Frost Sensitivity of *Opuntia ficus-indica* and *O. robusta* in a Semiarid Climate of South Africa♦

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ABSTRACT

There is a lack of information on the adaptability of different spineless cactus-pear cultivars under a range of environmental conditions. A study was conducted to evaluate the cold/frost tolerance of 10 cultivars of *Opuntia ficus-indica* (L.) Miller and one cultivar of *O. robusta* Wendl. over two growing seasons (2001/2002 to 2002/2003) in a semiarid climate of central South Africa. The cultivars of *O. ficus-indica* included Algerian, Gymno Carpo, Morado, Nudosa, Roedtan, Sicilian Indian Fig, Tormentosa, Van As, X28 and Zastron. The species *O. robusta* was represented by the cultivar Monterey. Frost damage was estimated visually, integrating the individual cladode damage over the entire plant. Frost damage only occurred in spring (late-seasonal frost: August to October) after a combination of frequent successive nights of freezing temperatures (between -2.06 and -9.6^{o}C) when the plants already started sprouting. In winter, during dormancy, no plants suffered any frost damage at freezing temperatures as low as -8^{o}C. For the one-year-old plants (2001/2002 season), Zastron suffered the most frost damage of all cultivars, with Monterey and X28 most tolerant to freezing temperatures. Algerian, Sicilian Indian Fig, Van As and X28 suffered 100% frost damage for the two-year-old plants (2002/2003 season). For the same season, frost damage to Tormentosa and Roedtan was 98%, 97% for Nudosa, 96% for Morado, and 95% for Gymno Carpo. The remaining two cultivars also suffered frost damage but to a lesser degree (Monterey 41% and Zastron 85%). The reason cactus-pear cultivars were killed can be debated, as there are other successful cactus-pear plantations in the study area. It is believed that freezing temperatures during springtime did not single-handedly cause the death of the cactus-pear plants, but water stress, plant health, and plant phonological stage could also have a bearing on that. To successfully cultivate cactus pear, whether for fodder or fruit production, it is important to select areas that are not prone to severe and late-season frost.

Keywords: Frost damage, *Opuntia ficus-indica, O. robusta*, phonological stage, plant health, semiarid, water stress

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1. INTRODUCTION

Developing countries of the world are facing huge challenges in providing enough food for their ever-escalating populations of people and animals. In the arid and semiarid regions of Southern Africa, where annual rainfall ranges from 150 to 300 mm, animal feed scarcity is also common (De Kock, 1965; Snyman, 1998, 2004a). The stock industry suffers major losses as a result of shortage of food during droughts and harsh winters in these areas. The *Opuntia* cactus is a xerophyte of about 200 to 300 species (Moßhammer *et al.,* 2006) which grows mainly in arid and semiarid zones, is due to their remarkable genetic variability, ecologically adapted to fill this changing gap in feed scarcity. Cactus pear is also a drought-resistant fruit crop (Brutsch, 1997; Gugliuzza *et al*., 2000; Ratsele, 2003; Galizzi *et al*., 2004). In many areas cactus-pear fruit is an important food source for satisfying the nutritional needs of people in their countries of origin (Schirra, 1996; Le Houérou, 1996) for about 3 to 4 months of the year (Inglese *et al*., 1995; Potgieter, 1995). Knowledge of its chemical composition, nutritional value and effect on human health has lead to a recent increase in the consumption of cactus pear (Livrea and Tesoriere, 2006; Moßhammer *et al.,* 2006). There is still scope for increased production on commercial scale for local and export markets of cactus-pear fruit (Feugang *et al.,* 2006). Prices obtained for cactus-pear fruit on the national fresh produce markets of South Africa for example, compare very favorably with those of more common fruits, such as apple, peach, and orange (Brutsch, 1994; Snyman, 2003). The value of spineless cactus pear in subsistence agriculture has been well documented (Le Houérou, 1992a; Brutsch, 1979, 2000; Barbera, 1995). In the future, declining water resources and global climate change may even increase *Opuntia* spp. importance as an effective food production system including both fruits and vegetable parts (Stintzing and Carle, 2005; Moßhammer *et al.,* 2006).

Cactus-pear species differ with respect to yield, quality, and also in sensitivity to biotic and abiotic factors, which may affect growth and productivity (Pimienta-Barrios *et al.,* 1993; Barbera *et al*., 1993; Le Houérou, 1996; Wang *et al*., 1997; Mizrahi and Nerd, 1999; Lahasasni et al., 2003; 2004; Snyman, 2004b; Felker *et al*., 2005). Although the decade of the 1990's has seen great expansion in plant physiology and orchard management of cactus pear (Nobel, 1997; Felker and Inglese, 2003), still little horticultural research has been devoted to its productivity under different environmental conditions and management systems (Inglese, 1995; Snyman, 2007). It is increasingly commercialized (Felker and Inglese, 2003) and there is, therefore, a need to evaluate different characteristics to improve the farmer's selection of cultivars and productivity (Wang *et al*., 1997; Oelofse, 2002). Cold or frost tolerance of a given cactus-pear species is difficult to assess in a precise way as it depends on a number of local factors (Nobel 1988, 1991, 1994, 2001; Le Houérou 1994, 1996; Valdez-Cepeda *et al*., 2001). According to Le Houérou (1994) there are no serious cold tolerance problems involved for cactus pear in most arid and semiarid areas. In contrast, Guevara and Estevez (2001) suggested that the cold temperatures of winter are the major limitation to cultivation of cactus pear in some areas. There is, therefore still a need for more intensive studies on the adaptability of this plant under different climatic conditions. Hybridization of cold-tolerant native species with highly productive but cold-sensitive commercial species should be a major objective of breeding programmes to expand cultivation of *Opuntia* (Gregory *et al*., 1993, Nobel and Loik, 1993; Mizrahi *et al.,* 1997, Wang *et al.,* 1997; Mondragón-Jacobo and Perèz-González, 2000; Valdez-Cepeda *et al.,* 2001). The most important *Opuntia* cultivars are generally irreversibly damaged at temperatures of -5 to $-12^{o}C$ (Nobel, 1990; Nobel and Loik, 1993). Cold hardiness of *Opuntia* spp. used for fruit, forage, or vegetable production has also been reported by Russell and Felker (1987); Gregory *et al.* (1993), Parish and Felker (1997), Wang *et al*. (1997) and Guevara *et al.* (2000). According to Le Houérou (1971; 2002) *Opuntia ficus-indica* is among the mildly cold-tolerant species (m > $3^{o}C$) and *O. robusta* is a fairly frost tolerant species (m > $1^{o}C$). The aim of this study was, therefore, to evaluate the frost or cold tolerance of different *Opuntia ficus-indica* and *O. robusta* cultivars in a semiarid climate of central South Africa.

2. MATERIALS AND METHODS

2.1. Site Description

The research was conducted on the farm Welgegund (28° 53′ S; 26° 56′E; altitude 1,304 m) near a small town called Verkeerdevlei, Free State Province, in South Africa, 60 and 90 km northeast of Glen Agricultural College and Bloemfontein, respectively. Other climatic data used in this study was obtained from a new weather station established in January 2001 close to the study area. Long-term data was obtained from Glen weather station (70 years data) (Botha, 1964) and stored on the national climatologically weather database of the Institute for Soil, Climate and Water of the Agricultural Research Council (ARC) in South Africa. All climatic data were obtained from automatic recorders on an hourly basis. The months December, January, and February are the hottest months, with long-term mean temperatures of 21.9, 22.7, and 22.0°C, respectively (Table 1). In general the winters are cold with mean minimum temperatures for the months June and July lower than 0°C. The first frost can be expected as early as 23 March (Botha, 1964). The mean frost set-in date is 28 April and last date that frost can be expected is 3 October (Botha, 1964). The variation in the end date of frost is greater than that of the frost set-in date (Botha, 1964). According to Botha (1964), the average maximum temperatures for Glen are 23.8, 20.2, 17.5, 16.4, 19.6, 22.8, and 25.8°C for April, May, June, July, August, September and October, respectively, and the average minimum temperatures for these months are 7.4, 2.4, –1.3, –2.4, 0.8, 4.7, and 8.3°C, respectively, over the long-term (Table 1).

Table 1. The long-term mean shelter and surface temperatures of Glen for the different months (National climatologically weather database of the Institute for Soil, Climate and Water 1922-1990) (Botha, 1964).

Month	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Mean Temperature (°C)	Mean Grass Minimum Temperature (°C)
July	17.3	–1.6	7.7	–4.4
August	20.4	0.7	10.5	–2.3
September	24.5	4.8	14.4	2.1
October	27.1	9.2	18.0	5.9
November	28.1	11.7	19.9	8.8
December	30.0	13.9	21.9	11.1
January	30.6	15	22.7	12.2
February	29.7	14.6	22.0	12.1
March	27.2	12.3	19.7	9.8
April	23.8	7.4	15.5	4.7
May	20.2	2.4	11.4	0.0
June	17.5	–1.3	7.9	–3.8

The experimental site is located in the semiarid (summer mean average rainfall of 548 mm) region of South Africa. The probability of rainfall higher than 50% is expected from October to April. The highest rainfall of 85 mm occurs in March. The rainfall reliability is only for seven months higher than 50%, with the highest reliability of 58% in January (Botha, 1964). The highest mean rain days of 10 are also in March (Table 2).

Table 2. The long-term rainfall characteristics of Glen for the different months (National Climatological Weather Database of the ARC, Institute for Soil, Climate and Water 1922-1990) (Botha, 1964).

Month	**Mean Rainfall (mm)**	**Reliability (%)**	**Mean Rain Days 1914-1964 (Botha, 1964)**
July	8.7	20.63	2.1
August	11.8	18.13	2
September	19.1	20.68	2.6
October	47.1	51.15	5.5
November	64.3	52.41	8.2
December	66.5	51.55	8.1
January	81.8	58.01	9.8
February	82.4	57.81	9.6
March	85.2	56.15	10.1
April	52.3	51.34	6.4
May	19.3	36.01	4.6
June	9.5	27.82	2.0

The soil is a sandy loam of the Valsrivier form (Aliwal family-11220) (Soil Classification Working Group, 1991). The average soil texture for 0-300 mm, 300-800 mm and deeper than 800 mm were 32%, 54%, and 56% clay, respectively. The decrease in sand percentage, phosphorus and zinc, and increase in clay percentage, electrical conductivity (EC), pH, Ca, Mg, K, and Na with increasing depth of the soil is not unusual (Table 3). Soil samples for laboratory analysis were collected from the three different horizons (0 to 300, 300 to 800 and >800 mm). Samples for analysis were obtained from two blocks (A and B) of 1.5 ha each, using a soil auger. According to Wessels (1988), the optimal levels of macro-elements in the soil for cactus plants should be 150 mg kg^{-1} for K, 12-15 mg kg^{-1} for P, and 80-100 mg kg^{-1} for Mg. The values for K and Mg (Table 3) were above the recommendations while P was low compared to the record provided by Wessels (1988).

Table 3. Laboratory soil analysis for sand, clay, electrical conductivity (EC), soil acidity (pH), calcium (C), magnesium (Mg),potassium (K), sodium (Na), phosphorus (P) and zinc (Zn) for different depths in the experimental site at Welgegund.

Depth (mm)	**Clay** %	**Sand** %	**EC** mSm^{-1}	**pH**	**Ca** mg kg^{-1}	**Mg** mg kg^{-1}	**K** mg kg^{-1}	**Na** mg kg^{-1}	**P** mg kg^{-1}	**Zn** mg kg^{-1}
Profile (0-300)	32.00	68.00	12.50	4.40	761.50	324.50	350.00	31.00	9.52	0.45
Profile (300-800)	54.00	46.00	19.00	5.95	1823.50	920.50	106.00	96.50	1.04	0.38
Profile (>800)	56.00	44.00	61.00	7.65	9298.50	1430.50	144.00	232.00	0.18	0.0

2.2. Treatments

The cactus-pear plant material (one-year-old cladodes) used during the study was collected on 8 August 2001 from Gillemberg Farms (Mokopane) in the Limpopo province of South Africa. Cladodes were washed with a Parathion dosage (60 ml per 100 litres water) to reduce possible incidences of cochineal infection before planting. The two *Opuntia* species used were *Opuntia ficus-indica (L.) Miller* and *O. robusta Wendl.* The 10 cultivars for the first-mentioned species were Algerian, Gymno Carpo, Morado, Nudosa, Roedtan, Sicilian Indian Fig, Tormentosa, Van As, X28 and Zastron (Figure 1). Monterey was the only cultivar used for *O. robusta* (Figure 1). The selection of cultivars was based on their adaptability and production potential according to research and literature (Potgieter, 1995). *Opuntia ficus-indica* is believed to have a higher cladode production than *O. robusta* (Guevara *et al*., 2000; Oelofse, 2002; Snyman, 2005, 2007). *Opuntia ficus-indica* can be used either for fruit or cladode production. *Opuntia robusta* is traditionally a fodder plant compared to *O. ficus-indica*.

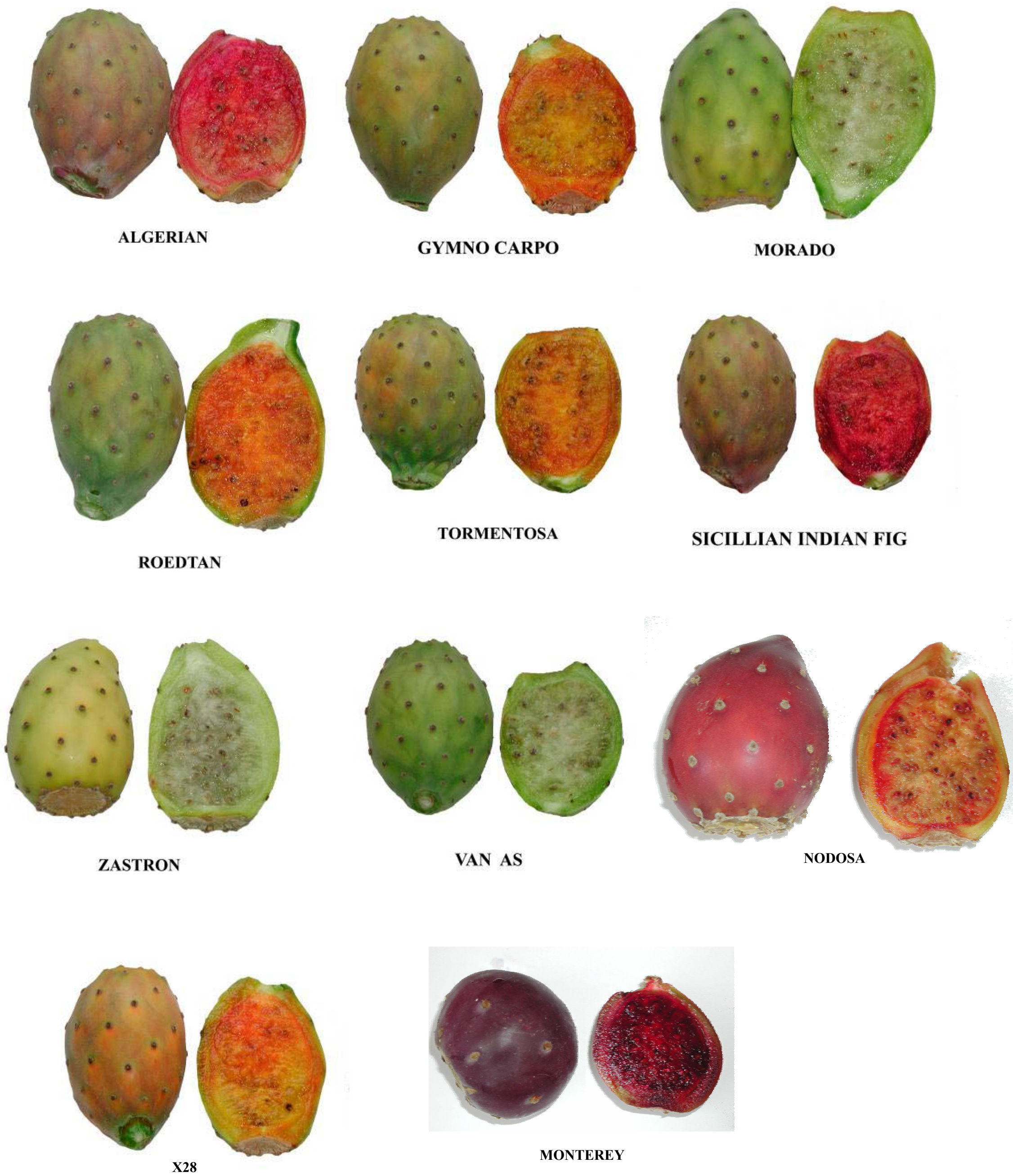


Figure 1. Internal and external views of longitudinal sections of fruit of different cultivars studied.

The experimental layout was a randomized block design consisting of cultivar, replicated 6 times (3 times per block) on 66 plots. Each plot consisted of 20 plants, planted in 2 rows of which 10 plants were randomly selected, marked, and used as data plants. The cladodes were spaced 5 m apart between rows and 2 m apart within the row. The plant density was 1,000 plants per hectare. Cladodes were planted on 18 October 2001 (70 days after cut) on a deeply tilled (300 to 400 mm) and well-disked soil, with no impervious soil layers present. Therefore, no deep ripping was done. No visible dehydration process occurred in the cladodes before planting. The cropping history of the field was maize and wheat cultivation over a few years. For a whole year, no cultivation took place before starting the cactus-pear study. The cladodes were planted upright, one-third into the soil. The row direction was North-South.

Liming to raise the soil pH, as per laboratory analysis used during the study, was 4 t (Calcite lime) per hectare. Super phosphate was added at 300 kg ha^{-1} (30 kg P ha^{-1}), with 75 kg ha^{-1} of N-fertilizer applied with establishment. Unfortunately, no topdressing of fertilizer was applied over the study period due to management problems.

A tractor-drawn disc cultivator was used to remove the weeds between the rows to reduce competition for water and nutrients. Chemical weed control (on plant row and also between rows) in the second season of the study was done using glyphosphate. To ensure that the chemical did not reach the plants, the cactus plants were covered by plastic containers before hand-spraying the herbicide.

2.3. Data Collection

As part of a larger study on the vegetative measurements, frost damage of cladodes was visually estimated, integrating the individual cladode damage over the entire plant and expressed as percentage. A 100% frost damage indicated that the plant was dead to ground level and 0% damage indicated that the plant had suffered no damage. These values were used to indicate the susceptibility of cultivars to frost damage. Frost damage was estimated about one month after the freeze, i.e., when the extent of necrosis from the freezing weather was fully expressed. Frost damage was observed three times, namely on 16 August 2002, 4 October 2002, and between 15 and 27 August 2003. Although this research project was planned for longer than a few years, the plants were, unfortunately, totally killed by frost after only two growing seasons (2001/2002 to 2002/2003).

2.4.Statistical Analysis

All data were analyzed using a one-way of variance ANOVA analysis (Winer, 1974) at 95% confidence level. Data for different frost dates and/or years were analyzed separately. The Number Cruncher Statistical System (2000) software package was used in the analysis (Hintze, 1997).

3. RESULTS

3.1. Climate

The monthly mean maximum temperatures for April, May, and June of 26.3, 20.1, and 16.3°C in the 2001/2002 growing season and 27.1, 20.4, and 17.9°C in the 2002/2003 growing season, respectively (Figure 2), recorded during the study (Figure 2), were not abnormal, compared to the long-term averages (Table 1). During the study, the recorded mean monthly minimum temperatures of –0.4, –3.3 and –0.1°C in the 2001/2002 growing season for the months April, May, and June, respectively, were below the long-term levels. During the 2002/2003 growing season, monthly minimum temperatures of 10.1, 2.1, and 2.9°C for April, May and June were recorded, which are not unusual when compared to the long-term readings (Table 1). For springtime (August to October) the recorded mean monthly minimum temperature of –3°C in the 2003/2004 growing season for the month August (Figure 2), is far below the 0.7°C long-term level (Table 1). In contrast, for the month of August 2002 the recorded monthly minimum temperature was 5°C (Figure 2) comparing to the only 0.7°C long-term value (Table 1). The number of hours of freezing weather and the absolute minimum temperatures for the coldest months, including minimum temperatures up to ≤–9°C (3°C intervals) for the 2001/2002 and 2002/2003 seasons, are shown in Table 4. Freezing weather totaled 343 hours in 2001/2002 and 447 hours in 2002/2003. There were more hours with temperatures of ≤–6°C in the 2002/2003 season than the 2001/2002 season. Details on the temperatures attained specifically during the late-seasonal freezes and the freezing periods that occurred with frost damage in 2001/2002 and 2002/2003 seasons are presented in Table 5.

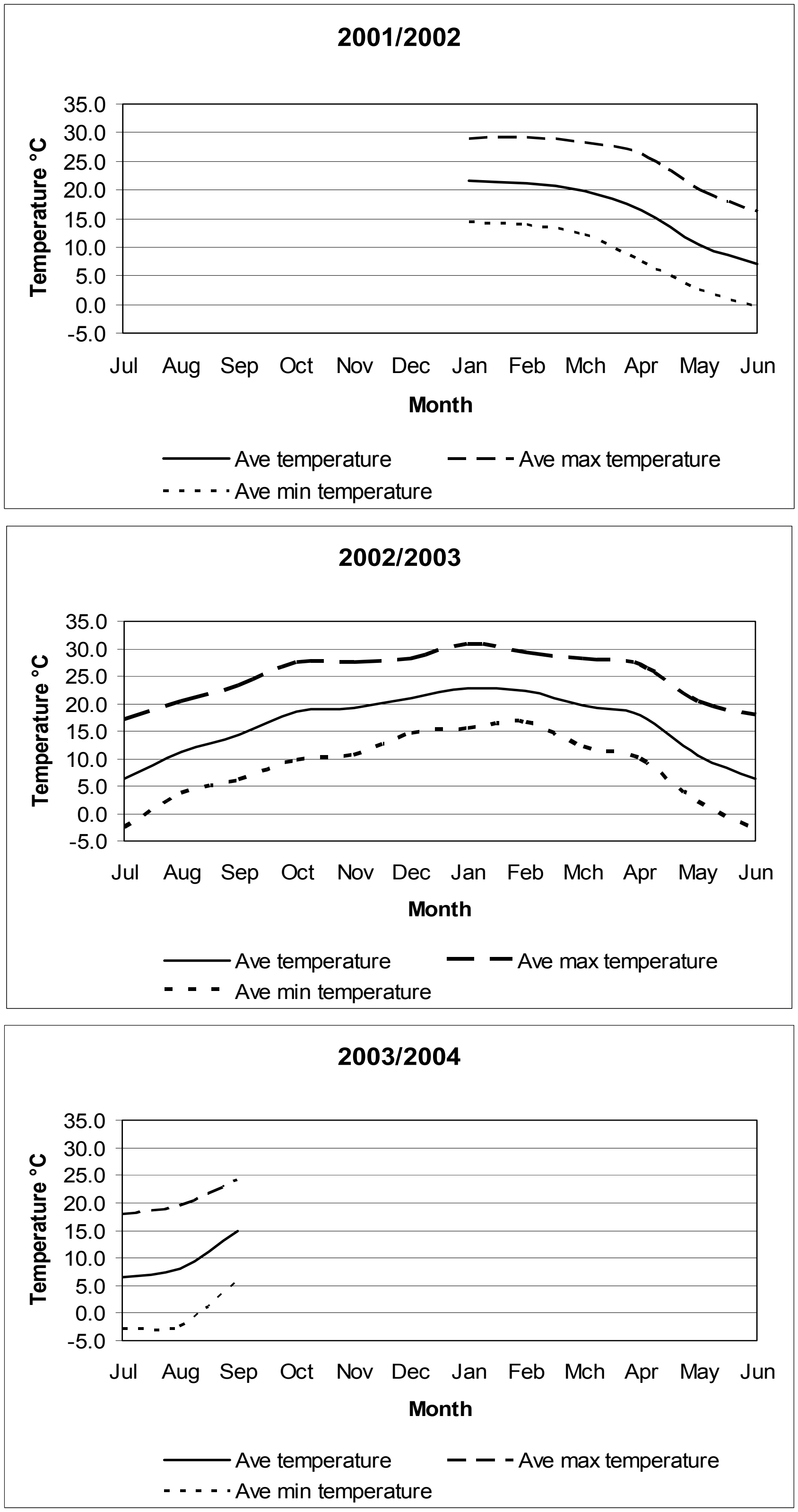


Figure 2. Mean monthly temperatures (°C) of study site for the 2001/2002, 2002/2003, and 2003/2004 growing seasons.

Table 4. Duration of freezing temperatures (hours) and absolute minimum temperatures occurring at the study site in 2001/2002 and 2002/2003 seasons.

Year	**Number of Hours of Occurrence of Temperatures**				**Absolute Minimum Temperature (°C)**
	0°C	**–3°C**	**–6°C**	**–9°C**	
2002					
May	34	3	0	0	–3.3
June	100	15	0	0	–4.7
July	189	67	7	0	–7.5
August	16	2	0	0	–3.7
September	0	0	0	0	0.6
October	4	0	0	0	–2.1
2003					
May	33	4	0	0	–3.6
Jun	196	63	11	0	–8.1
Jul	153	60	2	0	–6.3
Aug	57	31	11	3	–9.6
Sep	8	0	0	0	–1.9

Table 5. Freezing temperatures occurrence with frost damage during springtime for the 2001/2002 and 2002/2003 seasons.

Date	**Number of Hours of Occurrence of Temperatures**				**Absolute Minimum Temperature (°C)**
16/08/02	7	2	0	0	–3.69
04/10/02	3	0	0	0	–2.06
15/08/03	*	*	*	*	–4.98
16/08/03	*	*	*	*	–3.93
17/08/03	*	*	*	*	–8.07
18/08/03	*	*	*	*	–9.63
19/08/03	*	*	*	*	–8.05
20/08/03	*	*	*	*	–3.34
21/08/03	12	9	6	3	–9.63
22/08/03	8	8	5	0	–8.05
23/08/03	7	2	0	0	–3.34
25/08/03	8	3	0	0	–4.25
27/08/03	8	5	0	0	–4.93

* not available

The total rainfall of 677 mm recorded during the 2001/2002 growing season (Figure 3) was 24% higher than the long-term (547.5 mm) for Glen (Table 2 and Figure 3). The total rainfall of 93.7 mm recorded for April, May, and June during the first season of the study (2001/2002) was also higher (16%) than the long-term means for the same months. During the 2002/2003 growing season, the total rainfall of 484.1 mm was lower (12%) than the long-term levels for Glen. The total rainfall of only 5.3 mm for April, May, and June received during the 2002/2003 growing season, was far below (94%) the long-term means for the same months.

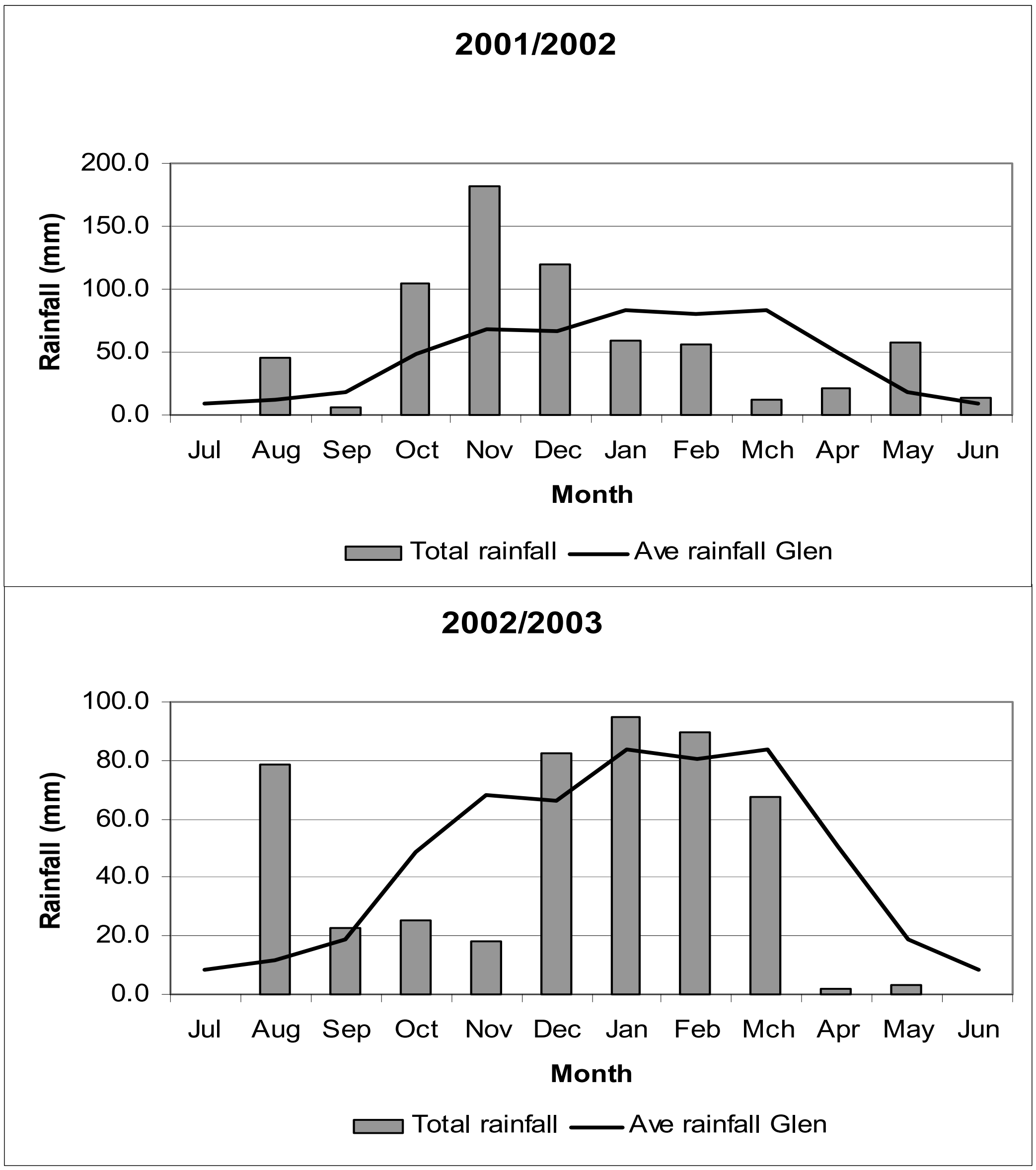


Figure 3. Long-term rainfall (mm) for Glen and total rainfall (mm) at study area for the 2001/2002 and 2002/2003 growing seasons.

3.2. Frost Damage

The average percentage frost damage per plant for the different cultivars and frost damage dates are illustrated in Table 6. During both seasons some cultivars were significantly more sensitive to frost damage than the others. For the 2001/2002 season, Zastron suffered the most ($P<0.01$) frost damage of all the cultivars. Other cultivars that were also sensitive to frost over the first growing season were Algerian and Tormentosa. The cultivars of the one-year-old plants that were less sensitive to frost included Monterey and X28. Although the frost damage was not as severe on the frost date of 4 October 2002, Nudosa suffered significantly ($P<0.05$) more frost damage than the other cultivars, with the exception of Zastron and Sicilian Indian Fig. The plants of all cultivars recovered from the frost damage of the 2001/2002 season. The two-year-old plants suffered frost damage to a great extent with the exception of Monterey. The frost damage of the last-mentioned cultivar was only 41.3% compared to up to 100% for most other cultivars.

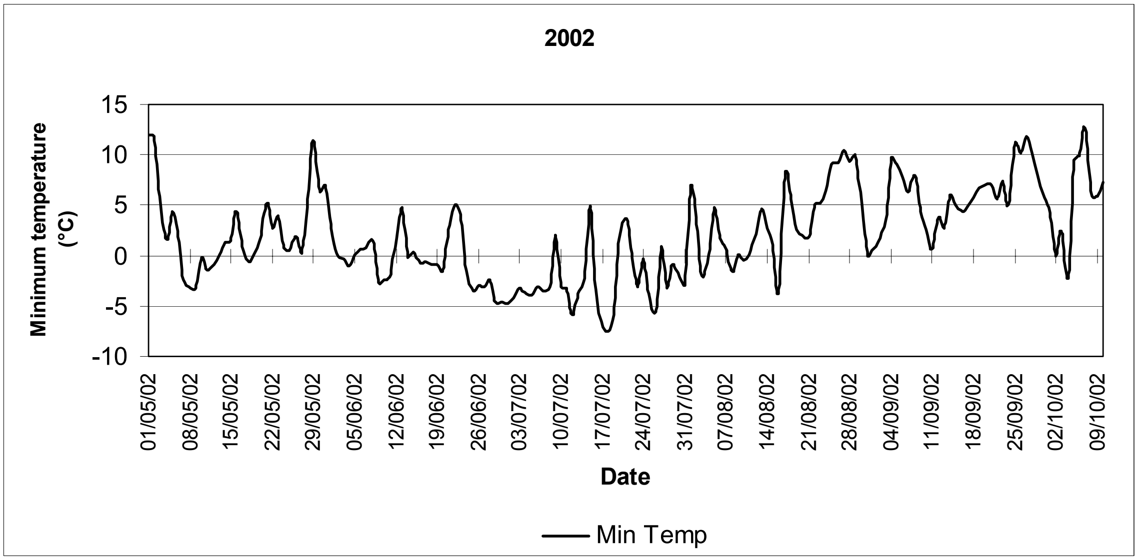
Table 6. Mean (±SE) frost damage (%) to cladodes measured at different dates for each cultivar. Means within a frost damage date with different superscripts differ significantly ($P\leq0.01$).

Cultivars	**Frost Damage Dates**		
	16/08/02	**04/10/02**	**15/08/03 to 27/08/03**
Algerian	40.1 (±3.14)^{b}	2.1 (±0.6)^{c}	100 (±11.11)^{a}
Gymno carpo	35.2 (±2.16)^{b}	2.2 (±0.5)^{c}	95.1 (±9.14)^{a}
Monterey	20.5 (±1.11)^{b}	2.5 (±0.5)^{c}	41.3 (±6.66)^{a}
Morado	30.2 (±2.15)^{b}	2.0 (±0.5)^{c}	96.1 (±8.14)^{a}
Nudosa	30.2 (±2.16)^{b}	4.0 (±0.5)^{c}	97.2 (±9.15)^{a}
Roedtan	33.1 (±3.14)^{b}	3.1 (±0.6)^{c}	98.1 (±10.22)^{a}
Sicilian Indian Fig	28.6 (±2.22)^{b}	3.4 (±0.6)^{c}	100 (±12.12)^{a}
Tormentosa	38.9 (±3.66)^{b}	1.6 (±0.4)^{c}	98.4 (±14.14)^{a}
Van As	35.2 (±3.14)^{b}	1.3 (±0.3)^{c}	100 (±12.96)^{a}
X28	22.1 (±2.12)^{b}	2.0 (±0.4)^{c}	100 (±13.12)^{a}
Zastron	43.2 (±3.79)^{b}	3.4 (±0.4)^{c}	85.1 (±9.14)^{a}

Only parts of the mother cladodes were still alive of those cultivars that suffered close to 100% frost damage at the end of the 2002/2003 growing season. The frost damage of Tormentosa, Roedtan, Nudosa, Morado, Gymno Carpo, and Zastron ranged between 85% and 98%. Algerian, Sicilian Indian Fig, Van As, and X28 suffered 100% frost damage. *Opuntia ellisiana*, although the slowest growing of all spineless *Opuntias* (Han and Felker, 1997), is the only spineless *Opuntia* fodder species that is completely cold hardy and could be a useful forage variety in locations that are too cold for *O. robusta* and *O. ficus-indica* (Han and Felker, 1997; Felker, 1995; Wang *et al.,* 1997; Guevara *et al*., 2003).

4. DISCUSSION

It was evident that the studied cactus-pear cultivars would be killed by frequent successive nights of temperatures below freezing point. *Opuntia* cultivars are generally irreversibly injured at temperatures between –5 and –10°C (Monjauze and Le Houérou, 1965; Franclet and Le Houérou, 1971; Russell and Felker, 1987; Nobel, 1988, 1991; Nobel and Loik 1993; Le Houérou 1994), even if those temperatures last only for a few minutes (Houérou, 1996). *Opuntia robusta* is somewhat more frost tolerant (–12°C) than *O. ficus-indica* (Le Houérou, 1992b; Guevara *et al*., 2000). The cultivar Monterey of the species *O. robusta* also showed less sensitivity to frost damage in this study. In contrast, Felker (1995) and Wang *et al*. (1997) reported that *O. robusta* does not tolerate frost (–12°C) as observed in Texas. Le Houérou (1994) reported that *Opuntia ficus-indica* survived absolute minimum temperatures which dropped to –12 and –16°C. In Texas (Gregory *et al*., 1993; Wang *et al*., 1997) and the Mendoza plains (Guevara and Estevez, 2001), the cold winter temperatures are the major limitation to cultivation of cactus. When night temperatures on these Mendoza plains dropped to –17°C the young cladodes from nine-month-old plants of *O. ficus-indica* were almost destroyed, while three-year-old plants of *O. ficus-indica* and *O. robusta* had mean frost damage of 25 and 2%, respectively. Guevara *et al.* (2000) also argued that due to high frequency of absolute minimum temperatures in some areas, it appears to be necessary to protect the plants in winter for 1 or 2 years after planting. On the other hand, Guevara *et al.* (2003) found that frost damage reached only 9% in two-year-old plants after freezes of –14.5 and –13.7°C in winter, with no damage on the one-year-old plants when temperatures dropped to –15°C. The severity of frost damage, therefore, also depends on the age of the plants (Wang *et al*., 1997; Guevara *et al*., 2000). The above controversy shows why most researchers argued that cold/frost tolerance of a given species is difficult to assess accurately because it depends on a number of climatic and plant factors (Nobel, 1988, 1991, 2001; Le Houérou, 1994). Although in this study there were a few successive freezing nights in midwinter of temperatures of –0.86 to –3.3°C, –2.08 to –2.67°C, –0.61 to –1.37°C, –0.37 to –4.65°C, –3.15 to –4.79°C, and –0.61 to –0.12°C, for 5 days (7 to 12 May 2002), 2 days (9 to 11 June 2002), 4 days (16 to 20 June 2002), and 6 days (24 to 30 June 2002), respectively, in the 2001/2002 season, all plants suffered no frost damage during this dormancy period (Figure 4). The number of hours of below-freezing weather for midwinter (June and July) for example were 289 (Table 4). In contrast, the incidence of a drop in temperatures of –3.69°C (7 hours at 0°C) and –2.06°C (3 hours at 0°C) on 16 August 2002 and 4 October 2002, respectively, of the same season, when young plants had resumed growth, is believed to have aggravated the degree of damage suffered by plants during springtime (Figure 4 and Table 5). Frost tolerance, therefore, also depends on whether or not plants have been able to become cold-hardened, i.e., whether the freezing temperatures occurred in a gradual way or abruptly (Le. Houérou, 1971; Wang *et al*., 1997), and also the phonological stage of the plants.



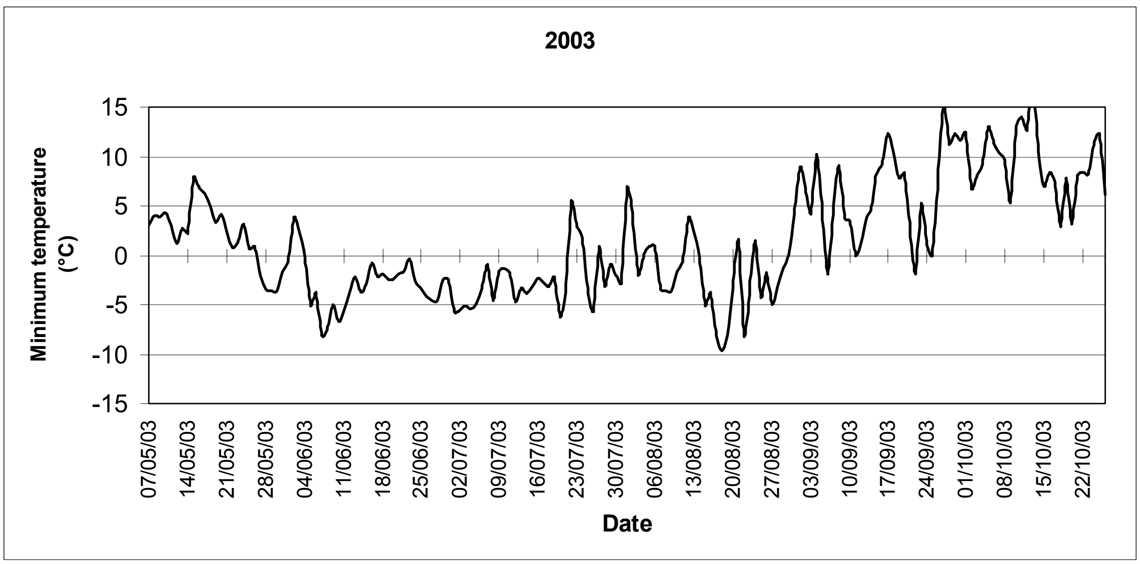


Figure 4. Daily minimum temperatures (^{o}C) for May to October for the 2001/2002 and 2002/2003 seasons.

In *Opuntias*, the lack of freezing resistance is probably not due to the lack of tolerance to cold temperature *per se*, but the range of day to night temperatures, from 28^{o}C down to –12^{o}C in a single day, which does not allow the plant to properly acclimatize (Gregory *et al*., 1993). This is supported by Le Houérou (1994) and Wang *et al*. (1997) who found that the contrast between day/night temperatures can also influence frost tolerance of cactus-pear plants. There may be a difference of 10^{o}C tolerance between 30/30^{o}C and 10/0^{o}C in *O. ficus-indica* (Nobel, 1988, 1991). Therefore, the less frost damage of cladodes in the second observation (4 October 2002) than that for the first one (16 August 2002) could be due to the lower range of day to night temperatures (20^{o}C down to –2.06^{o}C for 4 October 2002, compared with 21^{o}C down to –3.69^{o}C for 16 August 2002, within a single day), as well as the dropping of freezing temperature to –3.69^{o}C and shorter hourly duration of freezing temperatures.

Freezing night temperatures during the midwinter of the 2002/2003 season of –0.61 to –3.55°C for 4 days (27 to 31 May 2003), –0.2 to –8.07°C for 25 days (4 to 30 June 2003), –0.94 to –6.25°C for 20 days (1 to 21 July 2003) caused also no frost damage on any plants (Figure 4). The number of hours of below freezing for midwinter (June and July) were 349. On the other hand, freezing temperatures over several occasions of –3.3 to –9.6°C for 6 days (15 August to 20 August 2003), –9.6°C (3 hours at –9 °C) for 21 August 2003 and –3.3 to –8.1°C (5 hours at –6 °C) for 22 to 27 August 2003 during spring, should have been too much for the young cactus-pear plants to withstand the late-seasonal frost conditions (Figure 4 and Table 5). The ≤–9°C freezing temperatures occurrence for 3 hours in springtime was the lowest over all months and seasons. Nine of the 11 cactus-pear cultivars studied were killed to the ground in the second growing season due to these freezing spring (late-seasonal) temperatures at a time the plants already started sprouting. The remaining two cultivars also suffered high frost damage (Monterey 40% and Zastron 85%) where only some of the mother cladodes survived. The longer duration (43 hours compared to 10 hours below 0°C) and dropping (–9.6°C compared to 3.7°C) in temperatures during springtime of the second season (2002/2003) could be the main reason for the higher frost damage than during the first growing season (2001/2002). There may be up to 6 °C to 10°C difference in the temperature of a killing frost (Le Houérou, 1994). Le Houérou (1994) reported of *O. ficus-indica* killed to the ground at –8.5°C with a 25 °C to 30°C drop in day temperature in less than a week. According to Le Houérou (1994), maximum frost damage occurs when daytime temperature does not rise up to a positive value after a night of frost, and there is thus no thaw (Hastings and Turner, 1965). The absolute minimum temperature cacti can tolerate depends on the difference between maximum daytime and minimum night-time temperatures, both in absolute and relative terms (i.e., whether or not there is a midday thaw) and by the manner in which low temperatures occurred, i.e., suddenly or gradually (Le Houérou, 1996).

The turgescence and water content of leaf tissue and the salt content in the sap (its osmotic potential) and, therefore, the weather conditions (including rains) before the frost, can also negatively influence frost tolerance (Le Houérou, 1983, 1994, 1996). The reason cactus-pear cultivars were killed in the present study can, therefore, be debated because there are successful cactus-pear plantations in the central Free State Province and in the Karoo areas of South Africa. It is also clear from this study that low temperatures did not single-handedly cause the death of the cactus-pear plant. Drought for 4 months (April, May, June, and July) in 2002/2003 growing season could have a bearing on that as well (Figure 3). A long period of drought coupled to successive nights of low temperatures below zero experienced several times during the study (Figure 4), could have been too harsh for the young plants to survive. According to Cui and Nobel (1994) cladode thickness, water content, and water potential all decreased for *O. ficus-indica* during exposure to low temperatures, which could have a detrimental effect on the cold tolerance of the different cactus-pear cultivars in this study. In contrast, Guevara et al. (2000) found no relationship between water content of the cladodes and frost damage. Cui and Nobel (1994) and Han and Felker (1997) also reported of root water uptake decreasing immediately after exposing *O. ficus-indica* plants to lower temperatures. The 4.40 mm rainfall recorded over three months (April, May and June) in the 2002/2003 growing season could have been inadequate to allow young plants to attain full development. That amount of rainfall was far below the long-term levels (77.8 mm) for the same months. Of the 4.40 mm rainfall recorded for three months, 20% was received in April with 80% falling in May. No rainfall was recorded in June and July 2003. The tolerance to freezing temperatures for cactus species of cacti is often also accompanied by loss of tissue water (Levitt, 1980; Teskey *et al*., 1984; Cui and Nobel, 1994). Therefore, significant decreases in cacti cladode water content can occur during exposure to low temperatures (Loik and Nobel, 1991, Cui and Nobel, 1994). Understanding the water budgets of cacti at low temperatures is, therefore, fundamental to understanding their low-temperature tolerance and winter survival, which, in turn, affect their distribution. Unfortunately, water uptake from the soil and plant-water content was not determined in this study as well as the changes in cladode water content after lowering day/night air temperatures for the different cultivars.

When weed control between rows was carried out (3 times over the study period) to remove weeds between the rows, it is believed that the disc implement cut some of the roots. Cut roots were bound to reduce the capacity of the plants to take up water efficiently (Inglese and Pace, 2002). With some roots reduced, young cactus plants could find it hard to survive a long period of drought (Van der Merwe *et al*., 1997; Snyman, 2006a). It is well-known that the cactus-pear plant is shallow-rooted (Nobel, 1995, 2001; Snyman, 2005, 2006b). The cactus-pear roots can spread horizontally up to 4 to 8 m from the mother plant (Sudzuki, 1995; Drennan and Nobel, 1998). According to Ramakatane (2003) and Snyman (2005), the roots can spread as far as 1.5 to 1.7 m from the plant after only the first season of planting. Given the water stress, successive cold spring nights, phonological stage of the plants, and probable cutting of roots by cultivation, it is possible that the plant-available water was inadequate; therefore, the plants stood no chance of survival. The study was planned to continue beyond the third season after establishment but, unfortunately, it had to be terminated when most of the cultivars, except the mother cladodes of some cultivars, died.

5. CONCLUSIONS

It appeared that frost damage in this study only occurred in springtime (August to October) due to successive nights of freezing temperatures (between –2.06 and –9.6°C, and 53 hours below freezing) when the plants already started sprouting. On the other hand, the plants suffered no frost damage during the dormant midwinter period when temperatures dropped to –8.1°C over several occasions, also with a very high number of hours below 0°C. It was also clear that a combination of late-seasonal temperatures and soil-water stress could be detrimental to young cactus-pear plants. Optimal plant development, as influenced by soil fertility, could also play a negative role in its frost sensitivity, as well as the phonological stage of the plants. Most researchers only reported of frost damage during midwinter. Further research work is necessary to improve cold resistance characteristics in adapted cactus-pear cultivars. It would, therefore, be wrong to conclude that cactus-pear plantations cannot be successful in the studied area or similar cold areas, for there are a lot of successful fodder and fruit plantations of cactus pear in the Free State Province of South Africa. The success of cactus pear (especially young plants) is a function of both management and climatic conditions. It can be concluded that late-spring freezing temperatures may not have been directly responsible for 100% mortality of the cactus-pear plants, but factors like water stress, plant health, and phonological plant stage could also have a bearing on that. Perhaps the whole dynamics of cactus-pear plant development and adaptability are still not properly understood.

Because there has been an increasing interest in cactus pear for both fodder and fruit production over the last few years, more research needs to be carried out on the evaluation of different cultivars under different environmental conditions. Cactus pear is a multipurpose crop, which can be of great value in both developed and developing countries because of its ability to utilize the full potential of arid areas. The full potential of cactus pear has not, however, been realized in southern Africa. Spineless cactus pear in South Africa is increasingly commercialized and there is a need to establish a database to assist the South African farmers in the selection of cultivars for production under different climatic conditions.

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