DRY-MATTER PRODUCTION AND WATER EXTRACTION PATTERN OF *Opuntia ellisiana*

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Introduction

The prickly pears (Family Cactaceae, genus *Opuntia*) have received increasing attention from researchers, farmers, ranchers, and governments due to their unique water relations and many uses for humans (Russell and Felker, 1987).

In the semiarid and arid areas, among all environmental factors, water is the most limiting factor for crop and forage production. One of many uses of prickly pears is that during drought periods they are used as an emergency food for livestock or wildlife in Texas and other regions throughout the world (Russell and Felker, 1987; Hanmante, 1922). When prickly pears are used as forage, their dry-matter production (DMP) is of great concern. Dry-matter production of a plant community is determined by the kind of plant species the plant community comprises, the environmental conditions (water, temperature, and light), and the stages of the plant community (Larcher, 1975). Russell and Felker (1987) reported that dry-matter production of *Opuntia* spp. varied considerably over different regions and ranged from 6,600 kg/ha/year to 52,000 kg/ha/year. Nobel (1992) found that when irrigated and fertilized well, *Opuntia amyclea* and *O. ficus-indica* in Saltillo, Coahuila, Mexico, had an average productivity of 46,000 kg dry matter/ha/year. One objective of this study was to examine the dry matter productivity of *Opuntia ellisiana* in south Texas and the variation in dry-matter production from year to year for use in ranch and farm management.

Almost all water used by plants is absorbed by plant roots from the soil (Kramer, 1979). In the semiarid and arid areas, rainfall is low and erratic. Under rainfed conditions, soil acts as a reservoir and plays an important role in supplying water for plants during drought periods. However, this function also depends on the characteristics of plant root systems. Cable found that Velvet mesquite (*Prosopis* spp.) used water consistently to a depth of 3 m and outward 10 m beyond the crowns. According to our investigation, soil water contents in the 0 to 137.5 cm soil profile where Bermudagrass grew densely, were consistently about 2% to 4% lower than in locations without Bermudagrass and Johnsongrass. Most *Opuntia* spp. have a shallow root system (Nobel, 1988); therefore, their water-extraction pattern should be different from those of plants having a deep root system. Another objective of this study is to examine the water-extraction pattern of *Opuntia ellisiana*.

Materials and Methods

Site Description

The study site was on the northwestern part of the Texas A&M University campus at Kingsville, Texas.

Two soil series, Hidalgo series and Palobia series, were inventoried in the Kingsville area (USDA, 1975). The Hidalgo is most extensively distributed. This series is taxonomically identified as a member of the fine loamy, mixed, hyperthermic family of Typic Calciusfolls (USDA, 1978). These soils lack a fluctuating ground water table in their deep layers. They are well-drained, have slow runoff, and are moderately permeable. They have high inherent fertility and high production potentials.

The climate of the Kingsville area is semiarid and subtropical. The average annual temperature is 22.9°C with January the coldest month at the mean temperature of 14.2°C and August the warmest month at 30.2°C [National Oceanic and Atmospheric Administration (NOAA), 1991]. The mean annual precipitation is about 700 mm with 22.8% occurring during May and June and 29.8% during August and September. September is the month with the greatest amount of precipitation (NOAA, 1991). There is an average of 40 days per year when precipitation exceeds 2.5 mm.

Experimental Layout and Design

The experiment was designed to be conducted over a four-year period from 1991 to 1994. The experiment used a randomized complete-block design with 3 blocks and 4 treatments (harvest dates) per block (total of 12 plots). A control plot (bare plot), 3 m wide and 6 m long, was also constructed. The harvest dates were April 15, 1992 and 1993, and will be April 15, 1994 and 1995.

Opuntia ellisiana was planted using cladodes with a 1.5 m between-row spacing and a 1 m in-row spacing on April 1, 1991. Although this species is slower growing than other spineless species, such as *Opuntia ficus-indica*, it is the only spineless *Opuntia* species that survived the freeze in 1989 (-12°C) without any damage. Due to the necessity of working closely among the plants, it was desirable to use a spineless species.

Plots were separated from the field and from each other by dikes. As shown in Figure 1, the plots were numbered from 1 to 12 along the north-south direction. Each plot was 12 m long and 9 m wide. Thus, each plot had 6 rows and 12 plants in each row (Figure 2).

W
--↑--→ N

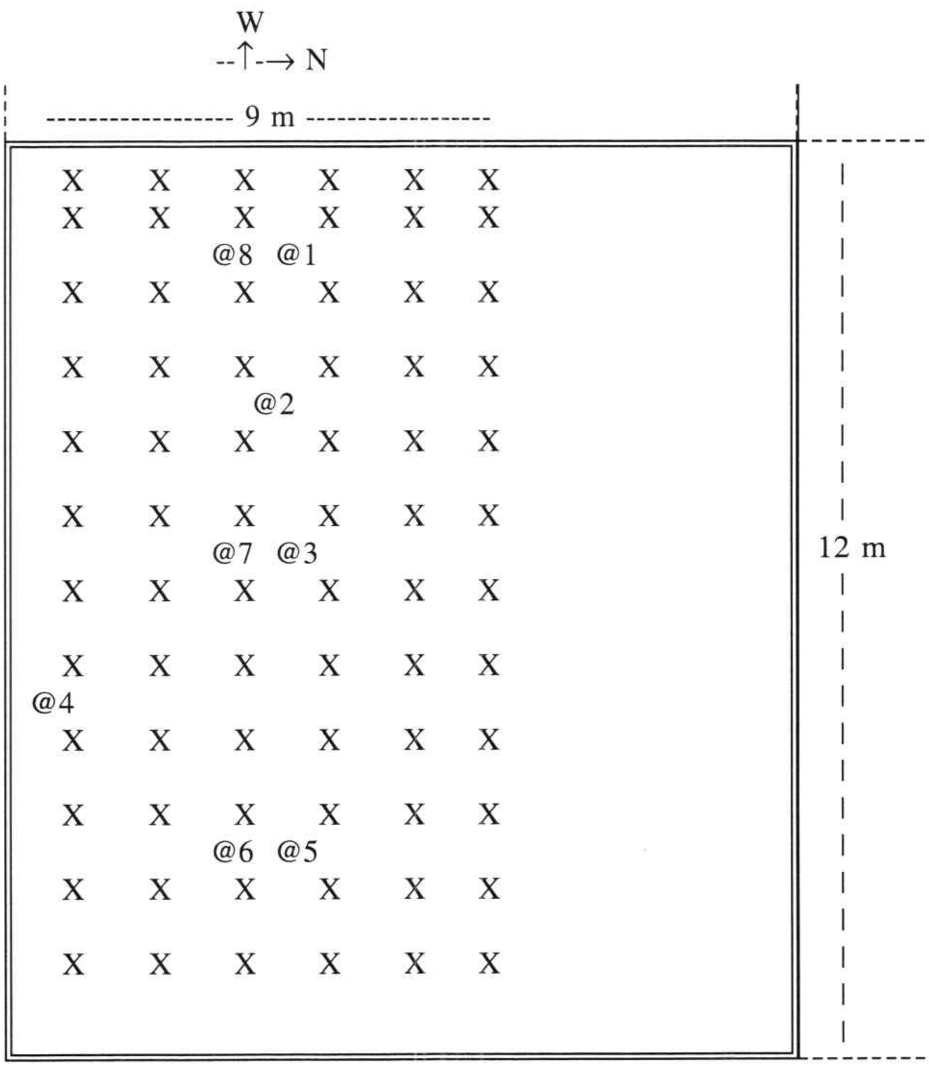
ROAD

B3	B3	B3	B3	B2		B2	B2	B2	B1	B1	B1	B1
12	11	10	9	8		7	6	5	4	3	2	1
Y2	Y4	Y1	Y3	Y3		Y1	Y4	Y2	Y4	Y3	Y2	Y1

Note: B: Block 1, 2, or 3
Y: Harvest at end of year 1, 2, 3, or 4

Figure 1. Site Layout

Plant dry-matter production is influenced by soil fertility. Therefore, 700 kg/ha of 13-13-13 fertilizer and 60 kg/ha of Peters micronutrient fertilizer were applied in all 12 plots to ensure that fertility was not a major factor influencing plant dry-matter production. The 13-13-13 fertilizer was applied March 19, 1991 and April 27, 1992. The micronutrient fertilizer, composed of 4.00% sulfur, 1.35% boron, 3.20% copper, 7.50% iron, 8.00% manganese, 0.04% molybdenum, and 4.50% zinc, was used on May 29, 1991.



Note: X = plants, @ = access tubes

Figure 2. Plot Size, Spacing, and Access-Tube Positions

Because unweeded cactus plots have 300% less biomass production in the first year of growth than weeded plots (Felker and Russell, 1987), herbicides were used for weed control. To control the troublesome perennial grasses, mainly Johnson grass (*Sorghum halepense*) and Bermudagrass (*Cynodon dactylon*), the herbicide Roundup (glyphosate N-(phosphonomethyl) glycine) was used at a concentration of 1.5%. For long-term preemergence weed control, the herbicide Spike (tebuthiuron N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N'-dimethylurea) was used at a rate of 2.5 kg/ha. The plots were virtually free of grasses and broadleaf weeds during the entire experimental period.

The fungicide BANROT (5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole and dimethyl 4,4'-O-phenylenebis), bacteriacide agri-strep (streptomycin sulfate), and insecticide ORTHENE [acephate (O,S-dimethyl acetylphosphoramidothioate)] were applied to prevent or control diseases and insects.

Measurements of Dry-Matter Production and Leaf-Area Index

The above-ground biomass production was measured by a complete above-ground harvest. While all plants in the plots were harvested, to avoid border-row influences on the biomass estimation, the data excluded the outer two rows on either side and the two plants on the end of each row. Thus, the entire weight of the 16 individual plants in the interior two rows was measured. Sample plants were placed in a drying room at 70°C until no further change in weight was observed in order to obtain the plant material moisture content as a percentage of the fresh weight. Using this moisture content, the fresh weight was converted into the dry weight.

Three plots were harvested at the end of each year. Figure 1 indicates the year in which the plots were harvested. The yearly dry-matter production is obtained by subtracting the dry-matter production (average over three plots) on one harvest date from that (average over three plots) in the subsequent harvest date. However, some error could be encurred due to the nonuniformity of soils and perhaps different microclimates among plots. To avoid these problems, the dry-matter production at plots that were not harvested at one specific harvest date were nondestructively estimated by regression techniques. To estimate the dry-matter production of the one-year-old plant community, a regression equation containing cladode fresh weight (FW) in grams and cladode maximum width (MW) in centimeters was developed by Han (1993):

$$FW = 0.58(MW)^{2.40}$$

To estimate the dry-matter production of the two-year-old plant community, a regression equation containing plant fresh weight (PFW) in kilograms and plant cladode number (PCN) was also developed by Han (1993):

$$PFW = -1.4662 + 0.4065(PCN)$$

Leaves (cladodes) are the assimilating area that determines photosynthesis and dry-matter production. A regression equation containing cladode area (Area) in square centimeters and cladode maximum width (MW) was established to nondestructively estimate the leaf-area index of the plant community at each harvest date. This equation, developed by Han (1993), is:

$$Area = -110.69 + 23.54(MW)$$

Measurement of Soil Water Content

To examine the plant water-extraction pattern, the soil water content must be measured without disturbing the soil profile. Among all methods used to measure soil water content, a Troxler 4300 neutron probe was chosen to measure volumetric soil water content. This probe was calibrated both in the field and in the laboratory by Han (1993).

In each of 12 plots, 5 access tubes were placed between two rows in the middle of the plots and 3 tubes were placed in the rows (Figure 2). This was done to assess differences in moisture use within and between rows.

Neutron probe readings were taken at 25 cm depth increments from 25 cm to 125 cm once a month. The measurements began on April 15, 1991 and will end on April 15, 1995. These readings were converted into volumetric soil water content through a calibration equation obtained by Han (1993). These data represented the average volumetric water content of a sphere of soil centered where the probe was located and having a diameter of 25 cm. Thus, for example, the data obtained at a depth of 125 cm represented the average volumetric water content of the soil profile from 112.5 to 137.5 cm.

These volumetric soil water-content data were used to examine the water extraction pattern of *Opuntia ellisiana*.

Results and Discussion

Dry-matter Production and Leaf Area Index

Dry-matter production was either directly determined by the harvest method or indirectly estimated by the regression method. Plots 1, 7, and 10 were harvested by the end of the first year. Dry-matter production at remaining plots for the first year was estimated using the regression equation described earlier. Plots 2, 5, and 12 were harvested by the end of the second year. Dry-matter production for the remaining plots was estimated using the equation described earlier. Table 1 provides a summary of above-ground biomass at each plot during the first year (from April 15, 1991 to April 15, 1992), the second year (from April 15, 1992 to April 15, 1993), and the two-year period (from April 15, 1991 to April 15, 1993).

Using the regression equation relating cladode area to cladode maximum width, which was presented in the Methods and Materials section, the leaf (cladode) area index of the middle two rows at plots 4, 6, and 11 was estimated. The average leaf-area index (LAI) of these three plots of the first and second harvest date were 0.06 and 0.39, respectively.

Both in the first year and in the second year, dry-matter production at plots 8, 9, and 10 was much lower than that at the other plots. One possible reason for the difference in dry-matter production between the plots 8, 9, and 10, and the other plots is that the vegetation at plots 8, 9, and 10 and the other plots before planting this cactus was totally different. Bermudagrass grew densely at plots 8, 9, and 10. At the other plots, Johnson grass and other broadleaf grasses grew sparsely. Dry-matter production data obtained from plots 8, 9, and 10 is not included in the following discussion.

Table 1. Above-Ground Dry-Matter Production for *Opuntia ellisiana* During the First Year, the Second Year, and the First Plus Second Year

	Dry-matter production (kg/ha)		
Plot Number	First Year	Second Year	First Plus Second Year
1	1622*	/	/
2	1805**	4681****	6486*
3	1902**	4517****	6419***
4	1901**	5867****	7768***
5	1880**	4693****	6573*
6	1581**	4328****	5909***
7	1942*	/	/
8	1210**	3127****	4337***
9	1307**	2965****	4272**
10	848*	/	/
11	1751**	4420****	6170***
12	1643**	4972****	6515*

* Obtained by the harvest method.

** Obtained by the equation: $FW = 0.58(MW)^{2.40}$

FW is cladode fresh weight

MW is cladode maximum width.

Total dry weight = R_1 * total fresh weight.

$R_1 = 0.071$, the ratio of dry weight to fresh weight for the first harvest time.

R1 was determined by the harvest method.

*** Obtained by equation II: $PFW = -1.4662 + 0.4065(PCN)$

PFW is plant fresh weight

PCN is plant cladode number.

Total dry weight = R_2 * total fresh weight.

$R_2 = 0.074$, the ratio of dry weight to fresh weight for the second harvest.

R2 was also determined by the harvest method.

**** Obtained by subtracting the first year's from the first plus second year's.

The average dry-matter production over all plots except plots 8, 9, and 10 was 1781 kg/ha in the first year and 4783 kg/ha in the second year. The dry-matter production in the second year was 2.7 times more than that in the first year. The production of a plant community is greater the higher the assimilating rate of the plant species comprising the community, the more completely the available light is captured by the assimilation surfaces (the leaf-area index, LAI), and the longer the time the plants can maintain a positive gas-exchange balance (duration of production period) (Larcher, 1975). The assimilating rate and duration of production period are influenced by the environmental conditions (water, light, and temperature). The environmental conditions might be different between two years. This difference might be attributed to the difference in dry-matter production. However, rainfall in the first year was 341 mm more than that in the second year. The water conditions have been more favorable in the first year than in the second year. In our study area, among all environmental factors, water was the most limiting factor for plant growth. Therefore, we can conclude that the difference in LAI between two years is the major factor leading to the difference in dry-matter production. LAI was 0.06 in the first year and 0.39 in the second year.

According to the review by Russell and Felker (1987), dry-matter production of *Opuntia* spp. could be as high as 52,000 kg/ha/year. When irrigated and fertilized well, *Opuntia amyclea* and *O. ficus-indica* in Saltillo, Coahuila, Mexico had an average productivity of 46,000 kg/ha/year (Nobel, 1992). The dry-matter production of *Opuntia ellisiana* in the first year and second year is much lower than those reported above. We think the low leaf-area index of the present *Opuntia ellisiana* community is the major reason for low dry-matter production. Generally, the LAI for production is about 3 to 4 or 4 to 6 (Sinclair, 1984; Larcher, 1975). With the increase of LAI, the much higher dry-matter production of *Opuntia ellisiana* could be expected.

Normally, a mature cow would consume about 9 kg of dry matter and drink about 65 kg of water per day (Perry, 1980). Based on the dry-matter production data and the water stored in the cladodes (23,303 kg/ha in the first year and 62,583 kg/ha in the second year) dry matter per hectare in the first year and in the second year is enough for one cow to consume for about 40 days and 3.5 months, respectively. Water stored in the cladodes per hectare in the first year and in the second year is enough for one cow to drink for about one year and three years, respectively. In the drought period, this is of great significance. For example, in South Texas, a drought lasting one or two months occurs almost every summer (July to August). During the drought period, all grasses turn yellow and become senescent. However, *Opuntia* spp. remains green and succulent. Therefore, *Opuntia* spp. can be a very good source of both nutrients and water for livestock during drought periods.

Water Extraction Pattern

By comparing the water contents of bare plots without grass and cactus, and plots that were harvested at the end of the first year to plots with actively growing cactus, it was possible to ascertain the water extraction pattern of *Opuntia ellisiana* as shown in Table 2. Plots 1, 7, and 10 that were harvested at the end of the first year had new cladodes regenerating from the roots at the beginning of the growing season in the second year. The bare plot constructed in the beginning of the second year had no vegetation. The remaining plots had two-year-old cactus.

Soil water was depleted in the 12.5 to 137.5 cm soil profile at all plots but the amount was small. The bare plot had 36 mm depleted, which was greater than the average amount over the plots harvested in the first year and the remaining plots of 22 mm and 29 mm, respectively. A one-way analysis of variance revealed there was no significant difference in soil water content change between the bare plots, the plots harvested in the first year, and the remaining plots (Table 3).

Tukey's mean separation analysis showed that there was also no significant difference in soil water content between any two of the three plot groups. These results indicate that water stored below 12.5 cm of the soil profile was not directly "explored" by *Opuntia ellisiana*. Perhaps this is just in accordance with the nature of the shallow root systems of this cactus.

Table 2. Soil Water Content Change in the 12.5 to 137.5 cm Soil Profile During the Second Year in the Bare Plot, Plots Harvested in the First Year, and the Remaining Plots

Treat	Plot Number	Soil Water Content Change (mm)
Bare plot	control	-36
	1	-29
Plots harvested in first year	7	-16
	10	-21
	2	-25
	3	-21
	4	-43
	5	-22
Remaining plots	6	-27
	8	-27
	9	-34
	11	-31
	12	-28

Note: '-' indicates plots lost water.

Table 3. Summary of Analysis of Variance of Soil Water Content Change During the Second Year Between the Bare Plot, the Plots Harvested in the First Year, and the Remaining Plots

Source	Df	Sum of squares	Mean squares	F-value	P-value
Treat*	2	166.35	83.18	1.82	0.21
Error	10	456.72	45.67		

* Three treatments: bare plot, plots harvested in the first year, and the remaining plots.

Average soil water contents by 25-cm depth interval from 25 cm to 125 cm at the beginning of the second year (April 15, 1992) and the end of the second year (April 15, 1993) for the bare plot, plot 7 representing the plots harvested in the first year, and plot 6 representing the remaining plots are presented in Figures 3, 4, and 5, respectively. Clearly, the pattern by which soil water below 12.5 cm was depleted was similar between the bare plots, the plots harvested in the first year and the remaining plots. It can be concluded that soil water contents below 12.5 cm were dominated by the processes related to the soil itself such as soil water redistribution, soil evaporation, and deep percolation and were not affected by plant root activities.

Average between-row and within-row soil water contents at each depth at plot 6 are shown in Table 4. These data were obtained on April 14, 1993 when it was neither too wet nor too dry. It was appropriate to compare the between-row soil water content and the within-row soil water content.

At each depth, the difference between the between-row and within-row soil water content was very small and less than 1% in volume. This further indicates that water stored below 12.5 cm of the soil profile was not directly "explored" by *Opuntia ellisiana* and soil water contents below 12.5 cm were dominated by the processes related to the soil itself such as soil water redistribution, soil evaporation, and deep percolation and were not affected by plant root activities.

Table 4. Average Between-Row and Within-Row Soil Water Contents at Each Depth at Plot 6.

Depth (cm)	Soil Water Content ($cm^3/100\ cm^3$) Between Row	Within Row
25	22.76	22.10
50	25.01	24.43
75	27.20	26.54
100	28.22	27.66
125	26.17	26.47

The deep, wide-spreading root system of plants is usually considered as a means to withstand a long period of drought (Kramer, 1977). *Opuntia ellisiana* has a shallow root system. Only water stored in the 0 to 12.5 cm soil profile is directly explored by this cactus. Based on our investigation at Kingsville, Texas, during the drought period, soil water content in the 0 to 12.5 cm soil profile could be consistently lower than 3% by volume for one month. However, *Opuntia ellisiana* remained green and succulent and only a few cladodes were shed. We think that the ability to almost completely prevent the cladodes and stems from losing water is the major mechanism for *Opuntia ellisiana* to withstand long periods of drought.

Summary

Dry-matter production of *Opuntia ellisiana* with a spacing of 1.0 x 1.5 m was 1781 kg/ha in the first year and 4783 kg/ha in the second year. Water stored in the cladodes was 23,303 kg/ha in the first year and 62,583 kg/ha in the second year. The dry matter per hectare in the first year and in the second year was enough for one cow to consume for about 40 days and 3.5 months, respectively. Water stored in the cladodes per hectare in the first year and in the second year is enough for one cow to drink for about one year and three years, respectively. Therefore, *Opuntia* spp. can be a very good source of both nutrients and water for livestock during drought periods.

Dry-matter production in the second year was 2.7 times more than that in the first year. The difference in dry-matter production between the two periods was mainly attributed to the difference in LAI. LAI was 0.06 at the end of the first year and 0.39 at the end of the second year. With the increase of LAI (approaching optimum leaf-area index, about 4), much higher dry-matter production of this cactus could be achieved.

Water used by plants is absorbed by their roots from the soil, but the extent to which water stored in the soil profile can be explored by plants varies among plant species. Only water stored in the upper 0 to 12.5 cm soil profile was directly explored by *Opuntia ellisiana*. Soil water status below 12.5 cm was dominated by the processes related to soil itself, such as soil water redistribution, soil evaporation, and deep percolation, and was not significantly affected by the root activity of *Opuntia ellisiana*. From the point of view of effectively utilizing the limited water resource and producing the maximum plant materials per unit of land in the semiarid areas, such a agroecosystem comprising both the shallow root species (*Opuntia* spp.) and the deep root species (mesquite and forage grasses) should be developed.

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