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Root distribution with changes in distance and depth of two-year-old cactus pears *Opuntia ficus-indica* and *O. robusta* plants

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Abstract

Opuntia is a drought tolerant crop and even the smallest amount of water is absorbed efficiently through the shallow and horizontally spread root system. However, there is a lack of knowledge on the root dynamics of cactus pear for sustainable production of fodder and fruit in the drier areas. This study, conducted during the 2003/2004 growing season on two-year-old *Opuntia ficus-indica* (L.) Miller (cultivar Morado–green cladode) and *O. robusta* Wendel. (cultivar Monterey–blue cladode) plants in the field was therefore aimed at quantifying root distribution with distance and depth from the stem. Root growth was expressed in terms of both mass and length, and water-use efficiency (WUE) was defined as the cladode dry mass production per unit of evapotranspiration. In both species most roots were concentrated in the first 150 mm soil layer. After only two growing seasons the roots spread as far as 2.5 m from the stem for both species. The total root dry weight production calculated per plant up to a depth of 1200 mm, was 239 and 316 g per plant or kg ha^{-1} for *O. ficus-indica* and *O. robusta* respectively. The thickest roots developed directly from the planted cladode and were 9.1 mm thick for *O. ficus-indica* and 6.3 mm for *O. robusta*. *Opuntia robusta* showed a finer root system than that of *O. ficus-indica*. After two growing seasons 3407 and 2702 kg ha^{-1} aboveground dry mass was produced by *O. ficus-indica* and *O. robusta* respectively. The WUE of *O. ficus-indica* (6.52 kg ha^{-1} mm^{-1}) was significantly higher than that of *O. robusta* (5.39 kg ha^{-1} mm^{-1}). The roots comprised only 11% of the total biomass for *O. robusta* and 7% for *O. ficus-indica*. Such root adaptations of this species are in addition to the classical physiological and structural modifications of CAM plants to tolerate prolonged drought.

Keywords: Cactus pear; Root/cladode mass; Root distribution; Root length

1. Introduction

In both natural and agricultural plant communities, the environment is seldom optimally fit for plant growth. Moreover, plant growth in most natural environments is limited by one or more environmental parameters, such as water and nutrient availability (Chapin III, 1991; Le Houérou et al., 1993; Snyman, 2004a). *Opuntia* is a drought tolerant crop, since even the smallest amount of water it absorbs is used efficiently (Le Houérou, 1996; Felker et al., 1997; Han and Felker, 1997; Snyman, 2003). It is able to do this due to its relatively shallow and horizontally spread root system and the ability to still withdraw water from the soil at a stage when other crops are not able to (Singh and Singh, 2003; Snyman, 2004b). These traits make it highly promising as a crop for soils poor in nutrients and with limited water supply (Silva and Acevedo, 1985). It can survive in regions with 200 to 300 mm rainfall, which are common in less developed countries (Brutsch, 1988). The specialized photosynthetic system in cacti, known as Crassulacean Acid Metabolism (CAM), provides greater water to dry matter conversion than the C_3 and C_4 photosynthetic pathways (Nobel, 1988; Han and Felker, 1997) and results in great potential for the production of flat stemmed Opuntias in arid lands (Mizrahi and Nerd, 1999; Galizzi et al., 2004; Felker et al., 2005).

The cultivation of *Opuntia* species (cactus pear), which requires little or no irrigation, may assume greater agronomic importance in the future, since a large fraction of the land area of southern Africa is destined to become arid or semi-arid due to global warming (Snyman, 2004b). The common opinion that cactus pear needs low inputs to give high yields have been so

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misconceived that very limited scientific information is available to farmers and the importance of appropriate orchard management has been largely neglected (Inglese et al., 1995). Cactus pear is capable of establishing a sustainable production system that will increase the efficiency and economic viability of small and medium sized farms of lower income farmers (Pimienta-Barrios et al., 1993). The complexity of cactus pear species, together with the relevance of their different uses, deserve more attention (Inglese et al., 1995; Felker and Inglese, 2003). The decade of the 1990's has seen a great expansion in national and international cooperative research and development on cactus, including plant physiology and orchard management (Felker and Inglese, 2003).

In order to obtain a clearer picture of the dynamics of the root system development in cactus pear, more intensive research on the root distribution in plantations of different ages and different soil types have to be carried out. Studies on water-use efficiency of CAM plants at plant community level under field conditions over a whole growing season is of great agronomic significance, both in theory and in practice (Han and Felker, 1997). The aim with this study was, therefore, to determine the root distribution pattern of two two-year-old cactus pear species in the field from in situ rooting profiles. Water-use efficiency was also quantified for these two spineless species (*Opuntia ficus-indica* and *O. robusta*) during the 2003/2004 growing season.

2. Materials and methods

2.1. Site description

The research was conducted in Bloemfontein (28°50′S, 26°15′E, altitude 1350 m), in the semi-arid, 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. 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 in which the plants were cultivated 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 (600–1200). The pH (KCI) was 4.5 over the first 0 to 300 mm layer. Bulk densities of the soil after cultivation were 1260 kg m^{-3} for the A horizon, 1563 kg m^{-3} for the B1 horizon and 1758 kg m^{-3} for the B2 horizon (Snyman, 2000). Planting took place during August 2002 under dry land conditions and the soil was well cultivated (300 mm deep) before planting. No additional fertilisation or cultivation took place over the trial period (2003/2004 season) or the preceding season (2002/2003 season). Weed control was done chemically.

2.2. Treatments

Three plants each of *O. ficus-indica* (L.) Miller (cultivar Morado) (green cladode) and *O. robusta* Wendl. (cultivar Monterey) (blue cladode) were studied. Planting (one-year-old cladodes) took place on 4th August 2002 in two lines, with 10 m spacing between rows and 10 m within a row. The test 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. Cladodes of *O. ficus-indica* were on average 506±46 mm long, 183±15 mm wide and 20±3 mm thick with an average fresh mass of 1406±170 g (means±SE, n=10). Cladodes of *O. robusta* were on average 261±46 mm long, 244±15 mm wide and 15±2 mm thick with an average fresh mass of 1354±130 g (means±SE, n=10). The cladodes were dried for 4 weeks in the shade to allow healing of the wound surface and then planted upright with one quarter of the cladode in the soil. The cladodes were facing North/South.

2.3. Data collection

The root mass and length of plants two years after planting were estimated at 50 mm intervals to a depth of 1200 mm from a sample of three soil cores obtained randomly over a distance of 2500 mm from the stem of each plant at 100 mm intervals. The soil cores were collected with an auger (70 mm diameter) at the end of the growing season. After collecting these samples, the soil between the sampling rows was washed out in the field to determine root distribution visually.

Roots obtained from washing the cores were sieved through a 2 mm mesh sieve followed by a 0.5 mm mesh sieve. Most of the roots were extracted after successive washings of the core. No attempt was made to distinguish between live and dead roots. The roots were then dried at 100 °C for 24 h. The length of the washed roots was measured by using a modified infrared root length counter (Rowse and Phillips, 1974) calibrated by using 10 pieces of string cut at different lengths ranging from 0.5 to 5 m. The regression function used to calculate the root length was $y=0+43.126x$, where y=root counter reading, x=root length (m) and $R^2=0.9555$. An average of six readings were taken from each core. The thickness of 10 randomly selected roots that developed from the planted cladodes, were measured with a vernier caliper.

Water-use efficiency (WUE) is defined as the amount of plant material (dry matter of cladodes) produced per unit of water used (evapotranspiration). Water-use efficiency was calculated as described by Snyman (2005).

Evapotranspiration (Et) was determined by the soil–water balance equation (Hillel, 1971). Rainfall (P) was measured daily with rain gauges. The change in soil water (ΔW) was calculated according to Moore et al. (1988), where (+) indicated an increase and (−) a decrease in the quantity 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 intervals down to a depth of 1 m every month. Due to 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 calculating the water balance (Snyman, 1998). Evapotranspiration was therefore calculated as follows:

$$\mathrm{Et} = P \pm \Delta W$$

2.4. Statistical analysis

The experimental layout was a fully randomised design consisting of two *Opuntia* species and three replicates of each. 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 and root length (Mendenhall and Sincich, 1996). Data on cladode mass and water-use efficiency was analysed using a one-way ANOVA (Winer, 1974). The method of Fisher (1949) was used to calculate $\mathrm{LSD_T}$.

3. Results and discussion

3.1. Root production

For both species, significantly more ($P \leq 0.01$) roots were found in the first 150 mm soil layer than deeper into the soil (Fig. 1). In both cases most roots were found at a depth of 50–100 mm and a distance of 0–200 mm from the stem. This finding is supported by Sudzuki (1995) who found the bulk mass of roots up to a depth of 300 mm. In the 0–50 mm soil layer root mass increased up to a distance of 600 mm from the stem in *O. ficus-indica* and 400 mm in *O. robusta*. At all other depths the root mass decreased with distance from the stem. Over a distance of 2.5 m from the stem, an average of 90% the roots for *O. ficus-indica* and 88% for *O. robusta* were distributed in the top 150 mm soil layer. After two years of growth only a few deep roots were detected directly underneath the stem for species, showing a more shallow and horizontal

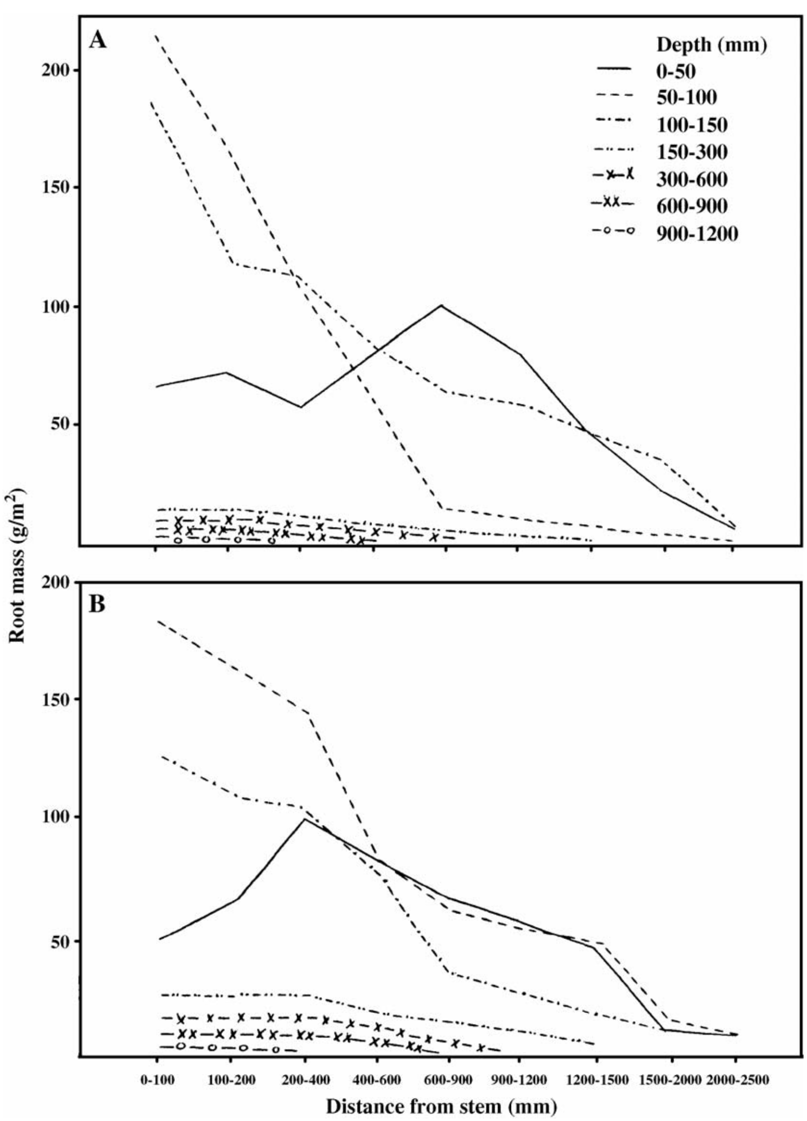

Fig. 1. Root mass (g m^{-2}) for *Opuntia ficus-indica* (A) and *O. robusta* (B) at a depth of 0–1200 mm and distance ranging from 0–2500 mm from the stem. $\mathrm{LSD_{0.01}}$: species = 1.32, depth = 5.41 and depth × distance = 3.16.

root spread. In both species, the root spread in the first 100 mm soil layer extended up to 2500 m away from the stem.

After two years the total root mass, up to a depth of 1200 mm, was calculated to be 239.06 g per plant or kg ha^{-1} for O. *ficus-indica* and 316.62 g per plant or kg ha^{-1} for *O. robusta*. The 32% higher ($P \leq 0.01$) total root mass found in *O. robusta* plants can be attributed to a denser and finer root system (Snyman, 2004a,b, 2005). In the same study area and soil, Snyman (2005) reported a total root mass per plant of 107.5 and 131.6 g or kg ha^{-1} for one-year-old *O. ficus-indica* and *O. robusta* plants respectively. The root mass more than doubled from the first to the second growth season.

It is clear from Fig. 1 that, up to a depth of 100 mm, the roots must have spread further than the 2500 mm from the stem. Efficient chemical weed control is, therefore, important to ensure effective water and nutrient uptake by the cactus pear (Ratsele, 2003). This is confirmed by the observations made after washing out the soil between the sampling rows. It appears that a two-year-old cactus pear plant is not a deep rooted plant. The root system of *O. robusta* generally showed a finer structure than that of *O. ficus-indica* (Snyman, 2005).

3.2. Root thickness

The average diameter of the thickest roots developing directly from the cladodes in the top 150 mm of the soil was 9.1 mm for *O. ficus-indica* and 6.3 mm for *O. robusta*. In the same soil and study area, Snyman (2005) found the largest root diameter for one-year-old plants of *O. ficus-indica* and *O. robusta* to be 3.3 and 3.3 mm respectively, indicating that root diameter could increase two to three times during the second year of growth. The average diameter of all the roots developing from the cladodes was 3.5 mm for *O. ficus-indica* and 2.5 mm for *O. robusta*. The higher root mass in the 50–100 mm soil layer (Fig. 1) could be ascribed to the fact that the thickest roots are found at this depth. According to Snyman (2005) the roots of *O. ficus-indica* were thickest near the stem at a depth of 50–100 mm, while that of *O. robusta* were thickest at a depth of 0–50 mm.

3.3. Root length

As in the case of root mass, the longest roots were found in the 50–100 mm soil layer at distances up to 200 and 400 mm from the stem for *O. ficus-indica* and *O. robusta* respectively (Fig. 2). Snyman (2005) found most roots from one-year-old plants at a depth of 0–50 mm on the same study area. This is an indication that roots spread deeper during the second season. Down to a depth of 150 mm, 81% of the roots were distributed over a distance of 2.5 m from the stem for *O. ficus-indica* and 83% for *O. robusta*. These findings agree 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 occurs chiefly in the upper 300 mm of the soil (Gibson and Nobel, 1986; Nobel, 1995; Snyman, 2005, 2006). Irrigation water is generally applied only to the usual rooting depth, but excessive irrigation can force roots to lower soil layers (Nobel, 2001).

It is well known that cactus pear is a shallow-rooted crop with a fleshy root system, which can spread horizontally from 4 to 8 m from the mother plant after a few years (Nobel et al., 1992; Sudzuki, 1995; Drennan and Noble, 1998). From this study it was clear that the root spread more than 2.5 m from the stem after only two years. For one-year-old plants the roots spread 1.8 m form the stem for *O. ficus-indica* and 1.7 m for *O. robusta* (Snyman, 2005).

In general, the roots of *O. robusta* were longer ($P \leq 0.01$) than that of *O. ficus-indica*, with the exception of the 50–100 mm soil layer. This could be ascribed to fewer lateral roots in *O. robusta* in comparison to *O. ficus-indica* (Snyman, 2004a, b), which allows better adaptation of the latter species to lower rainfall conditions. Lateral roots branching from main roots could account for up to 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).

4. Aboveground biomass production

4.1. Cladode mass

The rainfall over the study period was 392 mm, which is 40% lower than the long-term average for this area. Especially the first half of the growing season received abnormally low rainfall.

The percentage water in the cladodes did not differ significantly ($P > 0.05$) between the two species and ranged between 88.14% and 87.41% for the one and two-year-old cladodes (Table 1). More or less the same values were obtained for the two species by Snyman (2005). According to Lopez-Garcia et al. (2001) the total amount of water stored in the cladodes varies between species and varieties. The water content is also strongly influenced by environmental conditions such as rainfall and can range between 70% and 93% (Lopez-Garcia et al., 2001). According to most researchers cactus cladodes aged 1 to 3 years, are high in water content during summer and early fall and during 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 appears that *O. robusta* retained more water under water stress conditions.

The aboveground biomass production is presented separately for the one and two-year-old cladodes in Table 1. *O. ficus-indica* produced on average seven cladodes during the previous season and 17 new cladodes during the studied season, with an average fresh mass of 1268.14 g per cladode. This is 8% higher than that obtained for the same cultivar by Oelofse (2002). *Opuntia robusta* formed six cladodes during the previous season and 16 new ones during the study period with an average fresh mass of 1057.61 g per cladode. The fresh mass of the previous season's production was 94.00 g per cladode higher than that of the studied season for *O. ficus-indica* and 113.10 g per cladode higher for *O. robusta*. After two growing seasons *O. ficus-indica* and *O. robusta* produced 28.65 and 21.59 kg per plant or ton per hectare fresh mass respectively. This much higher than

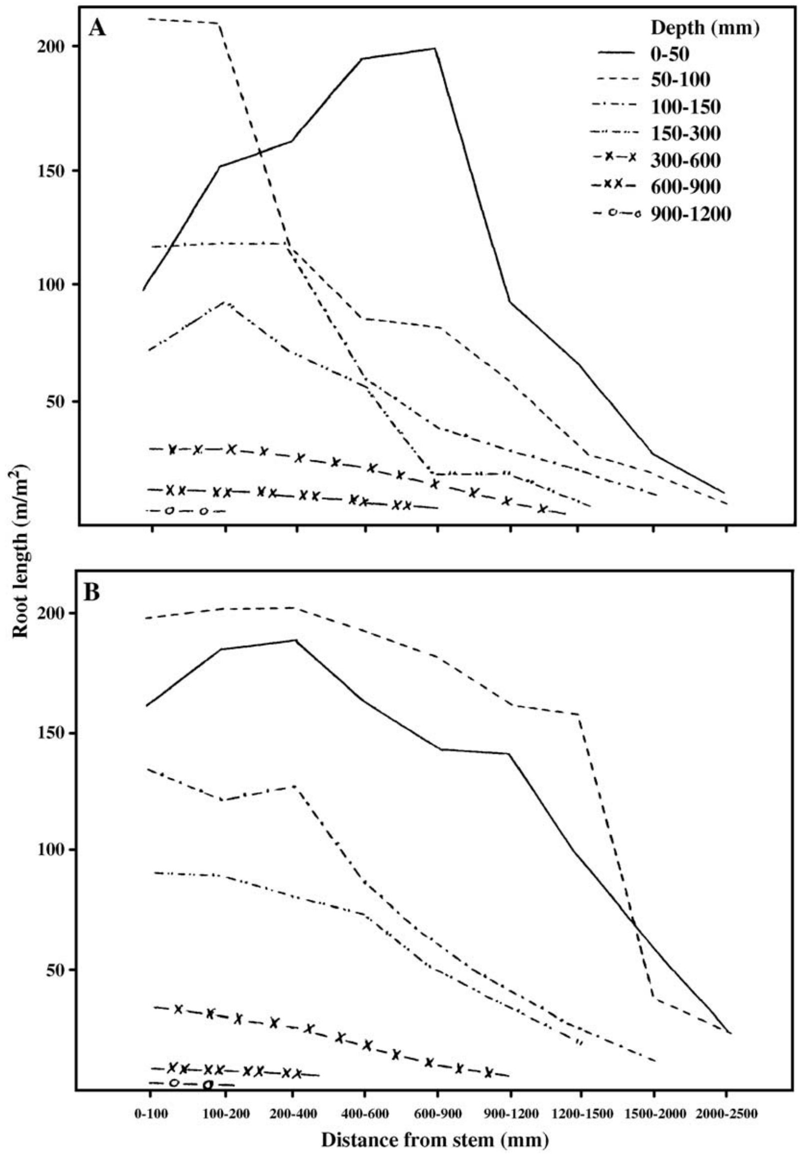

Fig. 2. Root lengths (m m^{-1}) for *O. ficus-indica* (A) and *O. robusta* (B) at a depth of 0–1200 mm and distance ranging from 0–2500 mm from the stem. $LSD_{0.01}$: species = 11.37, depth = 10.22 and depth × distance = 4.19.

the 5.26 ton per hectare obtained from two-year-old *O. robusta* (cultivar Monterey) plants in the Karoo (De Kock, 1980, 2001). Oelofse (2002) reported a fresh mass production of 78.84 kg per plant for five-year-old *O. ficus-indica* (cultivar Morado) pants.

Although *O. robusta* had the longest and heaviest roots, its aboveground dry mass was lower ($P < 0.01$) than that of *O. ficus-indica*. This could be ascribed to a strategy of *O. robusta* that favours survival rather than vegetative growth and is therefore

Table 1
Average fresh and dry weight and water content for one- (1) and two-year-old (2) cladodes, as well as the water-use efficiency (WUE) of *O. ficus-indica* and *O. robusta*

Species	Cladode mass				Water content in cladodes (%)		WUE (kg ha^{-1} mm^{-1})
	Fresh (g $cladode^{-1}$)		Dry (g $plant^{-1}$ or kg ha^{-1})				
Age (years)	1	2	1	2	1	2	2
O. ficus-indica	1315 ± 106	1221 ± 101	945 ± 81	2462 ± 81	88.02 ± 1.11	88.14 ± 1.02	6.52
O. robusta	1114 ± 98	1001 ± 90	701 ± 71	2000 ± 72	87.41 ± 1.01	87.51 ± 1.26	5.39
LSD	55.14	54.12	43.15	42.16	3.21	3.05	0.39

Data are means of seasonal growth and S.E. of 3 plants. Least significant differences (LSD) was calculated at a 1% level.

more adaptable to prolonged drought conditions than *O. ficus-indica*. Although extremely high (50 ton dry mass per hectare per year) productivity is possible for *O. ficus-indica* under ideal conditions, the predicted productivity of 5 to 6 ton per hectare per year under water-limited conditions can still surpass productivity of C_3 and C_4 species used traditionally for forage (Nobel, 2001). The production of 3407.38 g per plant obtained in this study for *O. ficus-indica* and 2701.88 g per plant for *O. robusta*, compared well with the fodder production results obtained by Oelofse (2002) and Potgieter (1998, 2000). 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; De Kock, 1998; Potgieter and Carstens, 1996). Cactus pear is able to produce up to 5 to 10 ton aboveground dry mass per hectare per year in arid zones, 10 to 20 ton in semi-arid areas and 20 to 30 ton in sub-humid zones, under close to optimum intensive cultivation (Monjauze and Le Houérou, 1965; Franclet and Le Houérou, 1971; De Kock and Aucamp, 1970; De Kock, 1980; Steynberg and De Kock, 1987; Nobel, 1988; Le Houérou, 1992a,b). Under such conditions, productivity is about 10 times higher than in standard rangelands (Le Houérou, 1994). In less than optimal soil and management conditions (no cultivation, no fertilisation) yield is still 3 to 5 times higher than in standard rangelands (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.

4.2. Water-use efficiency (WUE)

The WUE of *O. ficus-indica* was significantly ($P \leq 0.01$) higher than that of *O. robusta* (Table 1). This finding is in spite of the fact that vesicular arbuscular mycorrhizal fungi could enhance water uptake in *O. robusta* (Pimienta-Barrios et al., 2002). The WUE after two years was calculated to be 6.52 kg ha^{-1} mm^{-1} for *O. ficus-indica* and 5.39 kg ha^{-1} mm^{-1} for *O. robusta.* Rain-use efficiency was in the order of 2 to 5 kg DM ha^{-1} mm^{-1} in unspoilt (good ecological condition) arid rangelands (Le Houérou, 1994; 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 a WUE of only 7.4 kg DM ha^{-1} mm^{-1} from cactus pear in a 300 mm rainfall area in Argentina. According to them, this low WUE was probably due to a lack of proper weed control. 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). Han and Felker (1997), who studied three- and four-year-old plantations, argued that the water-use efficiency of cactus pear is among the highest of any plant species (including C_3 and C_4) that has been measured under long-term field conditions. The high WUE (62 kg DM ha^{-1} mm^{-1}) from a four-year-old plantation recorded by Han and Felker (1997) was the result of the high biomass production in the fourth year. Maximum WUE's of 40 to 60 kg DM ha^{-1} mm^{-1} have been attained with cactus pear in semi-arid and sub-humid climates under irrigation and cultivation with fairly high levels of fertilizing and/or manuring close to the biological limit for CAM species (Le Houérou, 1984; Nobel, 2001; Fisher and Turner, 1978). 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} found by De Kock and Aucamp (1970) and De Kock (1965, 1980, 1998, 2001) in arid areas, are questionable due to the fact that it is close to the biological limit for CAM species. According to Felker and Russell (1988) cactus pear is about 3 to 5 times more efficient in water-use than C_3 and C_4 plants such as maize, due to its Crassulacean Acid Metabolism (CAM) pathway (Nobel, 1995, 1997, 2001) and can therefore be cultivated with great success in drier areas.

4.3. Root/cladode ratio

The calculated root/cladode ratio (dry mass based) for *O. robusta* of 0.11, was significantly ($P \leq 0.05$) higher than the 0.07 for *O. ficus-indica*. The root/cladode ratios for *O. ficus-indica* (ranging from 0.07 to 0.14) obtained by Drennan and Noble (1998) and Nobel (2001) for mature plants, supported the very low values found in this study. In one-year-old plants Snyman (2005) calculated root/cladode ratios of 0.21 for *O. robusta* and 0.13 for *O. ficus-indica*. The roots comprise 11% of the total plant biomass for *O. robusta*, compared to only 7% for *O. ficus-indica*, which could be due to the finer root system of the former species.

5. Conclusion

The cactus pear with its shallow root system, occurring predominantly in the upper soil layers (0–150 mm) where soil–water content is heterogeneous, is well adapted to arid and semi-arid areas. It can take up water efficiently after light rain showers and therefore has the potential of improving the productivity of arid and semi-arid regions. After two years no deep tap root system developed in and both species was characterized by a shallow, horizontally spread root system. A deeper root system might develop after a few years depending on the type of soil and cultivation management.

After only two years the root systems of both species can spread as far as 2.5 m from the stem. Cultivation in-between rows must therefore be carefully planned to avoid root damage. Due to the shallow root distribution, cultivation around the plants must be avoided and for sustainable production chemical weed control is preferable. These practices are especially important during the early stage of plant development. Fertiliser must also be applied in small quantities over the season to avoid damage to the shallow root system. *Opuntia robusta* has a finer root system, higher root mass and longer roots than *O. ficus-indica*, which makes it more adaptable to drier conditions. Its various water-conserving strategies lead to a need for a small root system; indeed roots comprised only about 7% and 11% of the total plant biomass for *O. ficus-indica* and *O. robusta* respectively.

Cactus pear is useful not only because it can withstand drought, but also due to its efficient water-use and high productivity. In this study the aboveground dry mass production of two-year-old plants was already 3407 kg ha^{-1} for *O. ficus-indica* and 2702 kg ha^{-1} for *O. robusta*. The WUE of cactus pear can be about three times higher than that of C_3-plants and five times higher than C_4-plants. After only two years *O. ficus-indica* already produced 6.52 kg ha^{-1} for each mm water used, compared to 5.39 kg ha^{-1} mm^{-1} by *O. robusta*. Cactus pear is therefore particularly attractive as an animal feed in arid zones because of its efficient use of water in relation to biomass production.

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