A Case Study on *in situ* Rooting Profiles and Water-Use Efficiency of Cactus Pears, *Opuntia ficus-indica* and *O. robusta*♦

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ABSTRACT

Root distribution of cactus pear with distance from the mother plant and depth was determined in the field for one-year-old *Opuntia ficus-indica* (L.) Miller (cultivar Morado – green cladode) and *O. robusta* Wendl. (cultivar Monterey – blue cladode) in a semiarid climate. The roots were expressed in terms of root mass, root length and root thickness. In addition, the evapotranspiration water-use efficiency (cladode dry-mass production per unit of evapotranspiration) was quantified for these two spineless cactus pear species during the 2002/2003 growing season. In both species most roots were concentrated over the first 100 mm soil layer. After only one growing season of establishment the roots spread as far as 1.7 m and 1.8 m from the stem for *O. robusta* and *O. ficus-indica*, respectively. The root mass, root length, and root thickness decreased ($P \leq 0.05$), as expected, with depth and distance. The total root mass per plant, calculated for all depths were 107.5 and 131.6 g m^{-2} for *O. ficus-indica* and *O. robusta*, respectively. The root length and root mass relationship showed that a root mass of 1 g m^{-2} was equal to a root length of 3.17 and 3.79 m m^{-2} for *O. ficus-indica* and *O. robusta*, respectively. *O. robusta* showed a finer root system than that of *O. ficus-indica*. The evapotranspiration water-use efficiency for the two species ranged between 1.19 to 1.57 kg DM ha^{-1} mm^{-1} for *O. robusta* and *O. ficus-indica* respectively. The roots composed only 21% and 13% of the total plant biomass for *O. robusta* and *O. ficus-indica*, respectively. In the one-year-old plants no deep root system occurred in both species and was only characterized by a shallow horizontally spreading root system. These above-mentioned root characteristics of the cactus pear make it more appropriate for arid and semiarid crop production. The marginal drier areas with shallow soils can, therefore, be utilised to their full potential by the cactus-pear plant.

Keywords: cactus pear, root/cladode mass, root distribution, root length, root mass, root thickness, water-use efficiency

INTRODUCTION

South Africa is one of the dry African countries and, due to its relative dryness or aridity (mean annual precipitation/potential evapotranspiration ratio), 55% of the land area lies within the arid zone (aridity index of 0.05 to 0.2) and 39% is semiarid (aridity index of 0.2 to 0.5) (Le Houérou et al., 1993; Rutherford and Westfall, 1994; Hoffman and Ashwell, 2001). In these areas the phenomenon of annual or shorter seasonal droughts is an inherent characteristic (Fouché, 1992; Snyman, 1998). Therefore, when

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farming under rain-fed conditions, it is important for the available water to be used in the most efficient way (Snyman and Fouché, 1991). The cactus pear, with its adaptability to such water-stressed environmental conditions and its relatively low water requirements (De Kock, 1965, 2001; Brutsch, 1979, 1997; Singh and Singh, 2003; Lahsasni et al., 2004) is an important drought resistant crop (Russell and Felker, 1987; Felker and Inglese, 2003; Lahsasni et al., 2003). Mean annual rainfall of 200 mm corresponds to the minimum required to successfully establish rain-fed plantations (Le Houérou, 1994), provided soils are sandy and deep (Le Houérou, 1996). Although it is well adapted to arid and semiarid conditions, it will nevertheless respond favourably to light supplementary irrigation (Pretorius et al., 1997; Van der Merwe et al., 1997; Gugliuzza et al., 2000).

Cactus pear (*Opuntia* spp.) is a plant widely distributed in the Mediterranean area, Central and South America, and South Africa (Le Houérou, 1994; Lahsasni et al., 2003). A common feature of the area where the plant grows is a more or less marked degree of aridity to which the plant has adapted due to its specialized phytosyntetic system known as Crussulacean Acid Metabolism (CAM) (Felker and Russell, 1988; Nobel, 1995; Oelofse, 2002). This plant is characterized by a high potential of biomass production (Pimienta-Barrios et al., 1993; Galizzi et al., 2004; Lahsasni et al., 2004; Snyman, 2004a) and thus to digestible energy (Reynolds and Arias, 2001). Cactus pear is useful not only because it can withstand drought, but also because its conversion efficiency is greater than C_3 grasses and C_4 broadleaves (Han and Felker, 1997). These traits result in great potential for the flat-stemmed *Opuntias* in arid lands (Felker et al., 2005). Biomass generation per unit of water is on average about three times higher than for C_4-plants and five times higher than for C_3-plants (Nobel, 2001). Under optimal conditions, the various types of plants can produce similar amounts of dry matter per surface area, but under arid and semiarid conditions, CAM plants are superior to C_3-plants and C_4-plants (Han and Felker, 1997; Reynolds and Arias, 2001). Studies on water-use efficiency of CAM plants at plant community level under field conditions over a whole growing season have not often been reported in the literature (Snyman, 2004b). From an agronomical point of view, however, this kind of study is of great significance, both in theory and in practice (Han and Felker, 1997).

An important adaptive strategy for plants is to maximize water uptake from wet soil and to minimize water loss to dry soil (Nobel, 1991; Huang and Nobel, 1993). The cactus pear is characterized by a shallow, fleshy root system with horizontal root spreading (Nobel, 1988, 1995, 2001) for utilizing water efficiently (Snyman, 2004b). However, the root distribution may depend on the type of soil and cultural management (Sudzuki, 1995; Snyman, 2004b). Nevertheless, in all kinds of soil, bulk masses of absorbent roots are found in the first centimetres, with a maximum depth of 300 mm and spreading 4 m to 8 m (Sudzuki, 1995). In contrast with the shoot (cladode) system, the roots (Brutsch and Zimmerman, 1990), of Cactaceae have received little attention (Sudzuki, 1995; Nobel, 1995). The root system of cactus pear is very complex (Sudzuki, 1995) and therefore it certainly deserves more attention (Snyman, 2004b). Various responses to the environment and the cultivation of cactus pear are gaining popularity over the last 10 years as an alternative crop (fodder and fruit) for arid and semiarid areas (Barbera, 1995; Inglese et al., 1995; Nobel, 1997; Mondragón-Jacobo and Pérez-González, 2000; Felker and Inglese, 2003). Understanding the water budgets of cactus pear is fundamental to understanding their low-temperature tolerance and winter survival, which, in turn, affect their distribution, adaptability, and productivity (Cui and Nobel, 1994). Increasing knowledge of environmental influences on various cactus species and cultivars' productivity (fruit and fodder) and adaptability will allow more profitable and sustainable production. Therefore, this study aimed at determining the root distribution with distance and depth for the widely cultivated *Opuntia ficus-indica* (green cladode) and *O. robusta* (blue cladode) to serve as guidelines in management practices. Water-use efficiency was also quantified for the two one-year-old cactus-pear species during the 2002/2003 growing season.

MATERIALS AND METHODS

Site Description

The research was conducted in Bloemfontein (28°50´S and 26°15´E and altitude 1,350 m), in the semiarid, summer-rainfall (annual average 530 mm) region of South Africa. Rain falls almost exclusively during summer (October to April), with an average of 78 rainy days per year. The mean annual temperatures range from 17°C in July to 33°C in January. It has 119 average frost days per year (Schulze, 1979).

The soil is a fine sandy loam soil of the Bloemdal Form (Roodeplaat family -3200) (Soil Classification Working Group, 1991). Clay content increases down the profile from 10% in the A horizon (0-300 mm) to 24% in the B1 horizon (300-600 mm), and 42% in the B2 horizon (600-1,200 mm). The pH (KCI) was 4.5 over the first 0 to 300 mm layer. Bulk densities after cultivation were 1,260 kg m^{-3} for the A horizon, 1,563 kg m^{-3} for the B1 horizon and 1,758 kg m^{-3} for the B2 horizon (Snyman, 2000). The planting during August 2002 was under dry-land conditions and cultivated well (300 mm deep) before planting. No fertilisation or cultivation took place over the trial period. Weed control was done chemically by the herbicide Roundup™ (active ingredient-Glyphosate), with the cactus pear plants covered by plastic cans at the time of spraying.

Treatments

Three cactus pear plants for each of the species *Opuntia ficus-indica* (L.) Miller (cultivar Morado) (green cladode) and *O. robusta* Wendl. (cultivar Monterey) (blue cladode) were studied. The planting (one-year-old cladodes) took place on 4 August 2002 in two lines, with 5 m spacing between rows and 2 m within a row (1,000 plants ha^{-1}). The plants were randomly placed over the area.

One-year-old cladodes of the two species were obtained from the farm Waterkloof approximately 20 km west of Bloemfontein. The cladodes of *O. ficus-indica* were, on average, 506 ±46 mm long, 183 ±15 mm wide, 20 ±3 mm thick and 1,406 ±170 g fresh mass (means ± SE, n = 10). The cladodes of *O. robusta* were 261 ±46 mm long, 244 ±15 mm wide, 15 ±2 mm thick and 1 354 ±130 g fresh mass (means ± SE, n = 10). The cladodes were dried for 4 weeks in the shade to allow healing of the cutting area and then planted upright with one quarter of *O. robusta* (50 to 60 mm) and *O. ficus-indica* (100 to 120 mm) of the cladode in the soil. The cladodes were facing North/South.

Data Collection

The root mass and length were estimated at 50 mm intervals to a depth of 900 mm from a sample of three soil cores randomly distributed from the stem of each plant. This was done over a distance of 1,500 mm from the stem of each plant with 100 mm intervals. This means that at each distance, r, from the mother cladode, three cores were made on the soil, with these cores taken over the circle with radius r. The soil cores were collected with an auger (70 mm diameter) at the end of the growing season. Data collection took place (July 2003) from 11 month-old plants, which grew over a full growing season. After collecting the samples for root length and mass measuring with depth and over distance, the soil between the sampling rows was washed out to determine root distribution visually.

Sieving was through two sieves, a 2 mm mesh followed by a 0.5 mm mesh. Most of the roots had been extracted via successive washings of the core. The roots were then dried at 100°C for 24 hours. The length of the washed roots was measured by using a modified infrared root length counter (Rowse and Philips, 1974). The root counter was first calibrated by using ten pieces of string being cut at different well-known (range from 0.5 to 5 m) lengths. The string pieces were more or less of the same thickness as the roots. The cut string pieces (approximately 20) for each length were spread over the counter surface from where 6 replications of the readings were taken. Before each replication the string pieces were moved around over the counter. The counts from the root length counter were regressed against the length of the string. The regression function used to calculate the root length from the root counter readings, was $y = 0 + 45.349x$, where y = root counter reading, x = root length (m) and $R^2 = 0.9406$. The averages of six readings were taken from each core. The lengths of all roots in each soil core were calculated by this equation. The root thickness was measured in mm with a vernier caliper. The thickness of 10 roots randomly picked from each depth and distance from the stem was measured.

Water-use efficiency (WUE) is defined as the amount of plant material (dry matter – cladodes) produced per unit of water used (evapotranspiration). The water-use efficiency was calculated in two ways from the cladodes. First, only the newly formed cladodes were taken into account and second, the increase in mass of the mother cladode (planted cladode) was also included. In the last mentioned case, the mass of both newly formed cladodes and the increased mass of the mother cladode were added and used in the calculation of the total dry matter (DM) of the cladodes. The DM value for the mother (planted) cladode was obtained from 10 extra cladodes, although not planted, but more or less the same size as the planted ones. Those 10 supplemental cladodes were weighed before and after drying at 100^{o}C for 72 hours. The average weight of the supplemental cladodes (not planted) was used to estimate the starting weight of the measured plants. This DM increase was included in calculating the WUE. The average water content of the 10 cladodes for *O. ficus-indica* and *O. robusta* was 88.13% and 87.29%, respectively.

Evapotranspiration (Et) was determined by the soil-water balance equation (Hillel, 1971). Rainfall (P) was measured daily using rain gauges. The change in soil water (ΔW) was calculated following Moore et al. (1988), where (+) indicated an increase and (-) a decrease in the amount of water within the root zone. The soil-water content was determined gravimetrically by means of a Veihmeyer tube (Snyman et al., 1985) at 50-mm depth intervals (five samples per treatment) up to a depth of 1,000 mm every month. The water content of the five samples was averaged. In this deep soil and considering the low rainfall input of the study area, it is very difficult to obtain drainage (D) and hence it can be discarded as a term in the water balance (Snyman,1998). Evapotranspiration was, therefore, calculated as follows:

$$Et = P \pm \Delta W,$$

where P is precipitation and ΔW is the change in soil-water content.

Water evaporation from the soil surface is almost equal to class-A pan evaporation while the soil is saturated and then goes into stage two, namely, soil-water evaporation that is related to the diffusion of the soil from deeper layers to the soil surface (Han and Felker, 1997). This means that immediately after rainfall the soil evaporation will be highest and, in several days, the greatest soil-water evaporation will occur. By measuring soil-water evaporation on a monthly basis as done in this study, the term soil evaporation was basically lost and runoff was also not measured. Therefore, what was really measured in this study was WUEet or evapotranspiration water-use efficiency that includes plant transpiration plus soil-water evaporation and runoff. According to Han and Felker (1997) soil evaporation and runoff can account for 53% of the precipitation.

In calculating the root/cladode ratio, the total mother cladode mass was included.

Statistical Analysis

The experimental layout was a fully randomised design consisting of two treatments (*Opuntia* species) replicated thrice. The data collected was analysed by SAS (DOS program 6.04 version-Cary, 1988). A two-way of variance (ANOVA) at 95% confidence level (depth × distance) was computed for root mass, root length, and thickness (Mendenhall and Sincich, 1996). Data on cladode mass and evapotranspiration water-use efficiency were analysed using a one-way ANOVA (Winer, 1974). The Tukey test was used for significance between treatments. In determining least significant difference (LSD), the method of Fisher (1949) was used.

RESULTS AND DISCUSSION

Below-Ground Phytomass Production

Root Mass

For both species, 100-200 mm away from the stem, significantly more ($P \leq 0.05$) roots were found in the topsoil layer (100 mm) than any of the other soil layers (Figure 1). In *O. ficus-indica* the root mass over the first 0-150 mm soil depth was very high at 0-200 mm distance from the stem, but decreased markedly further away from the stem. In contrast, *O. robusta* seems to have a constant root distribution with depth and distance from the stem compared to that of *O. ficus-indica*. The conclusion can be made that after a year of establishment there are only a few deep roots exactly underneath the stem. Although, according to the literature, the cactus pear also develops a deep root system after a few years (Nobel, 1988; Sudzuki, 1995).

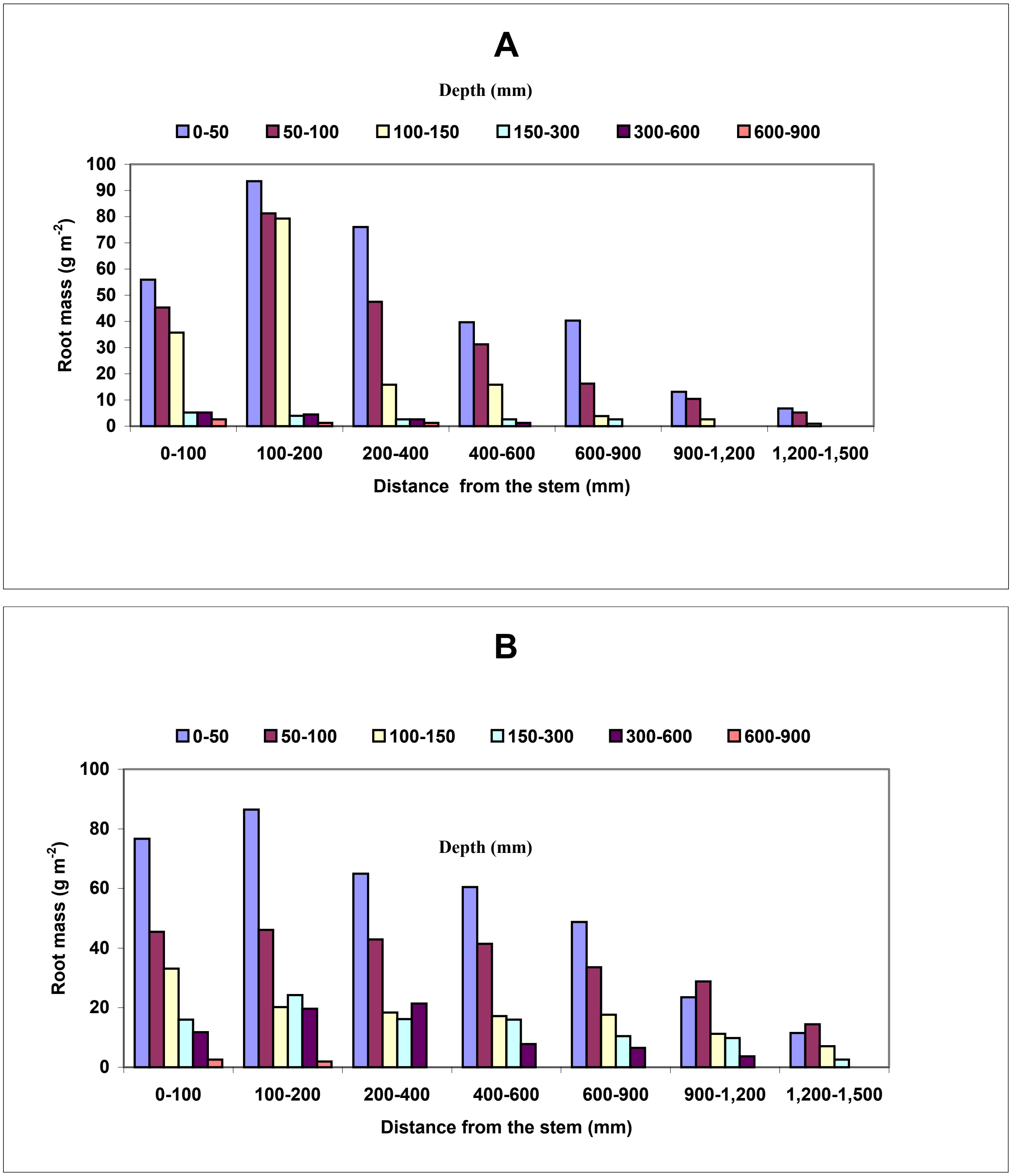


Figure 1. Root Mass (G M^{-2}) For *Opuntia ficus-indica* (A) and *O. robusta* (B) With Depth and Distance From the Mother Plant.
$LSD_{0.01}$: Species = 1.0255, Depth = 5.1119, and Depth × Distance = 3.1692.

The root mass decreased ($P \leq 0.05$) with distance away from the stem as well as with depth for both *Opuntia* species. At a distance of 600-1,500 mm from the stem, there were no roots at a depth of 300-900 mm for *O. ficus-indica*. In contrast, *O. robusta* had no roots at a depth of 600-900 mm from a distance of 200-1, 500 mm from the stem. At 1,200-1,500 mm away from the stem there were no roots at a depth of 300-900 mm for both species. A significant interaction ($P<0.01$) was obtained between root mass with soil depth for only *O. ficus-indica*.

If one extrapolates the trend (Figure 1) over distance from the stem where roots could still be found, the root spreading from the mother plant can be predicted as 1.6 and 1.7 m for *O. ficus-indica* and *O. robusta*, respectively. It is, therefore, clear that for both species the root distribution over the first 100 mm soil depth must have spread further than the 1,500 mm measured in this study.

The total root mass per plant, calculated for all depths, was 107.5 and 131.6 g m^{-2} for *O. ficus-indica* and *O. robusta*, respectively, after the first year of establishment. The 22% higher ($P \leq 0.01$) root mass in total of the *O. robusta* plants can be attributed to its denser and finer root system.

Percentage of Root Mass in Each Soil Layer

Table 1 again stresses that most of the roots are distributed over the first 100-mm soil layer for both species. Over a distance of 1,500 mm from the stem, an average of 75% and 68% roots for *O. ficus-indica* and *O. robusta*, respectively, were distributed over the top 100-mm soil layer. An interesting fact for both species is that the root distribution over the first 100-mm soil layer was relatively constant and even increased in some instances away from the stem. This is supported by Sudzuki (1995) with the bulk mass of roots found in the first few centimetres with a maximum depth of 300 mm. Therefore, according to Ratsele (2003), efficient weed control is important in ensuring effective water and nutrient uptake by the cactus pear. The average thickness of the roots at the top developing from the cladodes, were 3.3 and 3.2 mm for *O. ficus-indica* and *O. robusta*, respectively, after the first season’s growth. The conclusion can be made that a one-year-old cactus pear plant is not a deep-rooted plant, which was also clearly observed when the soil was washed out between the sampling rows in the field. Although not physically measured, the root system in general for *O. robusta* showed a finer structure visually than that of *O. ficus-indica* with its thicker appearance.

Table 1. Root Mass (%) Distribution per Depth for Increased Distance From the Mother Plant for *Opuntia* Species

Opuntia ficus-indica

Depth (mm)	Distance from the stem (mm)						
	0-100	**100-200**	**200-400**	**400-600**	**600-900**	**900-1200**	**1200-1500**
0-50	37	36	52	45	64	50	54
50-100	30	29	32	33	25	40	39
100-150	24	30	11	18	7	10	7
150-300	4	2	2	3	4	0	0
300-600	3	2	2	1	0	0	0
600-900	2	1	1	0	0	0	0
Total	100	100	100	100	100	100	100

Opuntia robusta

Depth (mm)	Distance from the stem (mm)						
	0-100	**100-200**	**200-400**	**400-600**	**600-900**	**900-1200**	**1200-1500**
0-50	41	44	40	42	42	31	32
50-100	25	23	26	29	28	37	41
100-150	18	10	11	12	15	15	20
150-300	9	12	10	11	9	12	7
300-600	6	10	13	6	6	5	0
600-900	1	1	0	0	0	0	0
Total	100	100	100	100	100	100	100

Root Length

The root length decreased ($P \leq 0.05$) with depth and distance from the stem for both *Opuntia* species (Figure 2). According to most researchers, the root distribution pattern of cactus pear also depends on soil type and cultural management (Sudzuki, 1995). It grows best on sandy loam soils (Drennan and Nobel, 1998). However cactus pear is adapted to many soil types and climatic conditions and is easily established with low labour requirements (Sudzuki, 1995). Most ($P<0.01$) roots in terms of length were found at a depth of 0-50 mm and 100-200 mm away from the stem for both species. As the case with root mass, further from the stem, root lengths decreased with depth. It is well-known that cactus pear is a shallow-rooted crop with a fleshy root system, which can spread horizontally from 4-8 m from the mother plant after a few years (Sudzuki, 1995; Drennan and Nobel, 1998).

A significant interaction ($P<0.01$) was obtained between root length with soil depth for both *Opuntia* species. The fact that the root length of *O. robusta* is higher ($P \leq 0.05$) over all depths further away from the stem than that of *O. ficus-indica*, is of great interest. This could be due to the fewer side roots found in this species. Therefore, the conclusion could be made that *O. robusta* generally has a more constantly spread root system with depth and distance than *O. ficus-indica*. This can allow better adaptation of this species to lower rainfall conditions. It can be predicted by extrapolating Figure 2 that, for both species, beyond 1,500 mm from the stem there could still be roots but not measured in this study. *Opuntia robusta* and *O. ficus-indica* could, therefore, have roots spreading over a distance of 1.7 and 1.8 m, respectively, for the one-year-old plants. Lateral roots branching from main roots could account for about 70% of the total root length for cacti (Huang and Nobel, 1993), and have a higher hydraulic conductivity than tap roots (Nobel and Sanderson, 1984). However, little attention has been paid to lateral roots, especially to their hydraulic and anatomical changes with distance from the root tip and with soil water availability (Huang and Nobel, 1993; Snyman, 2004b).

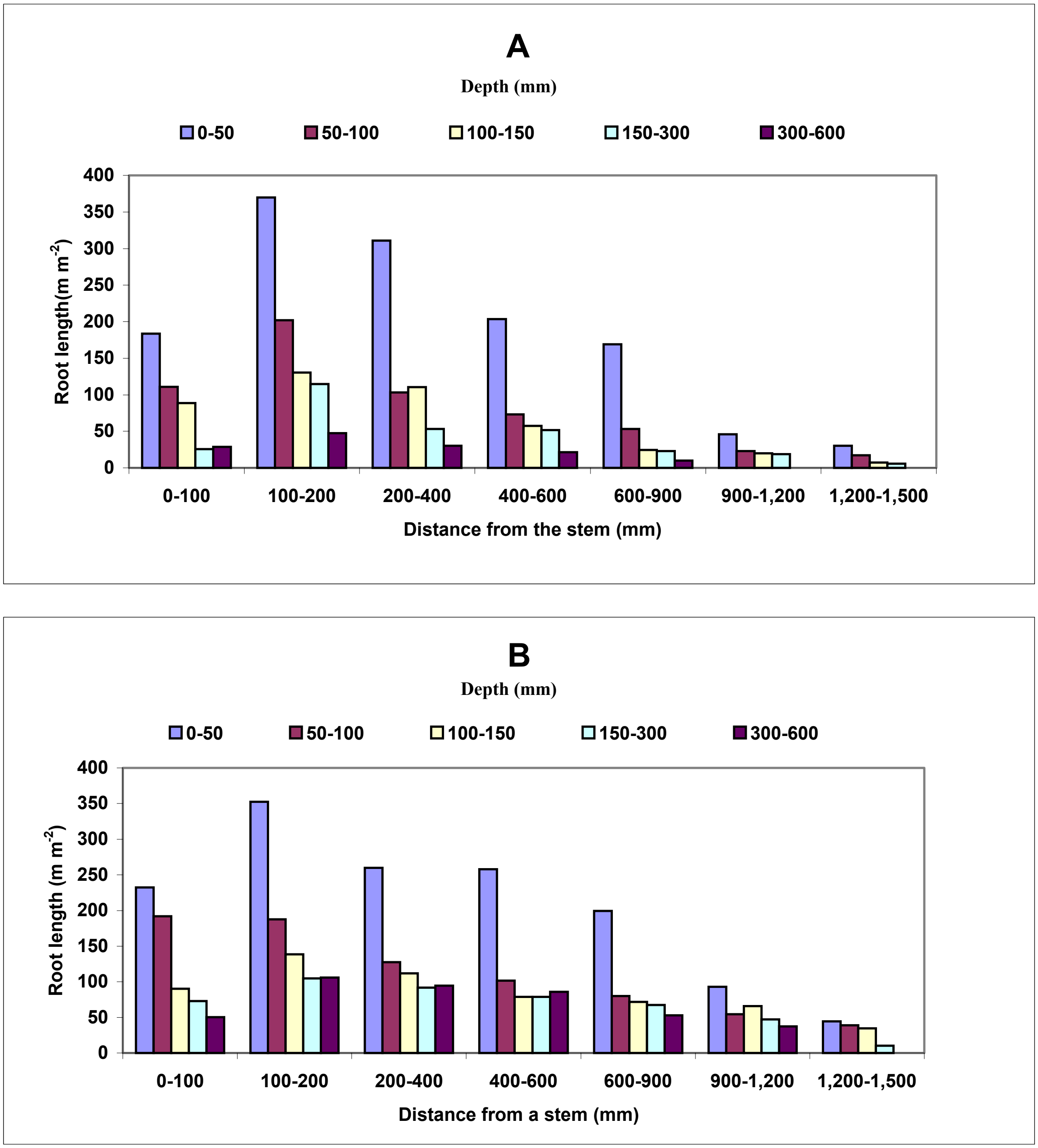


Figure 2. Root lengths (m m^{-2}) for *O. ficus-indica* (A) and *O. robusta* (B) at a depth of 0-600 mm and distance of 0-1,500 mm from the mother plant. $LSD_{0.01}$: species = 11.3663, depth = 10.1236 and depth × distance = 4.1736.

Percentage of Root Lengths in Each Layer

As also shown in Figure 2, most roots are distributed within the 0-100 mm soil layer (Table 2). On average, over this soil layer 68% and 55% of the roots were distributed over a distance of 1,500 mm from the stem for *O. ficus-indica* and *O. robusta*, respectively. More interesting is that over the first 50 mm depth, 47% and 35% of the roots of *O. ficus-indica* and *O. robusta*, respectively, were found 1,500 mm from the stem. These findings are in agreement with that of most researchers that the roots of cacti are typically shallow (50 to 150 mm deep) and, even for a large arborescent cactus, occur chiefly in the upper 300 mm of the soil (Gibson and Nobel, 1986; Nobel, 1995, 2001). Irrigation water is generally applied only to the usual rooting depth, but excessive irrigation can force roots to lower soil layers (Nobel, 2001).

Table 2. Root Length (%) Distribution per Depth for Increased Distance
From the Mother Plant for Both *Opuntia* Species

Opuntia ficus-indica

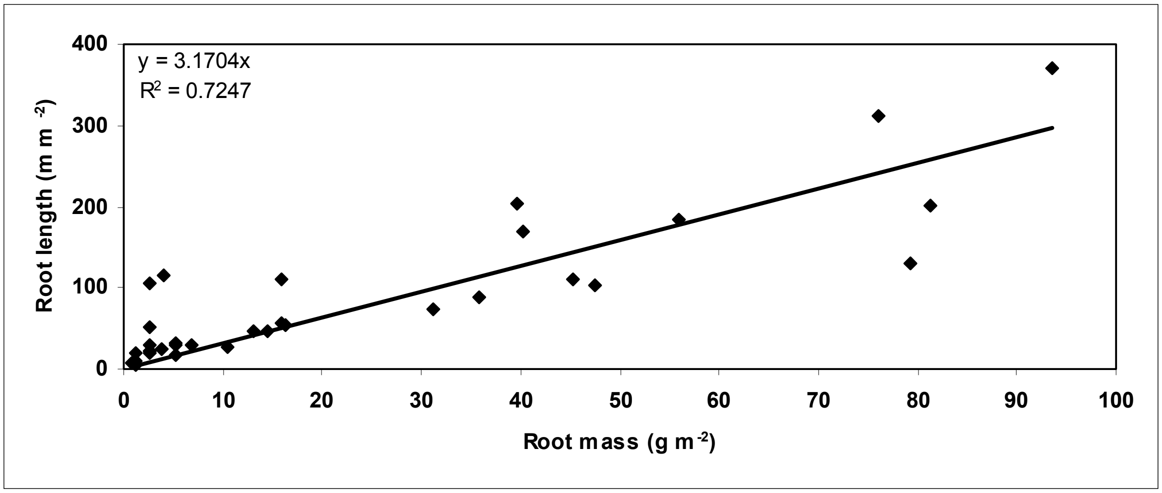
Depth (mm)	**Distance from the stem (mm)**						
	0-100	**100-200**	**200-400**	**400-600**	**600-900**	**900-1200**	**1200-1500**
0-50	41	43	47	50	61	42	50
50-100	25	23	16	18	19	23	28
100-150	20	15	16	14	9	18	12
150.300	7	13	16	13	8	17	10
300-600	7	6	5	5	3	0	0
Total	100	100	100	100	100	100	100

O. robusta

Depth (mm)	**Distance from the stem (mm)**						
	0-100	**100-200**	**200-400**	**400-600**	**600-900**	**900-1200**	**1200-1500**
0-50	38	38	38	43	42	31	31
50-100	29	21	19	17	17	18	27
100-150	14	17	16	13	16	22	23
150-300	11	12	13	13	14	16	19
300-600	8	12	14	14	11	13	0
Total	100	100	100	100	100	100	100

Root Length and Root Mass Relationship

Root length is regressed against root mass and the relationships for the two *Opuntia* species are presented in Figure 3. The root lengths for *O. ficus-indica* and *O. robusta* can be determined with an accuracy of 72% and 77%, respectively, if the root masses are known. These regressions imply that a root mass of 1 g m^{-2} is equal to a root length of 3.17 and 3.79 m m^{-2} for *O. ficus-indica* and *O. robusta*, respectively. As the root mass increased, the root length also increased for both *Opuntia* species.



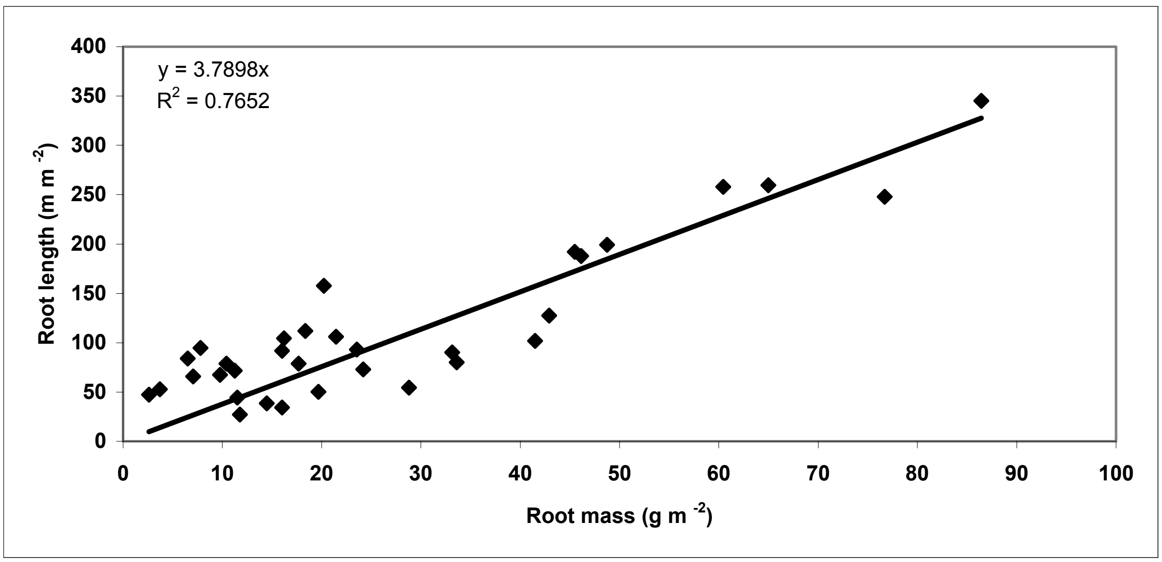


Figure 3. Relationship between root mass (g m^{-2}) and root length (m m^{-2})
for *Opuntia ficus-indica* (A);
y = 3.170x (R^2 = 0.7247; n = 33) and *O. robusta* (B); y = 0 + 3.7898x (R^2 = 0.7652; n = 33).

Root Thickness

The root thickness also decreased ($P \leq 0.05$) with distance from the stem. *Opuntia ficus-indica*'s roots were thicker near the stem at a depth of 50-100 mm, while that of *O. robusta* were thicker for most distances at 0-50 mm depth. From Figure 4 it is clear that the roots of *O. robusta* are still thick although spread far away from the stem in all depths. The roots of *O. ficus-indica*, on the other hand, showed a slight decrease in thickness with distance from the stem.

It is very clear that the roots of *O. ficus-indica* for most depths and over distances were thicker than those of *O. robusta*. Figure 4 again illustrated the finer root system of the last mentioned species. Root thickness could also be a function of soil-water content (Ramakatane, 2003; Snyman, 2004a,b). The time of measuring the roots in this study could, therefore, have an influence on root thickness. According to Nobel (2001), as the soil dries, fine lateral roots generally die, while larger roots become covered with a corky layer (periderm). Nobel (1997) also found that a root-soil air gap that develops as the roots of *O. ficus-indica* shrink in response to drying conditions helps retard water loss to the soil in the initial phases of drought, with cellular changes affecting the root hydraulic conductivity playing a secondary role and decreases in soil hydraulic conductivity becoming dominant after a few weeks of drought.

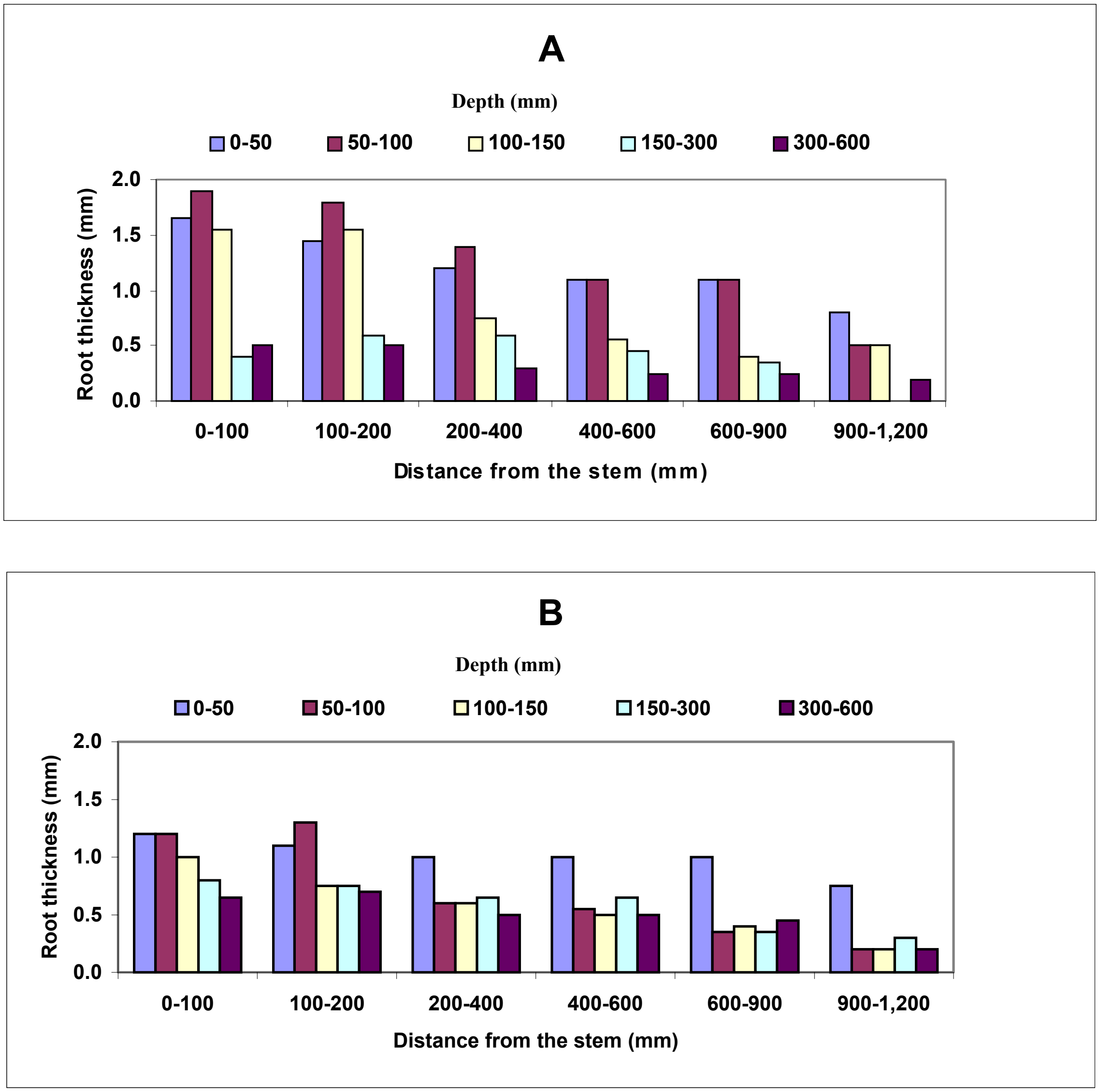


Figure 4. The thickness (mm) of roots with distance from the mother plant and depth for *Opuntia ficus-indica* (A) and *O. robusta* (B).
(n = 10). $LSD_{0.01}$: species = 0.2673, depth = 0.3146 and depth × distance = 0.1623.

Aboveground Biomass Production

Cladode Mass

The rainfall over the 11-month study period was 404 mm, which is 18% less than the long-term annual rainfall for the study area. The rainfall distribution followed more or less the same pattern as the long-term average values for each month.

The percentage water in the cladodes differed not significantly (P>0.05) between the two species and ranged between 88.28% and 87.37% (Table 3). In contrast, according to Lopez-Garcia et al. (2001) the total amount of water stored in the cactus pear cladodes also depends upon species and varieties. Clearly from this study, water content in the cladodes is also strongly influenced by environmental conditions, which can, according to Lopez-Garcia et al. (2001), range between 70% and 93%. According to most researchers, cactus cladodes aged 1 to 3 years, are high in water content (75%-85%) in summer and early fall and (85%-80%) in winter and spring (Monjauze and Le Houérou, 1965; Le Houérou, 1994; Felker, 1995; Nefzaoui and Ben-Salem, 1996; Ramakatane, 2003). Ramakatane (2003) found a decrease of the water content in the cladodes of *O. ficus-indica* with water stress, but it seems that *O. robusta* retained water more under such water stress conditions.

Table. 3. Average Cladode Mass Fresh and Dry, Water Content in Cladode, and Evapotranspiration Water-Use Efficiency (WUEet) for One-Year-Old *Opuntia ficus-indica* and *O. robusta* Plants. Data Are Means of Seasonal Growth and SE of 3 Plants. Least Significant Difference (LSD) Is Calculated at 1% Level.

Species	**Cladode Mass**		**Water Content in Cladode (%)**	**WUEet (kg ha^{-1} mm^{-1})**
	Fresh (g $cladode^{-1}$)	**Dry (g $plant^{-1}$ or kg ha^{-1})**		
O. ficus-indica	904 (±108)	636 (±82)	88 (±1)	1.57
O. robusta	763 (±96)	482 (±77)	87 (±1)	1.19
LSD	47	42	3	0.08

Opuntia ficus-indica produced, on average, six new cladodes over the growing season with an average fresh mass of 903.90 g $cladode^{-1}$ (Table 3). The cladode mass is 23% less than that obtained for the same cultivar by Oelofse (2002). In contrast, *O. robusta* formed only five new cladodes with an average fresh mass of 763.15 g $cladode^{-1}$. *Opuntia ficus-indica* produced over the study period significantly ($P \leq 0.05$) more than *O. robusta* (Table 3). The total fresh mass production for *O. ficus-indica* and *O. robusta* was 5.42 and 3.82 kg $plant^{-1}$ or t ha^{-1}, respectively. According to the study layout, the fodder production was calculated for 1,000 plants ha^{-1}. Although a planting density of 1,000 plants ha^{-1} is recommended for fruit production and 2,500 to 3,500 plants ha^{-1} for fodder (Potgieter and Carstens, 1996; Potgieter, 1998) the dry matter production obtained for the two species in this study of 481 to 635 kg ha^{-1} (or g $plant^{-1}$) compared well with fodder production results of Potgieter (1998) and Oelofse (2002). Unfortunately, there is a lack of one-year-old plant fodder production results to compare the finding of this study more intensively. Most researchers argued that the fodder production of cactus pear is variable over the first three years before obtaining a more constant production (Potgieter, 1995, 1998; Potgieter and Carstens, 1996; De Kock, 1998;). Cactus pear is able to produce up to 5 to 10 t aboveground DM $ha^{-1}yr^{-1}$ in arid zones, 10 to 20 t in semiarid areas, and 20 to 30 t in sub-humid zones, under appropriate and close-to-optimum intensive management (Monjauze and Le Houérou, 1965; De Kock and Aucamp, 1970; Franclet and Le Houérou, 1971; De Kock, 1980; Steynberg and De Kock, 1987; Nobel, 1988; Le Houérou, 1992a,b). Under such conditions productivity is about 10 times as high as on standard rangelands under optimal management conditions (Le Houérou, 1994). In less than optimal soil and management conditions (no cultivation, no fertilization) yield is still 3 to 5 times as high as on standard rangeland (De Kock, 1980; Le Houérou, 1984; Le Houérou et al., 1988). No fruit production was obtained over this study period from any of the two species.

Evapotranspiration Water-Use Efficiency

The evapotranspiration water-use efficiency (WUEet) presented in Table 3 also included the increase in mass of the planted mother cladodes over time. These values did not differ much (P>0.05) for both species when the mother cladode mass increase was excluded in the calculation. According to Felker and Russell (1988), cactus pear is about four times more efficient in water use than C_4-plants, such as maize, due to its Crassulacean Acid Metabolism (CAM) pathway (Nobel, 1995) and can, therefore, be cultivated with great success in drier areas. Han and Felker (1997) studied three- and four-year-old plantations and argued that *Opuntia* species are among the greatest water-use efficient of any plant species (including C_3 and C_4) that has been measured under long-term field conditions. The low WUEet obtained for both species in this study of one-year-old plants, which range between only 1.19 to 1.57 kg dry matter ha^{-1} mm^{1} (for *O. robusta* and *O. ficus-indica*, respectively), can be attributed to the well-known variable and poor fodder production of cactus pear over the first year of establishment (De Kock, 1998, Oelofse, 2002, Ratsele, 2003). The high WUEet (62 kg DM ha^{-1} mm^{-1}) from a four-year-old plantation recorded by Han and Felker (1997) was a result of the high biomass productivity in the fourth year after an achieved leaf-area index >2. The WUEet is very highly conditioned by leaf-area index (LAI) because the higher the LAI, the lower will be the soil evaporation both due to greater root densities and to shading by the cladodes. One would, therefore, presume that in this study at this early age that the LAI were very much less than 1. If continuing this study, one will find the WUEet increases dramatically over the next four years. Rain-use efficiency (RUE) is on the order of 2 to 5 kg DM ha^{-1} mm^{-1} in unspoilt (good ecological condition) world arid rangelands (Le Houérou, 1994; 1996; Snyman, 1998, 1999, 2000; Guevara et al., 2000; Holm, 2000; Ingram, 2002), compared to 10 to 15 kg DM ha^{-1} mm^{-1} of full grown cactus pear plantations under average standard deep soil and management conditions (Le Houérou, 1994, 1996). Guevara and Estevez (2001) reported RUE of only 7.4 kg DM ha^{-1} mm^{-1} from cactus pear in a 300-mm rainfall area in Argentina. The low yield was probably, according to them, due to its unweeded condition. Water-use efficiencies as low as 3.5 kg DM ha^{-1} mm^{-1} were also reported on a silty sand soil with a rainfall slightly higher than 200 mm (Guevara and Estevez, 2001). Maximum WUEs of 40 to 60 kg DM ha^{-1} mm^{-1} have been attained with cactus pear in semiarid and sub-humid climates under irrigation and cultivation with fairly high levels of fertilizing and/or manuring, which is close to the biological limit for CAM species (Fisher and Turner, 1978; Le Houérou, 1984; Nobel, 1988;). The high WUE values for cactus pear under rain-fed conditions in the arid Karoo of up to 43 kg DM ha^{-1} mm^{-1} by De Kock (1965, 1980, 2001) and De Kock and Aucamp (1970) in arid areas, are questionable due to the fact that it is close to the biological limit for CAM species. The combination of a very high RUE and WUE with drought-tolerance is shared by a small number of plants of economic value: cacti and agave are CAM species, while most saltbushes are C_4 -plants (Le Houérou, 1996).

Opuntia ficus-indica used water more efficiently ($P \leq 0.05$) than *O. robusta* over the study period (Table 3). The 13% larger cladode mass, as well as the more new cladodes formed per plant for *O. ficus-indica*, could be attributed to the better WUEet of this species compared to that of *O. robusta*. There is a lack of data on the WUE of different cactus pear species and cultivars to compare these findings with.

Root/Cladode Ratio

Dry-mass based, root/cladode ratio for *O. robusta* of 0.21 was significantly ($P \leq 0.05$) higher than the 0.13 of *O. ficus-indica*. The root/cladode ratio for *O. ficus-indica* ranging from 0.07 to 0.14 as found by Drennan and Nobel (1998) and Nobel (2001) of mature plants supported the very low values found in this study. As mentioned, *O. robusta* visually showed a finer root system than that of *O. ficus-indica*. Therefore, the root composing 21% of the total plant biomass for *O. robusta*, compared to only 13% for

O. ficus-indica, could be due to the finer root system of the first mentioned species. The low root/cladode ratio for cactus pear and its low respiratory cost for both root growth and maintenance (Nobel et al., 1992) contribute to the high cladode productivity of this CAM species (Drennan and Nobel, 1998).

CONCLUSIONS

Cactus pear could be introduced with great success on land presently deemed marginal. With its shallow root system occurring predominantly in the upper layers (0 to 100 mm) of the soil, where soil-water content is heterogeneous, it is well adapted to arid and semiarid areas. The first year of establishment, no deep tap root system developed in both species but was only characterized by a shallow, horizontally spreading root system. A deeper root system might be developed after a few years depending on the type of soil and cultivation management. It was clear from this study that after only the first season of planting the roots of cactus pear can spread as far as 1.5 to 1.8 m from the plant. It can also be concluded that *O. robusta* had more constant root distribution with depth and distance from the mother plant than *O. ficus-indica*. It was also clear that after one year of establishment, *O. ficus-indica* had a shallower and shorter root system than *O. robusta*. This might be due to *O. robusta*'s more and finer side roots than *O. ficus-indica*. Its various water-conserving strategies lead to a need for a small root system, indeed roots composed only about 13% and 21% of the total plant biomass for *O. ficus-indica* and *O. robusta*, respectively. In order to obtain a clearer picture of the whole dynamics of the root system of the cactus pear, more intensive research on the root distribution in older plantations has to be carried out in the future. This must also be done on soils with different clay contents to see how root distribution will vary under such conditions.

Due to the extensive and shallow cactus root growth, mostly found in the first 100-mm soil layer, for sustainable cactus pear production chemical weed control is important to avoid competition for water and minerals, especially during the early stage of plant development. Cultivation between rows to loosen the soil for better water infiltration must be avoided or carefully planned to avoid root damage. For cultivation around the plants' stems, the shallow root development over the first soil layers must be borne in mind. Fertiliser must also be applied in small quantities over the season to avoid burning the shallow root system.

The study showed that over the established season the cactus pear does not use rainfall as efficiently as one would expect from a cactus plant. After a few years of establishment one would hope for a more constant production and, therefore, a high WUEet as the plant is known for. Although *O. ficus-indica* may have a higher WUE, it could be slightly less tolerant to drought, in contrast to *O. robusta*. The finer and more compact spreading root system of last mentioned species, makes it more adaptable to drier conditions. With the shallow root system it is not surprising that drainage is an important ecological factor for cactus pear as it is very sensitive to lack of oxygen in the root zone and, therefore, cannot withstand any prolonged water logging. It thus tends to avoid clay soils, which may be temporarily saturated, poorly drained, or waterlogged. If irrigation is done, it must also be in smaller amounts over the season so that the widespread roots can utilise it efficiently. The complexity of cactus pear species and their root systems, together with the relevance of its different uses, would certainly deserve more attention in future.

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