indicating that root densities increased at some depths more rapidly than at others. Most of these bulges were found to be statistically significant (figures 6, 7, and 8).

In Vienna loam a bulge was first observed between 45 and 60 cm during midseason in both years. At maturity the bulge shifted further downward to the 60-75 cm layer.

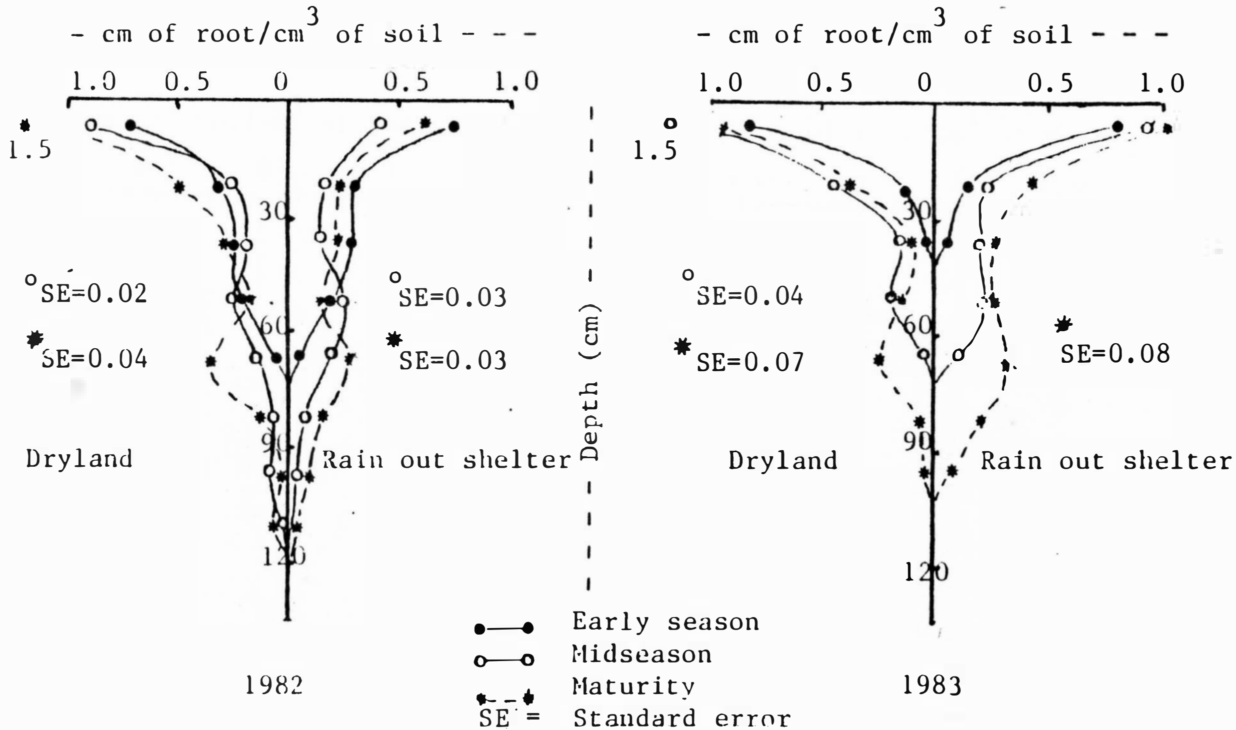

Figure 6. Root density profile in Vienna loam for three periods during the growing season in 1982 and 1983.

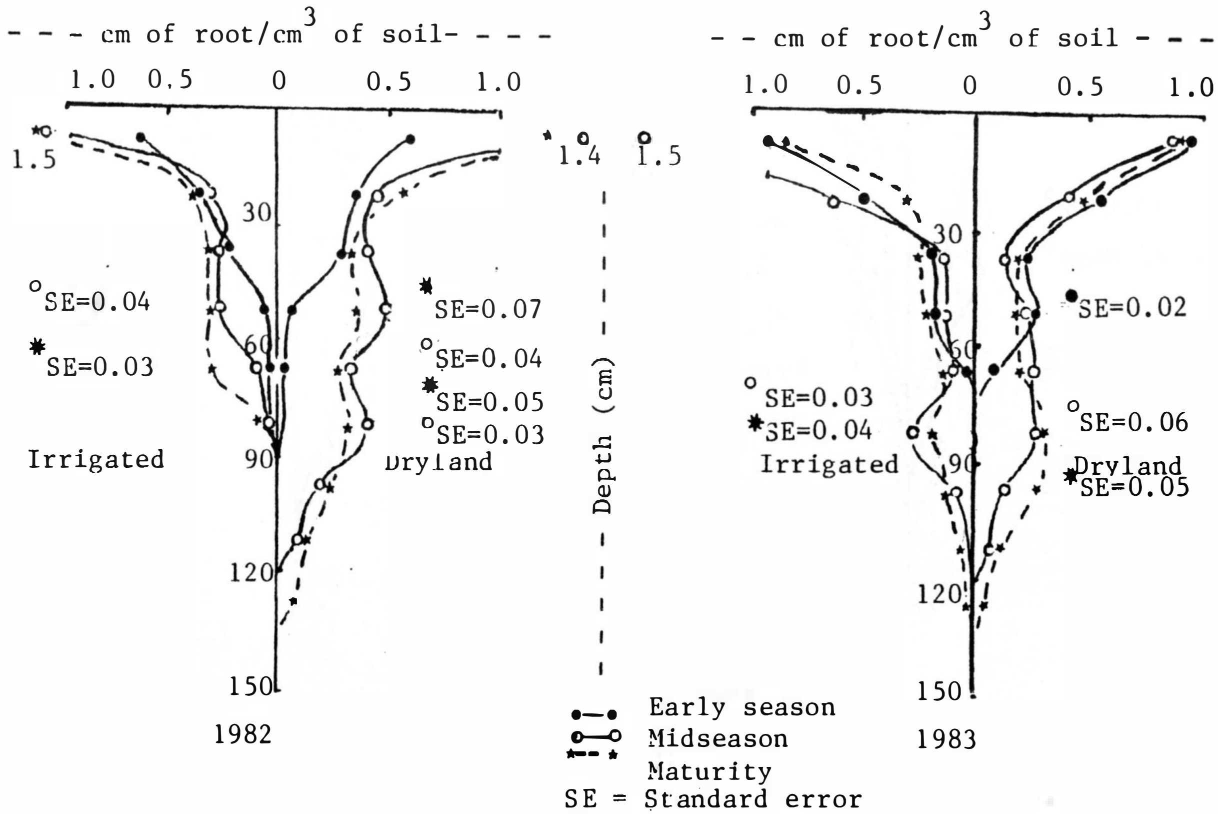

Figure 7. Root density profile in Great Bend silt loam for three periods during the growing season in 1982 and 1983.

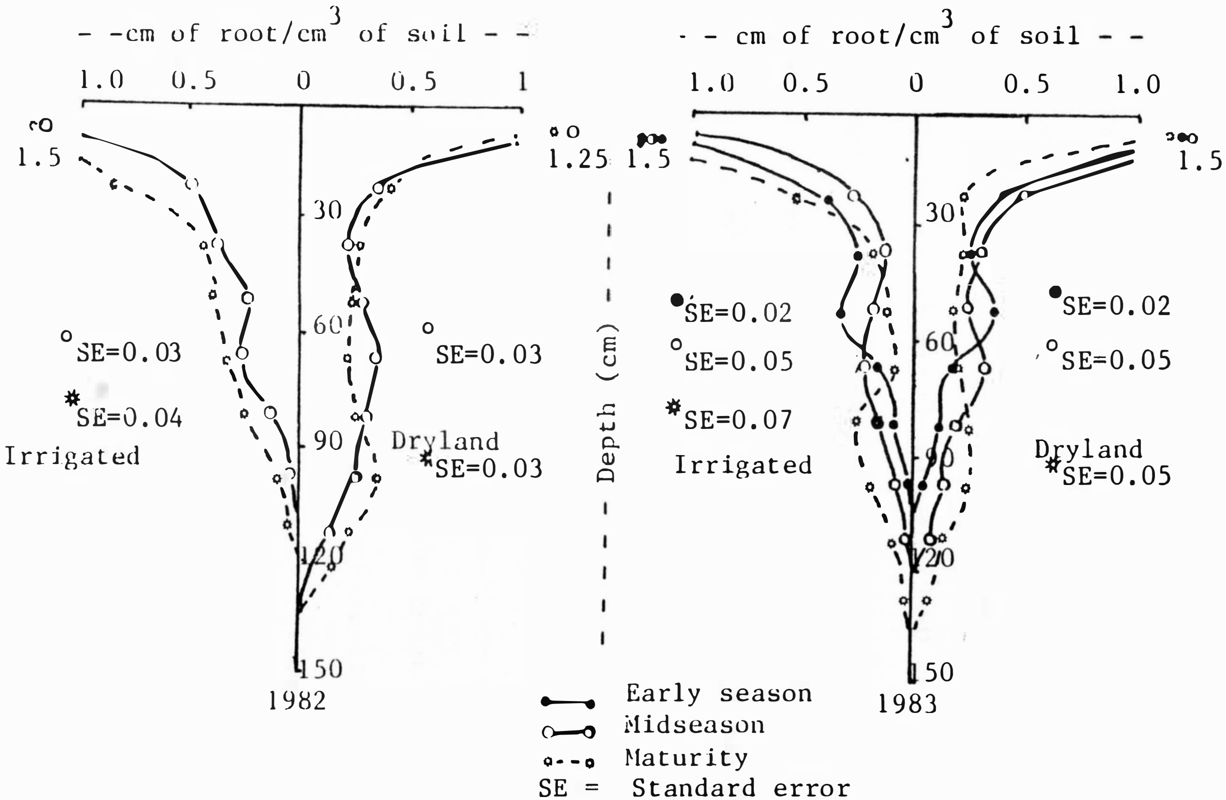

Figure 8. Root density profile in Lowry silt loam in 1982 and 1983

The first bulge in the other two soil types appeared at the same depth as in Vienna, except during the early stage of growth in the 1983 growing season. During the 1982 season, the sampling in Great Bend was done very early (31 days after planting) and the bulge was not observed. However the remnants of it were noticed at 45-60 cm. during the midseason sampling. Root samples were not taken for the early growth stage in Lowry in 1982.

The rooting bulge shifted downward with time. In the dryland treatment, it was observed between 75-90 cm during midseason in the Great Bend, but was spread over the 60-80 cm interval during both years in Lowry. This trend continued until maturity with the bulge reaching the 90-110 cm depth. In Great Bend the bulge was observed between 90-105 cm at maturity.

The rooting bulge in the irrigated treatment followed a similar trend but was less distinct and appeared at a shallower depth. At midseason it was at 45-60 cm and 60-75 cm respectively in Great Bend and Lowry, in 1982. At maturity the bulge was not apparent. As the irrigation treatments were made ineffective by rain in 1983 the irrigated plot root density very closely followed that of the dryland treatment.

Reicosky (1972) and Sivakumar (1977) reported the first appearance of a root density bulge approximately 60 days after planting at the 50-70 cm depth. Sivakumar (1977) and Jung (1980) reported that the bulge shifted downward with time to a maximum depth of 150 cm. The present investigation confirms the appearance, depth and shifting of the root density bulges.

The root length density in a profile layer generally increased with time until midseason. Root filling till midseason was mostly confined to the top 75 cm in Vienna and to 90 cm in the other two soil types. Approaching maturity root filling was mostly below these depths. These observations agree with those of Mitchell (1971), Willatt and Taylor (1978) and Jung (1980).

Root degeneration with approaching maturity appears to be a common feature under dryland conditions, especially in the top 75 to 80 cm. However, root densities were maintained above 0.2 cm/cm^3 at maturity; adequate for water uptake. Willatt and Taylor (1978) and Jung (1980) have observed similar features in their investigations.

4. Root Length and Root Growth Rate

Total root length under a unit surface area (L_A) was calculated by the procedure given under materials and method. The changes in total root length with time is shown in figure 9. Root length increased with time from early to midseason in all soils, during both years, except for the anomally of dryland in Vienna in 1982. This might have been due to an earlier root degeneration. With approaching maturity, root length usually continued to increase with time in the irrigated treatments in 1982. However, a decrease was observed under dryland conditions in Lowry both years and Great Bend in 1982. The decreasing trend for dryland soybean roots may be due to root degeneration in the top or middle layers of the profile. As the irrigation treatment effect was marginal or ineffective in 1983, except under the

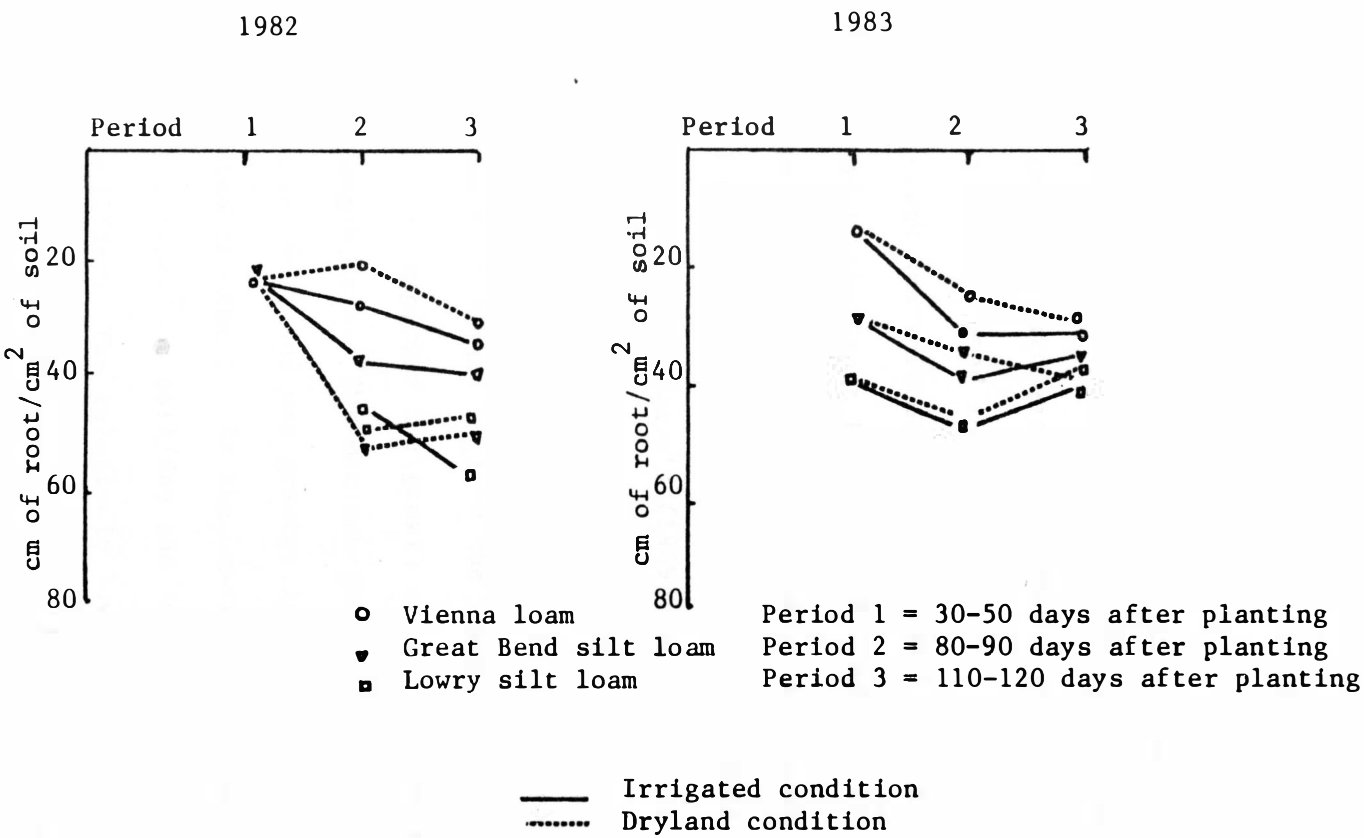

Figure 9. Root length under unit surface area (cm of root/cm^2 of soil) in the three soils, during the three periods in the growing season in 1982 and 1983.

rain-out shelter in Vienna, the differences in root length between treatments were marginal.

Root lengths under a unit surface area of 1 cm^2 during midseason, in the dryland treatments in 1982 for Great Bend and Lowry were 55 and 47 cm of root/cm^2 of soil respectively. The corresponding root lengths in the irrigated treatments were 37 and 44 cm of root/cm^2 of soil. During the 1983 growing season the root length at midseason was 35 to 45 cm/cm^2 regardless of the soil type and treatment. When the soil water was depleted in the upper layers in the dryland condition root growth was shifted downward. Thus the greater root length observed in the Great Bend dryland treatment during midseason in 1982 is due to deeper rooting compared to shallower rooting in the irrigated treatments. The root lengths calculated in the present investigation agree with Newman's (1969) data of 52 to 500 cm of root/cm^2 of soil reported for eight species.

Root growth rate (cm of root/cm^2 of soil/day) was calculated by dividing the root length (L_A) by the number of days in the observation period. As expected the growth rates followed a similar trend as the root length data. The maximum growth rate was observed during the midseason in 1982, and was greater in the dryland condition than in the irrigated treatment. In the Lowry soil the maximum growth rate was 0.6 cm of root/cm^2 of soil/day and in Great Bend it was 0.7 cm of root/cm^2 of soil/day. The relatively lower growth rate (0.4 cm of root/cm^2 of soil/day) in Vienna might be due to root degeneration. The accelerated growth rate during midseason suggests increased plant demand for water, and the higher values in the dryland treatment suggest greater soil volume exploration.

C. Water Uptake

1. Uptake Zones

The changes in volumetric soil water content (cm^3 of water/cm^3 of soil) with depth in time are shown in figures 10, 11 and 12. The area between curves (1) and (2) represent the uptake early in the season. The depth to which about 90% of water uptake took place is equal to the maximum rooting depth observed for that period. A similar trend was observed thoroughout the growing season.

The zone of the greatest water uptake during a period was observed in the region of the rooting bulge for that period. Thus an "uptake bulge" tended to overlap the rooting bulge. The shifting "uptake bulge" with time, corresponding with the rooting bulge, supports the hypothesis that water uptake from a profile layer could be increased by an increase in root density in that layer. However, when there was adequate water available in the upper layers through rain or irrigation, the zone of maximum uptake was shifted upward (Figures 10, 11, & 12).

The results support the work of others. Gardner (1964) reported that the water uptake pattern was most sensitive to relative root distribution. Reicosky (1972) noticed a maximum uptake early in the season in the top layers which progressively shifted downward with time. Willatt and Taylor (1978) showed that the depth of water extraction by the roots increased with increasing rooting depth. Thus, under dryland conditions, deep rooted crops can absorb more water than shallow rooted ones.

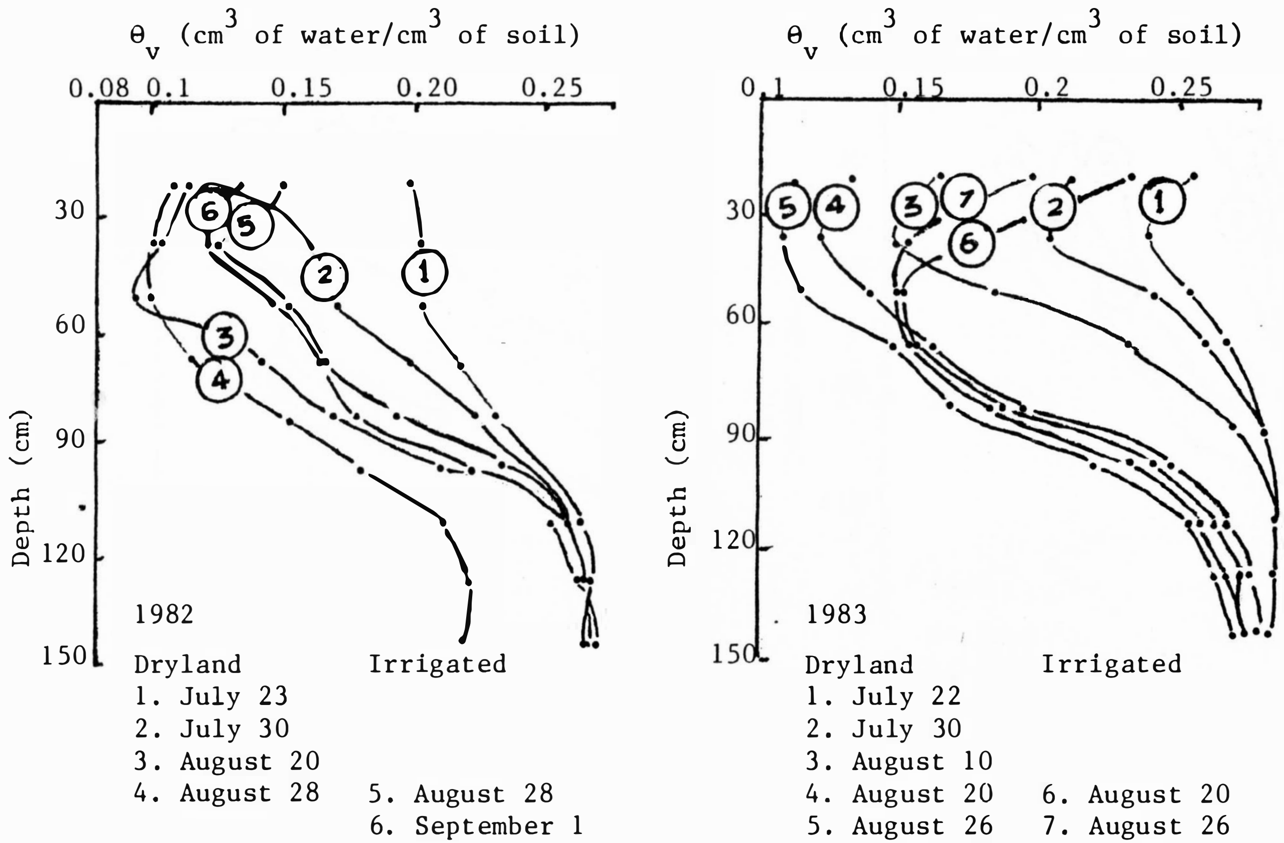

Figure 10. Soil water content (cm^3 of water/cm^3 of soil) in the Vienna loam profile in 1982 and 1983.

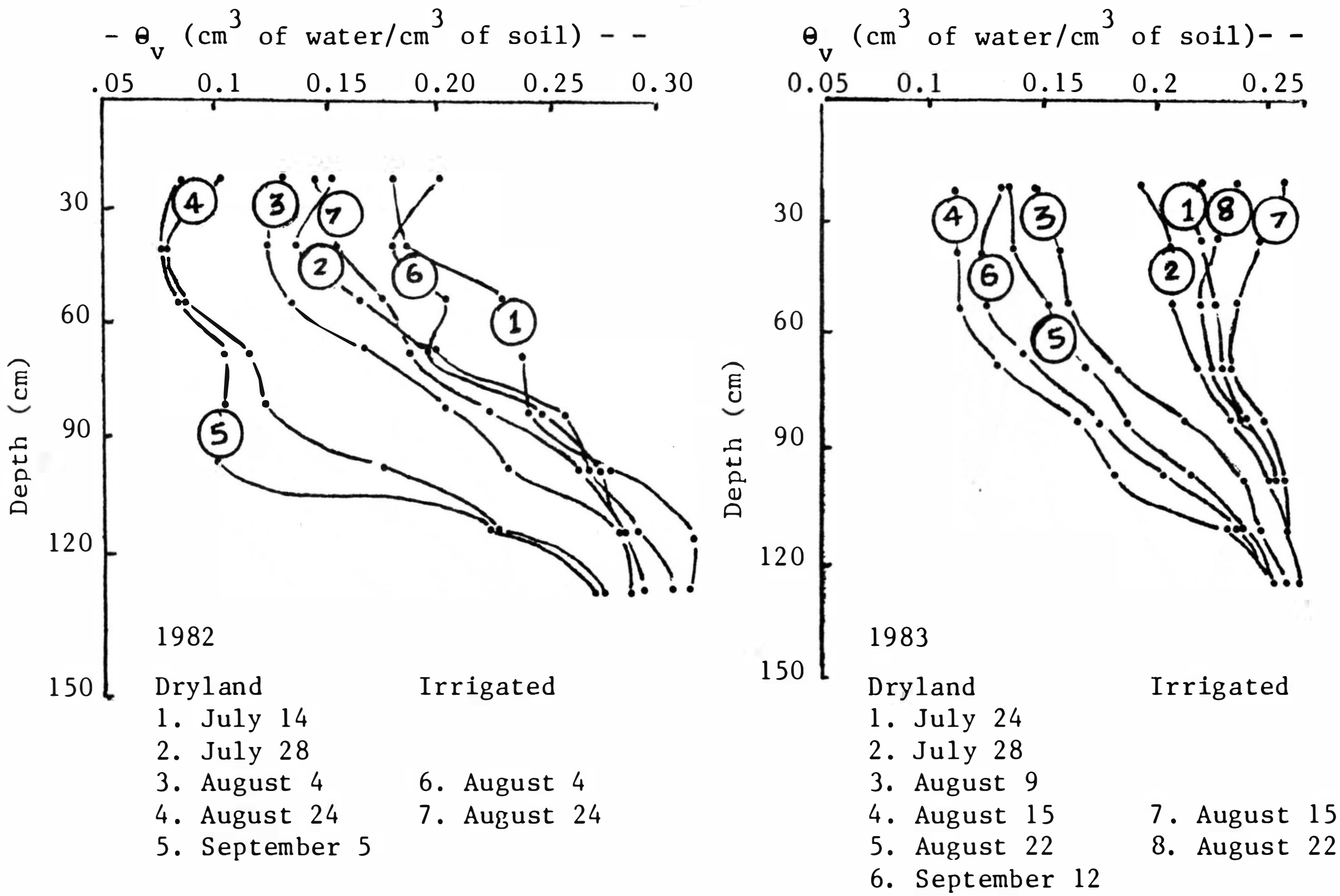

Figure 11. Soil water content (cm^3 of water/cm^3 of soil) in the Great Bend silt loam profile in 1982 and 1983.

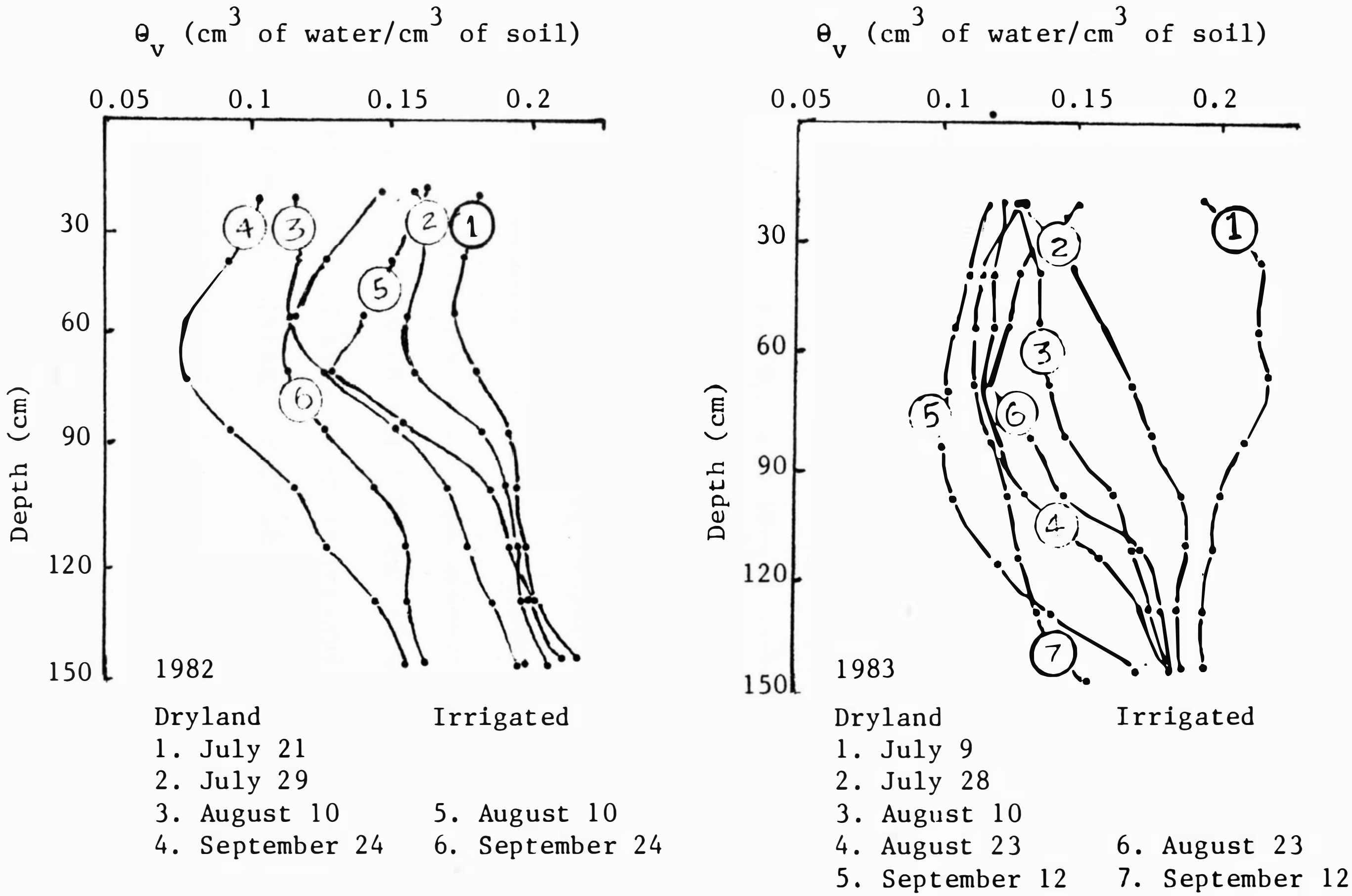

Figure 12. Soil water content (cm^3 of water/cm^3 of soil) in the Lowry silt loam profile in 1982 and 1983.

Though the water uptake pattern in general follows the rooting profile, there was a trend toward water uptake from the layer below the last one in which any roots were found (Figures 10, 11, & 12). This lends support to the observation made by Allmaras et. al (1975) that the determination of the water sink alone cannot predict rooting depth.

2. Age and Uptake

Under comparable climatic conditions but in different soil types, water uptake is largely determined by available water capacity (θ_v), matric potential (Ψ_m) and hydraulic conductivity. In the absence of data for the last soil water property mentioned, the significance of the first two will be taken up for discussion.

The data on water content in the soil profiles under different matric potentials is given in tables 5, 6 and 7. Mean available water contents from field measurements in Vienna, Great Bend and Lowry were 0.15, 0.18 and 0.10 cm^3 of water/cm^3 of soil respectively. About 50% of this water is generally believed to be easily available for root uptake. Most of this water (50%) is held between -0.3 and -3 bars matric potential in the three soil types. Thus the Lowry soil has the lowest water supply capacity.

The data on water uptake rates for selected periods during the growing season in 1982 and 1983 for both dryland and irrigated treatments is given in table 8. The recharge through capillary rise might have masked the total uptake in Vienna. The presence of a perched water table at 120 cm until early August in 1983 and the

Soil water content (θ_v) at different matric potentials Ψ_m (bars).

Table 5: Vienna loam

Depth (cm)	Matric potentials (bars) -0.1	-.3	-0.6	-1	-3	-6	-15
0-15	0.312	0.280	0.255	0.242	0.217	0.206	0.191
15-30	0.285	0.267	0.247	0.226	0.213	0.200	0.200
30-45	0.297	0.260	0.228	0.227	0.206	0.203	0.183
60-75	0.274	0.254	0.237	0.220	0.197	0.183	0.166

Soil water content (θ_v) at different matric potentials Ψ_m (bars).

Table 6: Great Bend silt loan

Depth (cm)	Matric potentials (bars) -0.1	-0.3	-0.5	-1	-3	-6	-15
0-15	0.332	0.292	0.260	0.249	0.199	0.108	0.089
15-30	0.343	0.305	0.270	0.260	0.174	0.128	0.098
30-45	0.315	0.287	0.267	0.256	0.182	0.146	0.130
45-60	0.334	0.303	0.287	0.267	0.180	0.142	0.132
60-75	0.322	0.286	0.256	0.230	0.182	0.141	0.120
75-90	0.346	0.340	0.300	0.277	0.189	0.140	0.126
90-105	0.360	0.350	0.292	0.270	0.211	0.146	0.142
105-120	0.380	0.360	0.300	0.282	0.250	0.178	0.168

Soil water content (θ_v) at different matric potentials ψ_m (bars).

Table 7: Lowry silt loam

Depth (cm)	Matric potentials (bars)						
	-0.1	-0.3	-0.5	-1	-3	-6	-15
0-15	0.241	0.209	0.190	0.179	0.165	0.146	0.124
15-30	0.214	0.194	0.172	0.159	0.144	0.131	0.118
30-45	0.200	0.185	0.176	0.152	0.152	0.132	0.127
45-60	0.218	0.195	0.182	0.154	0.134	0.121	0.106
60-75	0.239	0.200	0.198	0.164	0.136	0.103	0.100
75-90	0.250	0.221	0.177	0.160	0.154	0.116	0.113
90-105	0.253	0.234	0.196	0.178	0.166	0.143	0.136
105-120	0.257	0.234	0.197	0.175	0.164	0.148	0.146

Table 8: Water uptake rates (mm/d) during the season

	Vienna				Great Bend				Lowry			
	1982		1983		1982		1983		1982		1983	
	I	D	I	D	I	D	I	D	I	D	I	D
E	5.1	5.1	5.2	5.2	5.6	5.6	6.7	6.7	5.5	5.5	5.6	5.6
M	5.3	4.4	4.0	4.0	6.0	3.0	7.2	6.7	5.5	4.4	6.0	6.0
My	4.2	4.6	-	-	3.7	3.8	3.3	3.3	2.5	3.2	4.2	4.2

E - Early in the season

M - Midseason

My - Maturity

I - Irrigated

D - Dryland

existance of finer pores because of high bulk densities lend support to a capillary rise. The maximum uptake rates observed during mid-August in 1983 were 5.3, 7.2 and 6.0 mm/day respectively for Vienna, Great Bend and Lowry. The higher uptake rate from the Great Bend compared to Lowry might be due to its' greater available water capacity. Further the Great Bend profile was recharged during this period by rain, 4 cm, and irrigation 8 cm compared to 4.5 cm irrigation and 7 cm rain, which was received during the later part of the period, in Lowry (Figures 4 & 5).

The uptake rates during midseason were higher in the irrigated treatments than in the dryland in 1982. Also the uptake rates during midseason both in Great Bend and Lowry were greater during the 1983 growing season than in 1982. This is probably due to withdrawal of more water from the upper portion of the profile which was recharged by irrigation and rainfall (figures 4 & 5). This shows that the amount of water available in the profile influences the uptake. This is supported by the work of Willatt and Taylor (1978).

The potential evapotranspiration (Penman method) and the estimated evapotranspiration (Blaney-Criddle method) values are given in table 9 for the 1983 growing season.

The estimated values are approximately equal to the uptake rates reported for the corresponding periods.

Uptake rates reported here generally agree with those of Mason et. al. (1980). Their rates were 4.8, 7.1 and 3.8 mm/day respectively for 51-58, 77-80 and 91-97 days after planting. Their evapotranspiration rates for the corresponding periods were 4.6, 5.2 and 4.4

Table 9: Potential and estimated evapotranspiration during the 1983 growing season in Vienna loam and Great Bend silt loam.*

	Vienna		Great Bend	
	Late July	Mid-August	Late July	Mid-August
Potential evapotranspiration (mm/day)	5.3	6.0	6.5	7.5
Estimated evapotranspiration (mm/day)	5.0	5.8	7.0	7.2

*Weather Services: Agricultural Engineering Department, SDSU.
The data were not available for Lowry soil.

mm/day. Thus, it appears that the uptake in the dryland during the midseason in 1982 was low both in Great Bend and Lowry compared to 1983.

The data on water uptake from the profile layers exclusive of the 0 to 15 cm layer for two periods in 1982 is given in table 10. The uptake rate during late July in Vienna was 3.6 mm/day compared to 2 mm/day each in Great Bend and Lowry. The recharge of the top layer by rainfall during this period in Great Bend and Lowry might have shifted the major portion of the uptake to be withdrawn from the top layer. This is supported by the work of Kohl and Kolar (1976).

The contribution to the total water uptake from the 60 to 150 cm portion of the profile was 19-32% in late July, increasing to 65-83% by mid-August. The increased contribution from the lower layers continued until maturity. This is supported by the work of Reicosky (1972), and Allmaras et. al (1975). Increased uptake from the lower section of the profile as the supply in the top portion becomes less emphasized the importance of deep rooting.

3. Uptake Rates in the Profile Layers

The changes in water uptake rates in the profile layers as a function of depth and time in 1982 are given in figure 13. The uptake curves followed the same trend as the root density curves. Early in the season the uptake was higher in the upper portion of the profile. By midseason it shifted downward. The decrease in uptake rates with a decrease in soil water content in time observed in the present

Table 10: Water uptake (mm) during two selected periods in dryland (1982) for the three soils.

Depth (cm)	Vienna July 23-30	Vienna Aug. 6-9	Great Bend July 21-28	Great Bend Aug. 4-24	Lowry July 21-29	Lowry Aug. 10-24
	mm					
15-30	9.3	0.3	4.4	6.6	4.2	3.8
30-45	6.9	0.8	4.5	7.2	2.9	5.3
45-60	4.5	1.1	0.6	6.9	2.7	7.1
60-75	3.0	2.7	1.1	8.7	3.3	8.7
75-90	1.8	2.4	1.1	11.5	0.2	9.8
90-105	-	4.0	1.2	8.6	0.5	8.4
105-120	-	0.9	-	8.1	0.6	7.5
120-135	-	0.9	-	0.5	-	5.9
135-150	-	-	-	-	-	6.0
TOTAL(mm)	25.5	13.1	12.9	58.1	14.4	62.5
Y%	19	83	26	64	31	74

Y% = Percent contribution towards the total from the 60-150 cm. region of the profile.

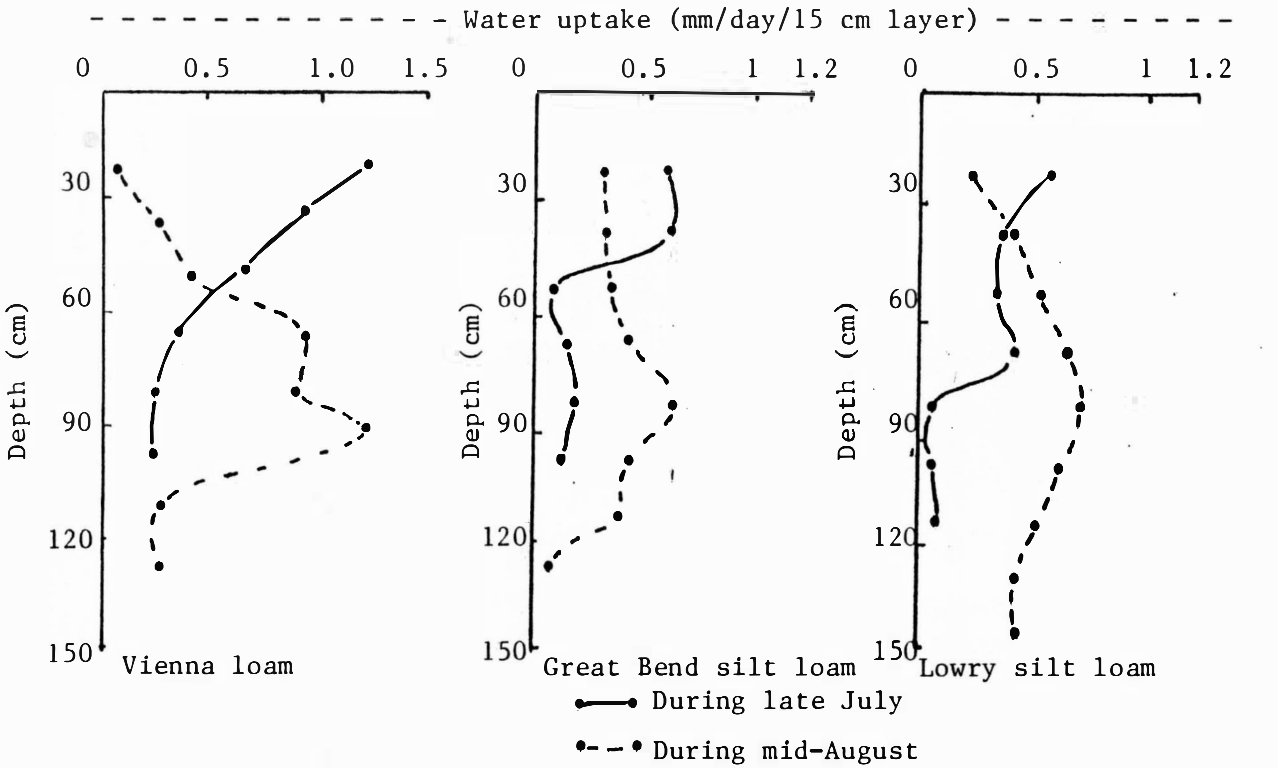

Figure 13. Water uptake rates from the profile layers (mm/day/15 cm layer) in 1982.

investigation is supported by the work of others (Willatt and Taylor 1978 and Mason et. al 1980). The uptake rates reached a high of 1.2, 0.64 and 0.70 mm/day/15 cm layer respectively in Vienna, Great Bend and Lowry. The relatively higher rate of uptake in Vienna might be due to the availability of more soil water.

The zone of maximum uptake in Vienna did not exactly correspond to the zone of the rooting bulge. Instead, the zone of the maximum uptake was shifted downward by about 25 cm. This might be due to the availability of more water in that region through capillarity. However, according to Jung (1980) the minimum root density required for significant uptake from a profile layer is 0.1 cm of root/cm^3 of soil. The observed root density in the zone of maximum uptake was 0.02 cm of root/cm^3 of soil. It appears that the root density is inadequate for such a high uptake rate. However, Bennett et. al (1979) reported that 3% of the root system in contact with a nutrient solution supplied all the water the plant needed. Thus the high uptake rates observed in the present investigation with only about 2% of the total root system in a capillary fringe might be possible. *Kohl found that 2% of the root system of corn plants in contact with the capillary fringe supplied sufficient water to obtain maximum yield while the remainder of the rooting profile did not reduce water contents much below field capacity.

*Unpublished data.

4. Uptake Per Unit Root Length

Uptake per unit root length was calculated by dividing the volumetric uptake (cm^3 of water/cm^3 of soil) from a profile layer by the corresponding root density. The results are given in Table 11. The uptake per unit root length increased with depth in time and the maximum rate was 0.2 cm^3 of water/cm of root/day in Vienna loam. These values are close to those of Reicosky (1972) and Allmaras et. al (1975). However, Reicosky reported a maximum uptake rate of 0.67 cm^3 of water/cm of root/day compared to Allmaras' of 0.2 cm^3 of water/cm of root/day. The high value of 0.67 cm^3 of water/cm of soil/day was observed at the depth of 70-80 cm with a water table just below 100 cm.

The mean values of uptake were around 0.03 cm^3 of water/cm of root/day. The lower value observed in Great Bend during the second period might be due to the longer length of the observation period; otherwise the modal values are supported by the work of Allmaras et. al (1975).

The increased rates of absorbtion per unit root length in the lower sections of the profile suggests that the roots absorb more water when the water is readily available. The major cause for decreased uptake in the upper portion of the profile with decreasing water content is more likely related to transmission characteristics of both soil and roots, than to root suberization. The return to normal uptake rates (Figures 10, 11, & 12) after rain or irrigation also suggests that aging is not a factor that interferes with uptake.

Table 11: Water uptake rates per unit root length.

Depth (cm)	Vienna July 22-30	Vienna August 6-9	Great Bend July 21-28	Great Bend August 4-24	Lowry August 4-24
	cm^3 of water/cm of root/day				
15-30	0.022	0.004	0.012	0.005	0.005
30-45	0.027	0.012	0.015	0.006	0.010
45-60	0.029	0.009	0.060	0.005	0.013
60-75	0.039	0.030	0.025	0.010	0.012
75-90	-	0.089	0.050	0.010	0.015
90-105	-	0.150	-	0.016	0.013
105-120	-	0.200	-	0.043	0.030
120-135					0.142
Mean	0.030	0.070	0.032	0.014	0.030

D. Grain Yield

The data on grain yield as related to water use (sum of the irrigation water applied, profile storage and rainfall) during the growing seasons is given in figures 14, 15 and 16. The total rainfall received during the 1982 growing season was 280, 207 and 143 mm respectively in Vienna, Great Bend and Lowry soil. And that received during the 1983 growing season was 335, 265 and 200 mm respectively on the three soils. The total profile depletion was 120-135, 160-170 and 220-230 mm respectively in Vienna, Great Bend and Lowry soil for both years. The bean yields varied from site to site and year to year. Yield is, however, the final result of not only water and nutrient supply but also insect and disease damage, atmospheric stress and field management. The impact of most of these factors is not known, especially quantitatively.

The 1983 yields on Lowry silt loam were reduced by grasshopper damage. The plot area was small and located on government program set-aside land (fallowed) adjoining a large field of brome-grass. When the bromegrass was cut for hay grasshoppers moved into the soybean plots. Repeated spraying would destroy the resident population until a new group moved into the plot area. Good insect control was not achieved; large holes appeared in the leaves and many pods were partially or entirely eaten. The extent of this damage was not quantified. The wooly bear caterpillar damage and the loss because of some unshelled pods passing through the combine harvestor from the plots in Vienna also were not quantified. However, some general conclusions can be drawn from the yield data.

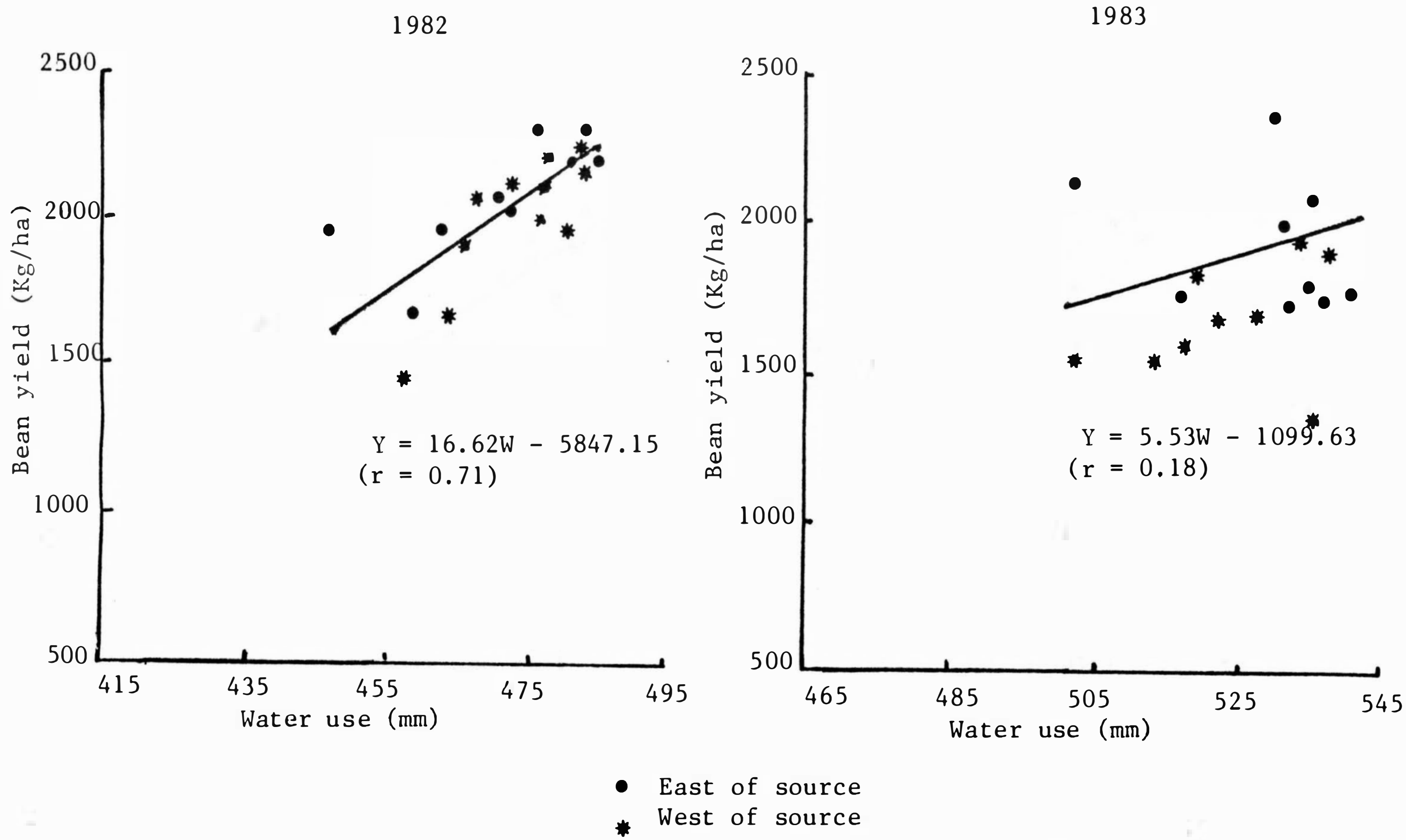

Figure 14. Bean yield versus water use in Vienna loam for 1982 and 1983

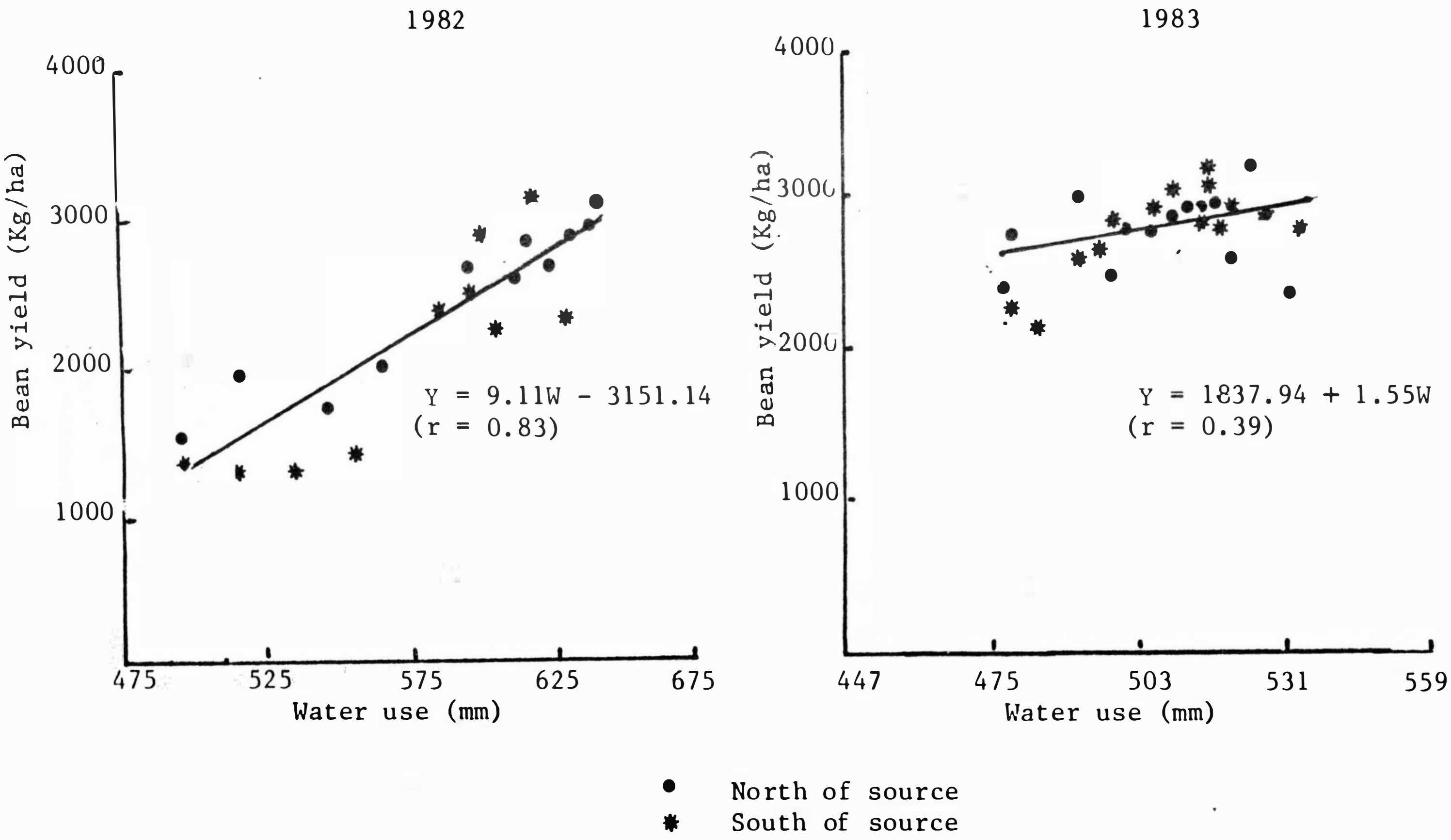

Figure 15. Bean yield versus water use in Great Bend loam for 1982 and 1983.

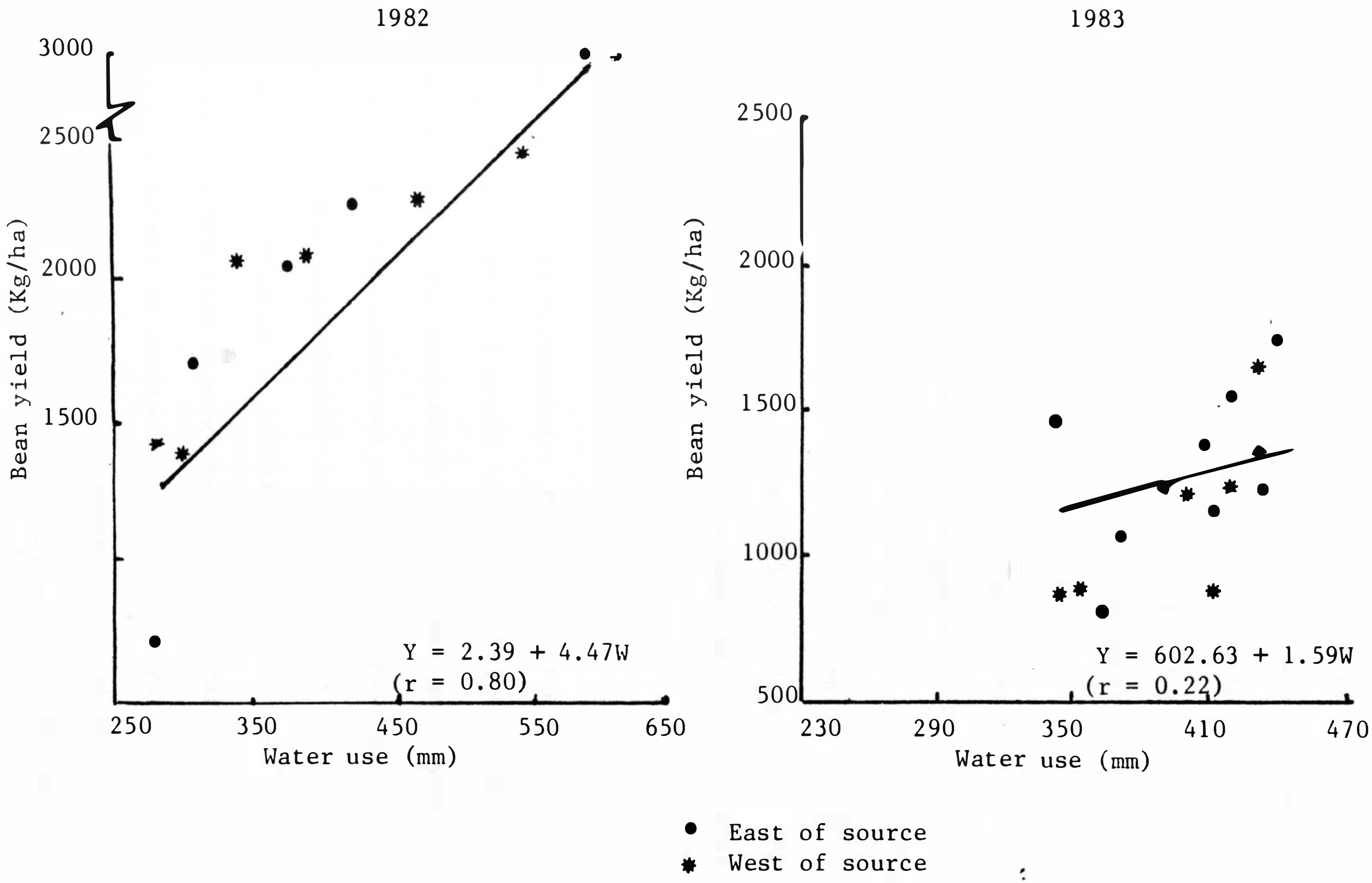

Figure 16. Bean yield versus water use in Lowry loam for 1982 and 1983.

The data points of the figures for 1982 (figures 14, 15 and 16) tend to show an increase in yield with water use. However, a clustering of most of the yield data points was observed in the region of maximum yields. The increase in trend of bean yield with water use is supported by the work of Doss et. al (1974). They reported that soybean yield was linearly related to the water received during pod fill.

The clustering of points in Vienna was observed between 465 to 485 mm and 515 to 535 mm of water use in 1982 and 1983 respectively. However, the supplementary irrigation supplied to reach these ranges was 40 mm in both years. The clustering of points in Great Bend was observed between 600 to 625 mm and 515 to 530 mm water use in 1982 and 1983 respectively. During the relatively dry 1982 growing season 225 mm of irrigation water was used to supplement the rainfall compared to 50 mm in 1983. The relatively high irrigation use in 1982 was partially due to over irrigation. For example the 145 mm single irrigation given on August 13 could have been reduced to one-half of the amount applied. The clustering in Lowry was more apparent in 1983 than in 1982. The clustering was observed between 390 to 420 mm of water use. The supplementary irrigation given to reach this range was 100 mm. The influence of irrigation water use, 300 mm, covering a long period, mid July through maturity, on grain yield is well shown by the spread-out of points in 1982 for Lowry.

From the foregoing it appears that, during the 1983 growing season the soybeans either received almost all the water they needed from rainfall and profile storage or were not strongly affected by defficiencies in water supply. However, during the 1982 growing season, with limited rainfall from late July through August, the uptake from the Great Bend and Lowry rooting profiles under dryland conditions appears to be inadequate to meet the environmental demand. Ritchie et. al (1972) and van Bavel (1967) showed that evapotranspiration remained at potential until almost 80% of the available soil water in the root zone had been withdrawn. The crop evapotranspiration then dropped linearly with decreasing available water. The corresponding yield data were not available though yield could be affected before evapotranspiration was reduced. However, Ritchie et. al (1972) stated that this threshold value varies with crop, season and soil type. In the present investigation about 65% of the available water was depleted by late August. Thus, it might be possible that the evapotranspiration rate might have been reduced under dryland.

Hanks et. al's (1976) published data on corn demonstrated a linear increase in yield with crop water use. Taken together with the data of Ritchie et. al (1972) one would expect a yield increase with an increase in water use from the profile. If the curve then flattens into a horizontal mode the maximum yield for water use would have been attained and any extra "water use" may result from drainage losses or measurement errors. The clustering of points toward the top of the figures tend to illustrate the above.

A SAS linear regression program was used to explore the relationship between bean yield (Y) and the amount of water used (W).

ie. $Y = f\ (W)$

The following equations were obtained from the program.

Soil	Year	Equation	r
Vienna	1982	$Y = 16.62W - 5847.15$	0.71
Vienna	1983	$Y = 5.53W - 1099.63$	0.18
Great Bend	1982	$Y = 9.11W - 3151.14$	0.83
Great Bend	1983	$Y = 1837.94 + 1.55W$	0.39
Lowry loam	1982	$Y = 2.39 + 4.47W$	0.80
Lowry loam	1983	$Y = 602.63 + 1.59W$	0.22

The slope of the equation tends to be small indicting that an addition of an increment of water applied produced only a small increase in yield. This was especially true for 1983 when rains provided most of the water necessary for growth and little irrigation water was needed. A much better correlation (0.71 to 0.83) was obtained for the dry year of 1982. In that year larger amounts of irrigation water were required to satisfy plant requirements resulting in a better gradient of well irrigated to dry plots.

SUMMARY:

Field experiments on the rooting density and water uptake of soybeans were carried out on three soils, separated by about 200 miles in eastern South Dakota, during the 1982 and 1983 growing seasons. The maximum rooting depth was observed under dryland conditions and was 135 cm each in Great Bend and Lowry silt loam soils and 120 cm in Vienna loam. High bulk densities (1.74 to 1.78 g/cm^3) and reduced soil aeration (less than 9%) in the lower sections of the Vienna profile are suspected causes in preventing root penetration below 120 cm. However, no conclusions were offered for root penetration being limited to 135 cm in the other two soil types.

Generally, vertical root penetration was continuous thoroughout the growing season in the dryland plots. However, the extension rates in general increased with age through early pod set and decreased during maturation. The root extension rates were greater for dryland treatments during the dry year, 1982, compared to the wet year, 1983, and compared to the irrigated condition. The roots penetrated to the maximum rooting depths by midseason in the dry year compared to at maturity in the wet year, indicating that the age of the plant did not interfere with root penetration.

The root density bulges observed in the rooting profile suggest that root distribution did not decrease monotonously with depth. The appearance of rooting bulges in the profile indicates increased root activity in those regions. The shifting of these

bulges downward with time suggest that the zone of maximum water uptake was also shifted down with time.

The root densities in the profile layers increased with time through podfill. Root degeneration with approaching maturity appears to be a common feature under dryland conditions, especially in the top 75 to 80 cm, but the root density in this region was maintained above 0.2 cm of root/cm^3 soil to maturity. Greater root length, 55 cm of root/cm^2 of soil, under a unit surface area in dryland field compared to 37 cm of root/cm^2 of soil in irrigated treatments indicates a larger soil volume exploration under dryland condition.

The depth of water extraction increased with time and rooting depth. The general trend for uptake from the layers below the last one in which roots were found suggests an upward capillary flux at the base of the root zone.

The uptake rate, 0.3 to 0.45 cm of water/day from the dryland profile in 1982 August appears to be inadequate to meet the environmental demand.

The uptake rates from the profile layers decreased with a decrease in soil water content. However, equally large uptake rates were observed at various depths in the profile during the growing season when water contents at those depths were ample.

The contribution towards the total uptake from the lower section of the profile increased with time from 20-30% in late July to 65-80% by mid-August under the dryland condition. Though the contribution towards the total uptake from the lower section of the profile increased with time, the amount taken to produce optimum grain yields in a dry year like 1982 appears to be insufficient. This means that the rooting profile observed (135cm) was not deep enough to supply adequate amounts of water.

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APPENDIX A

A SAS multiple regression program was used to explore the possible relationships between rooting depth (Rd) and

1. Bulk density (ρ_b)
2. Aeration porosity (Ea)
3. Total available water content in the rooting profile (T)
4. Days after planting (A)
5. Amount of water received (W)

i.e. $Rd = f(\rho_b, Ea, T, A \& W)$.

The following equations were obtained from the program.

Soil	Year	Equation	r
Vienna	1982	$Rd = 4.22A - (37.06 + 0.027A^2)$	1.0
Vienna	1983	$Rd = 1.054A + 7.74 - 0.0005A^2$	1.0
Great Bend	1982	$Rd = 0.023A + 163.95 - (4.29T + 0.025W)$	0.95
Great Bend	1983	$RD = 4.19A - (130 + 0.016A^2)$	1.0
Lowry loam	1982	$Rd = 570.59 + 0.094W - (51.16T + 0.0064A)$	1.0
Lowry loam	1983	$Rd = 93.46 - 0.0774A + 0.0041A^2$	1.0

It appears that rooting depth is a strong function of days after planting during the wet year. However, in the dry year it is a function of days after planting, total water content in the profile, and the amount of water received.

The high correlation coefficients are expected with only three sampling times in the year.